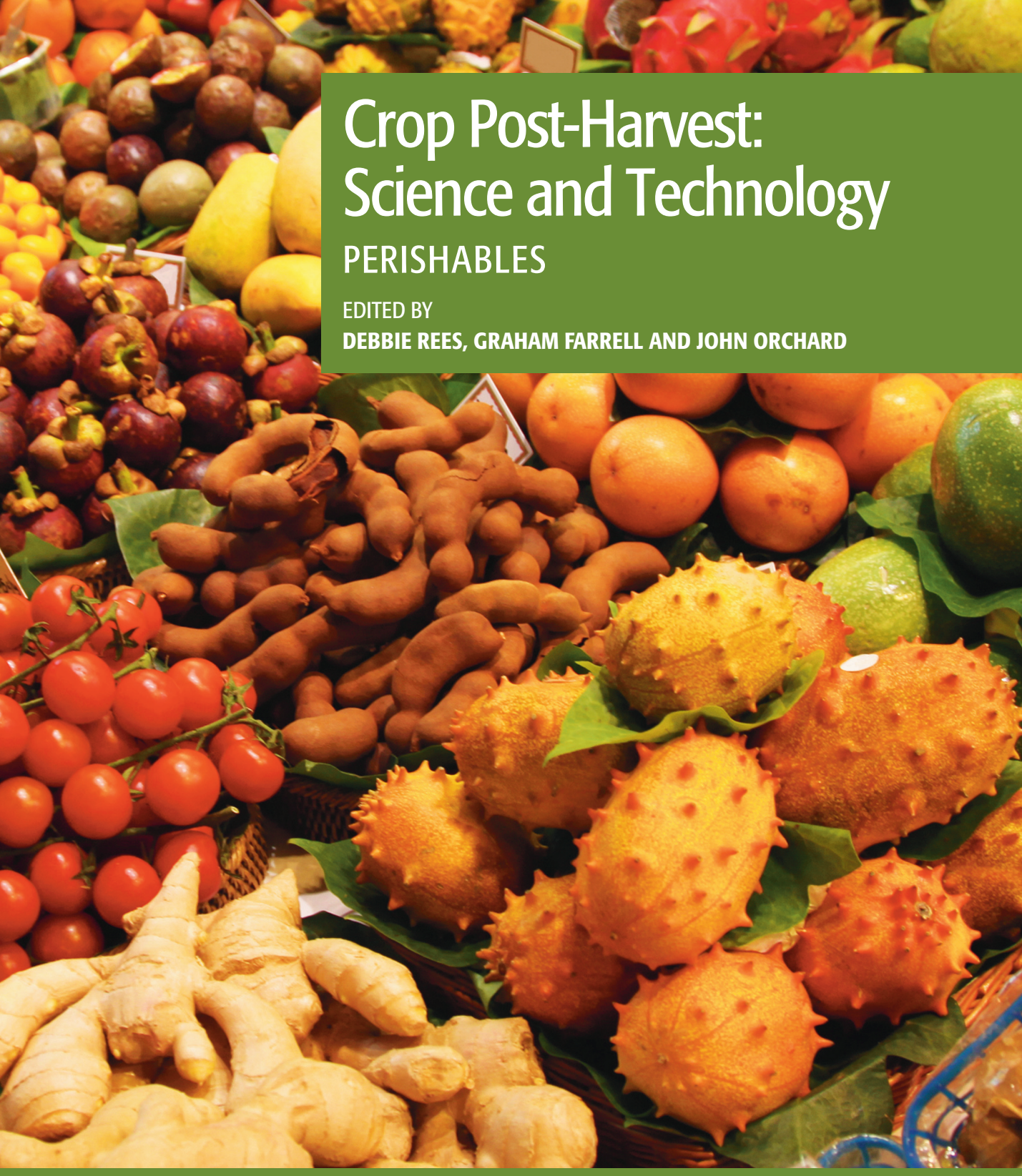

# Crop Post-Harvest: Science and Technology

## PERISHABLES

EDITED BY

**DEBBIE REES, GRAHAM FARRELL AND JOHN ORCHARD**

WILEY-BLACKWELL

the UNIVERSITY of GREENWICH
Natural Resources Institute

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# 1
# Introduction

*Debbie Rees*

## PERISHABLE PLANT PRODUCTS

The storage and transport of food are central to the way in which human civilisation has developed. Fifteen million years ago our human ancestors moved from living in tropical rain forests to savannah. One of the reasons that this migration was possible was that at the same time the human diet changed to include seeds and nuts, and our human ancestors learnt how to store these between seasons (Kays 1991). Seeds (grains) and nuts are often referred to as *durables* as they are less perishable than other food products and can be relatively easily stored. They are generally plant parts that have a physiological role that requires them to keep over extended periods of time; thus seeds may remain dormant over a considerable time before they sprout to form a new plant. Durables are distinguished from the *perishable* plant products by characteristics such as high dry matter content and hard texture, and they tend to be small and homogeneous in shape. Perishable plant products, on the other hand, have high moisture content and tend to be softer so that they are more susceptible to physical damage. Perishable plant products include fleshy fruits (apples, tomatoes bananas, mangoes), root crops (potatoes, cassava, sweet potato, yam, onion), leafy vegetables (cabbage, spinach, lettuce), and vegetables arising from stems (celery).

There is a wide range in storability among the perishables once they have been harvested. Root crops (storage roots and tubers) tend to be the least perishable. This is consistent with their physiological purpose to survive between growing seasons in order to produce a new plant. Fruits and flowers, on the other hand, are very perishable, often with a potential storage life of only a few days. As far as the plant is concerned, their physiological role is transient; once it is complete the tissues die, usually through the process of *senescence*, an active, programmed cell death. Leafy vegetables are very prone to water loss once they have been separated from the plant roots, which normally act as their source of water.

When considering the main constraints to storage for durable and perishable plant products, pests and diseases are very important for durables, whereas maintenance of quality in perishable products is very dependant on the physiological health of the plant tissues.

## FRUITS

Given their key importance in world economy, a large part of this book is devoted to fleshy fruits. Over the decades, as our understanding of their development and its control has increased, fruits have been classified into two types depending on the biological control of ripening, specifically the role of the plant hormone ethylene, and the respiratory characteristics (Rees & Hammond 2002).

### The classification of fruit into climacteric and non-climacteric

Biologically fruits are classified as *climacteric* or *non-climacteric* according to their respiratory behaviour and ethylene production rates during ripening. The volatile plant hormone, ethylene, stimulates a wide range of plant responses including fruit ripening (Oetiker & Yang 1995; Rees & Hammond 2002).

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Climacteric fruits are those whose ripening is accompanied by a distinct increase in respiratory rate (climacteric rise) which is generally associated with elevated ethylene production just before the increase in respiration. After the climacteric rise, ethylene production declines significantly. Ethylene is necessary for the co-ordination and completion of ripening.

Non-climacteric fruits are those that do not exhibit increases in ethylene and respiration, but rather undergo a gradual decline in respiration during ripening.

It is a general rule that climacteric fruit can be picked mature but unripe, and can then be ripened off the plant, whereas non-climacteric fruit will not ripen once picked. However, even in non-climacteric fruit the quality can change after harvest in such a way as to make the fruit more palatable. For example, pineapples will soften after harvest. Non-climacteric fruit such as pineapples and oranges can be artificially de-greened by the application of ethylene.

In the case of some fruit, the classification as climacteric or non-climacteric is not straightforward, and is still a matter of debate. For example muskmelon was originally thought to be climacteric, but is now considered by some scientists as non-climacteric (Obando *et al*. 2007). Several scientific papers have been published on guava; some scientists conclude that it is non-climacteric, and others that it is climacteric, while a few scientists suggest that varieties may differ in their classification (Brown & Wills 1983; Reyes & Paull 1995).

Table 1.1 lists a range of climacteric and nonclimacteric fruit. Examples of both classifications of fruit are considered in the following chapters within this book.

**Table 1.1** Classification of Fruit into Climacteric and Non-climacteric.

| Climacteric fruit | Nonclimacteric fruit |
|---|---|
| Apple | Blackberry |
| Apricot | Cherry |
| Avocado | Grape |
| Banana | Grapefruit |
| Cherimoya | Lemon |
| Kiwifruit | Lime |
| Mango | Longan |
| Nectarine | Loquat |
| Papaya | Lychee |
| Passion fruit | Mandarin |
| Peach | Muskmelon |
| Pear | Orange |
| Pepper (chilli) | Pepper (bell) |
| Persimmon | Pineapple |
| Plum | Pomegranate |
| Quince | Prickly pear |
| Sapodilla | Rambutan |
| Sapote | Strawberry |
| Tomato | Tamarillo |
| | Watermelon |

Source: Information collated from UC Davis (2011).

## NUTRITIONAL QUALITY OF PERISHABLE PLANT PRODUCE

Perishable plant products are extremely important for human nutrition. Root and tuber crops act as staples in many parts of the world. Overall, perishable produce is vital as a source of essential fatty acids, amino acids, vitamins and minerals. The contribution to human nutrition of individual commodities is addressed within the individual chapters, as well as being thoroughly reviewed in Terry (2011).

## POST-HARVEST TECHNOLOGY AND THE EXPANSION OF INTERNATIONAL TRADE IN HIGH-VALUE PERISHABLES

International trade in high-value perishables has grown enormously in the past few decades. In the developed world, consumers now expect to be able to eat perishable produce from all parts of the world, and in most cases throughout the year. Examples of the magnitude of international trade are given in the following chapters of this book. This trade is an important source of income for many, and is becoming increasingly important as a source of revenue for many tropical developing countries. This trade is possible only through the development of technologies for extending the storage life of perishable plant products. Some of the most important technologies are summarised below.

### Development of the cold chain

Temperature control is probably the single most important factor in the extension of storage life of perishable products. Generally a decrease in temperature slows metabolism and development. However, for all commodities there is a temperature below which tissue damage occurs. This varies by commodity, from −1°C for certain temperate commodities, such as pears, to 15°C for tropical products, such as bananas and sweet potato.

It is now appreciated that very significant quality improvements can be achieved by considering cooling immediately after harvest, and maintaining appropriate temperature through the whole handling chain. In developed countries this can extend even into the consumer's home, as the use of domestic refrigerators becomes more widespread. The

control of temperature through the whole handling chain is often referred to as the *cold chain*.

### Controlled atmosphere storage and modified atmosphere packaging

As well as by lowering the temperature, metabolic processes and development of perishable plant produce can also be slowed down through modification of the storage environment, usually by decreasing oxygen concentration, sometimes with an associated increase in carbon dioxide concentration. In some cases the atmospheric concentrations are closely controlled throughout the storage period (*controlled atmosphere storage*), and in other cases, after an initial modification period, the atmosphere may be allowed to alter through respiration of the commodity itself (*modified atmosphere storage*). Modified atmospheres may be used on a scale as large as a container or pallet (100s–1000s kg), or down to the scale of individual consumer packs (< 500 g). The technologies and how they are applied to a wide range of perishable plant products are thoroughly reviewed by Thompson (2010).

### Ethylene control technologies

The importance of ethylene control for maintenance of quality in perishable plant products is now widely recognised, and is discussed for the individual commodities in the following chapters within this book.

Ethylene gas ($C_2H_4$) is produced naturally by most plant tissues, especially ripening fruit. It is a plant hormone that controls many biological processes. Ethylene is a gas at ambient temperatures, so that if one plant or plant organ starts to produce ethylene, nearby plant tissues are also affected. For plants many processes involving tissue death, such as leaf drop in deciduous trees, petal drop in flowers and over-ripening of fruit, are actively controlled as part of the natural life cycle, and are controlled or stimulated by ethylene. For this reason, during handling of fresh produce exposure to ethylene can speed up deterioration.

As it controls so many processes associated with the quality of fruit and vegetables, ethylene is an extremely important chemical for the fresh produce handling industry. On the one hand, it is used to trigger ripening in fruits. Thus bananas are transported green to the United Kingdom and are then stimulated to ripen by being fumigated with ethylene within warm ripening rooms. On the other hand, as set out above ethylene will stimulate deterioration and senescence. Ethylene control strategies are therefore key for maintenance of quality.

The concentrations at which ethylene can affect produce are very low. There is evidence that many products are sensitive to concentrations well below 100 parts per billion (ppb). In the United Kingdom, ethylene is known to build up in packhouses to concentrations near 1000 ppb (= 1 part per million [ppm]) (Rees, n.d.), which is above the threshold of sensitivity of most produce. A study conducted on a range of perishable produce showed a 60% extension of post-harvest life when stored in <5 ppb compared with 100 ppb ethylene (Wills *et al*. 1999).

The biochemistry of how ethylene controls plant processes is complex (for an introduction, see Rees & Hammond 2002). Processes controlled by ethylene can be classified into two types, System 1 and System 2.

In System 1 ethylene stimulates the process. If ethylene concentrations are increased the process goes faster, and if ethylene concentrations are reduced or ethylene is removed completely then the process slows or stops. This is the case for ethylene stimulation of the deterioration or senescence of vegetables, the ripening of nonclimacteric fruit, the over-ripening or senescence of fruit (both nonclimacteric and climacteric), and the discolouration of cucumber and browning of broccoli.

In System 2 ethylene acts as a switch that cannot be stopped. Thus, ethylene triggers the process. If ethylene levels are reduced or ethylene is removed completely, then the process continues. This is the case for the initiation of ripening of climacteric fruit.

#### *1-Methylcyclopropene*

An important development in the management of ethylene during post-harvest handling of fresh produce was the discovery of the chemical 1-methylcyclopropene (1-MCP). 1-MCP acts as an ethylene antagonist by binding ethylene receptors within the cells of the plant tissues and thereby blocking the ethylene response. Other ethylene antagonists such as silver thiosulphate and ethylene synthesis inhibitors such as aminoethyoxyvinylglycine (AVG) were already known. However, 1-MCP has turned out to be an extremely useful chemical both as a tool to investigate ethylene physiology and as a commercial post-harvest treatment to counteract ethylene effects and extend shelf life (for a review, see Blankenship & Dole 2003). The use of 1-MCP for the handling of individual commodities is discussed in many chapters of this book.

## POST-HARVEST TECHNOLOGY, FOOD SUPPLY AND INCOME GENERATION IN DEVELOPING ECONOMIES

Many of the technological advances in the post-harvest handling of perishable commodities rely on a level of infrastructure that is not present in many parts of the developing

world. Thus in many places it is not possible to implement low-temperature storage, due to absence of electricity or lack of capital funds. However, even without such facilities an increase in our understanding of the behaviour of perishables allows the development of low-cost technologies that can extend storage life significantly. This is illustrated in particular by some of the storage technologies described in Chapter 18 ('Tropical Root Crops'). In some cases the efficacy of simple storage technologies can be improved where simple coverings allow modification of the storage atmosphere by product respiration. An appreciation of the effects and causes of physical damage allows the selection of appropriate packaging material to reduce damage during transport.

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# 2
# Tomatoes

*Elhadi M. Yahia and Jeffrey K. Brecht*

## INTRODUCTION

### Origin

The wild tomato, *Solanum lycopersicum* L., is native from the coastal plain to the foothills of the Andes of western South America, centred in Peru and extending north to central Ecuador and south to northern Chile (Peralta *et al*. 2005). It was later distributed by indigenous peoples into what are now Mexico, Colombia, Bolivia and other South American countries (Rick & Holle 1990). Currently, this species is known only from cultivation and escapes and is grown worldwide from sea level to 4000 meters. A number of other related species are also found in the same area of South America, several of which, such as *S. pennellii*, *S. cheesmaniae* and *S. pimpinellifolium*, are able to cross-pollinate with *S. lycopersicum* (Stevens & Rick 1986).

### Types of tomatoes

The tomato fruit is a berry consisting of two to several carpels with seeds borne on placental stalks within locules and surrounded by the locular gel, all contained within a fleshy pericarp (Figures 2.1 and 2.2). Modern commercial tomato types for fresh and processed use are mostly red and include a variety of different fruit types from small, 'cherry' and 'grape' tomatoes so named due to their similarity in size and shape to those fruits, to large, round tomatoes, pear-shaped tomatoes and oblong 'roma' or 'plum' tomatoes. Tomato varieties are bred specifically for consumption as either fresh tomatoes or processed tomato products. Processing requires varieties that contain higher dry matter content than varieties for the fresh market.

### Worldwide importance

The cultivated tomato that was carried by Spanish explorers from Mexico to Europe in the early sixteenth century was a rough-skinned, small-fruited type, and the earliest written account of it in Europe by Matthiolus in 1544 describes a round, yellow fruit (Gould 1992). The tomato slowly gained favour over succeeding centuries, but by the eighteenth century breeding of new cultivars in Europe was well underway. Tomatoes are now one of the leading horticultural crops worldwide in terms of value and amount consumed. The FAO reports world production of tomatoes in 2009 as 152 956 115 tonnes, with China, the United States, India, Turkey, Egypt and Italy the top six producers, respectively (FAOSTAT 2009). In the United States more than 80% of the tomatoes grown are consumed as processed tomato products (USDA ERS 2006). The fresh fruit is very sensitive to improper handling, storage and shipping conditions, and therefore proper pre-harvest and post-harvest handling are critical for high product quality, a prerequisite to successful marketing (Yahia *et al*. 2005).

## POST-HARVEST PHYSIOLOGY AND FRUIT QUALITY

### Ethylene and fruit ripening

Tomato fruit show a climacteric pattern of respiration, and therefore ripening can be initiated before or after harvest. Ethylene plays an important role in the ripening of tomatoes (Andrews 1995; Lelievre *et al*. 1997). Ethylene

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**Figure 2.1** Tomato fruit on the vine. Photo credit: J.K. Brecht, University of Florida.

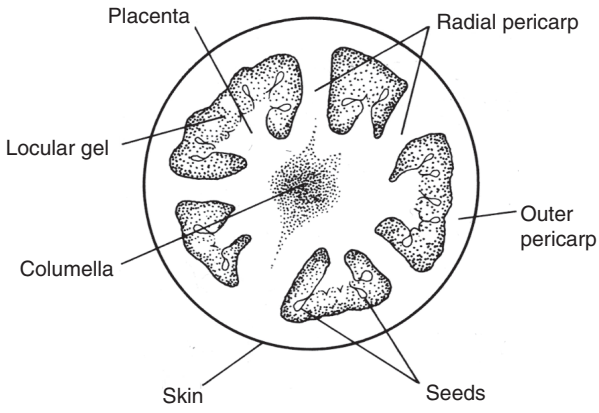


**Figure 2.2** Anatomical structure of a tomato fruit. Photo credit: J.K. Brecht, University of Florida.

production is generally high at the time of anthesis and for a short time after this. It then declines to a low level (less than 0.05 nl $g^{-1}$ fruit $h^{-1}$) during later fruit growth but increases significantly during ripening. At the onset of the respiratory climacteric, production is around 2–10 nl $g^{-1}$ fruit $h^{-1}$ (Grierson & Kader 1986). A transition of the ethylene production feedback mechanism from negative auto-inhibition to positive autocatalysis has been demonstrated in tomato fruit to occur only with ripening initiation and progress, and is responsible for the climacteric behaviour of tomato fruit (Atta-Aly *et al*. 2000). Ripening (and ethylene production) is initiated in mature-green tomatoes in the locular gel coincident with the disintegration of that tissue, the cell walls of which are completely degraded (Plate 2.1; Brecht 1987). From there, ripening proceeds through the placenta to the columella (core), with the first visible sign of ripening being the appearance of red (or yellow or orange) pigmentation at the distal or blossom end of the fruit, at which point the fruit is said to be at the 'breaker' stage. Ripening then progresses toward the proximal (i.e. stem) end of the fruit until the entire fruit attains its final, fully ripe colour (Plate 2.2).

Ripening of mature-green tomatoes (see Table 2.1) is accelerated by exposure to ethylene at concentrations >0.05 µl $l^{-1}$ (Wills *et al*. 2001). However, at the breaker and later stages of ripeness, tomato fruit are not affected by ethylene exposure as enough ethylene is produced endogenously to saturate the ripening processes. Therefore, exogenous ethylene removal is most effective at the mature-green stage for delaying ripening. Greenhouse tomatoes are usually harvested at breaker or later ripeness stages. Supplemental ethylene does not provide any benefits because the ripening process will continue with ethylene produced by the fruit. Tomatoes should not be stored or shipped with other products that are maintained at lower temperature and/or lower relative humidity, and those that are sensitive to ethylene. Mixed loads of tomatoes with ethylene-producing fruits such as bananas and apples can accelerate the ripening of tomatoes.

It has been suggested that ethylene acts as a rheostat rather than as a trigger for fruit ripening, which implies that ethylene must be present continuously in order to maintain transcription of the necessary genes (Theologis 1992). Therefore, interfering with ethylene biosynthesis or perception may affect the progression of ripening at any stage. Indeed, 1-methylcyclopropene (1-MCP), a potent inhibitor of ethylene action, delayed colour development, softening and ethylene production in tomato fruit harvested at the mature-green, breaker and orange stages (Hoeberichts *et al*. 2002). Ripening of mature-green tomatoes held at 20°C in air containing 0.1 µl $l^{-1}$ ethylene was substantially delayed by exposure to 1-MCP in the concentration range 0.1–100 µl $l^{-1}$. The delay was directly related to the concentration of 1-MCP and the exposure time. Exposure to 5 µl $l^{-1}$ 1-MCP for one hour resulted in about a 70% increase in the time to ripen, and is a good potential commercial treatment (Wills & Ku 2002). 1-MCP-treated fruit showed a reduced loss of titratable acidity during ripening, which resulted in a lower Brix:acid ratio compared to untreated fruit. 1-MCP applied to ripe tomatoes for two hours at 5–100 µl $l^{-1}$ resulted in an increase in post-harvest life based on fruit appearance, with exposure to 20 µl $l^{-1}$ giving a 25% increase in post-harvest life (Wills & Ku 2002).

**Table 2.1** Ripeness Classes of Tomatoes.

| Class | Description* |
|---|---|
| Immature-green | The surface is completely light to dark green. There is no jelly-like material in any of the locules, and the seeds are cut upon slicing the fruit with a sharp knife. |
| Mature green | Seeds are fully developed and are not cut upon slicing of the fruit. Jelly-like material is formed in at least one of the locules. This is the minimum stage of harvest maturity. |
| Breaker | Tomatoes at this stage are characterised by a definite break in the colour from green to tannish-yellow, pink or red on not more than 10% of the surface. |
| Turning | More than 10% but not more than 30% of the surface, in the aggregate, shows a definite change in colour from green to tannish-yellow, pink, red or a combination thereof. |
| Pink | More than 30% but not more than 60% of the surface, in the aggregate, shows pink or red colour. |
| Light-red | More than 60% of the surface, in the aggregate, shows pinkish red or red colour, provided that not more than 90% of the surface is red colour. |
| Red | More than 90% of the surface, in the aggregate, shows red colour. |

*All percentages refer to both colour distribution and intensity.

As mentioned above, the initiation of ripening can be accelerated in preclimacteric tomatoes by exogenous ethylene exposure. Commercial ripening of mature-green tomatoes may involve post-harvest application of ethylene to ensure uniformity in ripening and colour development. This is commonly done for domestic marketing and also when tomatoes are to be shipped long distances internationally, in order to better manage and control the ripening process. Maximum ethylene concentration should be between 100 and 150 ppm for rapid and uniform ripening. Duration of the ethylene treatment period is 24 to 48 h, depending on temperature, ethylene concentration and desired speed of ripening (Blankenship & Sisler 1991) – the need for longer ethylene exposure to initiate ripening indicates that the tomatoes were harvested immature. Good air circulation is needed to ensure uniform temperature throughout the room and to prevent $CO_2$ accumulation. The latter is because $CO_2$ at >2% will inhibit ethylene action and therefore will slow down or inhibit ripening. Adequate air exchange in ripening rooms is important to reduce the development of off flavours (Grierson & Kader 1986). Mature-green tomatoes ripened with ethylene at 20°C had more ascorbic acid content at the table-ripe stage than those ripened without added ethylene simply because the ethylene-treated fruit reached the red, fully ripe stage faster than fruit that were not exposed to ethylene (Kader *et al*. 1978c; Watada *et al*. 1976).

## Physiological disorders

The following is a brief description of various fruit disorders related to pre-harvest factors.

### *Blossom-end rot*

Blossom-end rot (BER) is a physiological disorder that causes extensive losses in production (Dorais *et al*. 2001). This disorder develops as a visible external depression of necrotic tissue (Plate 2.3) affecting the distal end of the placenta and the adjacent locular contents as well as the pericarp (Willumsen *et al*. 1996). In internal BER, also called 'black seeds', black necrotic tissue develops in the adjacent parenchyma tissue around young seeds and the distal part of the placenta (Adams & Ho, 1992). BER is believed to be caused by fruit calcium deficiency or stress (Saure 2001). Fruit susceptibility is related to lack of coordination during fruit growth between cell enlargement and calcium supply. The development is also positively correlated with the leaf K:Ca ratio, but is weakly correlated to the K:Ca ratio in mature fruit (Bar Tal & Pressman 1996). Factors affecting BER include daily irradiance, air temperature, water availability, salinity, nutrient ratios in the rhizosphere, root temperature, air humidity and xylem tissue development in the fruit. Several strategies have been suggested to avoid this disorder (Dorais *et al*. 2001), including (1) the use of resistant cultivars; (2) optimizing calcium and phosphate supply; (3) maintaining a dynamic balance between calcium and potassium and between nitrate and ammonium that will ensure sufficient calcium uptake; (4) the use of irrigation water or nutrient solution with low electrical conductivity (EC); (5) optimizing irrigation frequency; (6) avoiding high root temperature (>26°C); (7) avoiding excessive canopy transpiration by leaf thinning, shading, roof sprinkling and greenhouse fogging; (8) maintaining proper fruit:leaf ratios that can provide

adequate fruit growth rate and (9) spraying of young expanding fruit with 0.5–0.65% calcium chloride solution.

***Blotchy ripening***

Blotchy or irregular ripening is characterized by green and green-yellow areas on apparently normal red, ripe fruit (Plate 2.4). It is usually confined to the outer pericarp walls, but in extreme cases radial walls can also be affected. Blotchy areas of fruit walls contain less organic acids, dry matter, total solids, starch, sugars and nitrogenous compounds. Low potassium (Adams *et al*. 1978) and high fruit temperature (a temperature of >30°C affects pigmentation) are believed to be related to blotchy ripening. The cause of blotchy ripening is not fully understood, but is thought to be related to low light intensity, cool temperatures, high soil moisture, high nitrogen and low potassium or combinations of those factors. Tomato varieties differ in their susceptibility to this disorder.

***Cracking and russeting***

Tomato cracking can cause up to 35% losses in North American greenhouses (Dorais *et al*. 2001). Greenhouse tomatoes are more vulnerable to fruit cracking compared to field-grown tomatoes because greenhouse tomatoes are usually harvested later at the pink stage or beyond, and most greenhouse tomato cultivars lack cracking resistance. Fruit cracking not only reduces fruit appeal and marketing, but also can increase fruit susceptibility to decay and shorten shelf life. Cracking and splitting of tomatoes are usually initiated before harvest, generally about seven weeks after fruit set (Bakker 1988). Several types of cracking are known to affect tomatoes, including cuticle cracking (russeting), fruit bursting, radial cracking and concentric cracking. Cuticle cracking, fine cracks on the skin which impair quality and reduce shelf life, is the most common type in greenhouse tomatoes (Dorais *et al*. 2001). Cuticle cracks are usually initiated as small fissures in the outer epidermis and occur at right angles to the direction of expansion of the epidermal cells. In later stages, the complete epidermis and part of the underlying collenchyma tissue break down. Russeting was suggested to occur because the expansion of the epidermis could not keep pace with fruit enlargement. Higher numbers of fruit per plant decrease the incidence of cuticle cracking by increasing the competition among fruit for carbohydrates, and reducing the supply of sugars and water to the fruit. A fruit:leaf ratio of 1.24:1 to 1.28:1 is considered optimal for controlling russeting (Dorais *et al*. 2001).

The intensity of fruit cracking depends on cultivar, time of the year and environmental conditions. Fruit cracking is generally associated with the rapid movement of water and sugars towards the fruit when cuticle elasticity and resistance are weak (Dorais *et al*. 2001); there are differences in cultivar susceptibility, but the problem can be reduced by adequate calcium nutrition and avoidance of drought stress (Hao *et al*. 2000a). Fruit with high soluble sugar content is more susceptible to cracking, due to the greater pressure applied against the cuticle. Another cause for cracking is imbalance between the supply and loss of water, and therefore cultivars with a highly developed system of vascular tissue are more resistant to cracking (Cotner *et al*. 1969). Gibberellic acid application was reported to reduce tomato fruit cracking (Peet 1992). This effect is probably due to alteration of the calcium dynamics at the level of the pericarp (Bush *et al*. 1989), and an increased elasticity of the cuticle (Larson *et al*. 1983).

***Greenback or green shoulder***

This is a different disorder from blotchy ripening. The symptom is characterised by a persistent, firm green area around the calyx end due to undegraded chlorophyll, while the rest of the fruit is ripe and red in colour. The green area may turn yellow and thus be called ‘yellowback’ or ‘yellow shoulder’. This is generally thought undesirable, but in some countries such as Cuba and Taiwan it is actually preferred by some consumers. This disorder is genetically controlled and can be abolished by incorporating the ‘uniform ripening’ gene (Grierson & Kader 1986).

***Gold fleck, gold speckle or pox syndrome***

These are tiny, yellowish spots of less than 0.1 mm across occurring immediately below the epidermis, visible on ripe fruit and mostly affecting the proximal half of the fruit (Ilker *et al*. 1977). The disorder is associated with the formation of calcium oxalate crystals in the affected cells (De Kreij *et al*. 1992). This disorder affects the external appearance of the fruit (Goossens 1988), and it reduces its shelf life (Janse 1988) due to the eventual development of tan, ruptured, necrotic lesions (Ilker *et al*. 1977). Symptoms are commonly affected by those factors of cultivar, nutrition and growing environment that favour calcium transport to the fruit.

***Hollowness, puffiness or boxiness***

This disorder is characterised by lack of gel tissue surrounding the seeds, and open cavities between the outer pericarp walls and the locular contents in one or more locules (Plates 2.5a, b) (Grierson & Kader 1986). The affected fruit tend to be light in weight and become soft, and can be detected by flotation in water. The symptoms

commonly develop in early spring greenhouse crops, mostly due to low light intensity and inappropriate mineral nutrition, which reduce the carbohydrate supply to fruit.

***Solar injury (sunscald, sunburn or sunscorch)***

This is a common form of heat injury. When tomatoes are exposed to direct solar radiation, fruit temperature may increase by 10°C or more above the ambient (Grierson & Kader 1986). If the fruit temperature exceeds 30°C for a long period, the affected part of the fruit becomes yellowish and remains so during ripening (Plate 2.6). When the temperature of an exposed fruit portion exceeds 40°C, it becomes white and sunken. Tomatoes at the mature-green stage are especially susceptible. Affected areas may later develop *Alternaria* and *Cladosporium* rots.

***Watery fruit***

This disorder results from a massive influx of water into the fruit, due to excessive root pressure, which can increase the volume of the cells and may even damage them (Dorais *et al*. 2001). This disorder reduces the organoleptic quality and the shelf life of the fruit. Preventative measures include avoidance of over-irrigation before the end of the day, the development of a strong root system and the reduction of root pressure by maintaining the plant leaf area index at a reasonable level during summertime.

***Chilling injury***

Tomato plants and fruit in the field are subject to chilling injury at temperatures below 10°C (Barger *et al*. 1952; Morris 1953), but chilling injury is not normally a serious pre-harvest problem because tomatoes are typically grown in areas and seasons in which chilling temperatures are not normally encountered. In addition, tomatoes can tolerate significantly lower night temperatures because of the rewarming that occurs during the daylight hours. It has been reported that tomatoes harvested in the morning when cool are more chill resistant during storage than if harvested in the afternoon when warm (Saltveit & Cabrera 1987). If daily high temperatures remain below the chilling threshold temperature for some time, however, then pre-harvest chilling may occur. Morris (1954) showed that susceptibility of tomato fruit to post-harvest chilling injury was correlated to the number of hours below 15.6°C during the week before harvest.

**Quality components and indices**

Tomatoes are commonly selected by consumers on the basis of appearance, but repeated purchase will depend on flavour and quality (taste, texture, nutritional value and food safety). The most commonly used appearance quality indices include: (1) uniform colour: orange-red to deep red, and no green shoulder; (2) uniform shape depending on type: round, globe, flattened globe or oblong and (3) freedom from defects such as stem-end scars, growth cracks, sunscald, catfacing (Plate 2.7), insect injuries, bruises and mechanical injury.

High-quality tomatoes should have red colour, firm but juicy texture and good taste and flavour. High sugars and relatively high acids will result in good flavour, while low sugar content and low acids will result in poor flavour (Malundo *et al*. 1995; Stevens *et al*. 1979). Gel formation in the locules of the tomatoes is important for good flavour. Although appearance quality is important, increasing attention is given to other quality components such as flavour and nutritional aspects. Tomato quality components are influenced by genetic and environmental factors (temperature, light, nutrients, water supply, etc.) and post-harvest handling (Brecht *et al*. 1994; Soto-Zamora *et al*. 2000).

***Colour***

Colour is one of the most important quality components of horticultural crops. Tomato fruit are available in different colours including red, pink, yellow and orange. External colour of tomato fruit is the result of both flesh and skin colours. A pink tomato may be due to colourless skin and red flesh, while an orange tomato may be due to yellow skin and red flesh. Chlorophyll in green fruit is replaced in ripe tomatoes by oxygenated carotenes and xanthophylls, the most abundant of which are lycopene (red) and its precursor phytoene (colourless). Lycopene is responsible for the red colour of tomatoes and is important for human health due to its antioxidant activity. Therefore, its degradation is important from the standpoint of both sensory quality and health. Lycopene in fresh tomato fruit occurs mostly in the all-trans configuration, and the main causes of its degradation during processing are isomerization and oxidation (Shi & Le Maguer 2000). Isomerisation converts all-trans isomers to *cis*-isomers due to additional energy input, and results in an unstable, energy-rich state.

The lycopene content of fresh tomato fruit is usually about 30–50 $mg\,kg^{-1}$, while deep red varieties contain more than 150 $mg\,kg^{-1}$, and yellow varieties contain only about 5 $mg\,kg^{-1}$ (Hart & Scott 1995). Tomato lycopene synthesis is favoured by constant exposure to temperatures from 12°C to 21°C and is inhibited at temperatures above 30°C (Tomes 1963). The amount of lycopene in fresh tomato fruit depends on the variety, ripeness stage and environmental conditions under which the fruit ripened. Higher concentrations of lycopene and other

carotenoids were found in the stem end than in the blossom end of the fruit (Ellis & Hammer 1943). Lycopene concentration in tomatoes was higher in summer than in the winter (Heinonen *et al*. 1989). Tomatoes picked green and ripened in storage usually have lower levels of carotenoids than vine-ripened fruit (Gould 1992), probably because the fruit ripened in storage are not exposed to the most conducive temperatures for pigment synthesis. Colour development may also be limited by environmental conditions when tomatoes are ripened on the plant (Brandt *et al*. 2006), but post-harvest conditions can be optimised to favour lycopene synthesis. Lycopene formation is promoted by ethylene (Jeffery *et al*. 1984) and is inhibited by ethanol (Saltveit & Mencarelli 1988). Lycopene content in tomato can also be enhanced by fertilisers, proper harvest time, and varietal selection (Lampe & Watada 1971; Mohr 1979).

Several subjective scales and colour charts have been developed to classify ripeness according to fruit colour (Plate 2.2). There are six classes of tomato ripeness beginning with mature green that are recognised and used almost all over the world (Table 2.1). Objective measures of tomato colour are also available, including light reflectance and light transmittance techniques and chemical pigment determination (chlorophyll, lycopene, β-carotene). An estimation of lycopene content was correlated with colour measurements ($a^*$, $a^*/b^*$, and $[a^*/b^*]^2$) using a portable chroma meter (Arias *et al*. 2000).

***Size and shape***

Fruit size is also important, but preference for different sizes varies among cultivars, among consumers and according to the intended use of the fruit. Fruit shape varies between cultivars, which can be spherical, oblate, elongated or pear-like. Shape has no direct effect on fruit ripeness and flavour. However, an angular shape is undesirable because it reflects immaturity or puffiness (Plates 2.5 a, b; Kader 1984). Shape defects are commonly due to poor pollination and irregular development of some locules. These defective fruit are commonly discarded during harvest or during packinghouse grading operations. Minor defects that would not detract from eating quality are commonly considered to be acceptable. However, serious defects can detract from quality, cause shrivelling and enhance susceptibility to decay (Bender *et al*. 1992). Some of the defects that are known to occur before harvest include sunscald, insect damage, puffiness, catfacing (a puckered malformation with brown scarring at the fruit blossom end; see Plate 2.7), goldfleck or pox syndrome, radial and concentric growth cracks and irregular ripening. Several defects can occur after harvest due to mishandling (Plate 2.8) such as scuffing, cuts and punctures, vibration and compression injuries, abrasions and decay development (Olorunda & Tung 1985). Physical damage can also increase ethylene production (MacLeod *et al*. 1976) and therefore can accelerate fruit ripening and favour decay development.

***Dry matter content***

Dry matter represents about 5–7.5% of tomato fruit, of which about 50% is reducing sugars while protein, pectins, celluloses, hemicelluloses, organic acids, pigments, vitamins, lipids and minerals represent the remaining half (Petro-Turza 1986). Fruit with high dry matter content usually also have higher content of soluble solids, mostly consisting of sugars and acids, and thus have better taste and flavour (Hao *et al*. 2000b).

***Firmness***

Tomato firmness is closely related to quality and ripeness, and it is important in determining shipping ability and post-harvest life. Tomato fruit that can maintain good firmness beyond the table-ripe stage can be picked at a more advanced ripeness stage, and therefore can develop better flavour. The preference is for tomato fruit that are firm and without tough skin, and that do not lose too much juice upon slicing. Several factors can affect tomato firmness including cultivar, water content and turgor, cell wall composition and integrity, ethylene, temperature, relative humidity, irrigation and mineral nutrients. Objective measurement of tomato firmness can be destructive using resistance to force of penetration (fruit firmness testers, penetrometers), shearing (shear press), cutting, compression or their combination (Barret *et al*. 1998). A nondestructive method that includes the measurement of resistance to compression force applied at a single point or at multiple points was reported by Kader *et al*. (1978b).

Tomato firmness is related to the integrity of the cell wall tissues, the elasticity of the pericarp tissue and the activity of enzymes involved in fruit softening, including the degradation of pectins. Polygalacturonase (PG), which depolymerises pectin, is one of the important enzymes thought to be involved in cell wall degradation and in fruit softening. However, gene repression and inhibition of the accumulation of PG mRNA and its enzyme activity cannot prevent significant fruit softening (Sheehy *et al*. 1988). This suggests that PG is not the only factor involved in fruit softening. Pectinases are responsible for most of the de-methylation of cell wall pectins, and are thought to facilitate cell wall hydrolysis by PG. The β-galactosidases

are other enzymes that can contribute to fruit softening. Suppression of a ripening-related β-galactosidase in tomato reduced both galactose solubilisation and fruit softening (Smith *et al*. 2002). Expansins do not have hydrolytic activity, but are thought to influence the hydrogen bonding between the cellulose and hemicellulose cell wall components, causing cell wall swelling and increased porosity that allows degradative enzymes to more easily access their substrates (Brummell 2006). Suppression of a ripening-related expansin in tomato resulted in reduced pectin depolymerisation while overexpression resulted in increased depolymerisation and corresponding changes in fruit softening (Brummell *et al*. 1999).

### *Flavour*

Tomato flavour is a very important quality component. It is the perception of many taste and aroma constituents, and is affected by several factors. Sugars (mainly fructose and glucose in standard tomatoes, but some sucrose in cherry tomatoes) and acids (citric and malic) and their interactions are the most important factors responsible for sweetness, sourness and overall flavour intensity in tomatoes (Malundo *et al*. 1995; Stevens *et al*. 1977b, 1979). High sugar content and relatively high acid content are required for best flavour; high acid with low sugar content will produce a tart tomato and high sugar with low acid will produce a bland taste; a tasteless, insipid flavour is the result of low sugar with low acid.

The pericarp portion of the fruit usually contains more reducing sugars and less organic acids than the locular portion, and therefore cultivars with large locular portions and high concentrations of acids and sugars usually have better flavour than those with small locular portions (Stevens *et al*. 1977a). The sugar content, mainly in the locule walls, reaches a peak when tomatoes are fully ripe; malic acid decreases quickly as the fruit turn red, while the citric acid content is rather stable throughout the ripening period (Hobson & Grierson 1993). Fruity flavour, which best describes tomato flavour, was linked to increased levels of reducing sugars and decreased glutamic acid content (Bucheli *et al*. 1999). It has been suggested that changes in acid and sugar levels in ripening tomato are independent of ethylene and $CO_2$ production (Baldwin *et al*. 1991; Jeffery *et al*. 1984).

Aromatic (volatile) compounds are numerous in tomato fruit (Buttery *et al*. 1971). Some of the volatiles that were correlated with tomato aroma include n-hexanal, *trans*-2-hexenal, β-ionone, 1-penten-3-one, 3-methyl butanal, 3-methyl butanol, *cis*-3-hexen-1-ol, 2-isobutylthiazole and some unidentified $C_{12}$–$C_{16}$ volatile compounds (Buttery *et al*. 1988; Dirinck *et al*. 1976). Hayase *et al*. (1984) identified 130 volatiles in tomato fruit, but determined, using the gas-sniff method, that the most important for tomato aroma are hexanal, *trans*-2-hexenal, 2-isobutylthiazole, 2-methyl-2-hepten-6-one, geranylacetone and farnesylacetone, and that the concentration of these volatiles increased with ripening. Tomato volatiles are formed by different pathways including oxidative carotenoid breakdown (Buttery *et al*. 1988), de-amination and de-carboxylation of amino acids (Yu *et al*. 1968) and lipid oxidation (Hatanaka *et al*. 1986). Aroma volatiles in tomato are affected by several factors including cultivar, growing conditions, management practices and post-harvest handling conditions.

A relationship exists between tomato fruit colour and its volatile composition, especially those formed by the oxidation of carotenoids. Several other correlations were shown between taste descriptors and other fruit components (Baldwin *et al*. 1998). Off-flavours are formed in tomatoes picked green and ripened off the plant, and were related to higher concentrations of some volatiles such as 2-methyl-1-butanal. Bruising and other physical damage were found to cause more off-flavour and less 'tomato-like' flavour (Kader *et al*. 1978c; Moretti *et al*. 2002).

### *Nutritional and health values*

Tomato and tomato-based products are considered healthy foods because they are low in fat and calories, cholesterol free, and a good source of fibre, vitamins A (β-carotene and some other carotenoids are pro-vitamin A) and C, lycopene and potassium (Yahia *et al*. 2005). The interest in the nutritional and health benefits of tomato fruit and their products has increased greatly over the past two decades (Geeson *et al*. 1985; Giovannucci & Clinton 1998; Guester 1997). Vitamin C content in tomato (230 mg $kg^{-1}$) is not as high as in several other fruits, but its contribution is very important due to the extensive use of tomato in the diet of many cultures. A 100 g tomato can supply about 20% and 40% of the adult US recommended daily intake of vitamins A and C, respectively. The selection of tomato genotypes that are rich in vitamins A and C has been accomplished, and cultivars with very high vitamin A content have been developed, although their orange colour was not highly accepted by consumers. Epidemiological studies indicated that tomato fruit had one of the highest inverse correlations with cancer risk and cardiovascular disease, including stroke (Giovannucci *et al*. 1995).

Lycopene, the principal pigment responsible for the characteristic deep-red colour of ripe tomato fruit and tomato products, is a natural antioxidant that can prevent cancer and heart disease (Shi & Le Maguer 2000).

Although, unlike some other carotenoids, lycopene has no pro-vitamin A activity, it does exhibit a physical quenching rate constant with singlet oxygen almost twice as high as that of β-carotene. Increasing clinical evidence supports the role of lycopene as a micronutrient with important health benefits, due to its role in the protection against a broad range of epithelial cancers (Shi & Le Maguer 2000). The serum level of lycopene and the dietary intake of tomatoes have been inversely correlated with the incidence of cancer (Helzlsouer *et al*. 1989; Van Eenwyk *et al*. 1991). Protection for all sites of digestive-tract cancers (oral cavity and pharynx, esophagus, stomach, colon, rectum) was associated with an increased intake of tomato-based foods, and an increased supply of lycopene (Franceschi *et al*. 1994). People who ate at least one serving of tomato-based product per day had 50% less chance of developing digestive tract cancer than those who did not eat tomatoes (Franceschi *et al*. 1994). The intake of lycopene has also been associated with a reduced risk of cancers of sites other than the digestive tract, such as the pancreas and the bladder (Gerster 1997). Older subjects who regularly ate tomatoes were found to be less likely to develop all forms of cancer (Colditz *et al*., 1985). A study at the Harvard School of Public Health carried out on 48 000 men for four years reported that men who ate ten or more servings of tomato products (such as tomatoes, tomato sauce and pizza sauce) per week had up to 34% less chance of developing prostate cancer (Giovannucci *et al*. 1995).

Lycopene has a protective effect on oxidative stress-mediated damage of the human skin after irradiation with UV light (Ribaya-Mercado *et al*. 1995). In addition, it was found to prevent the oxidation of low-density lipoprotein (LPL) cholesterol and to reduce the risk of developing atherosclerosis and coronary heart disease (Agarwal & Rao 1998); the daily consumption of tomato products providing at least 40 mg of lycopene was enough to substantially reduce LPL oxidation. Lycopene is recognised as the most efficient singlet oxygen quencher among biological carotenoids (Di Mascio *et al*. 1989, 1991). Lycopene has also been reported to increase gap-junctional communication between cells and to induce the synthesis of the gap junction protein connexin-43 (Zhang *et al*. 1992), which is involved in intercellular communication. Fresh tomato fruit contains about 7.2 to 200 mg of lycopene per kg of fresh weight, which accounts for about 30% of the total carotenoids in plasma (Stahl & Sies 1996). In contrast to other pigments such as β-carotene, lutein, violaxanthin, auroxanthin, neoxanthin and chlorophylls a and b, which accumulate in inner pulp and in the outer region of the pericarp, lycopene appears only at the end of the maturation period, and almost exclusively in the external part of the fruit (Laval-Martin *et al*. 1975). Other tomato components that can contribute to health include flavonoids, folic acid and vitamin E (Dorais *et al*. 2001).

### *Safety factors*

Tomatine, a steroidal glycoalkaloid, accumulates in developing fruit of all tomato genotypes, and causes bitterness when fruit are harvested immature. However, during ripening tomatine concentration in the fruit declines to about 400 mg $kg^{-1}$ (FW), which is considered to be a safe amount given that the $LD_{50}$ value for tomatine is 500 mg $kg^{-1}$ body weight (Davies & Hobson 1981) and it would thus be necessary for a person to consume at least one tomato per kg of body weight to approach a dangerous tomatine level. Dehydrotomatine is another glycoalkaloid found in tomato at a concentration of 1.7 to 45 mg $kg^{-1}$ (FW) in green fruit, declining to 0.05 to 0.42 mg $kg^{-1}$ in red fruit (Friedman & Levin 1998). These glycoalkaloids are considered to function in defensive mechanisms that protect the plant against insects and pathogens. It has been suggested that low concentrations of some of these alkaloids might have health benefits. For example, Friedman *et al*. (1997) reported that feeding commercial tomatine to hamsters induced a significant reduction in plasma LPL cholesterol, and this reduction was higher when the animals were fed a high-tomatine green tomato diet than when fed a low-tomatine red tomato diet.

## POST-HARVEST PRACTICES AND PROBLEMS

### Fruit maturity and ripeness

Maturity at harvest and the harvesting operation can influence post-harvest tomato quality (fruit taste, firmness and shelf life), and the incidence and severity of physical injuries, which, in turn, can adversely affect tomato quality.

A six-class classification of tomato fruit from mature green to fully ripe (Table 2.1) has been widely adopted. For greenhouse tomatoes, the earliest stage for harvest is the breaker stage, but field-grown tomatoes are often harvested at the mature-green stage. Tomatoes harvested at the mature-green stage will ripen adequately, but immature-green fruit will ripen very poorly, and will develop poor quality post-harvest. Mature-green tomatoes are somewhat difficult for pickers to detect (difficult to distinguish from immature-green fruit). Besides the characteristics listed in Table 2.1, identification of mature tomatoes can also be aided by the following characters: (1) some cultivars turn whitish-green while others show certain coloured streaks at the blossom end, (2) waxy gloss

surface, (3) skin not torn by scraping, (4) the appearance of brown corky tissue around the stem scar in some cultivars and (5) the fruit size and position on the plant – larger fruit and those borne lower on the plant are likely to be more mature than smaller fruit higher up on the plant.

Tomatoes harvested at the mature-green stage or later will attain better flavour upon ripening than those picked at the immature or partially mature stages, and will be less susceptible to water loss because of their better developed cuticle (Kader *et al*. 1978c). Tomatoes harvested at the breaker stage were superior in flavour to fruit harvested mature green (Kavanagh *et al*. 1986). Vine-ripened tomatoes will accumulate more sugars, acids and ascorbic acid, and will develop better flavour than mature-green tomatoes ripened off the plant (Betancourt *et al*. 1977; Bisogni *et al*. 1976; Sakiyama & Stevens 1976; Soto-Zamora *et al*. 2000). Tomatoes harvested over-ripe were shown to have lower ascorbic acid content and higher ascorbate oxidase activity (Soto-Zamora *et al*. 2000; Yahia *et al*. 2001a). Intensities of sweetness, saltiness and fruity-floral flavour were higher in tomatoes harvested at the table-ripe stage than at earlier stages (Watada & Aulenbach 1978). Early harvesting is a practice for obtaining firmer fruit suitable for transport and to attain a longer marketable period (Auerswald *et al*. 1999). However, trade journals have begun recommending that tomatoes should be harvested at a later, partially ripe stage to satisfy consumer demands for better flavour (Janse & Knoys 1995; Watzl *et al*. 1995). Therefore, while tomatoes for distant markets should be picked at the mature-green or breaker stages, tomatoes for nearby outlets can be picked at the breaker, turning, pink or light-red stages. Cluster tomatoes are typically harvested at the light-red to the table-red stages and carefully packed in single-layer, padded trays.

**Harvest**

Tomatoes destined for fresh market are harvested by hand and usually in the morning to avoid the heat of the day. In most cases, individual fruit are removed from the vine by gentle twisting, without tearing or pulling. For cluster tomatoes and occasionally for cherry tomatoes, the whole fruit cluster is cut from the plant. Tomatoes should not be kept in the sun for an extended period of time after harvest. Greenhouse tomato fruit are usually harvested with the calyx and a short section of pedicel (stem) to distinguish them from field tomatoes. The freshness of the calyx is used as an indication of freshness and quality of the fruit. Care must be taken to avoid the pedicel puncturing other fruit, especially for tomatoes picked at a later stage, because they are much more susceptible to physical injury (Grierson & Kader 1986). Physical damage during the handling process increases the rate of respiration, ethylene production and fruit water loss. The physical damage also serves as an excellent entry point for pathogens.

**Fruit handling (washing, waxing and packaging)**

After harvest, tomatoes are usually washed to remove dust and other foreign materials. The wash water needs to be warmer than the tomato pulp temperature to avoid cooling the submerged fruit, which causes water and microorganisms to be drawn into the fruit (Showalter 1993). The wash water may be chlorinated (100–150 ppm chlorine) to disinfect the fruit surface and prevent microbial inoculation (Sabaa-Srur *et al*. 1993). The pH of the chlorinated water should be maintained at about 7.0 to maintain the chemical primarily in the hypochlorous acid form, which is the most effective sanitizer. Disinfection of tomatoes with sodium hypochlorite before packaging greatly reduced subsequent microbial spoilage (Bhowmik & Pan 1992). However, chlorination has no residual effect (Sawyer 1978), and therefore tomatoes exposed to pathogens after treatment remain susceptible to re-infection. A naturally derived plant compound, *trans*-cinnamaldehyde, has been shown to exhibit fungicidal effects, especially when applied as an aqueous solution (Smid *et al*. 1995, 1996). Treating tomatoes with an aqueous solution of 13 mM cinnamaldehyde reduced the number of bacteria and fungi by one order of magnitude within 10 and 30 min, respectively. With the tomatoes treated for 30 min, visible mould growth was delayed by seven days during storage under modified atmosphere at 18°C. Cinnamaldehyde is not currently in commercial use for tomato decay control.

After washing and disinfection, the fruit are usually dried with hot air, and waxing may be done after drying, using a heated food grade wax. Wax coating reduces water loss, enhances gloss of the fruit and may improve the lustre (Amarante & Banks 2001). Fungicides may be added in the wax for protection against fruit rot pathogens (Hall 1989).

After washing and disinfection, fruit are then sorted/graded and packaged. Automatic systems for fruit sorting based on weight and colour are widely used in large commercial greenhouses or packinghouses. Tomatoes are packed in a variety of packages, depending on the type of fruit, maturity or ripeness stage, and type of market and market requirements. The package should be sufficiently strong and adequately designed for sufficient ventilation, depending on the air circulation system employed in storage or during transit. Tomato packages are commonly constructed from double-wall corrugated fibreboard with

at least 2.75 MPa bursting strength. Cluster or vine-ripe tomatoes are usually cleaned by air blast and then directly packaged in a plastic net bag or other packages. The package should be designed in such a way that fruit physical injury is minimised during transport. Physical injuries such as cuts, punctures, scuffs and abrasions not only are unsightly but also result in increased water loss and susceptibility to decay. The affected areas may fail to develop normal red colour. Physical stress also stimulates $CO_2$ and ethylene production by tomatoes (MacLeod *et al*. 1976), which can accelerate fruit ripening and favour decay development.

**Storage, shipping and ripening**

***Temperature requirements and chilling injury***

Rapid cooling to at least 12.5°C immediately after harvest and packing is important to remove heat, retard ripening, and prolong storage and shelf life. Rapid cooling also reduces water loss and decay incidence. This process is especially important for tomatoes intended for distant markets and/or those harvested at the breaker or later ripeness stages. The optimum cooling method is forced-air cooling. However, room cooling can also be used, although it is slower than forced-air cooling. When room cooling is used, containers should be stacked with sufficient space between them to promote adequate air circulation and faster cooling.

Temperature affects several aspects of tomato quality, such as fruit firmness, colour and flavour development. High temperatures (38°C) inhibited lycopene production, while low, chilling temperatures inhibited both lycopene production and fruit ripening (Lurie *et al*. 1996). Cold storage has a negative effect on fruit aroma and consequently on its organoleptic quality (Lammers 1981). During short-term storage of tomatoes, Janse (1995) and Peters *et al*. (1998) observed decreases in acid content. The optimum air temperature for storage varies with fruit ripeness stages because of differences in sensitivity to chilling injury (Table 2.2). Fruit of advanced ripeness stages can tolerate lower temperatures than less ripe or unripe fruit. Mature-green tomatoes are the most sensitive to low temperature among the commercial fruit, and there is a risk to develop chilling injury if they are held below 13°C (Hardenburg *et al*. 1986). If tomatoes are harvested before physiological maturity, chilling sensitivity is even greater. Fruit are less sensitive to chilling as ripening advances. Sensitivity to chilling injury depends on the temperature, length of exposure period, maturity of fruit and variety. For example, chilling injury symptoms and increased decay may appear in mature-green tomatoes if fruit are held for longer than two weeks at 10°C, but in just 6–8 days if fruit are held at 5°C.

**Table 2.2** Temperatures and storage durations for different maturity or ripeness classes of tomatoes based on their susceptibility to chilling injury.

| Class | Temperature (°C) | Storage duration (days) |
|---|---|---|
| Mature-green | 12.5–15 | Up to 28 days |
| Pink | 10–12.5 | 7–14 days |
| Light-red | 9–10 | 4–7 days |
| Firm-ripe | 7–10 | 3–5 days |
| Pink-red, firm-red or vine-ripen | 7 | 2–4 days |

Symptoms of chilling injury include failure to ripen or uneven ripening (Plate 2.9), ion leakage, surface pitting, premature softening, failure to develop characteristic flavour, aroma and colour, mealy texture when ripened and increased decay (Paull 1990). *Alternaria* and *Cladosporium* rots are usually associated with chilling injury (Plate 2.10). Expression of symptoms is usually delayed until after exposure of fruit to room temperature for two days or longer. Tomato fruit stored for seven days at 5°C and ripened at 20°C had acidic taste and low flavour (Kader *et al*. 1978c).

Intermittent warming, which refers to periodic transfer of the product from a chilling temperature to a non-chilling temperature during storage, has been shown to reduce chilling injury in tomato (Artes *et al*. 1998). Intermittent warming during four cycles of six days at 6°C or 9°C and one day at 20°C prevented development of chilling injury, with no chilling injury symptoms appearing either during storage or during post-storage ripening for four days at 20°C (Artes & Escriche 1994; Artes *et al*. 1998). In comparison to continuous storage at 6°C or 9°C, the intermittent warming regimes enhanced surface colour and encouraged ripening after the fruit were allowed to ripen at 20°C. Fruit quality and shelf life of intermittently warmed fruit were better than or as good as fruit subjected to continuous storage at 12°C (Artes *et al*. 1998). In Canada, it was recommended that mature-green tomatoes should be stored at 10°C and ripened at 21°C for 2–6 days, and then held at 10°C for a further 8–10 days (Davies & Hobson 1981). It is thought that the mechanism by which intermittent warming alleviates chilling injury is by allowing metabolism of toxic chilling-related products in the fruit so that they remain below injurious levels.

Tomatoes will freeze at about −1°C depending on soluble solids content. Symptoms of freezing include water-soaked appearance, desiccated appearance of the locular gel and excessive softening and tissue breakdown (Grierson & Kader 1986).

***Heat treatments***

Heat treatments applied prior to low-temperature storage can also reduce sensitivity of tomatoes to chilling injury by activating the antioxidant system in the cells, protecting them from the damaging effects of reactive oxygen species that are associated with chilling stress (Soto-Zamora *et al*. 2005a, 2005b; Yahia *et al*. 2007). Exposing tomatoes to air at 38°C for three days (72 hours) reduced the detrimental effects of low-temperature storage on mature-green tomatoes (Hakim *et al*. 1995; Lurie *et al*. 1995; Lurie & Klein 1991; Lurie *et al*. 1997). Tomatoes exposed to either a short-term heated water treatment (42°C for one hour) or a long-term heated air treatment (38°C for 48 hours), stored at 2°C and then transferred to 20°C ripened normally; the short-term hot-water treatment extended the storage life equally as well as the long-term hot-air treatment, but altered some volatile profiles (McDonald *et al*. 1996, 1998).

Post-harvest (pre-storage) heat treatments have also been pursued to delay ripening and to enhance resistance to low temperature and to disinfect fruit (Lurie 1998). Pre-storage heat treatment of mature-green tomato fruit (treated in water for 42°C for one hour) effectively reduced fruit decay with only minimal adverse effects on fruit quality (McDonald *et al*. 1999). However, the effect of heat treatments on tomato fruit is variety-dependent. Heated forced air (38°C at 50% RH for 24 hours) injured mature-green 'Trust' tomatoes, preventing the normal development of red colour, increasing weight loss and decreasing the production of ascorbic acid (Soto-Zamora *et al*. 2000; Yahia *et al*. 2001b). Some pigments, especially lycopene, and some antioxidants in tomato fruit are very sensitive to heat treatments (Soto-Zamora *et al*. 2005a, 2005b; Yahia *et al*. 2007).

***Tomato post-harvest ripening***

Ripening of mature-green harvested tomatoes is commonly done at 18°C to 21°C. Tomatoes do not ripen normally at constant higher temperatures (Grierson & Kader 1986). Tomatoes ripened continuously at temperatures higher than 25°C are soft and poorly coloured, as high temperature hinders pigment (lycopene) formation. Slow ripening is done at temperatures of 14°C to 16°C. The lowest temperature at which ripening with good colour and flavour development occurs is 12.8°C (Grierson & Kader 1986). The build-up of volatile compounds is significantly reduced when fruit ripen at temperatures lower than 10°C, while temperatures higher than 20°C favour the production of volatile compounds (Stern *et al*. 1994). The production of volatile compounds associated with fruit taste depends more on the final ripening temperature than on the initial storage temperature (Stern *et al*. 1994). The optimum relative humidity during storage and transport is 90–95%, while the optimum relative humidity for ripening is 75–80% (Davies & Hobson 1981). Higher relative humidity will promote infection by fungi and the development of decay.

**Modified or controlled atmospheres (MA or CA)**

Modified atmosphere (MA) refers to an atmosphere that is different from ambient air achieved by product respiration in an environment with restricted ventilation, whereas controlled atmosphere (CA) refers to a precisely imposed and strictly controlled atmosphere (Kader 1986; Smock 1979). Modified atmosphere packaging (MAP) refers to the development of a modified atmosphere around the product through the use of packages constructed of semi-permeable polymeric film or with restricted diffusion through one or more pores (Kader *et al*. 1989). MAP is referred to as 'passive' if the atmosphere in the package is allowed to slowly establish itself by product respiration; 'active' MAP refers to more rapid atmosphere establishment achieved by flushing the package with nitrogen or a gas mixture near the expected equilibrium atmosphere.

Low $O_2$ reduces respiration and ethylene production, increases tolerance to low temperature and thus extends tomato shelf life (Grierson *et al*. 1985). Also, it reduces the loss of chlorophyll and the synthesis of lycopene, other carotenoids and xanthophylls, and delays ripening (Kader *et al*. 1989). Elevated $CO_2$ also retards ripening by competitively inhibiting ethylene action. An atmosphere of 3–5% $O_2$ + 0–3% $CO_2$ delays tomato ripening and retards fungal growth. Tomatoes can be kept in this atmosphere at 12.5°C for up to six weeks. Control of *Phoma destructera*, *Alternaria alternata*, *Botrytis cinerea* and *Fusarium* spp. can be achieved with 2.5% $O_2$ + 2.5% $CO_2$ at 13°C. Atmospheres containing 5–10% carbon monoxide and 4% $O_2$ reduced post-harvest decay incidence and severity without adversely affecting tomato flavour (Kader *et al*. 1978a). Mature-green tomatoes were stored for up to seven weeks at 12.8°C in 4% $O_2$ + 2% $CO_2$ + 5% CO, with acceptable quality. Nitrous oxide was also found to be effective against fungus growth and fruit decay

(Qadir & Hashinaga 2001). However, attempts to use low $O_2$ and high $CO_2$ to improve tomato eating quality have not been successful (Ratanachinakon *et al*. 1997). Atmospheres with ≤1% $O_2$ and/or >3–5% $CO_2$ can cause uneven ripening, uneven colour development, discolouration, softening and off flavours if exposure times are long (Kader *et al*. 1989). Application of heat treatments in low-oxygen atmosphere did not significantly decrease chilling injury (Soto-Zamora *et al*. 2005b; Yahia *et al*. 2007).

**Storage of fresh-cut tomato**

Fresh-cut produce sales have increased spectacularly during the last decade, especially in Europe and North America, mainly due to changes in consumer demand but also due to improvements in the cool chain and processing technology, including MAP. Quality and marketability of tomato slices deteriorate rapidly after cutting compared with other vegetables, and the effects of slicing on the post-harvest behaviour of fresh-cut tomato slices includes a rapid rise in $CO_2$ and ethylene production, which reduces shelf life (Artes *et al*. 1999). A long-life cultivar has been used for fresh-cut to slow ripening and extend storage life (Artes *et al*. 1999). Nonetheless, MAP is considered to be mandatory as a supplement to temperature control in order to successfully market fresh-cut tomatoes.

Surface sterilization of whole fruit with sodium hypochlorite as well as the use of potassium bicarbonate, calcium chloride and calcium lactate on the slices extend the shelf life of fresh-cut tomato (Gil *et al*. 1999). Most of the defects of fresh-cut tomatoes observed during processing and storage, such as tissue water soaking, juice accumulation and moisture condensation, have been overcome. A water absorbing paper in the trays prevented juice accumulation (Gil *et al*. 1999) and condensation is avoided by the use of anti-fog films. Water soaking development in fresh-cut tomato slices appears to be an ethylene-mediated symptom of senescence (Jeong *et al*. 2004) and not a symptom of chilling injury as had been suggested. Selecting light red fruit for processing and avoiding storage above 5°C minimized water soaking. Lowering the storage temperature was a more critical factor than MAP in reducing microbial counts (Gil *et al*. 2002). High $CO_2$ and low $O_2$ concentrations inhibited yeast and mould growth without off-favour development. The overall tomato slice quality was better at 5°C than at 0°C under high $CO_2$ (Gil *et al*. 2002). After ten days of storage, the quality attributes of tomato slices were maintained better at 2°C than at 10°C. When slices were stored at 10°C, both passive and active MAP reduced the rate of ripening. The best overall quality was achieved with 2°C storage temperature under active or passive MAP (Artes *et al*. 1999).

**Pathological disorders**

Tomatoes are sensitive to attack by several decay organisms. Tomato losses at the retail and consumer levels in the New York area were estimated at 11.4–14.2%, and were mostly due to diseases, principally *Alternaria*, *Rhizopus*, grey mould (*Botrytis*) and bacterial soft rots (Ceponis & Butterfield 1979). Most post-harvest decay problems of tomatoes originate during cultivation. Decay problems are minor in tomato production in modern greenhouses with good climate control, but can be more severe in low-technology greenhouses and field production. Decay can also be initiated in the packing line due to physical damage and contamination. Micro-organisms can enter tomato fruit through openings such as wounds, cracks, cuts, stems and stem scars. Tomatoes with defects that may provide entry to pathogens should be separated from good-quality fruit. Lower grades of tomato, which may have more abrasions and cuts and larger stem and blossom-end scars than higher grades, were found to develop higher incidence of decay and were also more likely to be infected when inoculated with the causal agent of bacterial soft rot, *Erwinia carotovora* (Bender *et al*. 1992). Chilling injury augments the incidence and severity of decay in tomato.

The most common decay problems in tomatoes are described as follows.

**Black mould or alternaria rot**

Caused by *Alternaria alternata*, the fruit become susceptible when exposed to <10°C for one week (Plate 2.10). Lesions are commonly found near the stem scar or at the blossom end of the fruit. They are flat or sunken, and usually covered by the sporulating black mycelium of the fungus. Preventive measures include avoidance of chilling temperatures and avoidance of mechanical injury.

**Grey mould**

Caused by *Botrytis cinerea*, it is favoured by cool, moist growing conditions and mostly occurs on greenhouse tomatoes, especially if they are film-wrapped. The affected tissue is usually firm, dry and brown to black in colour (Plate 2.11). Preventive measures include the use of adequate storage temperature, the avoidance of chilling and physical injuries and the use of appropriate pre-harvest fungicides.

**Bacterial soft rot**

This is caused primarily by *Erwinia carotovora* subsp. *carotovora*, but also by other pectolytic strains of *Erwinia*,

*Bacillus* and *Pseudomonas*. Infection is almost exclusively via wounds or other openings in the fruit, and is especially likely if fruit come in contact with contaminated water. Symptoms include soft and water-soaked areas that become liquefied, and bacterial ooze may leak from wounds, stem scars and stylar pores (Plate 2.12a–c). Control is by sanitation to reduce population levels, avoiding excessive submersion in dump tanks and flumes, avoiding damage to fruit and culling fruit with cuts, punctures, abrasions and large scars that can provide entry to the pathogen.

**Sour rot**

This is caused by *Geotrichum candidum*. Symptoms on mature-green fruit appear as pale lesions, dull and water soaked, with sour (vinegar) odour (Plate 2.13). On ripe fruit the infected tissue is usually dark, soft and watery. Symptoms usually start at the stem scar and resulting from wounding. Avoiding mechanical injury is an important preventive measure.

**Hairy or Rhizopus rot**

This is caused by *Rhizopus stolonifer* and characterised by soft, water-soaked and discoloured lesions with fermented odour (Plate 2.14). A coarse white mould may appear which then turns black (Plate 2.15). Preventive measures include adequate hygiene in the greenhouse and on the packing line, and avoidance of fruit injury. The fungus grows very slowly at around 10°C and lower.

**Phoma rot**

Caused by *Phoma destructera*, this disease is characterised by firm, sunken lesions that occur commonly at the stem end, but can also occur at any part of the fruit. The infected tissue appears brown in colour and then turns black. Preventive measures include eliminating diseased plants, avoiding fruit injury, using optimum temperature during storage and shipping and ensuring hygienic practices.

**Early blight rot**

This is caused by *Alternaria solani*. The symptoms are in the form of dark-brown lesions that commonly appear at the stem end, but may also appear at the blossom end or at the side of the fruit. Lesions are sunken and leathery in green fruit. Preventive measures include the chemical treatment of seeds before planting.

**Late blight rot**

This is caused by *Phytophthora infestans*. This problem can affect protected or outdoor tomatoes. Hard, lumpy, reddish-brown lesions can appear in different parts of the fruit, but commonly at the stem end. Preventive measures include adequate ventilation and reduced humidity in the greenhouse. Tomato cultivars vary in their susceptibility.

**Bacterial speck**

This is caused by *Pseudomonas syringae* pv. tomato. The symptoms are in the form of dark, minute (less than 1 mm) lesions, and the skin may appear tough. Preventive measures include seed treatment with hot water or with chemicals and greenhouse sanitation.

**Phomopsis rot**

Caused by *Diaporthe phaseolarum* var. *sojae*, the disease takes the form of soft and water-soaked lesions. The infected tissue may turn tough, dark and shrivelled. Greenhouse sanitation and careful handling are among the preventive measures.

**Pink mould rot**

Caused by *Trichothecium roseum* Link, it is characterised by firm greyish-brown lesions at the blossom end of the fruit. Lesions are usually water-soaked and in humid conditions give rise to characteristic orange-pink spores. Preventive measures include adequate ventilation in the greenhouse, avoidance of injuring the fruit and the use of adequate storage temperatures.

**Pleospora rot**

Caused by *Pleospora herbarum*, this disease is characterised by brown to black lesions at the edge of the stem scar or on wounds at any part of the fruit. Preventive measures include careful handling.

**Ring rot**

Caused by *Myrothecium roridum*, it is characterised by circular to oval, firm and slightly sunken lesions, with sharply defined margins. This decay extends deep into the fruit. Preventive measures include pre-planting treatment of seeds, hygiene in the greenhouse and packinghouse and the avoidance of mechanical injury.

## FUTURE CHALLENGES OR DEVELOPMENTS

New post-harvest technologies are poised to change the ways by which tomatoes are handled. Near-infrared and acoustic online sorting devices can be used to determine internal quality aspects related to maturity and ripeness such as sugar content and acidity, dry matter, juice content, internal structure as well as internal physical defects. The ability to sort out immature and defective tomatoes on the packing line can lead to improved tomato quality at the same time that handling efficiency is enhanced. Radiofrequency identification (RFID)-enabled

temperature sensors are being applied in managing the logistics of the cold chain by linking temperature monitoring to RFID communication, allowing temperature, time and location data to be transmitted and monitored during shipping. In the future, any number of biosensors may be associated with RFID tags to allow real-time monitoring of quality and safety indicators such as flavour or stress volatiles.

Tomatoes have received heightened recognition in recent years for their contribution of flavour and nutrition to the human diet. In fact, evidence of a direct relationship between tomato flavour volatile and phytonutrient abundance has recently been noted (Goff & Klee 2006). The fact remains, however, that quality traits have been diluted over time in the quest for improved fruit yield and field performance. Recently, combined metabolic and phenotypic analysis of tomato introgression lines has provided chemical markers that may accelerate the improvement of tomato fruit quality (Schauer *et al*. 2006). Schauer *et al*. used the strategy of metabolic genomics to correlate numerous metabolites and fruit quality traits in crosses of the cultivated tomato variety Roma with wild *Solanum pennellii*. This information can be of enormous importance for tomato improvement by "focus[ing] breeding strategies and improv[ing] efficiency and outcome" (Giovannoni 2006).

Joining technologies to detect immature fruit and manage post-harvest tomato ripening can remove the incentive to harvest tomatoes before they have developed their full flavour and nutrition potential. Development of improved tomato varieties via either conventional breeding or molecular manipulations promises the availability of tomatoes in the near future with improved genetic potential to develop better flavour and nutrition. As our understanding of how the postharvest environment can be managed to better maintain or even improve the nutritional and sensory value of tomatoes, this promise comes closer to reality.

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# 3
# Bananas (*Musa* spp.)

*David W. Turner and Jeanie A. Fortescue*

## INTRODUCTION

### Importance of bananas and plantains

Bananas (Figure 3.1) have had a long association with humans and so people have been dealing with post-harvest aspects of bananas going back at least 7000 years in Papua New Guinea (Denham *et al*. 2003), more than 2500 years in Cameroon (Mindzie *et al*. 2001) and possibly 6000 years in Uganda (Lejju *et al*. 2006). Wild bananas (*Musa* spp.) occur from India to Oceania, and the edible clones are derived from hybrids of the wild species *Musa acuminata* (A genome) and *Musa balbisiana* (B genome). Among the edible bananas, the triploid groups AAA, AAB and ABB are the most common. Plantains belong to the AAB group. At present, bananas and plantains are major sources of food in numerous countries in the tropics and are available as fresh fruit throughout much of the world. For gross value of production among world crops, bananas and plantains rank fourth after rice, wheat and maize. Each year about 105 million tonnes (Mt) are produced in the tropics and subtropics. About 16 Mt enter international trade that is dominated by AAA cultivars that are consumed as fresh fruit (INIBAP 2006). The European Union and the United States are the main importers of bananas, and Ecuador is the main exporter, followed by Costa Rica and the Philippines. Outside the international trade, India produces about 16 Mt of bananas and plantains annually. Uganda produces 10.5 Mt and Brazil 5.7 Mt. The annual growth rate in world production of bananas and plantains for the decade ending in 2002 was 3.3% (FAO 2006).

For human nutrition, bananas and plantains provide carbohydrates, either as starch in plantain and cooking bananas (Eggleston *et al*. 1992) or as sugars in dessert bananas (von Loesecke 1949). They also supply minerals, particularly potassium (Wall 2006), and vitamins, especially in populations for whom bananas and plantains are more than 10% of their staple diet (Englberger *et al*. 2003; Davey *et al*. 2006, 2007). Banana and plantain fruit are available all year, although there is variation in supply, often linked to weather conditions. The fruit is usually harvested green and is transported to market and ripened there. It is a perishable product and is consumed within a few days to three weeks after harvest. The perishable nature of bananas and plantains means that losses between harvest and consumption can be considerable. To determine the magnitude of losses is difficult because it depends on the local situation and the stage in the post-harvest system at which losses occur (Wills *et al*. 1998). Nonetheless, the perishable nature of the fruit and the distance from grower to market have driven development of sophisticated systems of post-harvest management (Hallam 1995) that are supported by knowledge of the biology of the fruit and appropriate technology.

In view of its commercial importance, a considerable amount of research has been undertaken and many reviews have been produced relating to the biology of the banana and the technologies developed to handle the fruit. This chapter concentrates on several areas of research where our understanding of this fruit has recently advanced. For

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**Figure 3.1** Banana (*Musa* spp.).

reviews dealing with the protocols of packaging, transport and ripening, see Thompson and Burden (1995) and Robinson (1996).

### Nomenclature

An aspect of post-harvest physiology that will become more significant in the future is the diversity of post-harvest behaviour among different cultivars of banana and plantain. In addition, this will rise in importance in banana breeding schemes (Dadzie 1998). Therefore, reports on the post-harvest behaviour of bananas and plantains need to include the name of the cultivar(s) studied. In the past, some articles do not mention the cultivar name at all and others use names that are not appropriate, such as the Linnaean binomial classification *Musa paradisiaca* and *Musa sapientum*. For the edible bananas, these names are incorrect because the vast majority of edible bananas are hybrids (Simmonds & Shepherd 1955). Simmonds (1959) argued the case, for the edible cultivars, for following the conventions of the International Code of Nomenclature for Cultivated Plants. He explained that Linnaeus gave the species names *paradisiaca* and *sapientum* to two edible hybrids. Simmonds (1959) suggested cultivars be referred to formally with the generic structure: *Genus* (Genomic Group, Subgroup) 'Name'. So, the triploid 'Grand Nain' cultivar would be *Musa* (AAA Group, Cavendish Subgroup) 'Grand Nain' and the diploid 'Sucrier' would be described formally as *Musa* (AA Group) 'Sucrier'. At least one formal reference to the cultivar(s) used should be included in research papers. Jones (2000) gives a more recent summary of cultivar names as well as their numerous synonyms.

## POST-HARVEST PHYSIOLOGY AND MANAGEMENT OF BANANAS

Bananas are a climacteric fruit and it is convenient to consider the pre- and post-climacteric phases. If harvested after completing only 45 days of growth in the tropics, banana fruit can ripen after exposure to ethylene, even though the fruit are quite thin. This capacity to ripen over a wide range of growth and development is of benefit for marketing. Normally, the fruit grows to a suitable size for market and is harvested when green. In the hard, green state (pre-climacteric phase), the fruit is transported to markets

where it is ripened and then distributed to consumers (post-climacteric phase). The duration of the pre-climacteric phase is the green-life of the fruit when it is firm and is characterized by a low respiration rate and a green peel. Ripening begins with autocatalytic ethylene ($C_2H_4$) production and the climacteric rise in respiration. This phase is noted for its high respiration rate and large changes in fruit chemistry and physical attributes. The peel changes from green to yellow, starch in the pulp changes to sugars and flavour and aroma compounds are produced. The fruit softens and becomes ready to eat. The shelf life of the fruit is best defined as the time between two different stages of yellowing of the peel and is distinct from green-life. At the end of shelf life the processes of senescence dominate and the fruit becomes over-ripe. These definitions of green-life and shelf life are not used consistently through the literature as some authors include green-life with shelf life.

'Green-life' and 'shelf life' are descriptive terms used for convenience and do not have any underlying physiological meaning. For marketing and transport, it is often desirable to extend the green-life of the fruit and a considerable amount of empirical research has been conducted to determine the factors that influence green-life. At the retail level, it can be desirable to extend shelf life. Empirical knowledge is gained by subjecting the fruit to various treatments with the objective of changing the green-life, shelf life or both. Empirically we know that the magnitude of green-life is affected by the conditions under which the fruit were grown, the maturity of the fruit (often expressed as its age or size), the presence of exogenous ethylene, temperature, light, mechanical damage and fungal infections. The ripening phase begins with the autocatalytic production of ethylene. We don't yet know the precise connections between the external factors listed above and when ripening begins, except that exposure of the fruit to $C_2H_4$ will stimulate autocatalytic $C_2H_4$ production and initiate the ripening process. In commerce, this knowledge is used to end green-life in preparation for ripening and distribution to consumers. The external factors present during fruit growth influence either the internal production of $C_2H_4$ in the pre-climacteric phase, the sensitivity of the fruit to $C_2H_4$, or both.

Complementing this empirical approach there is a need to know about the processes and mechanisms that influence the growth, development and ripening of the fruit at a physiological level. Sound management practices used after harvest depend on knowledge of how the fruit works.

Progress in research on the post-harvest aspects of bananas and plantains has been regularly reviewed (Gore 1914; von Loesecke 1949; Palmer 1971; Simmonds 1959, 1966; Stover & Simmonds 1987; Hassan & Pantastico 1990; Seymour 1993; John & Marchal 1995; Robinson 1996; Turner 1997; Muirhead & Jones 2000). The reviews of Palmer (1971), Seymour (1993) and John and Marchal (1995) emphasise the biochemical aspects of ripening, while those of Stover and Simmonds (1987) and Robinson (1996), which are book chapters, take an industry perspective. Muirhead and Jones (2000) provide an excellent coverage of post-harvest diseases.

Our purpose here is to draw attention to the unique features of the banana fruit after harvest and discuss progress in published research on post-harvest physiology and management of bananas and plantains.

## Manipulation of green-life

### *Green-life and fruit growth*

The banana fruit increases in size as it grows and its green-life decreases exponentially as it matures (Peacock & Blake 1970; Turner & Rippon 1973; Srikul & Turner 1995). Indeed, green-life can be taken as a quantitative measure of the immaturity of the fruit (Peacock & Blake 1970). In any given situation, the link between green-life and growth is close, but there is sufficient separation to cause problems in transport when some fruit ripen while others remain green ('mixed ripe' or 'premature ripe'), even though the fruit may be the same size or age. The work of Turner and Rippon (1973) and Srikul and Turner (1995) shows that management practices can change the rate of growth independently of the rate at which green-life changes during development. For example, increased N supply and soil water deficit promote tendency to ripen (i.e. reduce green-life), but N supply increases fruit growth rate while soil water deficit reduces it. Experiments on the effect of management practices on green-life usually only measure the green-life of the fruit at the end of the experiment and don't account separately for changes in fruit growth and green-life. In these experiments the impact of the treatment on the growth rate and green-life is confounded (Ramsay *et al*. 1990). This may not be too much of a problem, depending on one's objectives.

If the 'mixed ripe' problem is seasonal, harvesting fruit that is less mature reduces the problem. In this case it is necessary to sacrifice some yield, because the fruit is thinner, but it ensures that fruit are more likely to reach the market in a hard green condition.

### *Temperature*

Low temperature during storage extends fruit green-life (Blake & Peacock 1971) and is the main strategy used commercially, although it is expensive. The temperature

should be above that which can cause chilling injury. Commonly, 13°C is the lowest temperature used to transport bananas as the probability of chilling injury occurring increases below 13°C. Temperature influences the rate of metabolism of the fruit and the $Q_{10}$ is 2.0 to 2.5 (Gane 1936). At temperatures above 24°C the peel of the banana does not change to yellow as rapidly as it does at lower temperatures. Plantain cultivars de-green at high temperatures, while banana cultivars of the Cavendish group do not (Seymour *et al*. 1987). Above 30°C, the peel remains green during ripening. However, the ripening of the pulp is hastened by high temperature, producing fruit that are over-ripe but green in appearance. In the market, this is known as 'soft-green' fruit. Banana fruit ripened at 30°C to 40°C does not de-green, but soften. This softening is mediated by the effect of the increased temperature on increased synthesis of new $C_2H_4$ binding sites (Jiang *et al*. 2002). Temperatures of 3°C or 8°C, which cause chilling injury, reduce the synthesis of $C_2H_4$ binding sites and this prevents the fruit from ripening, a common observation in chilled banana fruit (Jiang *et al*. 2004). If temperature influences the rate of synthesis of $C_2H_4$ binding sites, then in practice this would mean the faster that fruit can be cooled after harvest, the longer would be the expected green-life because the fruit would be less sensitive to any ethylene present in the post-harvest chain.

***Sensitivity to ethylene***

Ethylene gas stimulates ripening of banana fruit and is used commercially to begin the ripening process. The time taken for the fruit to respond to the exogenous application of $C_2H_4$ is extended at low temperature and if the concentration of exogenous $C_2H_4$ is low. Inaba and Nakamura (1988) showed that at 25°C the minimum time to ripen (fruit more yellow than green) ranged from 5 h at 1000 µL $C_2H_4$ $L^{-1}$ to 15 h at 0.1 µL $C_2H_4$ $L^{-1}$ but these times extended to 18 and 50 h, respectively, at 15°C. More recently, Wills *et al*. (1999) showed that $C_2H_4$ concentrations below 0.1 µL $L^{-1}$, the lower limit used by Inaba and Nakamura (1988), were capable of inducing ripening in bananas. Wills *et al*. (1999) used air scrubbed of $C_2H_4$ as their control and assumed that it had a $C_2H_4$ concentration of 0.001 µL $L^{-1}$, below the detection limit of their instrumentation. The upper limit of their treatments was 1.0 µL $C_2H_4$ $L^{-1}$. Ethylene reduced green-life from a range of 27 to 44 days in the control fruit to 3.2 to 3.6 days at 1.0 µL $C_2H_4$ $L^{-1}$. Variation within a $C_2H_4$ concentration was caused by differences in the cultivar and source of the fruit. Their data show a linear decrease in the time taken to ripen with the logarithm of the increasing $C_2H_4$ concentration. They point out that their data support the conclusion of Peacock (1972) that there is no threshold concentration of exogenous $C_2H_4$ for the initiation of ripening in banana and that endogenous $C_2H_4$ is active during fruit growth and after harvest. This differs from the views of others who propose a threshold concentration of $C_2H_4$ needed to initiate ripening. In a number of different studies, summarized by Acedo and Bautista (1993), the threshold varied over a 100-fold range from 0.015 to 1.0 µL $C_2H_4$ $L^{-1}$, attributed to differences in fruit maturity, cultivars and methods used. In support of the 'no threshold' argument of Peacock (1972), Wills *et al*. (2001) found linear relationships between the time to ripen and the logarithm of the $C_2H_4$ concentration over the range of 0.005 to 10 µL $C_2H_4$ $L^{-1}$. The slopes of these lines indicate the sensitivity of the fruit to ethylene, which may in turn be influenced by temperature. At 20°C, banana was more sensitive to increased $C_2H_4$ concentration than other fruit, such as kiwifruit, custard apple, mango and tomato. The linear relationship between time to ripen and the logarithm of $C_2H_4$ concentration, over a very wide range of $C_2H_4$ concentrations, does not support the 'threshold' concept. In practice, where $C_2H_4$ is used to ripen fruit for commercial purposes, then a 'threshold' may be a useful idea, as it would indicate the minimum concentration of $C_2H_4$ needed to achieve commercial objectives.

Wills *et al*. (1999) measured $C_2H_4$ concentrations in cartons of hard green bananas arriving at markets in Sydney, Australia. Concentrations ranged from below detectable limits up to 0.28 µL $C_2H_4$ $L^{-1}$. Fifteen per cent of the cartons contained air with $C_2H_4$ concentrations above 0.1 µL $L^{-1}$. There was no link between the source of the fruit and $C_2H_4$ concentrations, even though some fruit had travelled 3000 km from tropical North Queensland (Lat 17°S) and others had travelled 500 km from subtropical Northern NSW (Lat 32°S). The $C_2H_4$ detected in the cartons may have come from the bananas themselves, and mechanical damage to the fruit may have been a contributing factor. Wounding the peel stimulates $C_2H_4$ production (McGlasson 1969), and the amount of $C_2H_4$ produced from a wound is less if the peel of the green fruit is harder (Chillet and de Lapeyre de Bellaire 2002).

Combining these observations on the concentration of $C_2H_4$ in cartons with their experimental data, Wills *et al*. (1999) concluded that if $C_2H_4$ concentrations in cartons could be reduced, then bananas could be transported without the need for refrigeration. This is an interesting conclusion since the work of Inaba and Nakamura (1988) includes the response of pre-climacteric bananas to a range of $C_2H_4$ concentrations at different temperatures, including the range likely to be used in refrigerated transport. However, the

**Table 3.1** The Effect of Modified Atmospheres (MA) on Extending the Green-Life of Banana Fruit in a Number of Studies.

| Cultivar | Treatment | Green-life extended by* | Reference |
|---|---|---|---|
| AAA Cavendish, 'Williams' | MA, ambient temperature | 7 days | Scott and Roberts (1966) |
| AAA Cavendish 'Williams' | MA, ambient temperature, $C_2H_4$ absorbent | 14 days | Scott *et al*. (1970) |
| AAA Cavendish 'Williams' | MA, cool room, $C_2H_4$ absorbent | 14 to 30+ days | Satyan *et al*. (1992) |
| AAA Cavendish | MA, ambient temperature, $C_2H_4$ absorbent | 16 to 18+ days | Jiang *et al*. (1999) |
| AAB 'Kolikuttu' | MA, cool room, $C_2H_4$ absorbent | 16 to 18+ days | Chamara *et al*. (2000) |
| AAA Cavendish | MA, 15°C | 13+ days | Stewart *et al*. (2005) |

* The + sign indicates that treatments were stopped before the maximum green-life was determined.

green-life of the control fruit in each paper differs by tenfold. For example, taking the green-life of fruit at 20°C and 0.1 μL $C_2H_4$ $L^{-1}$ in each paper, the green-life of the fruit used by Inaba and Nakamura (1988) is about 30 h, while that for Wills *et al*. (1999) is 250 to 300 h, almost 10 times longer. These large differences in green-life under the same conditions of temperature and exogenous $C_2H_4$ reflect, amongst other things, the differing status, including age, of the fruit used in the two sets of experiments. So, for transporting fruit over large distances without refrigeration, but with low exogenous $C_2H_4$ concentrations, it would be necessary to select fruit that has an inherently high green-life at harvest. In practice this is difficult, but experience shows that fruit harvested at certain times of the year or grown in different locations can have shortened green-life. There is a need to develop a method for predicting the green-life of harvested fruit.

The gas 1-methylcyclopropene (1-MCP) blocks ethylene action (Blankenship and Dole 2000) and could be expected to extend the green-life of bananas. In commerce, bananas with a range of maturities are marketed and so Harris *et al*. (2000) investigated the interaction between 1-MCP application and fruit maturity in cv 'Williams' (AAA, Cavendish subgroup). They worked on fruit that varied in diameter from 33 to 42 mm and found a strong interaction between fruit maturity and 1-MCP application. The green-life of larger fruit was extended by 1-MCP but was reduced in thinner fruit. Harris *et al*. (2000) concluded that this interaction limited commercial application of 1-MCP to extend green-life in cv 'Williams'.

### *Modified and controlled atmospheres*

Controlled atmosphere storage of temperate fruits was developed early in the twentieth century (Kidd & West 1927). Temperate fruit can be stored for many months under these conditions by controlling the $O_2$ and $CO_2$ concentrations of its atmosphere, and at a low temperature. Modified atmospheres can be used for bananas where refrigeration is not available, or is too expensive. In this case the fruit is sealed in a polyethylene bag and the fruit 'modifies' the surrounding atmosphere over time, depending on its respiration rate, the volume of gas around the fruit and the permeability of the enclosing polyethylene bag. In a modified atmosphere the $O_2$ concentration falls over time and the concentration of $CO_2$ increases as substrate is used in respiration. Other gases, such as ethylene, may accumulate. When using a controlled or modified atmosphere, there are two aspects of interest. One is the effect of the composition of the external atmosphere on the green-life or shelf life of the fruit. The other aspect is what mechanisms are involved in the response of the fruit to controlled or modified atmospheres. We require empirical and mechanistic knowledge to make progress in managing the post-harvest behaviour of fruits.

Scott and Roberts (1966) showed that the green-life of banana fruit could be extended at ambient temperatures, simply by placing the pre-climacteric fruit in a sealed polyethylene bag. Adding an absorbent of $C_2H_4$ further increased green-life (Scott *et al*. 1970). Since that time a number of studies have examined the effect of modified atmosphere storage on extending the green-life of banana fruit (Table 3.1).

### *Oxygen concentrations in fruit tissues*

Given the widespread interest in banana storage in modified atmospheres, especially during transport, to extend green-life, the implications for gas concentrations within the fruit tissues and how this impacts quality are very important. This section concentrates on oxygen and

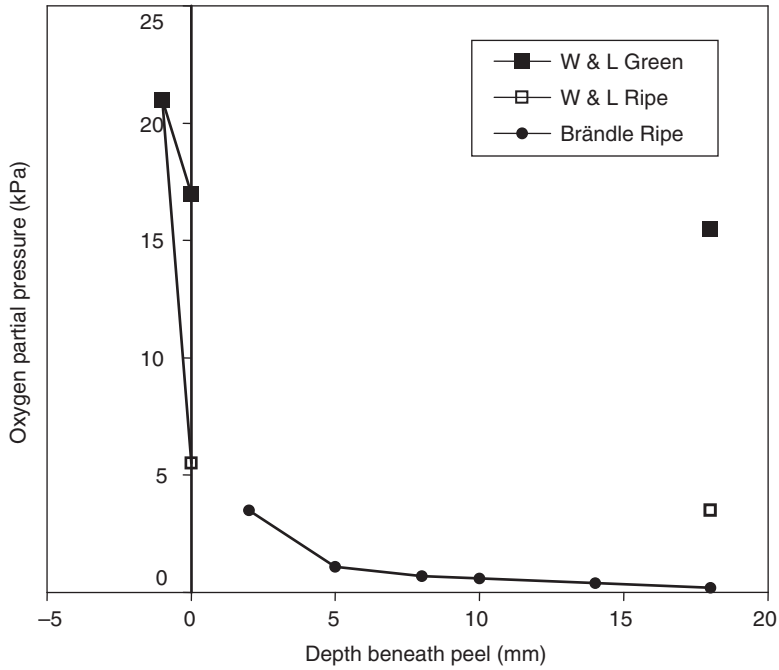


**Figure 3.2** Profiles of oxygen partial pressure in green and ripe banana fruit. The data 'W & L green' and 'W & L ripe' are from Wardlaw and Leonard (1940) and 'Brändle ripe' from Brändle (1968). The value of 21 kPa above the peel has been added to show the drop in oxygen partial pressure across the peel. The zero point on the x-axis is the border between the peel and the pulp. The W & L data at 18 mm are for the 'centre' of the fruit and were placed there for comparison with the data of Brändle (1968).

summarises both the status of our understanding of how to measure gas concentrations and the implications of the findings of scientific studies conducted over the past few decades.

It is worthwhile looking at the $O_2$ concentrations and profiles within green and ripe fruit so that the concentration of $O_2$ within tissues can be anticipated, if the external concentration is known. One concern in modified atmosphere storage is that if the external concentration of $O_2$ is too low, then areas of $O_2$ deficiency will develop within the fruit leading to problems in ripening and poor quality. On the other hand, if $O_2$ concentration is too high, then $C_2H_4$ synthesis will continue, as $O_2$ is required for this process. To extend green-life, the internal $O_2$ partial pressure would need to be less than 2.2 kPa (approximately 2.2%), which is the $K_m$ $O_2$ for the production of $C_2H_4$ in banana pulp, according to the methods used by Banks (1985a). This argument assumes there is a threshold concentration of $O_2$ below which green-life will be extended and another above which ethanolic fermentation can be avoided. However, Wills *et al*. (1982) show that the impact of short-term $O_2$ concentrations on extending green-life is proportional to the concentration of $O_2$ applied (see later). Hence, the idea of using $O_2$ concentration as a 'switch' to turn ethylene synthesis off does not seem applicable.

The $O_2$ concentration at any point in the fruit will be influenced by the rate of respiration of the tissues, the gradient to an external source and the resistance to gaseous diffusion provided by the intercellular spaces and the anatomy of the tissues. In addition, the contribution of photosynthesis by green chlorophyll in the peel to $O_2$ concentration in the fruit that may be in the light needs to be evaluated. Dynamic changes in metabolic activity and in the diffusion pathways of gases during ripening mean that internal $O_2$ concentrations decrease rapidly in ripening fruit.

Burton (1982) summarized the measurements of the concentration gradients of $O_2$ in the pulp of banana fruit made by Wardlaw and Leonard (1940) (AAA, cv 'Gros Michel') and Brändle (1968) (AAA, Cavendish subgroup) (Figure 3.2). In green fruit in air (21 kPa $O_2$), the partial pressure of $O_2$ beneath the peel was 17 kPa and in the centre of the fruit was 15.5 kPa. This gradient implies a greater

resistance to $O_2$ movement across the peel than through the pulp, assuming that their respiration rates are similar (this is the case for green fruit, on a fresh weight basis, but not so in ripening fruit; Dominguez and Vendrell 1994) and that the entry of $O_2$ into the fruit is mainly by a radial pathway (from the peel to the fruit centre) through the stomata (Banks 1984). Compared with green fruit, in ripe fruit the concentration of $O_2$ is greatly reduced and the gradient across the peel becomes very steep, up to 15 to 17 kPa (Figure 3.2), supporting the view that the peel represents a 'barrier' to the movement of $O_2$ into the fruit. Within the pulp of ripe fruit, there is a gradient of 2 to 3 kPa from just beneath the peel to the centre of the fruit. The lower partial pressures of $O_2$ in ripe fruit will be influenced by the increased respiration rate of the pulp and leakage of solutes and water into intercellular spaces that would decrease the movement of gases through the tissues. However, the relative magnitude of the effects of respiration and blockage of the intercellular spaces on $O_2$ concentration in ripening banana has yet to be determined. Burton (1982) thought that the $O_2$ concentrations of 3.5 to 0.2 kPa $O_2$ in the ripe pulp, measured by Brändle (1968), may be too low because of the method used. Brändle (1968) used a miniature Clark electrode pushed into the fruit to measure $O_2$ concentration. Burton (1982) considered that damage to the tissue caused by the electrode and the need for $O_2$ to flow to the electrode through this tissue would contribute to lower values than might exist in the undisturbed tissues. However, the values recorded by Brändle (1968) for ripe fruit are not dissimilar to those measured by Wardlaw and Leonard (1940) using a cannula method described by Wardlaw and Leonard (1939). They recorded $O_2$ concentrations of 2 to 5 kPa at the centre of ripe fruit that had been ripened at a relative humidity of 70%.

Assuming the values for partial pressure of $O_2$ given by Wardlaw and Leonard (1940) are indicative (Figure 3.2), then the external $O_2$ partial pressure would need to fall to at least 6 kPa for regions of anoxia to be induced in green fruit at 29°C. The situation would be quite different for ripe fruit where a small drop in $O_2$ partial pressure from 21 to 15 kPa would be sufficient to place most of the pulp in anoxic conditions. Anoxia causes an energy crisis in cells that then switch to alcoholic fermentation. If anoxia is extended, then permanent damage can occur.

Banks (1983) compared the cannula and syringe (direct removal) methods for estimating internal $O_2$ concentrations in banana fruit (Cavendish cv 'Valery') and found little difference between the two methods. Over five days of ripening, the internal concentration of $O_2$ was stable and ranged between 11 and 15 kPa in control fruit, indicating little change as the fruit changed from green to full yellow. Wardlaw and Leonard (1940) found that the concentration of $O_2$ in the centre of the fruit throughout ripening differed according to the relative humidity at which the fruit were ripened. During 5 days of green-life at 29°C, $O_2$ concentration fell gradually from 15 kPa to 8 kPa just before the climacteric rise in respiration. In fruit ripened at high humidity, the concentration of $O_2$ in the fruit returned to about 15 kPa after the climacteric rise in respiration and then declined gradually to 2–4 kPa in over-ripe fruit at 15 days. If the bananas were ripened at low humidity, the concentration of $O_2$ declined exponentially during the whole two weeks of storage and ripening, with no rise occurring after the climacteric peak in respiration. The impact of these differences in internal $O_2$ concentrations on fruit quality needs to be determined. More recently, Perez and Beaudry (1998) used cannula methods to estimate changes in the internal concentration of $O_2$ in ripening bananas. They found that while green, the internal $O_2$ concentration was 18–20 kPa for the first 7 days but then began to fall and reached about 12 kPa at 11 days coinciding with the peak of internal $C_2H_4$ concentration. Wills *et al*. (1982) measured the internal $O_2$ concentration in ripening bananas (Cavendish cv 'Williams') by placing the fruit in water, extracting gas under vacuum and then analysing the extracted gas. With this method, they observed changes in internal $O_2$ concentration similar to those recorded by Perez and Beaudry (1998) who used the cannula method. The internal $O_2$ concentration fell from 18–20 kPa when the fruit were green to 9–12 kPa in ripe fruit. Thus, in fruit exposed to air, in one experiment (Banks 1983) there was no significant change in internal $O_2$ concentration during ripening, but in another three experiments (Wardlaw and Leonard 1940; Wills *et al*. 1982; Perez and Beaudry 1998) the internal $O_2$ concentration was almost halved as the fruit changed from green to ripe.

Perez and Beaudry (1998) point out that use of the cannula method to estimate internal $O_2$ concentrations in fruit assumes a 'hollow sphere' model of gas movement in the fruit. This model is based on the skin being the main site of resistance to $O_2$ entry into the fruit and that there is little constraint on $O_2$ movement internally. In this case, no gradients in $O_2$ concentrations would be expected inside fruit. They tested this model for banana by coating, with wax, various fractions of the fruit and measuring the gradients in internal $O_2$ concentrations using cannulae sited at five positions along the fruit length. They found internal gradients of less than 1 kPa along the fruit length in uncoated fruit but up to 12 kPa in fruit that was half coated with wax. In addition, the gradients in the coated fruit

increased from 2 to 12 kPa along the fruit length, as the fruit ripened. Perez and Beaudry (1998) concluded that the 'hollow sphere' model of gas exchange was not appropriate for banana. To calculate $O_2$ gradients, Banks (1985a) adopted a cylindrical model, but applied it only to the pulp. However, the whole banana fruit consists of the peel and the pulp, and a more comprehensive model would need to take account of both tissues. The peel and the pulp can be considered as two concentric cylinders. Then, the equations used to calculate $O_2$ profiles across roots, which have layers of tissues arranged concentrically (Armstrong *et al*. 1991), can be adapted to the whole banana fruit. Assuming the supply of $O_2$ to the fruit is radial, the $O_2$ deficit from the outside of the peel to the centre of the fruit, $\Delta C_T$, is:

$$\Delta C_T = \Delta C_S + \Delta C_{S1} + \Delta C_P \quad \text{(Eqn 3.1)}$$

where $\Delta C_S$ is the *in situ* deficit across the peel caused by the respiration rate of the peel, $\Delta C_{S1}$ is the deficit across the peel caused by the respiration of the pulp (through flow) and $\Delta C_p$ is the *in situ* deficit across the pulp caused by the respiration rate of the pulp. The individual components of equation 1 are:

$$\Delta C_S = [Q_S\, r_P^2/4D_S]\, [(r_S^2/r_P^2) + 2\ln(r_P^2/r_S^2) - 1] \quad \text{(Eqn 3.2)}$$

$$\Delta C_{S1} = [Q_P\, r_P^2/2D_S]\, [\ln(r_S/r_P)] \quad \text{(Eqn 3.3)}$$

$$\Delta C_P = [Q_P\, r_P^2/4D_P] \quad \text{(Eqn 3.4)}$$

where $r_S$ is the outer radius of the peel; $r_P$ is the radius of the pulp; $Q_S$ is the respiration rate of the peel, per unit volume; $Q_P$ is the respiration rate of the pulp, per unit volume; $D_S$ is the diffusion coefficient of $O_2$ for the peel and $D_P$ is the diffusion coefficient of $O_2$ for the pulp. These equations apply only until the centre of the peel becomes anoxic.

An advantage of the miniaturized oxygen electrode used by Brändle (1968) is that no assumptions need to be made about the distribution of $O_2$ in the fruit because the electrode measures $O_2$ concentration *in situ*. Micro-electrodes are now available (Armstrong *et al*. 2000) and these would be particularly useful for measuring $O_2$ concentrations in fruit tissue. Data collected using electrodes will provide a suitable validation of the models assumed by the use of the cannula method for estimating $O_2$ concentration in the pulp.

Estimates of the radial (beneath the peel to the fruit centre) and axial gradients of $O_2$ partial pressure in the pulp can be made from the data of Wardlaw and Leonard (1940), Brändle (1968) and Perez and Beaudry (1998). The radial gradient within a green fruit was 90 Pa/mm (Wardlaw and Leonard 1940) rising to 210 Pa/mm in ripe fruit (Brändle 1968). The maximum axial gradient in ripe fruit, assuming a pulp length of 150 mm in the fruit used by Perez and Beaudry (1998), was 80 Pa/mm, similar to the radial gradient in green fruit obtained from the data of Wardlaw and Leonard (1940). However, this axial gradient applies only to the artificial situation where half the fruit is coated with wax. In uncoated fruit, the axial gradient is minimal at 7 Pa/mm. This small axial gradient supports the assumption of using two concentric cylinders to estimate $O_2$ concentrations within the fruit. These radial gradients of $O_2$ in banana pulp, although approximations for the data of Wardlaw and Leonard (1940) and Perez and Beaudry (1998) are of the same order as recorded in apples (Burton 1982) but are much greater than the theoretical radial gradients of 5–13 Pa/mm calculated by Banks (1985a). The difference between the calculated values and the measurements indicates a greater resistance to diffusion of $O_2$ through the tissues in reality, compared with the simplifying assumptions of the model used by Banks (1985a). In apples, gradients of $O_2$ partial pressure similar to those measured in banana are associated with breakdown disorders in fruit stored in controlled atmospheres. Thus, $O_2$ gradients in the pulp of banana may contribute to the negative impacts of controlled and modified atmospheres on fruit physiology. The picture that we have of $O_2$ distribution in the banana fruit at the moment is incomplete. Studies are needed of the anatomy of the peel and pulp, their separate respiration rates and the distribution of $O_2$ in the tissues in green and ripening fruit. Work on the fruit surface described by Banks (1984) needs to be complemented with measurements of $O_2$ distribution within the peel and pulp. This knowledge would support studies on why the ripening of fruit coated with waxes tends to be patchy, thus reducing their use in commerce.

Here we have focused on the concentration of $O_2$ in fruit tissues. In modified atmosphere storage, there is an increased concentration of $CO_2$ and $C_2H_4$ may accumulate in the tissues of fruit coated with impermeable substances (Banks 1983). In addition, if areas of anaerobic tissue develop in the fruit, then the products of alcoholic fermentation may accumulate. To advance the technology of modified atmosphere storage of banana, it is important to undertake studies on the individual components of the gas system before attempting to build an integrated picture.

### *Short-term oxygen deficiency*

Bananas are usually transported long distances in cartons containing 15 to 18 kg of fruit. The practical application of modified atmosphere technology in bananas using

polythene bags has been limited by uncertainties about the security of seals in individual cartons and the need to remove the polyethylene bags and $C_2H_4$ absorbent from each carton for purposes of ripening the fruit (Wills *et al*. 1982). To avoid these problems, treatments that prolong green-life, and that can be applied after harvest but before transport to market, have been sought. Wills *et al*. (1982) extended the green-life of bananas by exposing them to low (less than 1 kPa) $O_2$ concentrations for 2 to 3 days immediately after harvest. The internal $O_2$ concentration equalled that used for treatment and then returned to control levels within 24 hours of the fruit being returned to air. Two days of exposure to low $O_2$ concentration delayed ripening by 5 days, and 3 days of exposure delayed ripening by 7–8 days in one experiment and 12 days in another. Thus there was a net increase of 3–9 days in the green-life of the fruit, which is significant but somewhat less than that achieved by modified atmosphere packaging (Table 3.1). The extension of green-life, since it occurred after the fruit had been returned to air, was attributed to the effect of the $O_2$ deficiency on $C_2H_4$ synthesis supported by the observation that endogenous production of $C_2H_4$ was suppressed but the addition of exogenous $C_2H_4$ hastened ripening of the treated fruit. In another experiment, Wills *et al*. (1982) exposed fruit to a range of $O_2$ concentrations between 0 and 21 kPa for 3 days and found that the extension of green-life was inversely proportional to the concentration of $O_2$ used. The increase in green-life was 0.31 days/kPa $O_2$ as $O_2$ concentration fell from 21 to 0 kPa. Wills *et al*. (1982) point out that a threshold might be expected, especially since the $K_m$ $O_2$ for $C_2H_4$ production is 2.2 kPa (Banks 1985a), rather than a proportional increase in green-life over the whole range. While short-term $O_2$ deficiency may interfere with $C_2H_4$ synthesis on return of the fruit to air, it may also affect the sensitivity of the fruit to $C_2H_4$ through the synthesis of $C_2H_4$ binding sites. Oxygen concentrations in the range 21 to 100 kPa increase the rate at which banana fruit soften and this is attributed to the effect of $O_2$ in increasing the synthesis of $C_2H_4$ binding sites in Cavendish cv 'Williams' (Jiang and Joyce 2003).

Wills *et al*. (1990) extended the work of Wills *et al*. (1982) by evaluating the effect of 3 days of nitrogen treatment (low oxygen, <0.5 kPa) on cv 'Williams' (AAA, Cavendish subgroup) bananas grown in the tropics and subtropics and in different seasons in those locations. Low $O_2$ treatment extended green-life by about a week but caused some burning of the peel where it had been previously ruptured. The magnitude of the damage increased with the delay after harvest in applying the low $O_2$ treatment.

**Manipulation of shelf life**

An increase in shelf life would make fruit available to consumers for longer in retail shops and would extend the time over which fruit might be consumed in the home.

***Peel spotting***

The development of brown spots on the peel of ripe bananas indicates the end of shelf life in cultivars of the Cavendish subgroup (AAA) (Wardlaw and Leonard 1940). In the AA group cv 'Sucrier', spotting begins when the peel is slightly more yellow than green (Trakulnaleumsai *et al*. 2006). For consumers familiar with the 'Sucrier' cultivar, the spotting indicates the fruit is ready for eating. However, consumers more familiar with the Cavendish cultivars, perceive that the 'Sucrier' fruit is likely to be over-ripe if peel spotting has begun. This perception limits the ability of 'Sucrier' fruit to penetrate markets where Cavendish cultivars dominate, even though consumers are interested in greater diversity of cultivars of bananas to increase their choices.

The fungal organism, *Colletotrichum musae* (Berk. and Curtis) Arx, causes anthracnose, which exists in green banana fruit as a latent infection in the peel and appears as brown spots when the fruit ripens (Muirhead and Jones 2000). Trakulnaleumsai *et al*. (2006) point out the difficulty of distinguishing between anthracnose infection and peel spotting that may either have a physiological origin or indicate senescence of the peel tissue. While anthracnose is very common and causes brown spots on the peel of bananas, it is unlikely that all brown spots will be due to anthracnose. An additional difficulty is that fungicides applied to the peel surface, whether pre- or post-harvest, are unlikely to control a latent infection beneath the fruit surface.

Studies on peel spotting have examined the factors that limit the rate of browning, such as the activity of phenylalanine ammonia lyase (PAL), which converts phenylalanine to free phenolic substances, which form the substrate that polyphenol oxidase (PPO) converts to quinines producing the browning reaction (Choehom *et al*. 2004; Trakulnaleumsai *et al*. 2006; Maneenuam *et al*. 2007). In addition, environmental factors such as temperature (Trakulnaleumsai *et al*. 2006), vapour pressure deficit, $O_2$ concentration (Maneenuam *et al*. 2007) and modified atmospheres (Choehom *et al*. 2004) have been examined.

The association between the activity of the enzymes PPO and PAL, free phenolics and the level of browning of the peel seems to vary between experiments. Maneenuam *et al*. (2007) propose a model that integrates the enzymatic data from a number of experiments. The limiting factor in browning is the supply of $O_2$ over the range of 5 to 90 kPa. The activities of PPO and PAL and the amount of free

phenolics do not limit the browning reactions. However, dopamine, a free phenolic compound, decreases more rapidly where browning is more intense and it might be used as a substrate. Since PPO and PAL are not limiting in the case of peel spotting, Trakulnaleumsai *et al*. (2006) point out that control of browning by modulating these enzymes lacks promise.

Peel spotting develops more rapidly at high temperature (25–27°C) than at lower temperatures, and 12°C prevents peel spotting without causing chilling injury to the fruit (Trakulnaleumsai *et al*. 2006). However, 12°C is too cool for the peel to yellow and the pulp to ripen and so fruit cannot be continuously held at 12°C. Moreover, fruit held at 12°C develops peel spotting when returned to higher temperatures. The absence of peel spotting at 12°C, but at $O_2$ concentrations that are well able to support spotting, raises some questions. It is unlikely that this temperature is too cold for enzyme activity because changes in PPO and PAL activity are correlated with the appearance of browning in fruit of 'Sucrier' that are stored at 6°C or 10°C and that experience chilling injury (Nguyen *et al*. 2003, 2004). When fruit are chilled, the membranes in the tissues lose their integrity, which is a prerequisite for damage, and browning is a common symptom of this damage. At 12°C, in the absence of chilling injury in cv 'Sucrier', no peel spotting occurs, and so at this temperature the prerequisite rupturing of cells may not have been achieved and so brown spotting of the peel is suppressed. This implies a rupturing of the cells or membranes in the peel for spotting to proceed. Coincidentally, the optimum temperature for the growth of anthracnose is 27–30°C, and there is little growth below 15°C (Muirhead and Jones 2000).

Browning reactions occur when enzymes and substrate that are normally separate within cells are brought together. This is often associated with changes in membrane integrity and so studies on lesion development in the peel of banana, such as have been done with superficial blemishes (Williams *et al*. 1989), may provide a useful way forward for identifying the cause and subsequently managing peel spotting.

### *Finger drop*

When bananas are ripened in hands, the individual fruit may break at the pedicel when ripe. Some cultivars of banana are more susceptible to this condition than others, and it can be very important if fruit are ripened on bunches and then transported. Paull (1996) summarized work on this problem and undertook investigations into factors associated with finger drop in cv 'Prata Anã' (AAB, Pome group) bananas. Finger drop, which varied from 0% to 100% between treatments and occurred when the fruit were full yellow, was less in mature fruit that had been ripened at lower temperatures (17.5°C compared with 25°C) and that had received $C_2H_4$ treatment to initiate ripening.

### *Oxygen deficiency to extend shelf life*

Klieber *et al*. (2002) investigated N storage of ripe bananas (Cavendish cv 'Williams') for 6 to 24 hours to extend shelf life, based on the work of Wills *et al*. (1990) in extending green-life. The fruit were either more green than yellow or more yellow than green at the start of the treatment, and $O_2$ concentrations were limited to $<1.0$ kPa. Fruit were returned to air after treatment. N storage did not extend the shelf life, and the treated fruit displayed browning of the peel. Klieber *et al*. (2002) point out that the ripe fruit respond differently to short-term $O_2$ deficiency on return to air than do green fruit. Ripe fruit continue their ripening process when returned to air after exposure to $<1$ kPa $O_2$, but green fruit show a delay in ripening (Wills *et al*. 1982). However, when Wills *et al*. (1982) exposed green fruit to $<1$ kPa $O_2$ for 6 to 20 hours, the same time span as used by Klieber *et al*. (2002), they observed no effect of the treatment on green-life on return of the fruit to air. To delay the ripening of green fruit, exposure to low $O_2$ for 2 to 3 days was needed. Thus ripe and green fruit need not differ in their response to short-term $O_2$ deficiency when exposure is less than a day. In contrast to the results of Wills *et al*. (1982), Yi *et al*. (2006) extended the green-life of cv 'Brazil' (AAA group) bananas by 6 days by exposing the fruit to 0.05 kPa $O_2$ for just 9 hours, considerably less than the 2 to 3 days observed by Wills *et al*. (1982). A lesser or greater exposure time, within the range of 0 to 24 hours, had less effect. A difficulty in the interpretation of these responses is that we do not know what is happening inside the fruit during the treatment phase, in terms of either $O_2$ concentration or the metabolism of the pulp or peel.

These treatments, in another context, would be termed 'anoxic shock' (Gibbs and Greenway 2003), which is the sudden exposure of plant tissue to anoxia. The effect that 'anoxic shock' has on tissues differs from that when the tissue is exposed more gradually to the $O_2$ deficiency. There is a need to separate the effects of sudden imposition from gradual imposition of $O_2$ deficiency and to decide what might be desirable outcomes for the quality of the produce. Separating 'anoxic shock' from more gradual development of $O_2$ deficiency might not be easy in very bulky organs. As the banana fruit ripens over a period of days, the internal $O_2$ concentration decreases and regions of $O_2$ deficiency in the pulp would develop gradually. In this situation, it is likely that regions of anoxia may be

adjacent to aerobic regions within the fruit. This is a very different situation from that imposed by 'anoxic shock' treatments where the change in $O_2$ supply is not only sudden but also presumably throughout the whole fruit.

**Interactions between the peel and the pulp**

The banana and plantain fruit have two major morphological components, the peel and the pulp. The peel is the wall of the inferior ovary and has completed much of its growth in length just after the inflorescence emerges from the top of the pseudostem (anthesis). The pulp develops, after anthesis, from the outer edge of the loculus, that is, the internal walls of the peel. As the pulp grows, the fruit expands radially and the weight of the peel decreases as a proportion of the weight of the whole fruit. Bananas are growing rapidly when they are harvested and banana growers use the lateral dimensions of the fruit as a measure of maturity for harvest. Thinner fruit is sent to more distant markets because it is less mature and has a longer green-life than fruit that is more 'full'. Consumers judge the ripeness of the pulp by the colour of the peel and so it is important to match the stage of ripeness of the peel with that of the pulp. That the two can be separated is of interest in commerce and biologically. For the Cavendish cultivars, the temperature of ripening is a simple way to change the rate of ripening of the pulp, independently of the peel. At high temperatures, the pulp ripens in advance of the peel and the reverse is true at cool temperatures (Peacock 1980). Differences between the peel and pulp have been of interest to physiologists for many decades (Gore 1914).

***De-greening of the peel***

During ripening the chlorophyll in the peel breaks down, revealing yellow pigments. At temperatures above 24°C, chlorophyll breakdown is slowed down and the pulp may become over-ripe while the peel is still green (Seymour *et al*. 1987). Plantains do not show this behaviour (Blackbourn *et al*. 1990). Drury *et al*. (1999) followed the catabolism of chlorophyll in the peel of bananas ripened at 20°C or 35°C. Chlorophyll was degraded at both temperatures, but the rate of loss was reduced at 35°C compared with that at 20°C. They observed that all the steps involved in chlorophyll catabolism that they examined functioned at 35°C as well as at 20°C. Therefore, they suggested that the slower rate of chlorophyll catabolism at 35°C may be related to the release of the chlorophyll from the thylakoid membranes, preventing its movement to the chloroplast envelope where disassembly begins. Drury *et al*. (1999) found that the mechanism of retention of green colour in bananas ripening at high temperature differed from the 'stay-green' phenomenon seen in some plant species. In the 'stay-green' types, there is an inhibition of pheophorbide *a* oxygenase, but this was not the case for banana. Drury *et al*. (1999) evaluated ripening related gene expression in the peel at 20°C and 35°C. At the high temperature, the majority of clones was unaffected. This supported the view that the effect of high temperature on peel de-greening was not a reflection of the inhibition of the ripening process. They thought the important change was the down regulation of ATP-citrate lyase (ATP-CL) at 35°C compared with 20°C. They proposed that in senescence, ATP-CL may be involved in regulating the energy supply within cells and it may have a role in the conversion of chloroplast to chromoplast.

Plainsirichai *et al*. (2003) used auto-fluorescence to examine the changes in the chlorophyll of the peel of the dessert banana cv 'Chinese Cavendish' (AAA, Cavendish subgroup) and the cooking banana cv 'Bluggoe' (ABB group) ripening at 20°C or 30°C. They found that chlorophyll auto-fluorescence disappeared from the peel of both cultivars ripened at 20°C but was retained in cv 'Chinese Cavendish' at 30°C but only in the cells adjacent to the surface of the peel. In the remainder of the peel, chlorophyll auto-fluorescence disappeared as the fruit ripened. These observations are consistent with those of Drury et al (1999) and earlier studies, that chlorophyll is degraded at high temperature in bananas albeit at a slower rate than at 20°C. The retention of chlorophyll in the cells adjacent to the surface of the peel has implications for studies where the whole peel is macerated to extract biochemical components in an attempt to discover what is happening to the chlorophyll.

***The pulp and the peel during ripening***

The main issues are where does ripening start, pulp or peel, and what mechanisms control $C_2H_4$ biosynthesis and action in the peel and the pulp, given the central importance of $C_2H_4$ in the ripening of banana? In exploring these issues differences in methodology and the use of 1-methylcyclopropene (1-MCP) to block ethylene action are highlighted as we work towards uncovering the control mechanisms.

The pulp and the peel undergo ripening, and most of the genes that are up- or down-regulated in the pulp as it ripens (Medina-Suárez *et al*. 1997) also change in the peel (Drury *et al*. 1999). The degradation of chlorophyll during ripening is unique to the peel. The banana fruit ripens in response to exogenous $C_2H_4$ and so in commerce the peel is exposed to $C_2H_4$ before the pulp. Does exogenous $C_2H_4$ stimulate ripening in banana in the same way as endogenous $C_2H_4$? Dominguez and Vendrell (1993) investigated the capacity

of the pulp and peel to produce endogenous $C_2H_4$ in cv 'Dwarf Cavendish' (AAA, Cavendish subgroup) as the fruit ripened. They separated the pulp and peel while the fruit was green and then monitored $C_2H_4$ production by each tissue. Seven days after the experiment began the pulp began to produce $C_2H_4$, and maximum $C_2H_4$ production occurred 2 days later. After this, $C_2H_4$ production by the pulp decreased. The peel produced very little $C_2H_4$ during ripening, but some appeared when senescence began after 12–13 days. ACC oxidase activity differed between the peel and pulp. In the pulp, ACC oxidase activity rose and fell following the pattern of $C_2H_4$ evolution, indicating a close link between the two. In contrast, in the peel ACC oxidase activity began to increase 8 days after the experiment began and continued to increase until senescence. In the peel, there was no link between ACC oxidase activity and $C_2H_4$ evolution. However, Dominguez and Vendrell (1993) showed that the peel is well able to generate $C_2H_4$ provided sufficient 1-aminocyclopropane-1-carboxylic acid (ACC) substrate is supplied. They proposed that the ACC oxidase activity of the pulp was important for starting the autocatalytic $C_2H_4$ production needed for ripening. The response of the peel was then governed by the diffusion of $C_2H_4$ from the pulp. The banana ripens from the inside out, supporting observations of Wardlaw and Leonard (1940) on cv Gros Michel (AAA group, Gros Michel subgroup).

Dominguez and Vendrell (1994) subsequently obtained similar results to their earlier work by exposing either the whole fruit or slices or separate pieces of peel and pulp to exogenous $C_2H_4$. The pulp responded by increasing $C_2H_4$ production but the peel showed only a temporary increase and then returned to control levels. They suggested that the peel did not have the capacity for autocatalytic $C_2H_4$ production that was a feature of the pulp.

Moya-León and John (1994) point out that ACC oxidase requires ascorbate as a co-substrate and iron and carbon dioxide as co-factors for full expression of activity. They were concerned that the results of Dominguez and Vendrell (1993) could have been influenced by lack of co-substrate and co-factors for ACC oxidase. They added these to the peel and the pulp in their studies on ACC oxidase activity in cv Cavendish (AAA) bananas from the Caribbean. Moya-León and John (1994) obtained results that differed from those of Dominguez and Vendrell (1993) in one important respect. The peak in ACC oxidase activity in the pulp during ripening, observed by Dominguez and Vendrell (1993), did not occur when the co-substrate and co-factors were added. They suggested that this did not support the view that $C_2H_4$ production by the pulp triggered ripening in banana because the pulp is unable to sustain $C_2H_4$ evolution if ACC oxidase is limited by the supply of co-substrate or co-factors. Moya-León and John (1994) do not present any data on the $C_2H_4$ evolution of the whole fruit, pulp or peel in the absence of added ACC, and so it is not clear what is happening during the course of ripening in the fruit that they used. Dominguez and Vendrell (1993) separated the peel and pulp while the fruit were green and the two tissues ripened independently of one another. In addition, they showed that wound $C_2H_4$ lasted for only 24 hours and was far removed in time from the initiation of ripening. In contrast, Moya-León and John (1994) seem to have separated the peel and pulp during the course of ripening. In their case, the pulp and peel have ripened together in the intact fruit and the one may influence the behaviour of the other, as well as confounding any effect of the wounding on $C_2H_4$ production.

Inaba *et al*. (2007) point out that the evolution of $C_2H_4$ during the ripening of banana fruit is unique in that it rises to a peak within a day or two of the start of catalytic $C_2H_4$ production and then declines. This contrasts with other climacteric fruit where $C_2H_4$ evolution continues at a high rate. The peak in $C_2H_4$ production in banana can be readily observed in the data of Banks (1985b), Dominguez and Vendrell (1993, 1994), Golding *et al*. (1998) and van Luan *et al*. (2003), among others. Chilling injury (van Luan *et al*. 2003) or coating the fruit (Banks 1985b) modifies the pattern of $C_2H_4$ evolution by flattening and extending the peak.

Even though the fruit consists of two morphologically different tissues, the pattern of evolution of $C_2H_4$ from the whole fruit during ripening is dominated by the behaviour of the pulp. Golding *et al*. (1998) used 1-methylcyclopropene (1-MCP), a nonreversible blocker of $C_2H_4$ receptor sites, to investigate the role of $C_2H_4$ in the different stages of ripening. If 1-MCP stops or delays a process, this infers that the process is influenced by $C_2H_4$. 1-MCP was applied either when the fruit were green or at 6, 12 or 24 hours after the fruit were exposed to propylene to initiate ripening. 1-MCP delayed all ripening processes when applied either to green fruit or to fruit at 6 or 12 hours after ripening was initiated. However, at 24 hours after ripening began, 1-MCP did not alter the climacteric peaks of $C_2H_4$ evolution or respiration but did affect de-greening and the production of volatiles. All fruit treated with 1-MCP showed an increased production of $C_2H_4$, when it did occur, and a reduced rate of respiration. Propylene supplied continuously to fruit, suppressed $C_2H_4$ production and Golding *et al*. (1998) interpret this as a suppression of either ACC synthase and ACC oxidase or an increased conversion of ACC to the inactive malonyl-ACC. Each of

these actions would reduce $C_2H_4$ synthesis and Inaba *et al*. (2007) described it as a negative feedback regulatory mechanism. Golding *et al*. (1998) concluded that most changes in fruit biochemistry related to ripening depend on the functioning of $C_2H_4$ receptors during the first 24 hours after initiation of ripening by propylene and that sensitivity to $C_2H_4$ increases after ripening is initiated.

Since $C_2H_4$ is known to suppress $C_2H_4$ evolution in banana (Vendrell and McGlasson 1971), Inaba *et al*. (2007) investigated the feedback mechanisms of $C_2H_4$ in banana peel and pulp. They used cv 'Grand Nain' (AAA, Cavendish subgroup) grown in the Philippines. They applied 1-MCP before and after ripening had been initiated by propylene and measured $C_2H_4$ evolution as well as the activities of ACC synthase and oxidase, the genes associated with these enzymes and the content of ACC in the tissues. In the pulp, propylene stimulated $C_2H_4$ production within 24 hours and then, adding 1-MCP doubled the production of $C_2H_4$. By contrast, in the peel tissue, 1-MCP reduced $C_2H_4$ production to very low levels, compared with the effect of propylene alone. In addition, the peel began to produce $C_2H_4$ one day later, after ripening began, than the pulp. Inaba *et al*. (2007) suggest that the peel and the pulp have different feedback regulatory mechanisms for the biosynthesis of $C_2H_4$. For the pulp, an increase in $C_2H_4$ reduces ACC synthase activity and there is also an effect of the supply of co-substrate and co-factors to ACC oxidase which produces $C_2H_4$ from ACC. If co-substrate or co-factors become limiting then $C_2H_4$ production is reduced.

In the peel, 1-MCP suppressed activity of ACC synthase and ACC oxidase, implying that $C_2H_4$ has a positive feedback mechanism in this tissue (Inaba *et al*. 2007). Ethylene promoted the activity of ACC oxidase and ACC synthase and we would expect that this would stimulate $C_2H_4$ evolution. This is not the case because $C_2H_4$ promotes the activity of malonyl ACC transferase which deprives ACC synthase of substrate. While the peel displays a positive feedback mechanism for $C_2H_4$ biosynthesis, the amount of $C_2H_4$ produced is governed by the amount of ACC channeled to malonyl ACC, which is not available for synthesis of $C_2H_4$ (Dominguez and Vendrell 1993).

Inaba *et al*. (2007) proposed that in banana exogenous $C_2H_4$ induced ripening which in turn induced endogenous production of $C_2H_4$. In the pulp, $C_2H_4$ biosynthesis is under negative feedback control and in the peel, while under positive feedback control, $C_2H_4$ evolution is limited by the availability of free ACC. The combined effect of the two tissues is observed in the whole fruit, an increase in $C_2H_4$ evolution early in ripening followed by a decrease. However, this pattern can be modified by other environmental factors and so the contribution of pulp and peel to these changes needs to be separated. A heightened awareness of the differences between physiology of the peel and the pulp in banana may lead to deeper knowledge of the control mechanisms in each tissue and their interaction. It would be especially interesting to explore these effects in different cultivars, such as the cv 'Sucrier' (AA) with its peel spotting problem and a cultivar of the AAA, Cavendish subgroup where the peel and pulp respond differently to high and low temperature.

## Ethanol and acetaldehyde

There are two aspects of the metabolism of ethanol and acetaldehyde that are important for bananas. One is the endogenous production of ethanol by ripening fruits, even when in air and the other is the use of exogenous ethanol or acetaldehyde to modify ripening behaviour, reduce astringency or enhance flavours. Pesis (2005) reviewed experiments on the use of ethanol and acetaldehyde to modify the post-harvest behaviour of fruits.

### *Ethanol metabolism*

Ethanol is produced in anoxic tissue, *in situ*, when pyruvate decarboxylase (PDC) converts pyruvate to acetaldehyde, which in turn is converted to ethanol by alcohol dehydrogenase (ADH). The last reaction is reversible. Ethanolic fermentation is the main metabolic pathway that produces energy in anaerobic tissues in plants since $O_2$ deficiency inhibits pyruvate dehydrogenase, cutting off the tricarboxylic acid (TCA) cycle. However, the ethanolic fermentation pathway produces only one tenth of the energy, per unit of hexose metabolized, compared with the TCA cycle (Gibbs and Greenway 2003). Thus, $O_2$ deficiency creates an energy crisis in plant cells. Bulky tissues, such as fruits and storage roots, produce ethanol even when they are situated in air. The ethanol may be produced in regions of these organs that are deficient in oxygen, as suggested by Gustafson (1930, 1934) for ripening tomatoes, or it may be activated by other mechanisms such as a deficiency of energy (Gibbs and Greenway 2003) or by acidosis, an acidification of the cytoplasm (Longhurst *et al*. 1990). In fruit tissues under anoxia, ethanol accumulates during continued exposure, while acetaldehyde soon reaches a maximum level. Since plant tissue is permeable to ethanol it can readily diffuse from anoxic to more aerated regions of these organs and enter general metabolism. There it is oxidized to acetaldehyde, which in turn can be converted by aldehyde dehydrogenase to acetyl coenzyme A, a precursor of acetate esters. Acyl-CoA is the precursor for longer esters, compounds that are responsible for the aroma of ripened fruits.

In addition to being produced *in situ*, ethanol moves in the transpiration stream to other organs of the plant that are aerobic. In whole plants of the cottonwood tree (*Populus deltoides*), ethanol can be transported from the roots to the shoots and metabolized in the shoots with little loss of ethanol to the external environment (Kimmerer and MacDonald 1987; MacDonald and Kimmerer 1993). Ethanol is present in the leaves of cottonwood trees even in the absence of flooding, but flooding the root system increases the amount of ethanol in leaves considerably. Whether this happens in bananas and plantains is undetermined, but their roots are very sensitive to poor drainage in the field (Aguilar *et al*. 2003), and it is possible that fruit may contain ethanol at harvest, even if the fruit is aerated. The metabolism of the ethanol would then depend on the activity of ADH within the fruit tissues.

### *Is ethanol toxic?*

Anoxia injures plant tissues to a varying extent and the role of ethanol in this injury has been debated for a long time. Early thinking was that ethanol was toxic, but data now support the view that, in most systems, it is acetaldehyde that is responsible for injury. For example, carrot cells in culture are very sensitive to ethanol in the medium (Perata and Alpi 1991). The first oxidative product of ethanol is acetaldehyde, the sequence that might be expected in aerated tissues. When an inhibitor of ADH was added, the carrot cells showed no toxicity to ethanol, showing that acetaldehyde was responsible for the damage. In an earlier experiment, Jackson *et al*. (1982) tested the toxicity of ethanol by adding it to plant tissues experiencing $O_2$ deficiency. If the ethanol did not cause any further damage, this implied that ethanol itself was not toxic. Gibbs and Greenway (2003) point out that experiments under aerated conditions may not be relevant to the accumulation of ethanol under anoxia.

### *Ethanol and acetaldehyde in bananas*

Bananas ripening in air produce ethanol (Tressl and Jennings 1972) and contain ethanol in their tissues (Banks 1984; Bagnato *et al*. 2003). Exogenous ethanol application has been investigated as a treatment for managing green-life (Hewage *et al*. 1995), shelf life (Bagnato *et al*. 2003) and astringency (Esguerra *et al*. 1992, 1993) in bananas. Tressl and Jennings (1972) ripened cv 'Valery' (AAA, Cavendish subgroup) at 25°C and sampled the ventilated head space twice daily. Ethanol appeared at peak flavour, 3–4 days after ripening began. The concentration of ethanol in the head space rose until 6 days and then remained stable until 10–12 days, when the fruit were over-ripe and measurements ceased. Banks (1984) measured the concentration of ethanol produced by the pulp of ripening cv 'Valery' fruit. Measurements were made 1, 5 and 9 days after ripening began and showed an approximately linear increase in ethanol concentration in the pulp over time. Coating the fruit with an aqueous dispersion of sucrose esters of fatty acids increased the ethanol concentration in the pulp, compared with the control, by an amount that was similar in magnitude throughout the 9 days. In these fruit the internal $O_2$ concentration, measured by cannula methods, was stable at 5–6 kPa in the coated fruit and 11–15 kPa in the control fruit.

Bagnato *et al*. (2003) measured ethanol concentrations in the peel and pulp of green and ripe bananas of cv 'Williams' (AAA, Cavendish subgroup) that had been grown in the tropics and within three days of harvest. The fruit were ripened in air. When green, the peel contained 10 nl ethanol g $fwt^{-1}$ which increased 70-fold to 700 nl g $fwt^{-1}$ in fruit that were fully yellow. The pulp of green fruit contained 14 nl ethanol g $fwt^{-1}$ which increased almost 70-fold to 950 nl g $fwt^{-1}$ when the fruit were fully yellow.

In an effort to alter green-life, some studies examined the application of ethanol to green banana fruit. Interest in this arises, in part, from work with carnation flowers, *Dianthus caryophyllus* L. (Heins 1980) and tomato, *Lycopersicon esculentum* (Saltviet and Mencarelli 1988). In carnation and tomato ethanol delayed senescence or ripening, although the effect in tomato was subsequently shown to be caused by acetaldehyde rather than ethanol (Beaulieu *et al*. 1997). Ethanol, rather than acetaldehyde, mitigates chilling injury symptoms in some tissues (Frenkel and Erez 1996), and this is of interest in bananas. In addition to the work on carnation and tomato, it is argued that the ethanol that is produced and accumulates in anaerobic tissues, such as when bananas are placed in modified atmospheres, may 'interfere' with $C_2H_4$ metabolism, causing the increase in green-life observed (Hewage *et al*. 1995).

Ethanol, applied as a spray to the fruit of cvv 'Cavendish subgroup' (AAA), 'Señorita' (AA group) and 'Saba' (ABB), slowed the ripening of fruit that had received $C_2H_4$ (Agravante *et al*. 1994). Fruit without $C_2H_4$ treatment were not included in these experiments. The Cavendish and 'Señorita' cultivars are dessert bananas, but fruit of 'Saba' is used for cooking. In all three cultivars, ethanol hastened the reduction in tannins as the fruit ripened. 'Señorita' bananas have a much higher concentration of tannins (about fivefold) than do Cavendish cultivars. In Japan, 'Señorita' bananas imported from the Philippines are ripened in the same rooms as Cavendish fruit. This strategy releases the 'Señorita' bananas onto the market while they

are still astringent, creating resistance among consumers to purchasing them. Ethanol reduces the astringency of these fruit and makes them palatable (Esguerra *et al*. 1992, 1993).

Ethanol vapour, applied before or after fruit were exposed to ethylene, had no effect on the ripening of Cavendish bananas in experiments reported by Hewage *et al*. (1995). However, vapour of acetaldehyde, at an appropriate concentration, prevented ripening. In addition, acetaldehyde vapour damaged the fruit the severity being proportional to the concentration of acetaldehyde used. Ritenour *et al*. (1997) sought to delay the ripening of Cavendish bananas by exposing them to ethanol vapour but this treatment had no effect, although it delayed ripening in whole avocado and, if injected into the seed cavity, in honeydew and musk melon. Bagnato et al (2003) were concerned that the ethanol applied as vapour by Hewage *et al*. (1995) and Ritenour *et al*. (1997) did not penetrate the fruit and therefore was not able to act. They vacuum infiltrated cv 'Williams' (AAA, Cavendish subgroup) bananas and measured the concentrations of ethanol in the peel and pulp of control and treated bananas, immediately after treatment and when the fruit had subsequently reached the full yellow stage of ripeness. The vacuum treatment increased the ethanol concentration in the peel by 40-fold, but had no significant effect on the ethanol concentration in the pulp. These fruit ripened normally, with no effects of the vacuum infiltrated ethanol on the process. Bagnato *et al*. (2003) believed that if the ethanol was to affect ripening it needed to penetrate the pulp, which produces $C_2H_4$ in an autocatalytic process as it ripens, thus supplying $C_2H_4$ to the peel. The inability of the vacuum treatment to increase ethanol concentration in the pulp therefore precluded any effect. They also suggest that even though the vacuum increased ethanol in the peel, it may have been dissipated before ripening began, allowing the fruit to ripen normally.

There are a number of issues concerning the work on ethanol in bananas. Ritenour *et al*. (1997) mention the problem of penetration of the ethanol into tissues and the work of Bagnato *et al*. (2003) show that this is important for bananas. Ritenour *et al*. (1997) also suggest that lack of constitutive activity of alcohol dehydrogenase (ADH) to convert ethanol to acetaldehyde may be a problem, if it is the active factor as seems likely in banana (Hewage *et al*. 1995). Tan *et al*. (1987) measured ADH activity in pulp extracts of green and ripening fruit of cv 'Sucrier' (AA), including fruit stored in a modified atmosphere. During 10 days of storage, the $O_2$ concentration in the modified atmosphere around the fruit fell from 12 to 8 kPa and $CO_2$ concentration rose from 4 to 7 kPa. Over this time, the activity of ADH in pulp extracts increased about 12 fold irrespective of whether the fruit were in the modified atmosphere or whether they were ripening in air. In addition, Tan *et al*. (1987) showed no inhibitory effect of $CO_2$ on ADH activity in the range of 0 to 15 kPa $CO_2$. It appears that the pulp of banana contains sufficient ADH for ethanol metabolism and the concentrations of ethanol present in the peel of ripe fruit would imply that lack of ADH activity in the peel is not a problem. Ethanol is a volatile substance, alluded to by Bagnato *et al*. (2003). Ethanol may dissipate soon after application, even if it can be metabolized once it penetrates the target tissues. Heins (1980) was sensitive to this issue in his work on carnation flowers and dealt with it by renewing treatment solutions and measuring ethanol in the target tissues. In the experiments on bananas, only Bagnato *et al*. (2003) provide measurements of the effect of the ethanol treatment on the concentration of ethanol in tissues. Their measurements are very useful but, as they acknowledge, not frequent enough to tell us whether the concentrations were sustained over time in green fruit.

## CONCLUSIONS

Bananas and plantains are a major food crop for the world, and these fruits have a limited post-harvest life. For the international banana trade sophisticated post-harvest management systems are in place, but these are not perfect. Most of the bananas grown in the world do not enter the international trade. Green-life of bananas, the time from harvest until the beginning of ripening, can be extended by refrigeration but chilling injury needs to be avoided. Ethylene, even at very low concentrations, can shorten fruit green-life and the control of $C_2H_4$ in the post-harvest chain offers the possibility of extending green-life without using refrigeration. Modified or controlled atmospheres extend green-life, especially if $C_2H_4$ concentrations are minimized. The practical application of this technology depends on the local situation as modified atmosphere packaging is difficult for individual cartons of fruit but may be practical if large amounts of fruit can be treated at one time. Knowledge of the link between the internal gas composition of the fruit and its post-harvest behaviour needs further development to elucidate mechanisms. In recent years ethanol has been investigated as a means of extending green-life and shelf life. The results suggest that for bananas it is acetaldehyde that is likely to be the active molecule, but ethanol is used to deal with astringency in some cultivars.

Ethylene and its biosynthesis are central to the management and understanding of banana ripening, and the use of irreversible blockers of $C_2H_4$ receptors, such as

1-methylcylcopropane (1-MCP), has opened up exciting new knowledge and insights. The peel and pulp of banana have different feedback mechanisms for $C_2H_4$ biosynthesis. Once ripening has begun, in the peel ethylene reduces the activity of ACC synthase, ACC oxidase and MACC transferase, reducing subsequent ethylene evolution. In the pulp, once ripening has begun, ethylene enhances the activity of ACC synthase and ACC oxidase and ethylene evolution is promoted until the ACC oxidase runs out of co-factors. Ethylene evolution from intact fruit during ripening needs to be interpreted in the light of these differences between the peel and the pulp. Identification of the genes that are up- or down-regulated during ripening is invaluable for supporting physiological knowledge and opening new questions about ripening in bananas and plantains.

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# 4
# Citrus

*Lise Korsten and Peter Taverner*

## INTRODUCTION

Citrus (*Citrus sinesis* L.) is consumed as a fresh fruit and as juice, and is widely appreciated for its nutritional value and excellent taste. It is one of the most commonly produced (Figure 4.1a) and traded fruit crops in the world (Figure 4.1b), and is therefore of great importance internationally. Although citrus production exceeds volumes recorded for the other major fruit crops (i.e. grapes, apples and banana), it is only the second most important traded crop after banana. The somewhat robustness of the fruit makes it suitable for extensive handling, distribution and storage. However, due to cumbersome distribution systems and complex supply chains, citrus fruit is still often exposed to poor handling, contamination and temperature abuse conditions, increasing the likelihood of post-harvest decay. Reducing losses and retaining quality have therefore become two of the most important challenges facing the modern citrus industry.

Citrus is indigenous to Southeast Asia (Olsen *et al*. 2000), where it originated in the area between India, South China and Indonesia (Timmer *et al*. 2003). Today, citrus is cultivated in the subtropical and tropical regions of the world (between 40° north and south latitudes), in over 137 countries on six continents (Ismail & Zhang 2004). While citrus production is widespread, only 15 countries account for 84% of world production (Timmer *et al*. 2003). Of these countries, the biggest surface area planted under citrus (close to 2 million Ha), can be found in China, while Brazil is the largest producer (22 million tonnes) (Table 4.1). Other leading producers include the United States and Mexico (Table 4.1). Globally, citrus is cultivated on 8 million Ha of land with production volumes amounting to 122 million tonnes (mt) (FAOSTAT 2008).

The most commonly propagated citrus species are sweet orange (*Citrus sinensis*), mandarin (*C. reticulate*), grapefruit (*C. paradisi*), lemon (*C. limon*), calamondin (*C. mitis*), citron (*C. medica*), wild orange (*C. macroptera*), Kaffir lime (*C. hystrix*), sour orange (*C. aurantium*), Mexican lime (*C. aurantifolia*) and pomelo (*C. grandis*) (Manner *et al*. 2006). Some species, such as sweet orange and lemon, grow best in the subtropics, whereas limes and pomelo are produced primarily in the lowland tropics (Timmer *et al*. 2003). Oranges are the most important crop in terms of production (Figure 4.2a) and trade (Figure 4.2b). Fruit are mainly produced for the local fresh-fruit market, processing (mainly juice and some canning) and to a lesser extent fresh produce exports (Murata 1997). The main citrus export countries include Spain, the United States and South Africa, followed by Turkey and Morocco (Citrus Commodity Notes 2005; and see Table 4.2). Conversely, the largest importers of fresh citrus include the Russian Federation, Germany and France (Table 4.3).

In order to maintain quality, extend shelf life and prevent decay, several production, harvesting, packaging and trade best practices have to be, and are, followed. Effective control of post-harvest pathogens include the management of fungicide resistance, and the integration of chemical and other alternative disease control options. Implementing good agricultural practices and following food safety assurance systems can further contribute to

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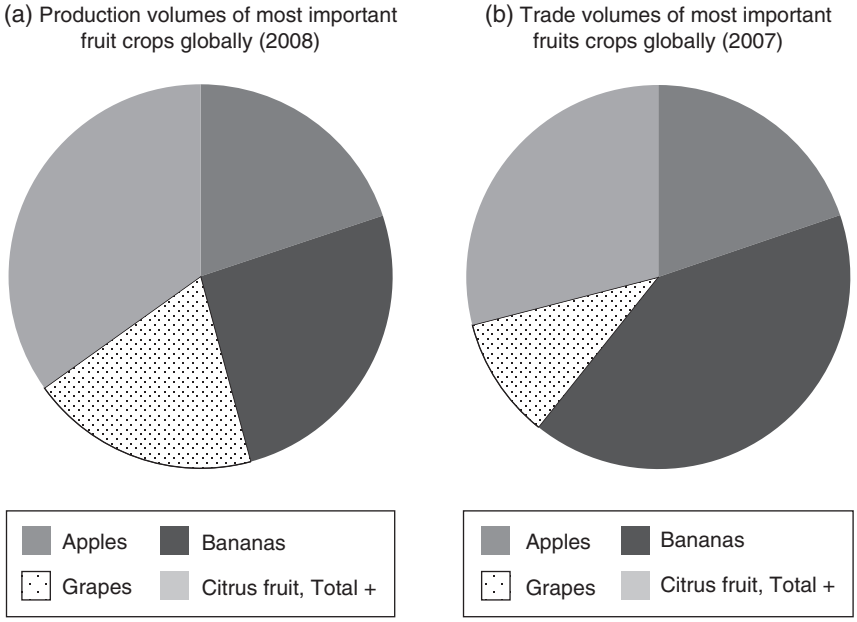


**Figure 4.1** Comparison of the most important fruit crops produced (A) and traded (B) globally.

**Table 4.1** Most Important Citrus Production Regions of the World Based on Area Planted (in Ha) and Ranking in Comparison to Volumes Produced.

| Country | Hectare | Number* | Tonnes | Number* |
|---|---|---|---|---|
| China | 1966711 | 1 | 22019156 | 1 |
| Brazil | 945913 | 2 | 20774752 | 2 |
| India | 810100 | 3 | 7168700 | 5 |
| Nigeria | 732000 | 4 | 3400000 | 9 |
| Mexico | 549191 | 5 | 7502917 | 4 |
| Egypt | 355374 | 6 | 3230986 | 10 |
| Spain | 342008 | 7 | 5911600 | 6 |
| United States of America | 339286 | 8 | 11692770 | 3 |
| Iran, Islamic Republic of | 245000 | 9 | 3756000 | 8 |
| Pakistan | 193211 | 10 | 2459500 | 13 |
| Italy | 166861 | 11 | 3900572 | 7 |
| Argentina | 148500 | 12 | 2722000 | 12 |
| Turkey | 113061 | 13 | 3026940 | 11 |
| Thailand | 97600 | 14 | 1130000 | 19 |
| Colombia | 84650 | 15 | 1235754 | 18 |
| Morocco | 80200 | 16 | 1239000 | 17 |
| South Africa | 71980 | 17 | 2192253 | 15 |

* Number in order of ranking.

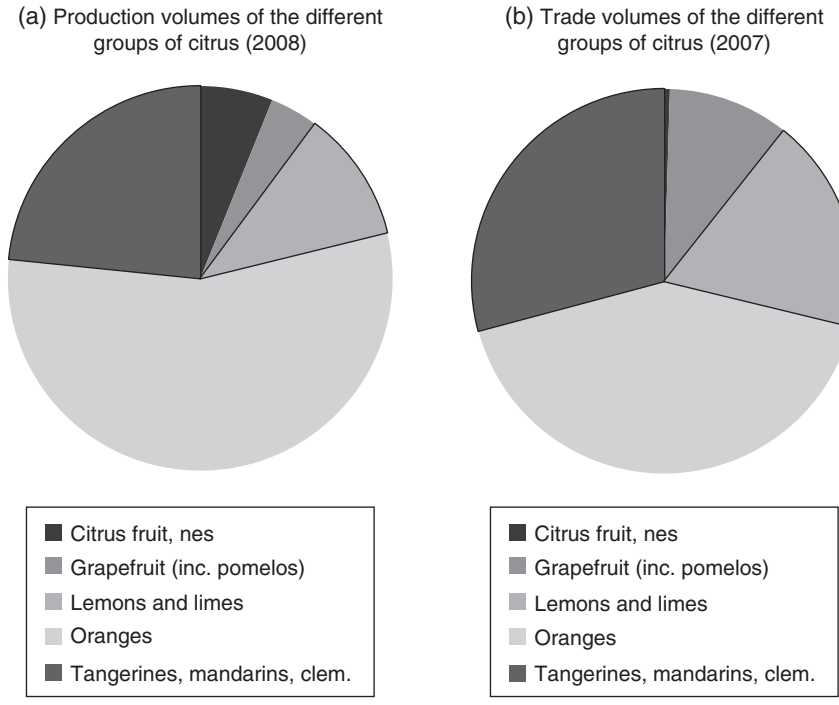


**Figure 4.2** Global citrus production (A) and trade volumes (B) for the different categories.

**Table 4.2** Most Important Countries That Trade in Citrus Fruit Reflecting Volumes and Types Traded.

| Country | Tangerine | Other | Grapefruit | Lemons | Oranges | Total |
|---|---|---|---|---|---|---|
| Spain | 1 652 428 | 3535 | 2 | 447 618 | 1 414 220 | 3 517 803 |
| South Africa | 106 447 | 1676 | 68 | 116 346 | 1 002 618 | 1 227 155 |
| Turkey | 257 935 | 11 | 378 998 | 286 240 | 175 525 | 1 098 709 |
| Argentina | 98 625 | 44 | 28 730 | 351 767 | 196 925 | 676 091 |
| China | 399 986 | 5377 | 84 675 | 3534 | 76 788 | 570 360 |
| United States of America | 23 036 | 2050 | 0 | 147 311 | 341 914 | 514 311 |
| Mexico | 5039 | 5536 | 11 674 | 462 868 | 28 193 | 513 310 |
| Morocco | 243 983 | 336 | 1387 | 2551 | 253 201 | 501 458 |
| Netherlands | 95 689 | 7225 | 85 964 | 83 137 | 221 552 | 493 567 |
| Egypt | 5403 | 91 | 7627 | 9751 | 271 551 | 294 423 |

the prevention of product contamination. In this chapter, an overview of fruit physiology, physiological disorders, post-harvest practices, and the major post-harvest citrus diseases are provided. In addition, disease control strategies and cold chain management practices are discussed as related to supply chain systems for commercial citrus production. Citrus pests are not included as part of this review.

## PHYSIOLOGY OF CITRUS FRUITS

### Basic fruit morphology

Citrus fruit are hesperidium berries that differ from other true berries such as tomato and grape, in having a leathery peel which surrounds the edible portion of the fruit. Citrus are nonclimacteric fruit that lack both a ripening cycle and a well-defined abscission period. Citrus fruit

**Table 4.3** Most Important Citrus Importing Countries Reflecting Volumes and Types Traded.

| Country | Tangerine | Other | Grapefruit | Lemons | Oranges | Total |
|---|---|---|---|---|---|---|
| Russian Federation | 479 331 | 1804 | 11 | 203 911 | 490 955 | 1 176 012 |
| Germany | 353 960 | 3575 | 67 735 | 140 911 | 487 717 | 1 053 898 |
| France | 355 616 | 2448 | 96 921 | 120 572 | 427 573 | 1 003 130 |
| Netherlands | 186 403 | 1779 | 33 | 130 372 | 543 553 | 862 140 |
| United Kingdom | 283 604 | 952 | 19 797 | 94 506 | 344 180 | 743 039 |
| United States | 112 089 | 633 | 46 | 431 336 | 115 104 | 659 208 |
| Saudi Arabia | 36 135 | 10 355 | 1 | 64 065 | 310 086 | 420 642 |
| Canada | 121 331 | 1776 | 54 675 | 58 516 | 171 600 | 407 898 |
| Poland | 165 917 | 437 | 1550 | 97 011 | 109 583 | 374 498 |
| Japan | 4605 | 47 | 212 838 | 63 021 | 85 803 | 366 314 |

therefore do not ripen after harvest and should thus be picked at the correct maturity stage. Citrus contains low starch reserves and undergoes very slow internal quality changes during storage (Davies & Albrigo 1994). Several distinctive tissue types are visible when a fruit is cut transversely; the most important are the segments containing the juice vesicles and the outer rind or peel. The peel is important since it protects the edible flesh and regulates water loss during post-harvest storage. Grierson (2006) provides a detailed morphological description of citrus fruit.

***External portion***

In citrus, the external portion or rind of fruit consists predominately of two tissues, the exocarp or outer rind, called the flavedo, and the inner mesocarp or albedo (Ladaniya 2008). The flavedo is the coloured portion of the rind, and consists of the epicarp, hypodermis, outer mesocarp and oil glands. The protective cuticle overlays the epicarp, with an outer layer embedded with waxy material. The surface of the epicarp is covered with lenticels, which function as the main pathway for gas exchange (Burg 1990). Epidermal cells in the flavedo tend to be polygonal in shape with no intercellular spaces. The hypodermal cells are just below the epicarp and surround the oil cells. The oil glands greatly vary in size and may be sunken or bulge from the surface contributing to the characteristic 'dimples' on the fruit rind. Fruit contain β-carotene, xanthophylls (diol), cryptoxanthin (monol) and violaxanthin (5,6-epoxide) as carotenoids, which are responsible for the orange colour of the rind and juice (Murata 1997). The carotenoid concentration may vary depending on the concentration and composition among citrus varieties as well as the growing conditions (Gross 1987). Some varieties of citrus fruit such as blood orange ('Tarocco', 'Moro', Vascaro', 'Red Oval', 'Malta Blood Red' and 'Ruby Red') contain anthocyanin pigments (Chandler, 1958) which cause the red colour in the flesh and rind.

The albedo is white in colour and consists of meristematic cells. Initially, albedo tissue consists of tightly packed cells, but as the fruit enlarges, the cells stretch to form 'multi-armed' cells which connect with eight neighbouring cells (Davies & Albrigo 1994). The resulting tissue, a web of thin walled cells with large intercellular spaces, is an extremely good cushion against pressure and impact. The albedo in mature citrus can range from a few millimetres to more than 10 mm depending on the cultivar and growing conditions. However, the albedo is absent in kumquats and little developed in mandarins (Tadeo *et al*. 2008).

***Internal portion***

The edible portion of citrus is a spheroid shape consisting of broadly triangular segments, each resembling a crescent moon. A continuous membrane (endocarp) surrounds each segment. Fruit pulp is green, orange, yellow or red, according to the carotenoid and anthocyanin composition (Tadeo *et al*. 2008). The interior of the segment contains many small juice vesicles (pulp) and varying numbers of seeds. Consumer preference is for fresh citrus with few seeds. Some cultivars are commercially marketed as 'seedless', but may still contain several seeds. Few cultivars are totally seedless.

**Nutritional value and chemical composition of fruit**

The composition of citrus fruit varies with cultivar, climate rootstock and cultural practices. Mature citrus pulp has a very high percentage of water (85–90%) and many other constituents which include carbohydrates, organic acids, amino acids, folic acid, ascorbic acid (vitamin C), minerals and small quantities of lipids, proteins, and secondary

metabolites, such as carotenoids, flavonoids, volatiles and lipids (Davies & Albrigo 1994). Although citrus fruit are very low in proteins and fats, they are a good source of fibre and pectins. Citrus fruit and juices are rich in several types of bioactive compounds and their antioxidant activity and related benefits are derived not only from vitamin C but also from the other phytochemicals which are mainly flavonoids (Martí *et al*. 2009). Citrus provides essential components required for human health, nutrition and well-being (Fallik 2004, Bijzet 2006) and is globally considered an important functional food.

### *Sugar and acid*

The sugar and organic acid concentration affect citrus fruit taste characteristics and organoleptic quality. Sugars, consisting of sucrose, glucose and fructose, are the major components of citrus juice soluble solids (70–80%) and responsible for sweetness (Rodrigo & Zaccarias 2006). The main organic acids of citrus fruit are citric (70–90%) and malic acids with trace amounts of tartaric, benzoic, oxalic and succinic acids (Karadeniz 2004). Total acidity of citrus juice is an important factor in overall juice quality and in determining time of fruit harvest (Harding *et al*. 1940). During ripening, a decline in titratable acidity (TA), due to catabolism of citric acid and an increase in sugars, is observed.

### *Ascorbic acid and mineral composition*

Fresh citrus and its juice are an important source of vitamin C. Ascorbic acid functions as a coenzyme and is an essential part of the human diet (Nagy & Attaway 1980). Levels of ascorbic acid are quite variable among citrus fruit and tend to decrease seasonally. Ascorbic acid levels are expressed as mg (100 ml juice)$^{-1}$ and range from 18 to 20 in some tangelos to over 70 for 'Pineapple' sweet orange.

### *Limonin*

The bitterness in citrus fruit is affected by limonin and naringin, which are generally recognized as the major two bitter compounds (Suwanna & Ratiporn 2009). Limonin is the bitter limonoid found in major citrus cultivars such as grapefruit and naringin is the bitter flavonoid. Limonin is an anti-oxidant and a member of the furanolactones subclass and can be found in the albedo, flavedo, segment membranes, juice and pit in different concentrations depending on the citrus cultivar. Most citrus varieties also contain flavonoids (naringin, rhoifolin, lomcerin, hesperidin, neohesperidin, citronin and tangeretin) in the rind and juice segments. Naringin (flavanone-neohesperidose), which tastes bitter, is found in grapefruit.

### *Flavour and aroma*

In citrus, volatile terpenoids, the principal components of essential oils are responsible for the aroma and flavour of the fruit. Citrus volatile compounds consist mostly of mono-(C10) and sesquiterpenes (C15) which are the major components of citrus essential oils, including derivatives such as alcohols, aldehydes, ketones and acids (Rodrigo & Zaccarias 2006; Tadeo *et al*. 2008).

### *Pectins*

Pectins are high-molecular-weight carbohydrates composed of chains of anhydrogalacturonic linkages. They serve as intercellular bonding materials in many fruit and vegetables. During maturation of citrus fruit, insoluble pectins are converted to water-soluble pectins and pectinates (Nagy & Attaway 1980). Total pectic substances decrease in the peel and pulp over the season, and water-soluble pectins increase as percentage of the total pectins. This change in pectin composition signals fruit softening or over-maturity.

## Maturation

Pre-harvest conditions and the degree of harvest maturity significantly affect the fruit quality after harvest. In temperate or subtropical regions, the fruit of most citrus varieties are generally harvested at the fully mature stage, at which colour is fully developed, except for the acid citrus group such as lemons and limes. Partly green citrus fruit are harvested after reaching full size in these areas (Murata 1997) and are often conditioned through de-greening. The sugar content in the rind and juice of the fruit tend to increase throughout fruit development. The acid content of the juice on the other hand tends to decrease after fruit reaches full size. The flavoured acid citrus group, including lemons and limes, should contain a high content of citric acid in the juice and should be harvested before reaching full fruit size, since the matured fruit has low acidity. Lemons that are harvested according to fruit size rather than colour or maturity require de-greening.

Since citrus is nonclimacteric (ripens on the tree), the fruit is harvested once physiological maturity is reached. Mature, sound citrus fruit show no respiratory peak and little ethylene production under normal harvesting conditions. The maturation curve for citrus is influenced by varietal characteristics, environmental factors such as air temperature, solar radiation, water availability in the soil and geographical factors including topography, elevation and exposure surface in the plant (Ortolani *et al*. 1991). In order to relate temperature and plant development, thermal summation or accumulative growing degree days (GDD) are

used. The GDD can be defined as the sum of the mean daily temperatures above a lower base – and below a maximum threshold value that will allow the plant to complete its total life cycle, or to reach a phenological stage (Souza 1990). This calculation is used to predict and plan harvesting times (Montenegro 1980, Ometto 1981, Warrington & Kanemasu 1983, Roberto *et al*. 2005). Citrus fruit gradually becomes edible on the tree and remains so beyond harvesting. Maturity therefore reflects the accumulation of sugars and the loss of acidity and a range of other biochemical changes. Temperatures also affect maturation of fruit. The lower the fruit temperature, the earlier the chlorophyll degradation and carotenoid accumulation will occur (Ladaniya 2008). Flesh maturity also differs between fruit harvested with the same rind colour. Changes in polygalacturonase, cellulase and pectinmethyl esterase activity have been observed during fruit maturation (Ladaniya 2008).

### *Maturity indices*

Sweet oranges, mandarins, grapefruits and pomelos are considered mature when juice content and the total soluble solids:acidity ratio have attained certain minimum limits for palatability. Total soluble solids constitute about 80% sugars, 10% acids and 10% nitrogenous compounds. In citrus fruit that are used for table purposes (such as fresh fruit) and that are processed into juices, maturity is determined mainly on the basis of the ratio of total soluble solids (TSS) to titratable acidity (TA) (Ladaniya 2008). Citrus fruit are marketable when a minimum TSS:TA ratio is reached. This minimum ratio varies with location and local standards, but generally ranges from 7–9:1 for oranges and mandarins; to 5–7:1 for grapefruit. The TSS:TA ratio is not of importance to lemon and lime producers, since the fruit are harvested based on minimum size and juice content and for processing, on acid and peel oil content (Davies & Albrigo 1994).

### Respiration and transpiration

During maturation and senescence, citrus fruit exhibit relatively low respiration rates and levels of ethylene production (Kader 1992). The respiratory rate of the rind is nearly ten times as high as that of vesicles (Murata 1972); the rind, therefore, has an important physiological role in the qualitative changes that take place during storage of the fruit. Respiratory rates of citrus fruit are affected by several factors, including temperature, humidity, air movement, atmospheric compositions ($O_2$, $CO_2$, $C_2H_4$ and other olefins), dropping, bruising and microbial infection. These factors all affect the fruit quality. Haller *et al*. (1945) measured the respiratory rates and heat of respiration of several varieties of citrus fruit at different temperatures, which showed the correlation of increased respiration rates with higher temperatures. The respiratory rates of citrus fruit are further influenced by humidity. Murata and Yamawaki (1989) showed that the respiratory rates of navel orange, Iyo tangor, Seminol tagelo, Natsudaidai, Hassaku and Anbokan are lower in fruit conditioned at low humidity (64% RH, 20°C) than fruit kept at high humidity (92%, 20°C), during and after conditioning. Citrus does not show any respiratory rise accompanied by major changes in flavour and biochemical composition after harvest in relation to ripening (Ladaniya 2008).

## PHYSIOLOGICAL DISORDERS

### Creasing

Rind mineral levels, rootstock type and irrigation management are all factors contributing to creasing or albedo breakdown. Fewer symptoms were observed in navels subjected to reduced water volumes, whether delivered as part of a partial root zone drying strategy or otherwise (Treeby *et al*. 2000). This work also highlighted the impact that reduced water volumes have on final fruit size. A particularly interesting outcome of this work was the recognition that low water volumes affected trees less on some rootstocks.

### Rind staining

Rind staining is a condition that can occur while the fruit are still on the tree, and symptoms may be expressed during storage (Agusti *et al*. 2001). The Spanish have serious rind staining problems with ‘Navelate’ fruit during maturation on the tree, but ‘Navelina’, ‘Washington navel’ and ‘Lane late’ fruit can also develop this disorder during post-harvest storage. These symptoms are seen on fruit harvested from inland Australia, where climatic conditions similar to the Mediterranean-type conditions in Spain prevail. Affected fruit are characterised by collapsed areas in the rind, which become reddish-brown over time. The symptoms appear on fruit at nonchilling temperatures, and fruit blemish increases with maturity. Water stress is thought to play an important role in its development. Delivery of bins to packing sheds should be prompt. Storing fruit at low temperatures (2°C) is considered useful to reduce the symptoms. De-greening with ethylene may also delay its expression.

### Oleocellosis

Oleocellosis (oil spotting) is cell collapse and blemish caused by the release of rind oils after impact or abrasion. Rupture of the oil glands result in necrosis of the adjacent epidermis, inducing the formation of irregularly shaped

yellow, green or brown spots in which the oil glands of the skin stand out prominently because of slight sinking of the tissue between them (Murata 1997). The disorder is well described by Knight *et al*. (2002). The incidence of oleocellosis is closely related to the turgidity of the fruit during harvest. The application of Ethephon as a pre-harvest spray to 'Shamouti; oranges at colour-break reduces fruit damage by oleocellosis (Erner 1982).

**Stem-end rind breakdown**

Stem-end rind breakdown (SERB) is symptomatically similar to the cell collapse that occurs in over-mature rind. However, SERB often occurs within a week of harvest, with Valencia oranges especially susceptible (Ritenour & Dou 2009). A distinguishing feature of SERB is a narrow band of undamaged rind around the calyx. This area is less prone to water loss, and subsequent cell collapse, due to a lack of stomata and thicker wax on the cuticle (Albrego 1972). Minimising water loss after harvest and storing at cool temperatures (4°C) substantially delay the expression of SERB (Dou *et al*. 2001).

**Post-harvest pitting**

Post-harvest pitting is a similar disorder to rind staining, and was first described on white grapefruit and 'Falglo' tangerine. This disorder occurs in waxed fruit, and appears associated with gas permeability. Navel oranges are prone to post-harvest pitting, and also express stem-end rind breakdown-like symptoms that are considered indistinguishable from post-harvest pitting (Petracek *et al*. 2006). Using more gas permeable coatings and prompt low-temperature storage, can reduce symptoms.

***Peteca in lemons***

Peteca resembles pitting, but the edges of the depressions are more gently rounded. The outer layer of the rind sinks, at first without losing its normal colour, and then oil glands begin to darken (Murata 1997). In lemon, increasing brushing times after harvest induces the incidence of peteca.

**Chilling injury**

Most citrus fruits, especially grapefruit, limes and pomelos are chilling-sensitive (Murata, 1988) and develop chilling injury (CI) symptoms in chilled storage and/or while in transit. Symptoms of CI in citrus fruit are pitting, discoloured patches, superficial brown staining of the rind, browning of the albedo and watery breakdown. According to Grierson (2002), fruit produced on drought stressed trees are very resistant to CI. The mechanism conferring resistance is not clear. It has been generally considered that chilling injury might be associated with the balance of gibberellins (GA) and abscisic acid (ABA); high ABA levels correlate with drought and chilling injury resistance. More recently, the role of ABA in protecting fruit from storage disorders has been disputed, with oxidative stress implicated in CI development, and high levels of antioxidants, such as carotenoids, thought to provide protection (Alferez *et al*. 2005). Chilling injury in lemon, grapefruit and other citrus fruit can be alleviated by temperature conditioning, intermittent warming, delayed storage with thiabendazole, imazalil and by film packaging (Murata 1997).

**Mechanical injury**

Wounding fruit contributes to increased decay and poor quality. Various mechanical injuries can occur from production to harvesting, transport, packing, re-packing and display and provide entry points for post-harvest pathogens. The following are the most important mechanical injury categories:

***Impact and compression damage***

Damage by direct impact with a sharp or blunt object may cause impact or compression damage. Mechanical injuries are often caused by long stems, fingernails, damaged bins or protruding objects in the packing lines. Small injuries and impacts also become more obvious during storage due to dehydration or development of oleocellosis (Taverner *et al*. 2009).

***Brushburn***

Damage to the citrus rind by abrasion is more common in late seasonal fruit and in new pack houses where protruding corners may expose fruit to wounding. The reddish-brown marks are associated with raised surfaces on the rind (Taverner *et al*. 2009).

***Zebra skin***

Reddish-brown stripes of the rind of citrus are referred to as Zebra skin caused by mechanical damage done to highly turgid mandarin rind through abrasions. These symptoms are more common when harvesting occurs too soon after rain or irrigation (Taverner *et al*. 2009).

**CITRUS POST-HARVEST DISEASES**

Citrus is attacked by several plant pathogens that can cause fruit and foliage diseases, root and trunk diseases, systemic diseases and post-harvest decays. Post-harvest diseases cause little or no damage to the tree. However, losses from post-harvest pathogens are economically more significant to the grower because they represent cumulative costs not

only from production, but also harvesting, packing and distribution. It is further difficult to determine actual end point losses due to the fact that at a retail level, hospitality sector, the informal market and kitchens, fresh produce losses in nutritional value and quality are generally overlooked (Wilson & Wisniewski 1989).

In developing countries, where protection and proper handling of fresh fruit is often inadequate, losses during transit and storage are even greater and primarily due to post-harvest decays. Losses can represent in excess of 50% of the harvested crop (Eckert & Ogawa 1985; Wisniewski & Wilson 1992). In countries such as Spain, the percentage of fruit rotting after harvest in a typical season is between 3% and 6% (Tuset 1987). However, under favourable disease conditions, losses up to 50% can occur during marketing (Eckert 1993, Abd-El-Aziz & Mansour 2006). In north-eastern Brazil, a survey of post-harvest diseases in citrus indicated a 21.9% incidence of fungal rots (Dantas *et al*. 2003). Post-harvest losses therefore remain an important challenge in sustainable food production.

The importance of different post-harvest diseases is characteristic of the climate of the production area, species and cultivar, time of harvest, infection during fruit growth and harvesting and handling practices. Post-harvest losses and decay of citrus fruits can be traced to infections that occur either between flowering and fruit maturity or during harvesting and subsequent handling and storage activities (Naqvi 2004). Post-harvest diseases where inoculation and infection are initiated during fruit growth are stem-end rot, alternaria rot, anthracnose, brown rot and grey mould. The wound pathogens (*Penicillium digitatum, P. italicum, Geotrichum candidum* and *Trichoderma viride*) on the other hand typically infect through wounds that form during harvesting and handling, as well as insect damage in the orchards (Eckert & Eaks 1989; Timmer *et al*. 2000). The following section deals with the epidemiology of the major citrus post-harvest diseases, control methods and the most important aspects of the various post-harvest diseases have been summarised in Table 4.4.

## Green mould

Green mould is caused by the fungus *Penicillium digitatum* (Pers.) Sacc., (1883) which is ubiquitous to all citrus growing regions and commonly causes post-harvest decay (Carlos 1982). It usually occurs in countries with a cooler climate or under cold storage conditions of citrus fruit (Food and Fertilizer Technology Centre [FFTC] 2003). Green mould is a common post-harvest disease of citrus in many Asian Mediterranean climate countries (Eckert & Eaks 1989). Green mould can be responsible for up to 90% of production losses during post-harvest handling (Macarisin *et al*. 2007), particularly in production areas characterized by low summer rainfall (Eckert & Eaks 1989) and is seen as one of the most important post-harvest diseases in citrus fruit (Lanza *et al*. 2000). Artificial inoculation done by Ortuno *et al*. (2009) indicated that the degree of fungal development is dependent on the citrus species. It was found that the mature fruit of *C. paradise* are more susceptible to *P. digitatum* than *C. limon* and *C. sinensis*.

### *Morphology*

*Penicillium digitatum* grows restricted and thinly on Czapek and other similar media. On malt agar, rapid growth appears velvety and changes to dull yellow green to greyish olive with age, with a strong decaying citrus odour. These colonies on artificial media are similar in appearance to the mould that develops on infected fruit. *Penicillium digitatum* produce conidia (4–7 × 6–8 $\mu$m) in chains, often with only one branch (Onions & Brady 1987; Timmer *et al*. 2000) that is at first cylindrical, becoming elliptical, smooth and thick walled (Carlos 1982).

### *Disease cycle and epidemiology*

Green mould survives in the orchard from season to season primarily as conidia and is produced in massive quantities on infected fruit (Olsen *et al*. 2000). Infection occurs as a result from these airborne spores that enter the peel of the fruit where there are small injuries or blemishes (Kuramoto 1979; FFTC 2003). Green mould is a necrotroph, requiring nutrients only for germination around the wound site. A minor injury to the oil glands during harvesting and transportation promotes infection (Brown 1973). The fungus can also invade fruit which have been damaged on the tree by chilling injury (FFTC 2003) and stem-end rind breakdown (Brown 2003a). Therefore, the disease can occur at any stage in the supply chain where the fruit is wounded (i.e. on the tree, in the packinghouse, in transit, in storage or in the marketplace). In packed containers, the fungus usually does not spread from decayed fruit to adjacent intact healthy fruit, although the abundant green spores that are produced can soil the skin of adjacent fruit (FFTC 2003). The infection and sporulation cycle can be repeated several times throughout the season in pack houses. Inoculum pressure increases as the picking season advances, therefore it is critical that precautions are taken (Janisiewicz & Korsten 2002). Contamination spreads when spores detach from diseased fruit during the opening of packing cartons. Green mould grows optimally at temperatures near 25°C but more slowly at temperatures above 30°C and below 10°C (FFTC 2003, Zhang & Swingle

2005). Rotting is mostly inhibited at freezing temperatures (0–1°C) (Plaza *et al*. 2004a).

### *Transmission*

The fungus survives in the field on soil debris in the form of conidia (FFTC 2003). Cooler autumn and winter temperatures favour fungal development, during which large numbers of spores are produced and carried by wind currents towards fruit surfaces in the tree canopies (Brown 2003a). In addition, airborne spores will contaminate the pack house and its equipment, storage rooms, transit containers, and even the retail marketplace. Spores will also accumulate in water drenchers and soak tanks (Brown 2003a).

### *Symptomology*

Initial symptoms of green mould are similar to those of sour rot and blue mould. The small decayed area appears as a soft watery spot that first grows on the peel and later turns green due to the large number of olive green spores produced (Timmer *et al*. 2000). White mycelia surround the sporulating area whilst the outer region of the lesion is composed of softened rind. White mycelia appear on the surface of the rind and after it reaches approximately 2.5 cm in diameter, olive green spores are produced (Syngenta 2007). The entire fruit is soon encompassed by a mass of olive green spores, which are easily dispersed by any physical motion or air currents (Brown 2003a). If the relative humidity is low, decayed fruit become soft and shrink. If the relative humidity is high, fruit become soft and decompose due to opportunistic moulds and bacteria (Timmer *et al*. 2000; FFTC 2003). More mature and overripe fruit also result in more decay, especially if left in the sun after harvest (Howard 1936).

### *Control*

#### *Preventative measures*

Control measures of green mould are to keep conidial inoculum levels low and careful handling of fruit during harvest and post-harvest (FFTC 2003). Stringent sanitary practices (i.e. removal and repacking of diseases fruit in a remote area that has been cleaned) must be enforced in order to limit airborne spore populations (Rada 2009). The pallets, pack house, packing line and washer brushes should be sanitized daily to eradicate inoculum accumulation. Aqueous solutions in drenchers and soak tanks should be treated continuously with a sanitizer (i.e. chlorine) to prevent the accumulation of green mould inoculum (Brown 2003a). Exhaust fans must be used to remove mould spores from pack houses and dumping areas must be where the air flow will not carry the mould spores back to the packing area (Rada 2009).

#### *Chemical control*

Post-harvest reduction of green mould inoculum is of primary importance due to an increase in pathogen resistance to chemicals. Post-harvest application of selected fungicides can aid by delaying green mould development, especially in combination with immediate cooling of fruit after packing (Olsen *et al*. 2000). Therefore, different combinations of applications and chemicals are continuously evaluated for effective control, for example the increased effectiveness of Imazalil (Smilanick *et al*. 1997) when fruit was treated with heated aqueous solutions of the fungicide and the control of a Thiabendazole (TBZ)-resistant isolate of green mould with TBZ at a reduced rate but at higher temperatures of 50°C (Schirra *et al*. 2008). New chemicals are regularly evaluated and three new fungicides (azoxystrobin, fludioxonil and pyrimethanil) are being registered for post-harvest use against *Penicillium* decays of citrus fruit in the United States (Kanetis *et al*. 2008a). The chemicals belong to different chemical classes, and it was shown that even *P. digitatum* isolates resistant to Imazalil or TBZ were sensitive to the new compounds.

Common food preservatives (i.e. potassium sorbate) were also evaluated alone or combined with fungicides and were found more effective when applied at high temperatures. Control was also achieved with potassium sorbate in combination with Imazalil and TBZ respectively even when tested against a resistant isolate of *P. digitatum* (Montesinos Herrero *et al*. 2009). The advantage of testing edible films and coatings are that most of them are classified as food additives or generally regarded as safe (GRAS) compounds by EU or US regulations. El-Mougy *et al*. (2008) also found that potassium sorbate and sodium benzoate have potential as nontoxic post-harvest fungicide applications. Sanitizing agents also have an antimicrobial effect; sodium hypochlorite and hydrogen peroxide in combination showed a significant delay in fungal infection by *P. digitatum*. The post-harvest treatment of citrus with essential oil amended coatings were active against *P. digitatum* (Du Plooy *et al*. 2009), as also were cyprodinil treatments at 150 mg/L (Schirra *et al*. 2009).

#### *Biological control*

Two species of *Candida* assessed for control against *P. digitatum* showed protective rates of up to 80% due to the fact that these yeasts actively increase and persist in wounds and on the surfaces of citrus fruit (Taqarort *et al*. 2008). Isolates of *Pseudomonas* spp., cultured from the fruit and leaf surfaces of citrus, in combination with a hot sodium bicarbonate treatment could provide a practical alternative for green mould control (Zamani *et al*. 2008).

**Table 4.4** Summary of Post-harvest Pathogens and Associated Citrus Diseases.

| Disease | Description of casual agent | Infection site | Fruit symptoms | Disease cycle and epidemiology | Control | References |
|---|---|---|---|---|---|---|
| **Pre-harvest infections** | | | | | | |
| Diplodia stem-end rot | *Diplodia natalensis*<br>Pycnidia aresubglobose to globose, 300–700 µm in diameter<br>Spores are 17–43 µm by 10–18 µm<br>Young spores are hyaline, non-septate and granular, whilst the mature spores are striated with one septum | Flower, young fruit<br>Flower, young fruit, navel | Lesions appear in 7–10 days of harvest as dark discoloration of the rind in the stem-end of the fruit<br>Typical decay is formed at both ends of the fruit before involving the entire fruit<br>Usually a sour, fermented odour, and sometimes the fruit will become black<br>Does not spread from diseased to healthy fruit in packed containers<br>Initial stages of infection indistinguishable between *Diplodia* and *Phomopsis*. *Phomopsis* seldom grows so rapidly through the core of the fruit that decay is exhibited at both ends | Fungus grows on dead wood on the tree where it produces spores<br>Spores are carried in rain water or irrigation water to immature fruits<br>Fungus becomes established in dead tissue of the button surface where it stays dormant until harvest<br>Favourable temperature and humidity in degreening rooms encourages growth of pathogen<br>Ethylene treatment causes senescence and abscission of the button that allow entry of the pathogen into the base of the fruit | Cultural practices including removal of dead wood from trees<br>Harvest at optimum maturity to reduce time required for degreening<br>Pre-harvest treatment with benlate or drenching with TBZ before degreening and application of TBZ on the packline<br>Immediate cooling of fruits after harvest | Brooks 1941<br>Brown & Wilson 1968<br>Barmore & Brown 1985<br>Eckert & Brown 1986<br>Eckert & Eaks 1989<br>Kucharek *et al*. 2000<br>Timmer *et al*. 2000<br>Sommer *et al*. 2002<br>Brown 2003d<br>Brown 2003e<br>Zhang & Swingle 2005<br>Syngenta 2007 |
| Phomopsis stem-end rot | *Diaporthe citri*<br>(Anamorph: *Phomopsis citri*)<br>Pycnidia (200–450 µm) are scattered, dark, ovoid, thick walled and erumpent. Alpha conidia (2.5–4 × 5–9 µm) and beta conidia (0.7–1.5 × 20–30 µm) are produced. The alpha conidia are unicellular, hyaline and biguttualte whilst the beta conidia or stylospores are filiform and hooked and do not germinate (predominate in older pycnidia). On twigs that have almost stopped producing pycnidia, perithecia (125–160 µm) develop | | | | | |

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| | that are spherical and have tapered beaks (200–800 µm long). The ascospores are hyaline, two celled and contains two guttulae | | | | | |
| Alternaria rot | *Alternaria citri* – Black rot<br>On PDA, the mycelia produced are yellowish or olivaceous hyaline<br>Conidia are short-clavate, oblong and dark olive brown (15–22 × 25–40 µm) and have four to six septa<br>*Alternaria alternata* – Brown spot<br>Characteristic of the genus is dark-colored multi-celled conidia formed in chains Conidiophores septate and brown | Flower, young fruit, navel | Fruit have a blackish discoloration at the blossom end. Internal tissue dark with unpleasant taste. An important disease for juice production<br>Brown to black dots to pock marks on fruit, leaves and twigs surrounded by a yellow halo<br>A host-specific toxin is produced that causes necrosis | Airborne conidia form a quiescent infection in styler end and forms infection when button becomes senescent<br>Spores are produced 10 days after infection. Favourable temperatures combined with 8–10 h of wetting period is required for infection | Preventing stress on fruit limits black rot<br>Remove infected fruit and delay harvest until infected fruit have dropped<br>No pre-harvest applications<br>Disease free nursery trees<br>Fungicide sprays with the aid of weather-based model | Eckert & Eaks 1989<br>Olsen *et al*. 2000<br>Timmer *et al*. 2000<br>Atsunorl *et al*. 2001<br>Cals 2005; 2007<br>Reqaeian & Aboutalebi 2007<br>Adaskaveg *et al*. 2008<br>Dewdney & Timmer 2009a; 2009b<br>Phytopathology 2009 |
| Anthracnose | *Colletotrichum gloeosporioides*<br>The fungal colony vary from white to gray or black<br>Acervuli are erumpent and superficial and 90–270µm in diameter<br>Conidia are oval or oblong, (10–16 × 5–7 µm)<br>Ascospores are hyaline, slightly curved and nonseptate (3.5–5 × 12–22 µm) | Fruit surface | Symptoms normally appear on fruit that are injured:<br>Brown or black spots appear on fruit<br>Decay may be dry and firm and as the decay progresses the rind becomes grayish and eventually a soft rot occurs | Conidia are produced on dead twigs and spread through water<br>Ascospores germinate on fruit surface but remain dormant until fruit tissue is weakend by other factors<br>Ethylene treatment triggers fungal growth and increases the susceptibility of further rind invasion | Careful handling of fruits to avoid injury<br>Reducing amount of dead wood available for inoculum production<br>Pre- and postharvest fungicide applications | Echert & Brown 1986<br>Eckert & Eaks 1989<br>Timmer *et al*. 2000<br>Barkley 2003<br>Ritenour *et al*. 2003<br>Taverner 2003<br>USAID 2004<br>Zhang & Timmer 2007<br>Infonet 2009 |

**Table 4.4** *Continued*

| Disease | Description of casual agent | Infection site | Fruit symptoms | Disease cycle and epidemiology | Control | References |
|---|---|---|---|---|---|---|
| Black spot | *Guignardia citricarpa*<br>Ascocarps are aggregated and globose (100–175 µm)<br>Asci are clavate cylindrical and eight-spored.<br>Ascospores are aseptate, hyaline, multiguttulate, cylindrical and swollen in the middle (4.5–6.5 × 12.5–16 µm)<br>Conidia are obovate to elliptical, elliptical, hyaline, aseptate and multiguttulate with a colourless subulate appendix (5.5–7 × 8–10.5 µm) | Most critical at fruit set<br>Affects rind but does not cause decay | Various types of symptoms may occur on fruit: hard spot, virulent spot, freckle spot and cracked spot<br>Leaf symptoms are round, sunken necrotic spots with grey centres surrounded by a dark brown ring and yellow halo (lemon) | Ascospores from dead leaves on the orchard floor are the major source of inoculum, whilst conidia are a minor source<br>During conidia germination, a germtube and an appressorium are produced. The cuticle is penetrated by a thin infection peg (from appressorium) that expands into a mycelium mass between the cuticle and the epidermal wall. When the fruit becomes mature the fungus grows further into the rind tissue and produces a black spot 6 months after fruit set | Good agricultural practices<br>Pre harvest fungicide applications<br>Storage and shipment in dark, cool conditions | Kiely 1948<br>Schüepp 1961<br>Kotze 1962; 1981; 1996<br>McOnie 1964; 1967<br>Whiteside *et al*. 1988<br>Timmer *et al*. 2000<br>Ayres 2001<br>Baayen *et al*. 2002<br>FFTC 2003<br>Magarey & Borchert 2003<br>Obagwu 2003<br>Agostini *et al*. 2006<br>Meyer *et al*. 2006<br>Pascholati *et al*. 2007<br>EPPO 2009<br>FABI 2009<br>Rappussi *et al*. 2009 |

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| Brown rot | *Phytophthora citrophthora* and *P. nicotianae* (syn. *P. parasitica*)<br>*P. citrophthora* – Sporangia more elongated than *P. parasitica* (45–90 × 27–60 µm)<br>*P. nicotianae:* – Pear shaped to spherical sporangia (38–50 × 30–40 µm). Produce abundant chlamydospores and oospores (22–29 µm) | Fruit surface | Affected area is light brown and leathery<br>White mycelium forms on the rind surface under humid conditions<br>Effected fruits have a rancid odor, which distinguishes it from stem-end rots | Under high moisture and temperature conditions zoospores are released and spread from the soil onto low hanging fruits<br>Spores produced on fruit are then splashed higher into canopy<br>Fruits infected before harvest may not show symptoms until in storage | Cultural practices that include Proper irrigation and drainage<br>Pruning to remove low hanging branches<br>Avoid harvesting:<br>From poorly drained grooves<br>During harvesting<br>Fruits lying low close to the ground | Timmer & Menge 1988<br>Whiteside *et al*. 1988<br>Eckert & Eaks 1989<br>New Zealand Citrus Growers Incorporated (NZCGI) 1997<br>Timmer *et al*. 2000<br>Futch & Timmer 2001<br>Hardy 2001<br>Oren & Yogev 2002<br>Sommer *et al*. 2002<br>Barkley 2003<br>Naqvi 2004<br>Adaskaveg *et al*. 2008<br>Graham & Timmer 2009 |
| Gray mould / Botrytis rot | *Botrytis cinerea*<br>The fungal colony is greenish gray or dark olive<br>Conidia (4–11 × 6–18 µm) are colorless to dark brown, elliptical to oblong, smooth and arranged in clusters around conidiophore tips | Flower, young fruit | At very high humidity, distinctive patches of gray brown to olive spore masses appear on the fruit surface<br>A brown leathery decay develops on the fruit<br>Usually associated with frost damage, injuries or shell bark<br>Infection spreads from diseased to healthy fruit in packed containers | Pathogen inoculum is produced on decaying organic debris in orchards and dispersed by wind, rain splash or insects<br>Dispersed inoculum infects mostly flowers but can also penetrate wounds<br>Fungus forms a quiescent infection at the stem-end of the fruit<br>The fungus becomes active after harvest and causes a postharvest decay | Avoid harvesting fruit on or close to soil surface<br>Minimize injuries to fruits<br>Packhouse treatment applied for control of *Penicillium* diseases are also effective against gray mould | Klotz 1973<br>Coley-Smith 1980<br>Thomas *et al*. 1983<br>Whiteside *et al*. 1988<br>Eckert & Eaks 1989<br>Timmer *et al*. 2000<br>Hardy 2001<br>Hong *et al*. 2001<br>Raposo *et al*. 2001<br>Online Information Service for Non-Chemical Pest Management in the Tropics (OISAT) 2005<br>Syngenta 2007<br>Adaskaveg *et al*. 2008<br>BCAGF 2009 |

**Table 4.4** *Continued*

| Disease | Description of casual agent | Infection site | Fruit symptoms | Disease cycle and epidemiology | Control | References |
|---|---|---|---|---|---|---|
| **Post-harvest infections** | | | | | | |
| Green mould | *Penicillium digitatum*<br>Grows restricted and thinly on Czapek and other similar media. On malt agar, growth is velvety and changes to dull yellow green to grayish olive with a strong decaying citrus odour<br>Olive green sporesvary in size and shape<br>The conidia (4–7 × 6–8 $\mu$m) are produced in chains that are at first cylindrical, becoming elliptical, smooth and thick walled | Fruit injuries | Similar to sour rot and blue mould<br>The fungal colony appears watery with white mycelium on rind surface and olive green spores<br>Entire fruit is encompassed by olive green spores and easily dispersed when fruit is handled or exposed to air currents When RH is low fruit becomes soft and shrink<br>When RH is high fruit become soft and decompose due to opportunistic moulds and bacteria | Pathogen survives as conidia<br>Infection is from air borne spores that invade fruit at injuries or bruises<br>Infection cycle can be repeated many times during season | Stringent sanitary practices must be enforced to limit spore populations in packhouses<br>Post harvest chemical applications in combinations with heat treatments, food preservatives, biological control agents and sanitizers | Howard 1936<br>Brown 1973<br>Kuramoto 1979<br>Carlos 1982<br>Eckert & Eaks 1989<br>Smilanick *et al*. 1997<br>Lanza *et al*. 2000<br>Olsen *et al*. 2000<br>Timmer *et al*. 2000<br>Janisiewicz & Korsten 2002<br>Brown 2003a<br>FFTC 2003<br>Zhang & Swingle 2005<br>Macarisin *et al*. 2007<br>Syngenta 2007<br>Canamas *et al*. 2008<br>El-Mougy *et al*. 2008<br>Kanetis *et al*. 2008a; 2008b<br>Leelasuphakul *et al*. 2008<br>Taqarort. 2008<br>Schirra *et al*. 2008; 2009<br>Zamani *et al*. 2008<br>Du Plooy *et al*. 2009<br>Montesinos Herrero *et al*. 2009<br>Ortuno *et al*. 2009<br>Rada 2009 |

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| Blue mould | *Penicillium italicum*<br>Produces pale-green colony on artificial media – pale brown to yellowish or orange brown on reverse side – with a characteristic sweet odour<br>Some isolates produce a clear exudate on the colony and a brown soluble pigment in the artificial media<br>Spores vary in size and shape<br>Cylindrical to elliptical or ovate conidia (2–3 × 3–5 $\mu$m) are produced in long, disordered chains | Fruit injuries | Infection almost identical to green mould and sour rot, with the exception of a blue conidial mass that form on decaying fruit<br>Diseased tissue becomes soft, watery and slightly discoloured<br>White powdery growth of mycelium develops on surface of lesion | Similar to green mould<br>Blue mould grows faster below 10°C compared to green mould therefore more prevalent in cold storage fruit<br>Prolific conidia production ability enables fungus to develop resistant strains against chemical fungicide treatments | Similar as for green mould | Gutter 1975<br>Carlos 1982<br>Onions & Brady 1987<br>Whiteside *et al*. 1988<br>Eckert & Eaks 1989<br>Pitt 1991<br>Timmer *et al*. 2000<br>Sommer *et al*. 2002<br>Brown 2003b<br>FFTC 2003<br>Droby *et al*. 2007<br>Nunes *et al*. 2007<br>Syngenta 2007<br>Azizi *et al*. 2008<br>El-Mougy *et al*. 2008<br>Karimi & Rahemi 2008<br>Prado *et al*. 2008<br>Travallali *et al*. 2008 |
| Sour rot | *Geotrichum candidum*<br>Grows rapidly on PDA, producing a dull gray-white colony with chains of arthrospores<br>The mycelium is hyaline and septate<br>Conidia can vary between 2–8 × 3–50 $\mu$m and 3–6 × 6–12 $\mu$m | Fruit injuries | Initial symptom similar to blue or green mould<br>Lesions first appear as water soaked, light to dark yellow slightly raised spots<br>Cuticle is more easily removed from epidermis than in lesions formed by blue and green mould<br>Cell degrading enzyme produced by the fungus causes the fruit to disintegrate into a slimy watery mass<br>Following exposure to high RH the lesion may be covered with a yeasty sometimes wrinkled layer of mycelium | Fungus occurs commonly in soil from where it is dispersed to fruit surfaces<br>Fungus invades the rind through insect or mechanical damage<br>Susceptibility of infection increases with fruit maturity<br>Amount of moisture on the rind greatly influences the susceptibility of fruit<br>Spore laden watery debris from infected fruits spread decay to healthy fruits | Minimize injury to fruits<br>Immediate storage of packed fruit to 10 °C to delay onset of the disease<br>Proper hygiene at packhouse<br>Pre-harvest fungicide treatment with guazatine gives some measure of control | Butler & Eckert 1962<br>Baudoin & Eckert 1982<br>Whiteside *et al*. 1988<br>Eckert & Eaks 1989<br>Sommer & Ewards 1992<br>Droby *et al*. 1998<br>Timmer *et al*. 2000<br>Brown 2003c<br>Plaza *et al*. 2004b<br>Mercier & Smilanick 2005<br>Syngenta 2007 |

**Table 4.4** *Continued*

| Disease | Description of casual agent | Infection site | Fruit symptoms | Disease cycle and epidemiology | Control | References |
|---|---|---|---|---|---|---|
| Trichoderma rot | *Trichoderma viride*<br>The fungus is an ubiquitous soil saprophyte but grows readily on wood products<br>Conidia (3.6–6.8 $\mu$m) are globose and rough<br>Spore are yellow to emerald green | Fruit injuries | Diseases fruit becomes cocoa brown and the infected peel remains leathery and pliable<br>Rotted fruits have a coconut odor<br>The pathogen cannot penetrate sound fruit directly | Spores may be disseminated with soil particles<br>Infection may be initiated at any location on the fruit, but decay normally start at the stem-end or stylar end of the fruit<br>A deep wound is required for infection where the incidence is increased by the release of peel oil | Good agricultural practices:<br>Removal of dead wood to remove inoculum source<br>Minimize injury to fruits<br>Rapid cooling of fruits after harvest because fungus does not spread fast at 10°C<br>Prompt removal of infected fruits | Cole & Wood 1970<br>Eckert & Eaks 1989<br>Timmer *et al*. 2000<br>Brown 2003c |

Another biological control agent, *Bacillus subtilis* also showed the ability to suppress growth of *P. digitatum* in the post-harvest protection of citrus (Leelasuphakul *et al*. 2008). Canamas *et al*. (2008) indicated that it is also possible to control *P. digitatum*, using bacteria such as *Pantoea agglomerans* as a pre-harvest treatment.

Different treatments (i.e. sanitary practices, 'reduced risk' fungicides (GRAS) and biological control agents) have shown to decrease the incidence of *Penicillium* decay. These treatments do not necessarily show the same effectiveness as fungicides applied in pack houses and must therefore be used in integrated approaches, such as the use of an in-line recirculating drench application with a fungicide-sanitizer (sodium bicarbonate) to increase fungicide efficacy and to minimize the selection for resistant isolates of the pathogen (Kanetis *et al*. 2008b).

## Blue mould

Blue mould is caused by the fungus *Penicillium italicum* Wehmer (1894), and causes much less decay than green mould (Brown 2003b).

### *Morphology*

*Penicillium italicum* produces a pale grey-green colony on artificial media (pale brown to yellowish or orange brown on the reverse side) with a characteristic sweet odour (Onions & Brady 1987; Pitt 1991). Some isolates of this species produce a clear exudate on the colony and a brown soluble pigment in the artificial media (Pitt 1991). Conidiophores are smooth and produce conidia in long disordered chains that are typically cylindrical at first, becoming elliptical or ovate at maturity (2–3 × 3–5 $\mu$m) (Carlos 1982; Pitt 1991; Timmer *et al*. 2000).

### *Disease cycle and epidemiology*

Disease cycle and epidemiology is similar to that of green mould. However, when Valencia oranges or Clementine mandarins are stored for long periods at temperatures below 5°C, blue mould becomes more important since it grows faster than green mould at temperatures below 10°C (Whiteside *et al*. 1988; Timmer *et al*. 2000). Blue mould is therefore most prevalent in cold stored fruit where it is able to develop slowly at cold temperatures (Sommer *et al*. 2002). The infection and sporulation cycle can also be repeated several times in a pack house and during extended storage. This prolific conidia production ability of *P. italicum* enables it to eventually develop resistant strains against chemical fungicide treatments (Brown 2003b).

### *Transmission*

Conidia of *P. italicum* are airborne and large numbers of these blue spores are produced by the fungus that can cover the entire surface of the infected fruit (Timmer *et al*. 2000; Sommer *et al*. 2002), and are easily dispersed by physical movement or by air currents. These conidia contaminate the pack house, equipment, water used in drenchers and soak tanks, storage rooms, transit containers and even the retail market area (Brown 2003b). The fungus survives in the field on soil debris and produces spores that infect split and injured fruit in the tree and on the ground. During favourable conditions (cooler autumn and winter temperatures), large numbers of spores are produced and transported by air currents to surfaces of fruit in tree canopies (Brown 2003b). In contrast to *P. digitatum*, *P. italicum* conidia are able to spread from fruit to fruit in packed containers, through uninjured skin, and create nests of decayed fruit (Eckert & Eaks 1989). Spoilage occurs when masses of conidia produced on infected fruit contaminate surfaces of healthy fruit in the carton, therefore soiled fruit must first be cleaned before retail sale (Brown 2003b).

### *Symptomology*

Symptoms of early blue mould infections are identical to green mould and sour rot with the exception of a blue conidial mass that forms on decaying fruit. Diseased tissue becomes soft, watery and slightly discoloured. A white powdery growth of mycelium develops on the surface of the lesion and eventually blue spore mass forms (Timmer *et al*. 2000, Syngenta 2007). The area of sporulation is surrounded by a narrow band of white mycelium, which is encompassed by a definite band of water-soaked rind (Timmer *et al*. 2000; Brown 2003b).

### *Control*

#### *Preventative measures*

Preventative measures to control blue mould are the same as for green mould, e.g. keeping conidial inoculum levels low and careful handling of fruit during harvest and post-harvest (FFTC 2003). Similar stringent sanitary practices used for green mould control are also applicable to blue mould.

#### *Chemical control*

Blue mould can be controlled with the same chemical treatments as used for green mould. Blue mould can also predominate in fruit treated with benzimidazole fungicides, since resistance to these materials occur more

frequently in isolates of *P. italicum* than in *P. digitatum* (Gutter 1975). Resistance problems can be minimized with the use of effective sanitation procedures. Resistance can also be minimized with the use of two or more chemically unrelated fungicides. Sanitizing agents (i.e. hydrogen peroxide, calcium chloride) and chitosan produced commercially from chitin, were tested against *P. italicum* and showed a reduction in linear growth and spore germination (El-Mougy *et al*. 2008). Similar results were obtained for *P. digitatum*. Other alternatives to fungicides, such as essential oils of clove and thyme, reduced the decay percentage of *P. italicum,* to the same level as was obtained with Imazalil (Karimi & Rahemi 2008). Azizi *et al*. (2008) obtained similar results when green mould, blue mould and brown spot were exposed to different concentrations of essential oils of medicinal plants. In addition, a nonprotein amino acid, ß-aminobutyric acid (BABA), significantly reduced disease incidence and the lesion diameter of *P. italicum* (Tavallali *et al*. 2008). This can be due to induced resistance against the pathogen infection in orange fruit by BABA treatment and shows promise for alternative disease control.

*Biological control*

Prado *et al*. (2008) illustrated the potential use of *Saccharomycopsis schoenii* to control *P. expansum*, *P. digitatum* and *P. italicum*. Similarly, Obagwu and Korsten (2003) showed the effectiveness of *Bacillus* spp in controlling Penicillium decay in post-harvest treatments. Droby *et al*. (2007) showed that the performance of biocontrol agents could be increased by combination with disinfectants and additives. Other physical treatments that can contribute towards more effective control of *P. italicum* include storage temperatures of 18°C or less. Blue mould can also be inhibited with biocontrol treatments and curing of fruit at 40°C for 18h, storing for five days at 5°C and storing for seven days at 20°C (Brown 2003b; Nunes *et al*. 2007).

## Sour rot

Sour rot is caused by *Geotrichum candidum* Link ex Pers. (anamorph) which is a common inhabitant of citrus soils (Brown 2003c). Sour rot develops on fruit that is wounded during harvesting and handling (Eckert & Eaks 1989).

### *Morphology*

*Geotrichum candidum* grows rapidly on potato dextrose agar, producing a dull grey-white colony with chains of arthrospores (Butler & Eckert 1962). Conidia vary between 2–8 × 3–50 $\mu$m and 3–6 × 6–12 $\mu$m (Timmer *et al*. 2000).

### *Disease cycle and epidemiology*

The pathogen is commonly present in soils and spreads to fruit surfaces. As the fruit mature, it becomes more susceptible to sour rot infection (Baudoin & Eckert 1982, Timmer *et al*. 2000). High levels of rind moisture (such as with fruit harvested early in the morning following irrigation or rainfall) play an important role in enhancing conidia germination and growth. The fungus penetrates the fruit only through injuries, particularly deep injuries that can be caused by insects or mechanical means, such as thorn or stem punctures or by plugging at harvest. Disease development depends on high humidity and temperatures above 10°C, with the optimum range between 25°C and 30°C (Timmer *et al*. 2000; Brown 2003c). Upon infection, the sour odour associated with the advanced stages of sour rot attracts flies (*Drosophila* spp.), which can disseminate the fungus and cause other injured fruit to become infected.

### *Transmission*

*Geotrichum candidum* is present in soil from where it is dispersed to fruit surfaces by air currents or water (Syngenta 2007). Higher populations of the fungus are recovered from fruit located in the lower part of the tree, and from fruit surfaces where soil is entrapped (i.e. scarred surfaces or areas under the button). Fruit dropped to the ground also contain higher fungal populations due to adhering soil (Brown 2003c). Conidia are also removed from the fruit as it comes in contact with the packing line, as well as any area where water is recirculating. If high conidia levels in the water are not controlled, all fruit is exposed and small wounds are likely to become infected. Contaminated water can therefore spread conidia to dip tanks, drenchers, washer brushes, belts and to other fruit on the packing line. This fungus can also spread by contact after packing to create a nest of infected fruit in boxes (Taverner *et al*. 2009).

### *Symptomology*

Sour rot can cause significant losses in high rainfall years (Mercier & Smilanick 2005). The sour rot infection has the most unpleasant smell of all decays known and the initial symptoms are similar to those of green and blue moulds. The cuticle is more susceptible in comparison to the lesions formed by *Penicillium*-induced moulds (Sommer & Edwards 1992). Extracellular enzymes produced by the fungus degrade the rind, segment walls and juice vesicles, causing the fruit to disintegrate into a slimy, watery mass. The lesions first appear water soaked, light to dark yellow and slightly raised (Brown 2003c; Syngenta 2007). At high relative humidity, the lesions may be covered with a yeasty,

sometimes wrinkled layer of white or cream-coloured mycelia (Baudoin & Eckert 1982; Timmer *et al*. 2000).

### *Control*

*Preventative measures*

Similar stringent sanitary practices used for the control of green and blue mould are used for sour rot, as well as careful harvesting and handling of fruit to minimize injuries. It is also very important to prevent any contact of the fruit with soil, due to the presence of *G. candidum* in soil. Other preventative measures such as the delay of harvest until later in the day will aid in reducing peel moisture and fruit turgidity that enhance injury. Fruit should also not be harvested when it has reached an excessively mature stage (Brown 2003c). Sanitary practices for the control of green and blue mould at the pack house and on the packing line are also similar for sour rot (Brown 2003c).

Packaging materials that physically separate individual fruit or layers of fruit in packed cartons will help reduce the spread of sour rot from infected fruit to healthy fruit. Storage temperatures of 10°C or below significantly decrease sour rot development, however the fungus will rapidly resume growth when fruit is transferred to a higher temperature for retail sale (Brown 2003c).

*Integrated control*

Sour rot is not controlled with the currently registered fungicides imazalil and thiabendazole (TBZ), and only partially controlled by sodium *o*-phenylphenate (Eckert & Eaks 1989). Other alternative control methods considered to be safer and more effective are biological fumigation, or biofumigation. Biofumigation with volatile compounds produced by the fungus *Muscodor albus* Worapong, Strobel and Hess have shown promise for the control of sour rot and green mould. Effective control was achieved when fruit was treated in storage rooms and shipping packages (Mercier & Smilanick 2005). Biocontrol products have however shown limitations in efficacy as stand-alone treatments for citrus fruit. Combinations of chemical treatments, such as TBZ, with a commercial biocontrol product Aspire™, containing the yeast *Candida oleophila,* were found to be highly effective against sour rot. In tests conducted at the end of the growing season, when the fruit is most susceptible to the development of sour rot, this treatment proved to be superior to the commercial treatment (Droby *et al*. 1998). Bio-Save (active ingredient: *Pseudomonas syringae*) is another biocontrol product that has been registered for the control of sour rot. This can be applied as a post-harvest application. A study conducted by Plaza *et al*. (2004b) illustrated that integrating a curing treatment at 40°C for 24 h with the de-greening process on early season citrus fruit also reduced the presence of sour rot diseased fruit.

## Trichoderma rot

*Trichoderma viride* Pers. ex Gray is a relatively minor disease of citrus since it develops more slowly than most other diseases. Lemons are more susceptible to *Trichoderma* rot than oranges and grapefruit (Eckert & Eaks 1989; Timmer *et al*. 2000).

### *Disease cycle and epidemiology*

*Trichoderma viride* infest wood or decayed fruit in contact with the soil. A relatively deep wound where an oil gland has been ruptured is a prerequisite for infection. Decay usually starts at the stem or stylar end of the fruit and develops optimally on fruit stored at 15°C or higher. Decay development is usually inhibited at temperatures below 5°C (Timmer *et al*. 2000).

### *Transmission*

*Trichoderma viride* is a common soil inhabitant and spores are transmitted through soil particles (Timmer *et al*. 2000).

### *Symptomology*

Infected fruit become brown and the peel remains leathery. The decaying fruit have a characteristic coconut odour that distinguishes it from other brown rots (Eckert & Eaks 1989; Timmer *et al*. 2000). Clumps of white mycelium with yellow-green to dark green spores are visible under humid conditions. *Trichoderma viride* is not able to penetrate sound fruit directly, but juice from decayed fruit can affect neighbouring fruit, allowing infection to occur (Cole & Wood 1970). Nests of fruit covered in mycelia and conidia can be observed in storage boxes (Eckert & Eaks 1989).

### *Control*

*Preventative measures*

Good agricultural practices are the best way of controlling Trichoderma rot. These measures include the removal of dead wood in order to remove the inoculum source, minimizing injury to fruit, rapid cooling of fruits after harvest and prompt removal of infected fruits (Brown 2003c).

## Stem-end rot

Stem-end rot may be caused by either *Diploida natalensis* or *Phomopsis citri* (Timmer *et al*. 2000).

**Diplodia stem-end rot**

*Diplodia* stem-end rot is an important citrus post-harvest disease in warm and humid growing regions of the world. In a typical summer-rainfall production area, 13–42% of untreated fruit may develop stem-end rot symptoms (Eckert & Brown 1986). All citrus cultivars are susceptible to this disease. The incidence and severity of stem-end rot can be increased by ethylene de-greening treatments (Brown 2003d).

***Morphology***

Pycnidia (spore producing structures) are subglobose to globose and 300–700 µm in diameter. The young spores are hyaline, nonseptate and granular, whilst the mature spores (17–43 µm × 10–18 µm) are striated with one septum (Timmer *et al*. 2000).

***Disease cycle and epidemiology***

Spores of the fungus are produced in specialized structures called pycnidia, which are formed on the surface of dead wood on the tree. Initial infection of deadwood is caused by airborne spores that are produced on debris found in the soil. These spores are dispersed to the fruit during the warm, rainy, summer months. The fungus colonizes dead tissue of the button surface where it remains dormant until after harvest. After harvest, the fungus invades the stem end of the fruit when the button abscises, which provides a temporary natural opening for the hyphae to penetrate the cells of the fruit core and rind (Brown & Wilson 1968).

***Transmission***

Sporulation rarely occurs on infected fruit and contamination of handling and packing equipment by the fungus is therefore not a major source of transmission (Brown 2003d). The decay also does not spread from infected to healthy fruit in packed containers.

***Symptomology***

Initial symptoms (i.e. lesions) of *Diplodia* stem-end rot are similar to that of *Phomopsis* stem-end rot. Infection occurs more frequently at the stem end of the fruit but occasionally occurs through injuries on the side or stylar end of the fruit. The fungus grows rapidly through the spongy central axis of the fruit and unevenly through the rind, which produces finger-like projections of brown tissue on the infected fruit (Syngenta 2007). Decay forms at both ends of the fruit before covering the entire fruit. A sour, fermented odour is usually present and sometimes the fruit will become black (Brown 2003d). Decayed tissue is initially firm but later becomes watery and soft. Surface mycelia appear only in advanced stages of infection at high relative humidity levels.

Ethylene de-greening significantly enhances stem-end rot due to the stimulation of abscission by ethylene (Barmore & Brown 1985). The temperature and relative humidity used in de-greening also favours fungal growth and disease development (Brown 2003d). After harvest it was shown that *Phomopsis* stem-end rot was a more common cause of decay than *Diplodia* stem-end rot when oranges were not treated with ethylene (Brooks 1941). In addition, it was observed that *Diplodia* was almost always the cause of decay on fruit when ethylene de-greening was used.

***Control***

*Preventative measures*

Good agricultural practices that produce healthy trees with minimal amounts of deadwood or removal of deadwood by pruning can aid in the control of stem-end rot. Proper ethylene concentrations of 5–10 ppm needed for de-greening should be maintained, since higher levels will not enhance de-greening, but will significantly increase the incidence of *Diplodia* stem-end rot. Spot picking or delayed harvest for better natural fruit colour development, will significantly reduce the time of de-greening required and the occurrence of decay (Brown 2003d).

*Chemical control*

Treatments applied prior to de-greening are much more effective than ones applied after. Zhang and Swingle (2005) illustrated that temperatures of 30–35°C significantly reduced green mould, but increased stem-end rot. In addition, it was indicated that fruit drenched with thiabendazole, followed by curing at 35°C for 48 h before packing, was effective in controlling both green mould and stem-end rot (Zhang & Swingle 2005).

**Phomopsis stem-end rot**

Phomopsis stem-end rot is caused by the fungus *Diaporthe citri* F.A. Wolf (anamorph *Phomopsis citri* H. Fawc. non Sacc. Traverso & Spessa). Phomopsis decay becomes more prevalent after the de-greening season and is more prevalent in humid subtropical and tropical regions (Timmer *et al*. 2000). All types of citrus are susceptible and no other hosts for this fungus have been identified yet (Kucharek *et al*. 2000).

***Morphology***

Pycnidia (200–450 $\mu$m) are scattered, dark, ovoid, thick walled and erumpent. Alpha conidia (2.5–4 × 5–9 $\mu$m) and beta conidia (0.7–1.5 × 20–30 $\mu$m) are produced. The alpha

conidia are unicellular, hyaline and biguttualte whilst the beta conidia or stylospores are filiform and hooked and do not germinate (predominate in older pycnidia). On twigs that have almost stopped producing pycnidia, perithecia (125–160 $\mu$m) develop that are spherical and have tapered beaks (200–800 $\mu$m long). The ascospores are hyaline; two celled and contains two guttulae (Timmer *et al*. 2000).

***Disease cycle and epidemiology***

The fungus produces ascospores (sexually produced) and pycnidiospores (asexually produced). Ascospores are formed on decaying wood on the soil or on dead branches are produced in relatively small numbers. Pycnidiospores are produced abundantly on dead branches, within a pycnidium (Kucharek *et al*. 2000). These spores are transported by rainfall to the immature fruit during late spring and summer months (Brown 2003e). On early season immature fruit, infections of the fruit surface cause small pustules to be produced (melanose). The fungus also colonizes dead tissue on the surface of the button. This infection remains quiescent until after harvest after which the fungus will invade the stem end of the fruit when the button senesces and the fungus can enter by natural openings. Symptoms usually begin to appear after 10 days. Sporulation rarely occurs on infected fruit; therefore, contamination of handling and packing equipment by the fungus is not a major problem in comparison to green and blue mould. Also, Phomopsis stem-end rot does not spread from infected to healthy fruit in packed containers (Brown 2003e).

***Transmission***

Ascospores are windborne and can easily spread over long distances. However, the pycnidiospores are spread over short distances within a tree or to an adjacent tree by water (Brown 2003e).

***Symptomology***

In initial stages of infection, stem-end rot caused by *Phomopsis* is indistinguishable from that caused by *Diplodia* without isolation and culture of the causal organism (Brown 2003e). The optimal temperature for Phomopsis stem-end rot is 23–24°C, with a minimum temperature of 10°C (Sommer *et al*. 2002). Infections are softening of the rind, with a tan or brown discolouration. The internal core of the fruit becomes infected and turns dark. *Phomopsis* seldom grows so rapidly through the core of the fruit that decay is exhibited at both ends, as with *Diplodia*. Also, the advancing margin of *Phomopsis* lesions are even, compared to fingerlike lobes developed at the margins by *Diplodia* (Sommer *et al*. 2002). Later season fruit are more prone to stem-end rot than early season fruit.

Warm temperatures associated with ethylene de-greening after harvest is more favourable for development of *Diplodia*, than for growth of *Phomopsis*. *Phomopsis* becomes more prevalent than *Diplodia* later in the season when naturally coloured fruit do not require de-greening (Brown 2003e). Also, the incidence of Phomopsis stem-end rot will increase in fruit grown on older trees where more inoculum is likely to be present.

***Control***

Stem-end rot is reduced by utilizing numerous control measures in the field during production and during harvest and post-harvest handling periods. As the calyx of immature fruit on the tree are also infected during periods of melanose infection, fungicide sprays and removal of dead wood for melanose control will contribute to *Phomopsis* stem-end rot control. In the pack house the use of fungicides in a post-harvest application are necessary regardless of prior control measures (Brown 2003e). In addition, a 'reduced risk' pesticide with fludioxonil as the active ingredient can also be applied as a dip, drench, flood or post-harvest spray application (Syngenta 2007).

**Alternaria rot**

Alternaria rot usually occurs at the stem-end rot of fruit stored for long periods of time but can also be found on the stylar end of fruit in the orchard (imperfections at navel infection) where it can cause premature fruit drop. Only a small amount of rot causes a bitter taste and the black fragments spoil the appearance of fruit (Timmer *et al*. 2000). Black rot and brown spot are morphologically indistinguishable pathogens of citrus: one causes rot by macerating tissues and the other causes necrotic spots by producing a host-specific toxin (Atsunorl *et al*. 2001).

**Alternaria Black rot**

*Alternaria citri* Ellis & N. Pierce in N. Pierce causes *Alternaria* black rot. There are many strains of the pathogen *Alternaria citri,* but the strain that causes black rot is a non-toxin-producing strain and the strains on mandarin causing brown spot have been referred to as *A. alternata* pv. *citri* (Adaskaveg *et al*. 2008).

***Morphology***

On potato dextrose agar, the mycelia produced appear yellowish or olivaceous hyaline. The conidia are short-clavate, oblong and dark olive brown (15–22 × 25–40 $\mu$m) and have four to six septa (Timmer *et al*. 2000).

***Disease cycle and epidemiology***

*Alternaria citri* is a saprophyte that grows on dead citrus tissue and produces airborne conidia. The pathogen establishes a quiescent infection in the button or stylar end of the fruit. Infection occurs mainly through growth cracks from the stylar end. The pathogen will not colonise the fruit from the button until senescence sets in and the fruit has been weakened by adverse conditions in the field, during storage or when the fruit has becomes over mature (Olsen *et al*. 2000). Large numbers of conidia are produced in infected fruit and this then becomes the survival mechanism of the pathogen.

***Transmission***

*Alternaria citri* produces airborne conidia which can attach and grow on the blossom end of the fruit (Cals 2005).

***Symptomology***

Premature colouring and fruit drop are the best signs of infection (Cals 2005). The rot is not always evident on the outside of the fruit. Eventually (frequently not until after harvest) a dark slightly sunken spot appears on the blossom end (as opposed to the stem end) of the fruit (Olsen *et al,* 2000). Diseased fruit have a brown to blackish discolouration at the blossom end and the discolouration and decay may be restricted to the blossom end or it may extend deep into the central cavity (Olsen *et al*. 2000). When fruit is cut, the infected tissue becomes soft and darkens, and the surfaces reveal a soft, thin coating of mycelium (Phytopathology 2009). Downy mycelium development begins already within a few hours after having the fruit cut. First it is white in colour, than darkens quickly as the conidia and conidiophores are formed. This rotten spot may eventually cover as much as one-quarter of the fruit and the juice of the entire fruit has an unpleasant taste (Cals 2007). It is therefore an important disease for the processing industries because of the juice being contaminated by masses of black fungal mycelium found in the interior of the infected fruit. In lemons, the disease is most common during storage. Certain environmental factors that cause splitting often predispose navel oranges to infection (Olsen *et al*. 2000). The incidence of splitting is higher in sunburned fruit and in trees stressed by drought and frost injury.

***Control***

*Preventative measures*

Proper fertilization and irrigation will significantly reduce the incidence of this disease (Cals 2005). Healthy, good-quality fruit are more resistant to black rot than stressed or damaged fruits, especially oranges with split navels. Preventing stress can reduce the incidence of splitting and the occurrence of black rot. It is also important to remove infected fruit from sites and to properly dispose of them (Cals 2007). Delaying harvest until infected fruit have fallen has been used as a strategy to prevent inadvertent inclusion of infected fruit in harvested crops. However, unaffected fruit should be harvested at optimum maturity.

*Chemical control*

There are no pre-harvest chemicals that are presently recommended for control and fungicide treatments are usually ineffective. Post-harvest treatments with imazalil, 2,4-D, or both have provided some control. The growth regulator 2,4-D delays senescence, thereby restricting colonization of the host (Adaskaveg *et al*. 2008). Further studies on the effect of different chemical treatments to control black rot illustrated that the combined use of sodium carbonate, thiabendazole, 2,4-D and storage at 6°C decreased the presence of black rot (Reqaeian & Aboutalebi 2007).

**Alternaria brown spot**

Brown spot is caused by *Alternaria alternata* Fr. (Keissler) pv. citri and severely affects the tangerine cultivars (Minneola, Orlando, Nova and Lee, Murcotts and Sunburst tangerines). Minneolas are the most susceptible cultivar of the tangerine hybrids and control is the most difficult. This disease does not affect oranges, but may cause some spotting on grapefruit if they are adjacent to heavily infested tangerines or tangelos (Dewdney & Timmer 2009a).

***Morphology***

Characteristic of the genus is dark-coloured multi-celled conidia that are produced in chains. The conidiophores are septate and brown (Timmer *et al*. 2000).

***Disease cycle and epidemiology***

Conidia are produced on leaves 10 days after symptoms appear, primarily on old lesions of mature leaves. Conidia production continues for up to 50 days after infection. In addition, conidia are produced in lower numbers on fruit and twigs remaining on the tree. For an infection to occur, temperatures must be favourable (20–29°C) and the length of the wetting period about 8–10 h (Timmer *et al*. 2000).

***Transmission***

The release of conidia into the air is triggered by rainfall or by a sharp change in relative humidity. Once the spores are released, they are distributed by air currents to susceptible tissue (Dewdney & Timmer 2009a).

***Symptomology***

*Alternaria alternata* attacks young fruit, leaves and twigs, producing brown-to-black lesions. Severe fruit infections, especially shortly after petal fall, result in the drop of young fruitlets. The remaining fruit usually have lesions that vary in size and form (dots to large, corky pock marks on the peel). On occasion, *A. alternata* is able to penetrate the citrus rind and cause localized necrosis, but this is relatively rare (Dewdney & Timmer 2009a).

***Control***

*Preventative measures*

Planting with disease-free nursery trees helps prevent brown spot. Even though conidia are air-borne, they tend not to travel long distances, therefore plantings of healthy trees can remain healthy for long periods. Highly susceptible cultivars should be planted at a wider spacing to promote rapid drying of the canopy and make the disease more manageable. It is also important not to promote excessive vegetative growth by over watering or excessive nitrogen fertilization (Dewdney & Timmer 2009b).

*Chemical control*

Fungicides are the primary means of controlling brown spot. The preferred method to time fungicide sprays is with the use of a weather-based model such as the one used in Florida (the ALTER-RATER). The model is based on the fact that brown spot is most severe when rainfall is greater than 2.7 mm, daily leaf wetness duration exceeds 10 h and average daily temperature is between 20°C and 28°C (Dewdney & Timmer 2009b).

**Anthracnose**

Anthracnose is caused by the fungus *Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc. in Penz. The expression of this disorder is commonly associated with the use of ethylene during the de-greening of citrus (Taverner 2003). Anthracnose can be an important pathogen on Robinson tangerine and certain other tangerine hybrids such as Fallglo and Sunburst that are harvested early in the season and that usually require long periods of ethylene de-greening to give the fruit an attractive appearance (Eckert & Brown 1986). The disease is most severe on the more poorly coloured fruit following de-greening. Anthracnose is, however, a minor problem on oranges, grapefruit and lemons (Eckert & Eaks 1989).

***Morphology***

The fungal colony varies from white to grey or black. Acervuli are erumpent and superficial and 90–270 µm in diameter. The conidia are oval or oblong, (10–16 × 5–7 µm). Ascospores are hyaline, slightly curved and nonseptate (3.5–5 × 12–22 µm) (Timmer *et al*. 2000).

***Disease cycle and epidemiology***

Conidia of *C. gloeosporioides* are disseminated to the fruit surfaces during the warm, rainy summer months. Here the conidia will germinate on the fruit surface to produce appressoria which form germ tubes that will penetrate the healthy rind within 12 hours (Eckert & Eaks 1989). The appressoria are highly resistant to some commonly used fungicides and can remain dormant for many months until the fruit is susceptible for infection (Taverner 2003). Early season cultivars can develop significant high levels of anthracnose symptoms following ethylene de-greening which stimulates the remaining appressoria to germinate. However the decay will not spread from infected to healthy fruit in packed containers (Ritenour *et al*. 2003).

***Transmission***

*Colletotrichum gloeosporioides* is a saprophyte that grows on dead plant parts in the citrus grove. During rainfall, spores are produced and dispersed by air currents and rain to developing fruit (Eckert & Eaks 1989).

***Symptomology***

The fungus is usually present, but some seasonal factors, i.e. increased fruit sensitivity and high levels of ethylene during de-greening, stimulate symptom expression (Taverner 2003). Disease symptoms on uninjured de-greened fruit start as a silvery grey and leathery decay on the stem-end or on the side of the fruit (Eckert & Eaks 1989). The same degree of firmness and elevation is retained as the adjacent healthy rind. The bruised or injured rind becomes brown to reddish brown or black spots (1.5 cm or more in diameter) appear. The decay may appear firm and dry or, if sufficiently deep-seated, may cause the fruit to become soft. Under high humidity, masses of pink or salmon-coloured conidia develop on the lesion surface (Taverner 2003). Under drier conditions, these conidia appear brown or black. 'Anthracnose tear staining' mainly occurs in grapefruit when cold water (from heavy dews) runs down the surface of fruit, injuring the rind (Barkley 2003).

***Control***

*Preventative measures*

Good cultural practices that produce healthy trees with minimal amounts of deadwood, or removal of deadwood by pruning can aid in the control of anthracnose. Regular

orchard sanitation is vital in order to reduce the pathogen source (Infonet 2009). During harvest, spot picking or delayed harvest for better natural fruit colour development will reduce the time of de-greening required and subsequently reduce decay (US Agency for International Development [USAID] 2004).

*Chemical control*

A proper ethylene concentration of 5–10 ppm is required to ensure that optimum de-greening is maintained. Higher concentrations of ethylene will not enhance de-greening, but will significantly increase the incidence of anthracnose (Ritenour *et al*. 2003). Therefore, an appropriate treatment for the effective control of anthracnose should be applied before fruit de-greening rather than after. Thiophanate methyl and benomyl have shown effective control of anthracnose. In addition, pre-harvest application of copper sprays (Barkley 2003), as well as thiabendazole as a post-harvest dip or drench, can be applied on some varieties to reduce the incidence of anthracnose (Ritenour *et al*. 2003). Immediate cold storage of fruit after packing will also aid in suppressing anthracnose development (Taverner 2003).

**Grey mould**

Grey mould is caused by *Botrytis cinerea* Pers. ex Fr. and is mostly a problem for lemons in cool, wet weather during flowering (Timmer *et al*. 2000). Since *Botrytis* will grow on almost any decaying plant material, its host range includes almost all plants (British Columbia Ministry of Agriculture and Food [BCAGF] 2009). It infects all citrus varieties but is mainly a problem on lemon fruit (OISAT 2005).

***Morphology***

Colonies of *B. cinerea* on potato dextrose agar consist of pale grey, abundant aerial mycelium in which black, irregular and large sclerotia are produced. A single conidiophore forms grape-like clusters of conidia (Hong *et al*. 2001). Conidia are globose to subglobose or ellipsoidal, unicellular, pale brown and smooth (4–11 × 6–18 µm) (Timmer *et al*. 2000).

***Disease cycle and epidemiology***

The fungus overwinters in the soil and in plant debris and only becomes active during cool, moist conditions. The sclerotia are considered the most important survival structures of *B. cinerea* and can survive in the soil for five to nine months (Coley-Smith 1980, Thomas *et al*. 1983). However, in warm-dry climates, no sclerotia were found. This suggests that *B. cinerea* commonly survives as mycelium (Raposo *et al*. 2001). During fungal growth, conidiophores bearing conidia are produced. The conidia are thin-walled and easily dispersed by air currents and water. Free moisture is necessary for conidia germination. The conidia will enter the host plant through wounds and generate fresh mycelia which invade the fruit tissue and ultimately cause the total disintegration of the cells.

***Transmission***

The fungus lives on decaying organic matter and conidia are carried by air currents, water and insects. Infected petals are the main source of infection of fruit and twigs (Hardy 2001).

***Symptomology***

Cool, rainy spring and summer weather favours grey mould development, as well as plants that are heavily fertilized with nitrogen (OISAT 2005). Gray mould appears in distinctive patches of grey brown to olive conidia masses on the fruit surfaces, later becoming a leathery decay. Gray mould is usually associated with frost damage, injuries or shell bark (Timmer *et al*. 2000).

***Control***

*Preventative measures*

General preventive measures, such as avoiding mechanical injury and pruning regularly to improve air movement may help reduce the incidence of grey mould (Adaskaveg *et al*. 2008). The pathogen can over-winter as tiny, black sclerotia embedded in dead plant tissue. It is therefore important to remove plant debris.

*Chemical control*

Treatment with copper and benzimidazole fungicides before rainfall or fog may aid in reducing disease incidence, but frequent treatments are required during prolonged cool, wet environmental conditions which might not be economically viable (Adaskaveg *et al*. 2008). The fungicide Graduate, with active ingredient fludioxonil is classified by the U.S. Environmental Protection Agency (EPA) as a ‘reduced-risk’ pesticide and offers effective control of grey mould and can be applied as a post-harvest dip, drench, flood or spray application (Syngenta 2007).

**Brown rot**

Brown rot, which develops mainly on fruit growing near the ground (Timmer & Menge 1988), is caused by *Phytophthora citrophthora* (R.E. Sm. & E.H. Sm.) Leonian and *P. nicotianae* Breda de Haan (syn. *P. parasitica* Dastur) (Timmer *et al*. 2000). The disease can affect all *Citrus* spp.,

but is usually most severe on early maturing sweet orange cultivars (Graham & Timmer 2009). In New Zealand it is a serious problem on lemons and grapefruit (NZGI 1997). It causes infection from the damping off of seedlings in nursery beds to decay of fibrous roots, crown rot, foot rot, gummosis and the brown rot of fruits in groves and as post-harvest decay during storage (Naqvi 2004).

***Morphology***

The sporangia of *P. citrophthora* are more elongated than *P. nicotianae* (45–90 × 27–60 µm) whilst *P. nicotianae* produce pear shaped to spherical sporangia (38–50 × 30–40 µm) and abundant chlamydospores and oospores (22–29 µm) (Timmer *et al*. 2000).

***Disease cycle and epidemiology***

*Phytophthora* species are able to survive unsuitable environmental conditions over several years as dormant resting spores (oospores or chlamydospores) (Timmer *et al*. 2000). When environmental conditions become favourable, resting spores germinate. Sporangia release large numbers of motile, biflagellate zoospores that can swim in short distances in water (Adaskaveg *et al*. 2008). Zoospores are infective agents and form germ tubes on the fruit surfaces that penetrate directly through the epidermis at any point of the fruit surface. After 3–4 days at temperatures between 24°C and 28°C, brown spots become visible. At room temperature after about seven days the entire fruit becomes diseased (Eckert & Eaks 1989).

Susceptibility of fruit increases as the fruit mature and the highest infection rate occurs just before harvest. Free water is required for infection and the development of brown rot depends on a long period of rain and fog. Optimum temperature range for maximum fruit infection and brown rot development was found to be 27–30°C with wetness durations of 3h or more (Timmer *et al*. 2000).

***Transmission***

During prolonged periods of rain and fog, the fungus sporulates on the soil and infected fruit and the motile spores (zoospores) are dispersed by rain splash and air currents to low hanging fruit on the tree. Infection is therefore generally limited to the lower third of the tree canopy (Sommer *et al*. 2002).

***Symptomology***

The disease is not very common, but all cultivars can be affected with early varieties showing greater susceptibility, especially during long, rainy periods. Highest infection occurs on fruit that mature at the time rainfall occurs (Futch & Timmer 2001; Barkley 2003). Fruit is most susceptible to brown rot just after colour break. Symptoms on fruit include a tan to olive brown leathery appearance (Sommer *et al*. 2002). Under humid conditions, white growth on the surface of the fruit may develop (Futch & Timmer 2001). Brown rot from *Phytophthora*-infected fruit can be distinguished from other brown rots by a characteristic pungent spicy odor (Eckert & Eaks 1989). Infected fruit usually drop but some may be picked unnoticed and decay manifested post-harvest (Futch & Timmer 2001).

***Control***

*Preventative measures*

Skirting of trees reduces the opportunity for the soil-borne inoculum to contaminate fruit in the canopy (Barkley 2003). The edge of the herbicide strip can also be maintained inside the dripline of the tree to minimize the exposure of bare soil to direct impact by rain, which will limit rain splash of soil onto the lower canopy. Precautions should be taken during harvesting not to include fruit affected by brown rot, in the field containers (Graham & Timmer 2009). Other preventative measures include:

- Proper irrigation management.
- Mowing to prevent growth of ground vegetation.
- Pruning to remove low hanging branches.
- Maintain adequate soil drainage to limit contamination of fruit with soil-borne inoculum (Barkley 2003).

*Chemical control*

Aliette, Phostrol and ProPhyt are systemic fungicides that protect against post-harvest infection and can provide control for 60–90 days. Copper fungicides can also be applied and are primarily protective, but are also capable of killing sporangia on the fruit surface thereby reducing the level of inoculum (Graham & Timmer 2009). Copper sprays applied particularly to the skirt and the under-tree areas are also effective in preventing brown rot (Hardy 2001). A potassium phosphite product (Canon®) was evaluated for the control of brown rot on oranges and grapefruit and exhibited effective disease control (Oren & Yogev 2002).

**Black spot**

Citrus black spot (CBS) is caused by *Guignardia citricarpa* Kiely and is a fruit disease that affects the rind, but does not cause internal decay (Timmer *et al*. 2000). Black spot attacks leaves, branches and particularly fruit of sweet oranges, lemons, grapefruits, some tangerines and several hybrids (Ayres 2001). Lemons are particularly susceptible (FFTC 2003) and heavy losses may also occur on Valencia

and navel oranges and in grapefruit. Black spot causes substantial economic losses in all major citrus producing countries subject to summer rainfall. Countries in which CBS occurs include Argentina, Brazil, Peru, Venezuela, Uruguay, summer-rainfall regions of South Africa, Nigeria, Uganda, Kenya, Zimbabwe, Swaziland, Mozambique, India, China, Hong Kong, Taiwan, Japan, Philippines and coastal regions of Australia (Meyer *et al*. 2006). The disease is absent in Mediterranean regions subject to winter rainfall (i.e. Europe) and the state of California, United States (Kotze 1996; FFTC 2003).

### *Morphology*

Ascocarps are aggregated and globose (100–175 µm). Asci are clavate-cylindrical, bitunicate and eight-spored. Ascospores are hyaline, aseptate, multiguttulate, cylindrical and swollen in the middle (4.5–6.5 × 12.5–16 µm). Conidia are obobate to elliptical, hyaline, aseptate and multiguttulate with a colourless subulate appendix (5.5–7 × 8–10.5 $\mu$m) (Timmer *et al*. 2000).

### *Disease cycle and epidemiology*

The citrus black spot fungus has two sexual stages. *Guignardia citricarpa* is the teleomorph (sexual) stage during which ascospores are produced and *Phyllosticta citricarpa* (asexual) stage during which conidia or pycnidiospores are produced (Kotze 1962). The disease life cycle starts with infected fallen leaves on the orchard floor (Magarey & Borchert 2003). Ascospores are the major source of inoculum, whilst conidia are a minor source (McOnie 1964, 1967). Infection by ascospores occurs in the presence of moisture when spores germinate and produce appressoria (Obagwu 2003). A thin infection peg penetrates the cuticle and expands, forming a small mass of mycelia between the cuticle and epidermal wall (McOnie 1967). This stage represents a latent infection. In some countries the citrus trees have evergreen leaves and in others, seasonally, which can have an effect on the availability of inoculum. The most critical period for infection occurs at fruit set and can persist for the first few months after petal fall. Early symptoms of black spot are not evident for more than six months after fruit set (Kotze 1981). Symptom expression can also appear post-harvestly as typical red spot.

### *Transmission*

*Guignardia citricarpa* conidia are dispersed naturally over short distances. Both spore types are dispersed with the aid of moisture and air currents (Kotze 1962). Whilst the conidia may cause infection, the primary source of infection are the ascospores. Dark brown-black pycnidia are mainly present on dead leaves but may also be observed on fruit. The fungus has been intercepted in the United States on fruit from several countries, however, only the pycnidiospores form on the fruit and these are not airborne. Therefore, the risk of CBS spread on fruit is relatively low (Whiteside *et al*. 1988).

### *Symptomology*

Citrus black spot produces a spectrum of symptoms both on leaves and fruit and is primarily a pre-harvest fruit disease (Timmer *et al*. 2000). However the disease can lead to significant post-harvest losses. Fruit sometimes show no visible symptoms when picked but later develop the characteristic red spot lesions of the disease. This stage of symptom development starts during storage or in retail outlets, depending on temperature and humidity conditions. Therefore, citrus fruit from areas affected by this latent infection represent a risk for introduction of *G. citricarpa* into disease-free areas (Agostini *et al*. 2006). This resulted in the European Community and the United States regulating importation of fresh citrus fruit from countries where the disease is prevalent (Baayen *et al*. 2002). These regulations may restrict potential market access for mostly southern hemisphere countries and reduce the availability of the fruit for northern hemisphere consumers in the off-season.

### *Control*

#### *Preventative measures*

In areas where citrus is produced mainly for processing, disease control is aimed at reducing the inoculum source, thereby eliminating the possibility of premature fruit drop. Since the disease is mainly cosmetic and does not affect the internal characteristics of the fruit or the quality of the juice (Ayres 2001) symptomatic fruit can be used for processing. Once the pathogen is introduced into the orchard, eradication is almost impossible. Therefore a preventive disease control approach is important to ensure that the disease does not spread to CBS free production areas. Preventive measures include:

- Nursery inspections and certification schemes.
- Access control for people, vehicles, machines and implements to nurseries and orchards.
- Washing and disinfection of vehicles, machines, equipment and material used for harvesting.
- Maintaining plant health and ensuring good nutritional and health conditions.
- Inspecting groves frequently.
- Elimination of plants in an advanced state of decline.

- Removal of litter
- Removal of mature fruits before the new crop set, to prevent pycnidial inoculum getting washed down (Ayres 2001).

*Chemical control*

Once detected, an effective chemical control programme is required. Spraying with protective copper compounds or systemic fungicides (especially the benzimidazoles) can protect the newly formed fruit. Although field fungicide spray applications reduce the disease incidence to sustainable levels it does not eradicate quiescent infections, even at low harvest incidence (Agostini *et al*. 2006). Other procedures that might aid in disease control include:

- Early harvesting particularly to prevent late seasonal infection.
- Controlling weeds between the rows with post-emergence herbicides before blooming in order to cover the infected fallen leaves with mulch.
- Mulching and removal of litter.
- Irrigation of the groves in the dry months to avoid excessive fall of leaves and the predisposition of the plants to be attacked by the fungus.
- Installing windbreaks in the groves to minimize the dissemination of fungus ascospores.

Storage and shipment of fruit in the dark at cool temperatures decrease symptom development and will reduce the amount of fruit discarded at the destination. Post-harvest fungicide treatments are not considered effective (Agostini *et al*. 2006). An alternative post-harvest treatment using chitosan exhibited antifungal effects against *G. citricarpa* and also the potential to control the development of black spot lesions on 'Valencia' oranges by stimulating defence responses in the citrus skin (Rappussi *et al*. 2009). The search for further alternative post-harvest treatments resulted in effective control of *G. citricarpa* with the following potential agents: *Lentinula edodes* (Shitake mushroom), *Agaricus blazei* (medicinal mushroom) and *Saccharomyces cerevisiae* (Pascholati *et al*. 2007).

***Phytosanitary risk***

*Guignardia citricarpa* has been added to the quarantine list of the European and Mediterranean Plant Protection Organization (EPPO). It is an A1 quarantine pest (not present in that area) for Caribbean countries (CPPC) and an A2 quarantine pest (present in that area but not widely distributed there and being officially controlled) for the Far East, Indian subcontinent, Australia and New Zealand (APPPC) and African countries (IAPSC/CPI). The disease could establish and cause significant losses if introduced into the European and Mediterranean citrus growing areas and has recently been reported in the United States (EPPO 2009).

## MINOR DECAYS

### Aspergillus rot

Aspergillus rot is caused by *Aspergillus niger* van Tiegh and usually occurs on fruit that has been left in the sun for several days, fruit that was not cooled after picking or that was held in storage at high temperatures (Eckert & Eaks 1989; Timmer *et al*. 2000).

***Symptomology***

This fungus is usually present on fruit stored at relative high temperatures (27–32°C), and does not decay fruit held at temperatures lower than 20°C. Peel decay first appears light coloured and soft and can easily be punctured (Eckert & Eaks 1989; Timmer *et al*. 2000). This early symptom can easily be mistaken for blue mould or sour rot, but the decaying area becomes sunken, darker and covered in masses of black spores (Klotz 1973).

***Control***

Specific control recommendations are not necessary for *A. niger* since it only occurs on fruit that are stored in the sun for several days after harvest. Aspergillus rot can easily be controlled by storing fruit at or below 15°C and by using benzimidazole fungicides or imazalil (Timmer *et al*. 2000).

### Pleospora rot

Pleospora rot caused by *Pleospora herbarum* (Pers.:Fr.) Rabenh. is reported as a minor fruit disease in several citrus production areas (Eckert & Eaks 1989; Timmer *et al*. 2000).

***Symptomology***

*Pleaspora herbarum* enters the fruit either at a wounded site or at the stem end (Klotz 1973). Initially the affected tissue remains firm but later becomes leathery. Decayed fruit are dark brown to black internally and externally (Timmer *et al*. 2000).

## DISEASE CONTROL

Synthetic fungicides have been the main method of citrus post-harvest disease control (Eckert 1990). There is however, a growing international concern over the often indiscriminate use of synthetic fungicides on food crops because of the possible harmful effects on human health and the

environment (Norman 1988). The continuous use of synthetic chemicals has also led to the proliferation of resistant strains of pathogens (Archbald & Winter 1990, Eckert 1990). Different viable technologies have therefore been developed as part of a holistic integrated control approach and this can be achieved through effective pre- and post-harvest management of diseases, improved handling, transport, storage, packing and marketing. Alternative post-harvest treatments can also be used in combination with synthetic fungicides, such as the use of microbial antagonists integrated with commercial chemicals (Droby *et al*. 1998), hot water (Obagwu & Korsten 2003), chloride salts (Wisniewski *et al*. 1995), carbonate salts (Obagwu & Korsten 2003), natural plant extracts (Obagwu 2003) and other physical treatments such as curing and heat treatments (Ikediala *et al*. 2002). Alternative post-harvest control options such as biological agents or natural plant extracts have further become important since it is perceived as being environmentally safer and more acceptable to the general public (Janisiewicz & Korsten 2002). Whatever treatment(s) that industry adopts, it must be more environmentally friendly, safer for human health, economically viable, able to minimise post-harvest decay and able to extend shelf life to ensure successful trade in both the domestic and distant export markets (Naqvi 2004).

## Chemical control

In general, most fruit industry sectors have experienced a serious reduction in registered available pesticides with few new additions, if any. New EU and US legislation that required re-registration of all pesticides introduced stricter requirements in terms of health, environment and safety. This necessitated major pesticide companies to focus on major industries and the most important diseases. In general, citrus pesticides remain important in the global arena, despite growing chemophobia.

### *Pre-harvest applications*

Pre-harvest fungicide applications are an effective approach for control of post-harvest diseases, such as anthracnose and stem-end rot on citrus as discussed in previous sections.

### *Post-harvest applications*

Several fungicides are presently used post-harvest for control of citrus decay-causing fungi. Examples of post-harvest fungicides include thiabendazole, dichloran, and imazalil. However, when compared to pre-harvest pest control products, the number available to the industry is limited. Build-up of pathogen resistance in the post-harvest environment has also been reported for blue and green mould on citrus (Eckert 1988). Resistance to thiabendazole and imazalil is also widespread (Holmes & Eckert 1999). This has further contributed to industry pressure to introduce alternative protectants. Several new fungicides, including the active ingredients fludioxonil and pyrimethanil offer effective control of the pathogens that cause green and blue mould, *Diplodia* stem-end rot and grey mould. Fludioxonil is classified as a 'reduced risk' pesticide that is based on having very low toxicity to humans and other mammals, low risk of environmental contamination, a low risk to soil and ground water contamination and is compatible with integrated pest management practices (Syngenta 2004). Pyrimethanil is also combined with other fungicides, such as imazalil, with the advantage that they have different single site modes of action. This combination provides effective mould control when used as a post-harvest treatment on citrus (Vorstermans *et al*. 2005). Spectrophotometry has been used effectively to set up a feedback control system to control the variation of imazalil concentrations in dipping tubs for citrus fruits (Altieri *et al*. 2005).

### *Preservatives or antimicrobial food additives*

Preservatives or antimicrobial food additives are not generally considered post-harvest treatments but they do control decay, and in some cases is the only option available for producers. Some of these products include sodium benzoate, the parabens, sorbic acid, propionic acid, $SO_2$, acetic acid, nitrites and nitrates and antibiotics such as nisin (Chichester & Tanner 1972). The advantage of using such products are that they are often used in the food industry, are often considered as GRAS compounds, are cheap and are able to integrate with other disease control strategies (Molinu *et al*. 2005). Since the early twentieth century, sodium carbonate and bicarbonate were investigated for control of *P. digitatum* and *P. italicum* on citrus fruit (Molinu *et al*. 2005).

## Nonchemical control

### *Biopesticides*

The development of alternative post-harvest disease control options using either microbial agents (Conway *et al*. 1999; El-Ghaouth *et al*. 2000a; Korsten *et al*. 2000; Janisiewicz & Korsten 2002; Pang *et al*. 2002; Ismail & Zhang 2004) or natural plant products (Kubo & Nakanishi 1979; Dixit *et al*. 1995; Wilson *et al*. 1997; Obagwu & Korsten 2003) have become more important as successful commercial applications have gained ground. This alternative control strategy has the potential to be more environmentally safe and more acceptable by the general public

for human use. Biological control systems include various modes of action such as: production of antibiotics (Fravel 1988), competition for nutrients and space (Janisiewicz *et al*. 2000), induction of host resistance (Droby *et al*. 2002; Poppe *et al*. 2003), synthesis of phytoalexins and/or the accumulation of an extra-cellular matrix (Janisiewicz 1988; Lima *et al*. 1998; Chan & Tian 2005), siderophore production and direct interaction with the pathogen (Neilands 1981; Schwyn & Neilands 1987; Buyer *et al*. 1989) and/or volatile production (Fravel 1988). During the last decade research on citrus, biocontrol focused on microorganisms colonising the wound site and competing with pathogens for nutrients.

In citrus, several bacterial antagonists such as *Bacillus spp*. have been reported to reduce post-harvest decay (Huang *et al*. 1992; Obagwu & Korsten 2003). *Bacillus subtilis* tested by Yang and Ye (2006) showed that the higher concentration inhibited the incidence of rot on navel orange fruit better than the lower concentrations. A formulated product of *Pantoea agglomerans* in combination with heated sodium bicarbonate solutions also showed excellent decay control in mandarins and oranges inoculated with both *P. digitatum* and *P. italicum*. This treatment showed no rind injuries or residues on treated fruits (Torres *et al*. 2007). Two biological control strains of *Serratia plymuthica* suppressed *P. digitatum* and *P. italicum* when used in combination. These two strains showed different modes of action against the pathogens (Meziane *et al*. 2006).

Commercial testing of yeasts to control post-harvest diseases on citrus fruit, have also been evaluated in combination with conventional fungicide treatments at lower rates. The yeast *Kloeckera apiculata* could effectively control the decay of several citrus cultivars and did not alter the quality parameters of fruit (Long *et al*. 2007). *Candida oleophila* strain O effectively controlled *P. digitatum* in a post-harvest application (Lahlali *et al*. 2005). Biofumigation with the volatile-producing fungus *Muscodor albus* also showed promising results for use in storage rooms or shipping packages (Mercier & Smilanick 2005).

Commercial biopesticide products available for use on citrus are *Pseudomonas syringae* (BioSave 10 LP and 11 LP) which are applied in pack houses to prevent post-harvest fungal diseases during storage of citrus (Stockwell & Stack 2007), and *Candida oleophila* (Aspire) to control *Penicillium* on citrus and pome fruit. BioSave has been registered with the US Environmental Protection Agency for plant disease suppression (Stockwell & Stack 2007) and Aspire by Ecogen Inc. in the United States (Shachnal *et al*. 1996). *Bacillus amyloliquefaciens* (PPCB004) has been shown to be effective for the control of post-harvest citrus diseases (Arrebola *et al*. 2009) and a dossier has been prepared for product registration in South Africa. A possible mode of action has been reported as iturin A, which resulted in abnormal conidial germination and germ tube development (Arrebola *et al*. 2009).

### *Natural products*

Plant extracts from *Withania somniferan* and *Acacia seyal*, were evaluated as potential natural biopesticides on citrus. Inoculated fruit did not show decay symptoms after 21 days of storage when tested against *P. digitatum* (Mekbib *et al*. 2007). Chitosan, extracted from the exoskeleton of crustaceans, can be used as a fruit coating (Harrison 2009). Chitosan has the mode of action to boost the ability of plants for defence against fungal infections. This resulted in the decrease of *P. digitatum*, *P. italicum* and *A. citri* incidence on Valencia fruit and it has been suggested that it can be commercially used for the control of post-harvest diseases (Abd-El-Aziz & Mansour 2006). Other natural products include essential oils extracted from the epicarp of *C. sinensis* which show fungitoxicity against ten post-harvest pathogens (Sharma & Tripathi 2006) and essential oils of oregano, fennel, aremisia, laurel and lavender which also showed different degrees of control against *P. digitatum* (Soylu *et al*. 2005).

## Cultural and physical requirements

Cultural and physical activities represent nonchemical disease control strategies that require manipulation of the environment in order to decrease disease pressure. In field management systems, soil drainage improvement, use of ridges (to allow air movement and draining during the initial phase of crop growth), use of block raising techniques for better spacing and removal of the inoculum sources are amongst the most prominent practices used in citrus production (Dixon 1984).

At fruit harvesting, maximum care is required to prevent punctures, bruises, and abrasions on fruit rind. Harvesting by clipping reduces the possibility of inflicting wounds as compared to pulling (Claypool 1983). Citrus fruit subjected to dehydration at low relative humidity after harvest is prone to stem-end rind breakdown, a physiological injury which can predispose fruit to decay (Wardowski & Brown 2001). Therefore, temperature and humidity management in the post-harvest arena is crucial to avoid deterioration of produce and initiation of infection. Hong *et al*. (2007) showed that different treatments above 50°C effectively decrease the manifestation of stem-end rots, mould decay and black rots on satsuma mandarins.

Effective control of *P. digitatum* and *P. italicum* was also seen by Nunes *et al*. (2007) during curing of Valencia oranges.

Effective sanitation practices during pre- and post-harvest handling can greatly reduce the incidence of decay. Separation of sound fruit from the decayed ones in storage or distribution or repack centres reduces possible sources of inoculum and prevents contamination (Wardowski & Brown 2001). Gaseous ozone treatments in storage rooms can also decrease the load of inoculum and inhibit the surface growth of mould on packages, walls and floors. This will result in a reduction in the amount of inoculum available for re-infections of stored products (Renzo *et al*. 2005). Other physical treatments, such as ultraviolet-C irradiation and heat treatment, using hot-water dips or hot air curing, separately, or in combination, also reduced *P. digitatum* and *P. italicum* (D'Hallewin *et al*. 2005; Ben Yehoshua *et al*. 2005). A low dosage of ultraviolet-C light treatment on its own can also control green mould when fruit is treated on its stem end (Stevens *et al*. 2005). These physical control strategies are considered a potential additional tool in the decay control of citrus fruit in combination with current fungicides.

### Integrated control options and strategies

Although there is no doubt that biopesticides provide for an effective alternative control strategy, they do not always give consistent results and are often less effective compared with commercial fungicides (Janisiewicz *et al*. 1992; El-Ghaouth *et al*. 2002; Leverentz *et al*. 2003). Therefore, to achieve a similar level of efficacy provided by conventional chemicals, the use of microbial antagonists integrated with commercial chemicals (Korsten 1993; Droby *et al*. 1998; Kienay *et al*. 2005; Stockwell & Stack 2007), hot water (Korsten *et al*. 1991; Pusey 1994; Auret 2000; Nunes *et al*. 2002; Palou *et al*. 2002; Obagwu & Korsten 2003; Kienay *et al*. 2005), chloride salts (McLaughlin *et al*. 1990; Wisniewski *et al*. 1995), carbonate salts (Smilanick *et al*. 1999; El-Ghaouth *et al*. 2000b; Palou *et al*. 2001, 2002; Obagwu & Korsten 2003; Smilanick *et al*. 2005) and/or natural plant extracts (Vaugh *et al*. 1993; Mattheis & Roberts 1993; Wilson *et al*. 1997; Obagwu *et al*. 1997; Obagwu 2003) and other physical treatments such as curing and heat treatments (Leverentz *et al*. 2000; Ikediala *et al*. 2002; Plaza *et al*. 2003; Kinay *et al*. 2005; Smilanick *et al*. 2006; Zhang & Swingle 2005) provide a potential effective alternative disease control strategy. In most countries, an integrated disease control strategy is followed for citrus.

## CITRUS HANDLING PRACTICES

### Harvesting

Citrus fruit are manually harvested by means of snap-picking (Kruger & Penter 2006). In certain countries, trunk shakers and abscission chemicals are used (Mukhopadhyay 2004). Injuries that occur during harvesting and transportation of the fruit to the pack house provide entry sites for wound pathogens that cause green or blue mould and sour rot. Nail inspections prior to harvesting are therefore practiced in some countries and may contribute to reduce wounding and decay. Once picked, the fruit is placed into picking bags and moved to centralised collection areas in the orchard. Once filled, the picking bag is usually carried to a central point in the orchard and emptied out into large wooden crates, plastic bins or trailers before being transported to an on- or off-farm packing facility (Timmer & Duncan 1999). Adequate awareness about careful picking practices will reduce damage to fruit during harvesting, off-loading, transport and packing. In general fruit are not harvested when wet, since the moisture on the fruit surface may favour post-harvest infections (Agrios 2005).

### Good agricultural practices

Basic good agricultural practices (GAP) include a variety of well-known systems that should be implemented effectively and audited for compliance to one or other of the required voluntary standards. Management commitment and continual training and inspection often provide an effective framework for GAP. Some examples of GAP include the following:

- Effective orchard hygiene practices include removal of infected fruit in or under the tree to prevent build-up of pathogen inoculum levels.
- Best hand harvesting practices include gentle handling of the product to prevent bruising and wounding.
- Citrus fruit handlers should also maintain short clean nails to prevent bruising and nail inspections prior to picking and packing is standard practice in some countries.
- The effective implementation of good personal hygiene practices by workers includes continual training and awareness campaigns and the provision of adequate ablution and hand washing facilities.
- A general good harvesting principle is to avoid direct fruit – soil contact, because the particles may cause abrasive injuries during fruit handling and negatively affect the efficacy of chlorine wash treatments.

- The time of day when harvesting operations are conducted and the time interval between irrigation, or rainfall and harvest, can also influence decay and peel injuries.
- The duration of time that fruit remains in the orchard after harvest prior to removal can also affect fruit quality at the end of the supply chain.
- The mode of transferring the harvested product from the picking bag to the crates or bins may also cause wounding and affect the quality of the final product, if not done with care.
- General hygiene maintenance practices of continual practical cleaning of picking bags, crates or bins or the trailer used in transport of fruit from the orchard to the pack house, are essential to reduce potential build-up of inoculum due to the retention of infected fruit debris contaminating the next batch harvested.

**Packing facilities and processes**

Pack houses generally consist of a receiving area, packing line with sizing and grading areas and storage/dispatch areas. Common pack house practices and the order that they occur in are given below.

***Bin drenching***

It is common practice in some countries to use bin drenching at the pack house prior to fruit off-loading. The concept is to apply the first fungicide application to fruit as soon as possible after harvest, and preferably as a bulk dip or high-volume drench on arrival at the packing facility. Dipping or drenching bins of citrus with fungicides are undertaken because most injuries and subsequent inoculation of fruit, occur during harvest. A recommended practice is to apply fungicide treatments within 24 hours after harvest to prevent or reduce mould development (Tugwell 1999). However, this recommendation is often considered impractical or costly and not adequate for all fungicide groups (Wild & Spohr 1989). Alternative practices include the use of disinfectants in washing water and soaps to remove field dust from fruit at the point of receival. Washing water is often also recirculated and should therefore be sanitised or filtered to remove inoculum in the receival tank at the pack house.

***De-greening***

Many citrus cultivars can be palatable while their peel colour is still green. However, consumer perception is that green citrus are associated with immaturity and the use of ethylene to 'de-green' the fruit is therefore a common commercial practice in many countries. This method is mainly used to improve the visual quality of, otherwise, mature fruit. Citrus fruit showing some natural colour is harvested and in most cases first treated with a fungicide prior to placing it in de-greening rooms or under plastic tents. The 'trickle' method is the most common way to apply ethylene, which involves continually replacing the air in the de-greening area with a low concentration of ethylene. The commercial successful application of de-greening has been reported (Cohen 1978). The concentration of ethylene is usually around 5 ppm, and should not exceed 10 ppm. Early citrus varieties can also be de-greened by using ethephon (2-chloroethyl phosphoric acid; 2-CEPA; Murata 1997). De-greening can be achieved at 15–25°C depending on the volumes of fruit treated, the facility design and concentration of ethylene used. Efficient airflow and ventilation allows even distribution of the ethylene and removes accumulated carbon dioxide. The common air ventilation recommendation of one room volume per hour is empirical, but its success is related to good room design and automated humidity control (Wardowski *et al*. 2006). The most undesirable effect of de-greening under low humidity is fruit softening, and exacerbation of injuries and rind weaknesses.

***Ethylene effects on citrus colouring***

Ethylene is a natural growth regulator produced by most fruits as a response to stress or during the natural ripening process. Ethylene does not ripen citrus fruits; as such, the acid, sugars and flavour of the juice are unaffected. Goldschmidt *et al*. (1993) observed the response of citrus fruit to ethylene which resulted in colour change due to an increase in chlorophyll degradation and the promotion of carotenoid biosynthesis. Ethylene thus destroys chlorophyll, and promotes the development of yellow and orange carotenoids in the flavedo (Stewart and Wheaton 1972). Under conditions of mild stress, such as cold nights, citrus de-green naturally. The post-harvest use of ethylene seeks to chemically hasten the de-greening process.

***Ethylene effects on decay***

Ethylene promotes senescence (aging), which increases the susceptibility of citrus to decay. The temperature (typically 22°C to 24°C) and high humidity (ideally 95% RH) required for ethylene de-greening also provides ideal conditions for the development of post-harvest disease. Ethylene accelerates senescence of the fruit calyx, which favours 'stem-end rots' (e.g. *D. natalensis*, *P. citri* and *A. citri*). Ethylene also plays a role in the induction of anthracnose decay (*C. gloeosporiodes*). The level of ethylene used in de-greening is considered important. Ethylene

levels above 5 ppm do not hasten de-greening or improve colour, but may cause serious losses from anthracnose disease. Exogenous ethylene causes germination of the appressoria that will result in the onset of the infection process. However, ethylene can also induce physiological changes required for the development of fruit resistance (Kader 1985). The role of ethylene in anthracnose development is complex, and well described by Timmer and Brown (2000).

### *Dumping*

Citrus fruits are dumped from crates or large bins into a hopper or receival tank at the start of a conveyor or packing line. The dumping procedure can produce impact damage or abrasion unless appropriate control measures are taken. Fruit can be dumped into water to cushion impact, but water creates greater risks to food safety and pathogen control. Wet receival is usually associated with the implementation and maintenance of an effective water quality management system. Effective chlorination of the water and or filtration may support a reduced need to regularly replace the water that could impact on the water footprint of the pack house. Water replenishment rates vary depending on the volumes of fruit handled. If water in a receival bath is not adequately managed, biofilms could develop and contribute to a build-up of microbial loads. Dry dumping is recommended, provided the fruit velocity can be reduced by controlling the fall, and the hard surfaces can be padded. Fruit on fruit contact is preferred to fruit on hard metal surfaces.

### *Washing*

Citrus fruit is washed inline to remove orchard spray residues, microbes, soil and other organic contaminants, such as sooty mould (most commonly, *Capnodium citri* Penz.) (Davies & Albrigo 1994). Effective washing includes wetting of the fruit over a brushing unit. The unit consists of transverse cylindrical brushes set at a right angle to the fruit, and overhead water sprays. Fruit cleaning can be assisted by the use of detergents, and recirculated water should be sanitised to avoid the accumulation of viable microbes. The washing process should be completed with a fresh potable water rinse. Barkai-Golan (1966) reported that citrus peel was almost free from spores (especially *Penicillium*) after the fruits were washed in a bath of sodium ophenylphenate (SSOP).

### *High-pressure washers*

Since their introduction in the 1970s, the role of high-pressure washes has evolved. Initially, washers or 'descalers' were primarily used to remove insects, such as red scale (*Aonidiella auranti*). The pressures used to remove red scale were 36 bar (525 psi) and exposure times were short (15–20 seconds). However, pressures have been progressively reduced to reduce the risk of fruit damage. Lower pressures of 10–13.6 bar (150–200 psi) are considered effective given longer periods of exposure (Walker *et al*. 1999). High-pressure washes remove surface pests, but are more commonly used for the removal of sooty mould and general fruit cleaning. Developments in hot-water immersion treatment (HWT) and hot-water rinsing and brushing (HWRB) technologies have shown to kill decay causing pathogens, while maintaining fruit quality during prolonged storage and marketing (Fallik 2004). Higher temperatures require shorter treatment periods which can prevent heat damage. Cultivar, fruit maturity, fruit size and condition during the growing season are all factors that should be considered when determining the exposure time and temperature of treatments (Fallik 2004).

## Fungicide application

Citrus fruit are often stored and transported long distances to markets. With the more extended supply chain, substantial losses can occur unless spoilage pathogens are controlled and the cold chain is effectively maintained. Consumer and environmental concerns have generated substantial interest and, consequently research activity, into controls that leave little or no residues on fruit. However, chemical fungicides remain the most effective and commonly employed treatment to control post-harvest disease. Chemical fungicides can be applied in aqueous solutions to fruit or can be incorporated into waxes. The aqueous application of fungicides typically uses high volumes to ensure good coverage. Under high-volume application, the fruit is either immersed in tanks or drenched from above as it moves over rotating rollers. Alternatively, low volumes of a fungicide solution can be sprayed over fruit rotating on brushes. The brushes apply the fungicide to the fruit and only sufficient volumes of fungicide are applied to maintain continuous saturation of the rotating brushes. Unlike high-volume applications, the solutions are not recovered and re-circulated. When fungicides are used as a dip treatment, it is important to monitor the fungicide concentration and use adequate replenishment rates to ensure effective control. Chemical fungicides can also be directly incorporated into waxes. Fungicide in wax forms a concentrated barrier on the surface of the fruit, which is useful in the control of mould sporulation (Brown & Dezman 1990; Smilanick *et al*. 1997). The application of waxes is described in the next section.

**Waxing**

The appearance of fruit is important in attracting the eye of the buyer. The aim of citrus waxing is to provide a good shine and reduce weight loss during storage. Most wax formulations used are water-based emulsions containing carnauba, shellac and/or polyethylene depending on the regulations of the country. The application of wax is very important, with the amount of wax and uniformity of coverage critical factors to success. Waxes are usually dripped or sprayed onto fruit over a bed of slowly rotating brushes. A bank of fixed dippers or spray jets can be employed, spray jets can be mounted on travelling arms that move across the fruit in a 'wig-wag' fashion, or waxes can be applied using controlled droplet spinning disks. Spinning disks use centrifugal forces to disperse a fine mist of wax emulsion onto fruit. It is important to monitor fruit flow rates and adjust the wax rates accordingly.

**Drying**

Fruit drying can occur at various sections of the packing line, but large drying tunnels are required after waxing. Efficient drying is achieved by running high velocities of air over the fruit. Driers often consist of wide-open conveyors with vertical fans mounted above fruit flow. Heater fans are spaced in the drying, but their use is dependent on ambient conditions. The drying process is time, temperature and humidity dependant, with at least 2–3 minutes generally required to dry waxed fruit. In Australia, drying tunnels are commonly heated up to 50°C. In certain countries with dry hot summers, heating is seldom required (Tugwell 1999). Fruit should not roll continuously, but should turn once in the drying tunnel to ensure even drying.

**Sorting**

Sorting is necessary to remove blemishes and damaged fruit and grading is done according to market specifications. Electronic sorting equipment is usually placed at the start of a packing line to remove a proportion of blemished fruit. Some blemishes are difficult to sort electronically, and hand sorting is still required after waxing. Grading areas need to be comfortable with good lighting. The flow of fruit is usually diverted into narrow lanes (30 cm wide), and one sorter is responsible for each lane.

**Sizing**

Citrus fruit must be sized accurately to enable packages to be correctly filled and uniformly presented in the market place. Citrus fruit can be sized using electronic optical sizers or weight sizing equipment. Electronic volumetric sizing is more accurate and less damaging to fruit than mechanical sizing. Mechanical sizing is carried out with belt or roller sizing or expanding roller equipment.

**Quality standards**

Several international quality standards exist for citrus and are based on Codex Alimentarius product quality standards. Codex standards are available for oranges, grapefruits and limes (CODEX STAN 213-1999 [CODEX Standard for Limes 1999], CODEX STAN 245-2004 [CODEX Standard for Oranges 1999] and CODEX STAN 214-1999 [CODEX Standard for Grapefruit 1999]).

**Packaging**

Corrugated full-telescoping fibreboard cartons with vent holes are the primary containers used for the packaging and transport of citrus fruit. This is to protect fruit from mechanical damage during transport and should also provide a suitable micro-environment to retain fruit quality. Fruit is also packed into polyethylene mesh or transparent perforated polyethylene consumer packs in fibreboard cartons. The design of carton and the arrangement of cartons in unitized stacks are important to allow proper fruit temperatures and ventilation (Timmer & Duncan 1999). Film with the correct perforation is required to prevent the accumulation of excess moisture and high $CO_2$ levels. Fruit packed in mesh bags should be maintained under high relative humidity to prevent excessive moisture loss and shrivelling. Cartons should be stacked on wooden pallets, wrapped with mesh, tape or plastic, and protected with corner boards to provide maximum protection during long transit times.

**Storage**

Citrus fruit are held in cool rooms and distributed in refrigerated road transport to maximise shelf life. However, there is no ideal temperature for the storage of citrus but some recommendations for different cultivars are used in some countries (Tables 4.5 and 4.6). Recommended storage and carriage temperatures are a compromise between the temperature below which cold-induced rind blemish will develop, and the desire to minimise loss of quality due to shrinkage, loss of flavour and the development of mould wastage. The sensitivity of citrus to chilling injury varies according to cultivar, growing region and seasonal conditions. Often fruit is stored at low temperatures to maintain freshness and then quickly marketed before the expression of rind blemish. It is recommended to rapidly pre-cool citrus (to below 10°C) prior to loading into refrigerated containers. Container and road transport refrigeration units are not designed for pre-cooling and slow cooling of hot fruit

**Table 4.5** Examples of Storage Conditions Used Commercially for Citrus Fruit.

| Activity | Valencia/navel oranges | Lemons | Mandarin | Grapefruit |
|---|---|---|---|---|
| Pre-cooling conditions | Most packing houses do not pre-cool, need pulp temperature of 20°C for degreening | Most packing houses do not pre-cool, need pulp temperature of 20°C for degreening | Most packing houses do not pre-cool, need pulp temperature of 20°C for degreening | Most packing houses do not pre-cool, need pulp temperature of 20°C for degreening |
| Degreening | Ethylene 1–5 ppm<br>Temperature 20°C in CA; 25C in FL<br>Humidity 90–95%<br>Carbon dioxide <1% | Ethylene 1–5 ppm<br>Temperature 20°C in CA; 25C in FL<br>Humidity 90–95%<br>Carbon dioxide <1% | Ethylene 1–5 ppm<br>Temperature 20°C in CA; 25C in FL<br>Humidity 90–95%<br>Carbon dioxide <1% | Early season<br>Ethylene 1–5 ppm<br>Temperature differences in different areas<br>Humidity 95% |
| Optimum storage temperature | 3–8°C for 3 months | 7–12°C for 6 months | 5–8°C for 3–6 weeks | 12–14°C for 6–8 weeks |
| Relative humidity | – | 85–95% | 85–90% | 95% |
| Chilling sensitivity | Moderate susceptible | Most susceptible | Moderate susceptible | Moderate susceptible |

Source: Perishable Products Export Control Board (PPECB 2009).

**Table 4.6** Commercial temperature regime for export citrus.

| | | Optimum carrying and minimum delivery air temperatures (degrees Centigrade –°C) and fresh air ventilation (cubic meters per hour – m3.h-1) | | |
|---|---|---|---|---|
| Type of Citrus | Commercial storing temp (Shipping) | Optimum carrying temperature | Minimum air delivery temperature | Fresh air circulation m3.h-1 |
| Kumquats | 4.5–11.0°C | Not given | Not given | Not given |
| Lemons | 7.0–10.0°C | 7.0°C | 3.5°C | 15 |
| Oranges | 4.5°C | 3.5°C | 2.5°C | 15 |
| Limes | Not given | 11.0°C | 7.0°C | 15 |
| Soft citrus | 3.5°C | 3.5°C | 3.5°C | 15 |

Source: Perishable Products Export Control Board (PPECB 2009).

can result in dehydration and the development of rind disorders (Tugwell 1999).

**Cold chain management**

Effective cold chain management is important to ensure product integrity and prevent spoilage. Most crops benefit from refrigeration, which slows down metabolism and reduces water loss (Shewfelt *et al*. 1987, 1989). Furthermore, low temperature storage conditions are generally not conducive to disease development and can thus be exploited to ensure quality and extended shelf life (Fitzell & Muirhead 1983; Banik *et al*. 1998). Improper cooling or interrupted cooling will also promote microbial growth that will ultimately result in product spoilage (Hobbs & Gilbert 1978). Yang and Irudayaraj (2003) reported that the surface of produce that is exposed to improper storage conditions could be susceptible to microbial contamination. Jacobs and Korsten (2004) reported on the presence and dominance of several *Penicillium* spp prevalent in the citrus supply chain isolated from cold-rooms at pack houses, ports, distributions centres and retailers. Although it is well known that the cold chain

should be maintained, in practice, it is often not effectively managed and temperature fluctuations have been reported. These interruptions were mostly associated with on- and off-loading at various points such as at ports (for conventional shipping) or distribution and retail centres (Keesenberg 2005; Jacobs & Korsten 2004).

### *Humidity*

The relative humidity (RH) of fruits kept in pallet boxes should be 90% to 98%, whereas in fibreboard cartons between 85% and 90% to prevent carton deterioration (Wardowski & Brown 2001). Fruit stored in wooden or plastic containers are at near 100% RH (Timmer & Duncan 1999). Water loss from fruit during storage results in shrinkage and fruit softening. High humidity should be maintained and free water should not be allowed to accumulate on fruit. This often happens as a result of temperature fluctuations during storage, and typically, during the movement of fruit in and out of refrigerated storage during transport. Moisture on fruit in the post-harvest environment is conducive to pathogen infection and disease development.

### Controlled atmosphere

Recommended controlled atmosphere (CA) conditions for maintaining quality in citrus is 0–1% $CO_2$ and 10–15% $O_2$ (Ookagaki & Manago 1977). Controlled atmosphere storage conditions effectively reduces rind breakdown. However, different citrus fruit types respond differently to CA storage, and therefore factors such as maturity, variety, humidity and techniques need to be taken into account (Ladaniya 2008).

### Shelf life

Duration of maturity varies with cropping season and can be 1–2 months for mandarin and tangerines or tangerine hybrids, 5–6 months for oranges and up to 8 months for grapefruit (Ladaniya 2008). Extending shelf life is an important marketing tool for retail and may allow for more extensive distribution systems.

### Phytosanitary challenges

Exportation of fresh citrus often requires a low-temperature quarantine treatment for control of the Mediterranean fruit fly (*Ceratitis capitata* Wiedemann) for instance (Rodov *et al*. 2000). These quarantine treatments are commonly applied to fruit before or during transit to ensure that pests such as fruit flies or scale are not introduced into the importing country. Fruit may be subjected to either a standard treatment or a short-term cold treatment.

## FOOD SAFETY

In recent years, food-borne disease outbreaks have been linked to the global increase in consumption of fresh and minimal processed produce. Annually, millions of people are affected by the consumption of contaminated fresh produce, negatively affecting the economy of the country and general trust in the supply chain. In the United States alone, an estimated 76 million cases of food borne illnesses are reported annually (World Health Organisation 2004). However, in most countries, a formal link between contaminated fresh produce and food borne disease outbreaks cannot be made due to a general lack of effective monitoring, reporting and regulatory systems. Food borne disease outbreaks are mainly caused by *Salmonella* spp., *Campylobacter* spp., *Escherichia coli* and *Jejuni* spp. Several fruit and vegetables (i.e. leaf lettuce, iceberg lettuce, radish, sprouts, alfalfa sprouts, strawberry and carrots) have also been associated with disease outbreaks (De Roever 1998).

Extended global distribution networks and new post-harvest technologies allow for the marketing of year round fresh produce (Beuchat 2002). However, some existing production practices and newly introduced technologies may allow for product contamination. Any fresh food product has the potential to become contaminated with food borne pathogens during production, handling or distribution (Brackett 1999). Contamination of fresh produce can also occur at any point in the fresh produce supply chain and may represent any of the following improperly managed pre-harvest practices (i.e. the use of untreated manure or sewage, or contaminated irrigation water and unhygienic human handling) (de Roever 1998; Brackett 1999). In the post-harvest environment, contamination may occur due to soiled wash water, human handling, equipment or unhygienic transportation vehicles, cross-contamination between fruit and improper storage conditions (De Roever 1998).

Microbial contamination of fresh produce is largely associated with the contamination of the fructoplane, while the internal part of the fruit is generally considered free of human pathogens (Beuchat 1996). The citrus fruit peel serves as a natural protective barrier which prevents microbial contamination of the interior flesh. However, damage to or removal of the fruit rind exposes the edible portion to potential microbial invasion and spoilage. Cross contamination can also happen from the peel to the fruit pulp and this could be of importance in processing. For instance, an outbreak of salmonellosis was associated with fresh orange juice in 1995 (Goodrich 1998).

The ource of contamination was linked to inappropriate plant hygiene practices. Pao *et al*. (1998) investigated the survival and growth of *Salmonella spp*., *Escherichia coli* O157:H7, *Listeria monocytogenes* and *Staphylococcus aureus* on freshly peeled Hamlin orange subjected to room (24°C) and refrigeration (4°C or 8°C) temperatures. Refrigeration temperatures effectively inhibited the growth of all pathogens and caused population reduction of *Salmonella spp*. and *S. aureus*. Maintaining the cold chain during transport and distribution are therefore critical to retain fruit quality and prevent any potential growth of contaminants.

Correct harvesting, handling, grading and cleaning practices within the citrus supply chain are therefore essential to ensure high quality and safe fresh fruit or minimally processed or processed products. This requires the establishment of preventative practices and food safety assurance systems. Private schemes such as Globalgap for on farm assurance and Hazard Analysis Critical Control Point (HACCP) based standards for pack houses and processing plants (ISO 22000; British Retail Consortium (BRC), Safe Quality Food (SQF) etc.) are now commonly used by the citrus industry globally to prevent or reduce likelihood of contamination.

## SUMMARY

A more sophisticated holistic approach to total fruit production within a framework of GAP will ensure a safe quality product and provide retail with the desired extended shelf life. Ensuring such a holistic approach starts in the orchard using practical basic sanitation – and hygiene practices with timely effective disease control spray programmes. By following an approach of continual worker training to ensure more careful product handling and effective implementation of hygiene and sanitation practices and management to ensure effective resistance prevention strategies, will ensure that fungicides will be retained longer in the market providing much needed protection at the retail end. Integrating various disease control methods can also provide a more sustainable practical solution for citrus producers. Effective management of the cold chain to ensure a seamless in transit and storage temperature can ensure that conditions are not favourable for pathogen germination, infection and ultimate decay development. Several biocontrol agents have been shown to be effective when used on their own, but often provide more durable consistent control if integrated with other chemical products. Several alternative disease control options are available and have shown some potential for total citrus quality.

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# 5
# Apples

*John Golding and Jenny Jobling*

Apples are one of the success stories of agriculture. They have been eaten and cultivated since the early days of civilisation and are now grown and enjoyed around the world. The apple is known for its special traits such as juiciness, crispness, flavour and visual appeal. It is also quite unique in that it has a relatively long postharvest life. The genetic potential of apples both in terms of quality and storability has enabled mankind to develop technologies and methods for growing and using apples that enable apples to be available year round. This development continues today with apples becoming to be a major crop throughout the world; indeed, nearly 60 million tonnes of apple fruit were produced around the world in 2005 (Table 5.1).

The apple is classified as a pome fruit and is a member of the Rosaceae family (Westwood 1993). However, the specific origin and ancestry of the modern apple *Malus* x *domestica* Borkh. complex remain unknown. When the apple was first described in 1803, it was believed to have developed as a hybrid derived from *Malus sylvestris* (L.) Mill., *M. dasyphyllus* Borkh. and *M. praecox* (Pall.) Bork. Recently, however, *M. sieversii* (Ledeb.) M. Roem., which is widespread in the mountains of central Asia, has been hypothesized as the key species in its origin (Luby 2003).

During the late nineteenth and twentieth centuries, *M.* x *domestica* varieties from Europe, Russia, North America, New Zealand, Japan and Australia were introduced throughout the world and form the basis for most current commercial apple production (Luby 2003).

In 1826 the Royal Horticultural Society of England recognized at least 1200 different varieties of apples. This diversity of apple varieties was reflected in the range of harvesting dates of each variety, where apples were harvested and marketed in sequence 1–2 weeks apart for many months. This sequential harvesting of different varieties extended the market window for apples to consumers. However, in the twentieth century, this marketing system and the range of varieties changed dramatically as growers installed refrigerated cool rooms, where apples could be stored at low temperatures for many months. This allowed for a longer marketing periods of up to 6–8 months after harvest.

During the 1960s, another technical revolution occurred with the introduction of more advanced cool storage techniques (including controlled atmosphere storage) matched with superior strains of the 'Red Delicious' variety. This combination allowed for marketing of apples over 12 months. At this time many of the older varieties disappeared from the commercial scene. Although 'Red Delicious' is still the most commonly planted variety worldwide, it is being replaced by newer varieties such as 'Gala', 'Fuji', 'Braeburn' and 'Cripps Pink' ('Pink Lady™'), as apple breeders seek to tempt consumers with new tastier and more colourful varieties. In addition, the recent introduction of 1-methylcyclopropene (1-MCP) into the supply chain may again change world apple storage and marketing.

A special mention of Chinese apple production must also be made. Apple production in China is huge, with 20 million tonnes in 2005, accounting for over one-third of all world apple production (Table 5.1). The Chinese market is dominated by the 'Fuji' apple variety that accounts for

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**Table 5.1** Main Apple Producing Countries (2005, in tonnes).

| | Country | Apple production | | Country | Apple production |
|---|---|---|---|---|---|
| 1 | China | 20 406 500 | 11 | Chile | 1 350 000 |
| 2 | United States | 4 474 640 | 12 | Argentina | 1 262 440 |
| 3 | Turkey | 2 550 000 | 13 | Japan | 870 000 |
| 4 | Iran | 2 400 000 | 14 | Brazil | 843 919 |
| 5 | France | 2 246 351 | 15 | Ukraine | 804 000 |
| 6 | Italy | 2 192 000 | 16 | Spain | 797 700 |
| 7 | Poland | 2 050 000 | 17 | South Africa | 778 630 |
| 8 | Russian Federation | 2 050 000 | 18 | North Korea | 669 000 |
| 9 | Germany | 1 600 000 | 19 | Mexico | 580 000 |
| 10 | India | 1 470 000 | 20 | Egypt | 550 000 |
| | | | | Other countries – total | 9 646 796 |
| | | | | Total world production | 59 591 967 |

Source: Food and Agricultural Organisation of the United Nations (November 2006), http://www.fao.org.

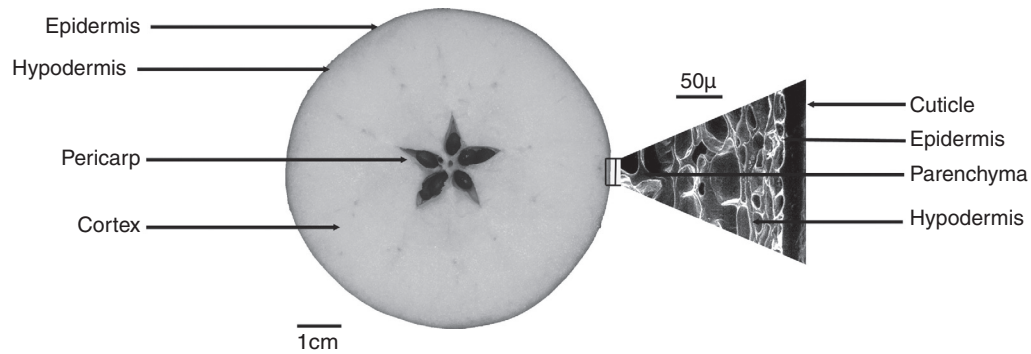



**Figure 5.1** Transverse section through mature 'Granny Smith' apple fruit. The insert is a peel section showing cuticle, epidermis, hypodermis and fleshy parenchyma.

an estimated 45% of the total Chinese production (O'Rourke *et al*. 2003). Most of the apples produced in China are consumed domestically or exported to neighbouring countries. However, as supply chains and fruit quality improves this situation is likely to change.

## APPLE FRUIT ANATOMY

It is now widely agreed that the anatomical origin of the apple fruit is best explained by the outer fruit tissue being derived from fused floral parts. The fruit is appendicular in origin (MacDaniels 1940; Esau 1977). This is a mature, ripened inferior ovary in which the pericarp plus the receptacle tissue becomes fleshy (Roth 1977). Five ovaries of the apple flower are fused at the base, which along with the receptacle becomes the fruit (Esau 1977). Figure 5.1 outlines the basic anatomy of an apple fruit and the peel.

### Core

The core and pericarp of the apple are derived from two kinds of tissue; the parenchyma tissue and the cartilaginous tissue made of sclereids lining the locules (Esau 1977). Each ovule generally contains at least one seed. Interestingly, there is a strong relationship between the number of seeds and the long-term storability of some apple varieties such as 'Jonathan', where preharvest factors such as pollination which increase the number and viability of seeds, improves storability in these apple varieties (Little & Holmes 2000).

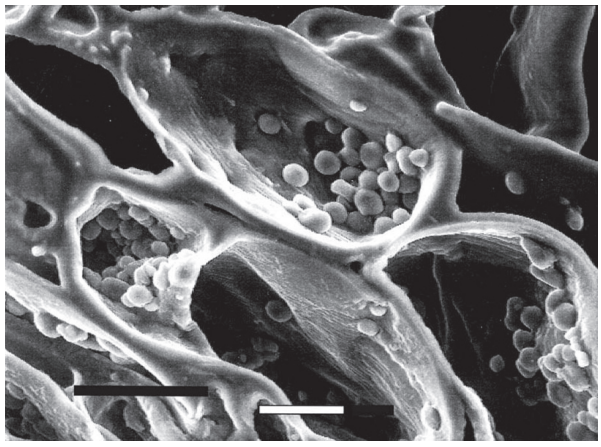


**Figure 5.2** Rounded starch grains in fleshy parenchyma cells of new season 'Granny Smith' apples. An intercellular airspace can be observed at the top left-hand corner. The white scale bar represents 20 μm.

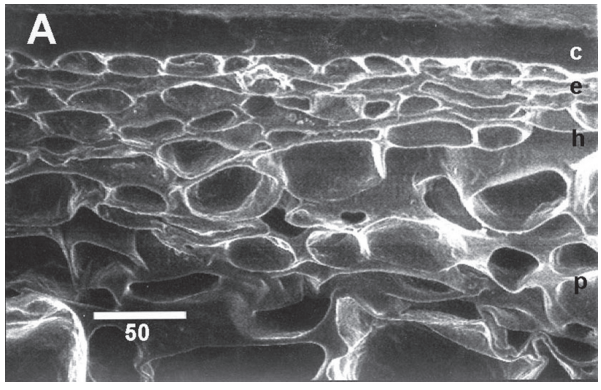



**Figure 5.3** Transverse section of 'Granny Smith' peel. The white scale bar unit is 50 μm. c, cuticle; e, epidermis; h, hypodermis; p, parenchyma.

### Flesh

In mature fleshly cells, these parenchyma cells have very thin walls with large intercellular spaces. These large intercellular spaces vary greatly in size and are up to 2000 μm in length and 100–200 μm in diameter (Reeve 1953) (Figure 5.2). The mean volume of intercellular spaces is between 22% and 40% and does not appear to be related to cell size (Reeve 1953). This high level of intercellular spaces in mature apple fruit allows apples to float in water that enables water transfer and handling.

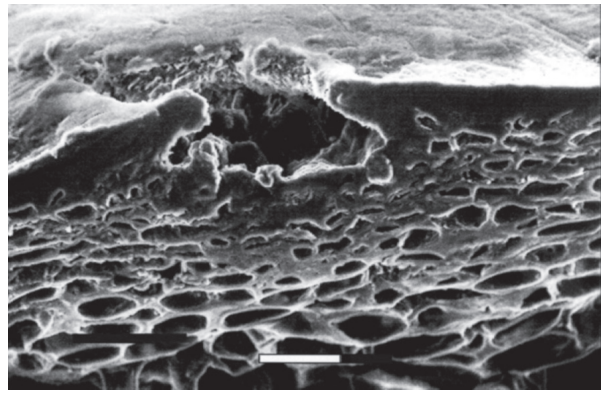


**Figure 5.4** Transverse section of a wax=encrusted lenticle in the skin of 'Crofton'. The white scale bar represents 50 μm.

This handling system has significantly reduced handling and bruising injuries in the packinghouse.

### Skin

The skin of the apple fruit is composed of the epidermis and the hypodermis, is usually 4–7 cells deep and contains chloroplasts and anthocyanins (Figure 5.3). The skin is an important cosmetic feature of apples and even though these cells have thick cell walls with thickened corners, they are susceptible to compression and impact damage leading to fruit bruising.

### Lenticels

Stomata and trichomes are present on young immature fruit, but are replaced by lenticels in mature fruit (Roth 1977). The walls of the guard cells of the old stomata become thickened and the substomatal cavities are blocked by suberisation of the cells (Figure 5.4). Although lenticels are functionally closed by the formation of a cuticle or suberisation of the sub-epidermal cells (Roth 1977), they are sites of many postharvest disorders such as lenticel breakdown, particularly in 'Gala' and 'Fuji' apples.

### Cuticle

The cuticle is an external, noncellular membrane and is thought to consist of various layers containing cutin, wax and cellulose. A pectic layer lies immediately below the cuticular membrane and is immediately above the epidermis (Esau 1977). The cuticle protects the fruit from external pathogens and also significantly reduces water loss from the fruit. However, in some varieties such as 'Granny Smith', generation of excess wax during storage

can make the apple feel 'greasy', and if severe, the fruit can become unmarketable.

## APPLE PHYSIOLOGY, MATURITY AND RIPENING

Apples are a climacteric fruit that show a burst of ethylene production and an increase in respiration during ripening. The manipulation of ethylene production and action has become very important in efforts to improve quality and extend storage life of apples. Given its importance, the following section focuses on the physiological role of ethylene (further information can be found in Volume 1, Chapter 2).

### Ethylene

Ethylene is a plant hormone that acts along with other plant hormones (auxins, gibberellins, kinins and abscisic acid) to exercise control over ripening processes ( Pech *et al*. 2002; Wills *et al*. 2007). In addition to its recognition as a 'ripening hormone', ethylene is involved in a range of other developmental processes including flowering, abscission and senescence of various organs in responses to environmental stress. As a ripening hormone, ethylene is a promoter of aging and senescence that causes cells to shift from a growth program to that of senescence (Fluhr & Mattoo 1996). The regulation of ethylene production in higher plants such as apples is regulated by endogenous and exogenous biotic and abiotic factors (Fluhr & Mattoo 1996).

Ethylene synthesis in higher plants takes the following sequence: methionine → S-adenosylmethionine (S-AdoMet) → 1-aminocyclopropane-1-carboxylic acid (ACC) → $C_2H_4$ (ethylene) (Kende 1993; Fluhr & Mattoo 1996; Alexander & Grierson 2002). Generally, the rate limiting steps in the ethylene biosynthesis pathway are catalysed by the enzymes 1-aminocyclopropane-1-carboxylic acid synthase (ACS) and 1-aminocyclopropane-1-carboxylic acid oxidase (ACO) (Fluhr & Mattoo 1996), and the formation of ACC is the major rate limiting step in the biosynthetic pathway. Positive feedback regulation of ethylene biosynthesis is also a characteristic feature of ripening where exposure to exogenous ethylene results in a large increase in ethylene production due to the induction of ACS and ACO (Alexander & Grierson 2002). Both of these enzymes are encoded by multigene families and their expression is differentially regulated by various developmental, environmental and hormonal signals.

It has been shown that ethylene affects the transcription and translation of many ripening related genes (Alexander & Grierson 2002). The resulting biochemical changes that precipitate ripening in apple fruit include increases in the activity of the enzymes responsible for ethylene biosynthesis, cell wall degradation, and aroma volatiles accumulation.

Although ethylene is the dominant trigger for ripening in climacteric fruit, it has been suggested that both ethylene dependent and ethylene independent gene regulation pathways coexist and coordinate the ripening process in climacteric fruit. For example, sugars and acid accumulation has been shown to be ethylene independent, whereas flesh softening has been shown to have both ethylene dependent and ethylene independent components. This is because softening is regulated by a series of differentially regulated genes.

### Fruit softening

Fruit softening is a key aspect of apple ripening and it is often used as a predictor of fruit quality. The softening of apples is the consequence of cell wall degradation by enzymes including polygalacturonase enzymes, pectin methyl esterase and glycosidases (Kays 1991). The softening process is regulated by the presence of ethylene. It is important to note that there are marked differences between apple varieties in terms of their rate of softening (Johnston *et al*. 2002). Work has shown that the different rates of softening between varieties can in part be explained by different expressions of polygalacturonase genes (Wakasa *et al*. 2006).

As well as softening, other changes that occur during ripening are the changes in background colour from green to yellow, loss of acidity, the conversion of starch to sugar and the synthesis of aromatic compounds. These all lead to a product that is edible and enjoyable to eat (Watkins 2003).

### Determination of commercial apple maturity

For the longest storage life with optimum eating quality, apples should be harvested just before the rise in the climacteric (Little & Holmes 2000). However, if the fruit are harvested too early, they will not ripen properly, have reduced flavour and will be susceptible to storage disorders such as superficial scald and bitter pit. Conversely, if the fruit are harvested when the fruit are well into their climacteric (i.e. over-mature), the fruit do not store well, soften rapidly, develop off-flavours and are susceptible to disease. The determination of optimal apple maturity is difficult, but it is critical to optimise fruit storage and quality (Faragher *et al*. 1984). In addition, a number of factors can significantly influence fruit maturity between and within orchards and among fruit within a single tree. For example rootstock, the nutrient status of the fruit and

the tree crop load can all have significant effects on fruit maturity (Little & Holmes 2000). These interactions highlight the need for widespread maturity assessments to be conducted on commercial orchards.

Apples exhibit various forms of the climacteric ripening behaviour (Jobling & McGlasson 1995). Measuring the respiration and ethylene production rates in fruit details the physiological state of the fruit and therefore can be used to assess its commercial maturity. This can be done by measuring the internal ethylene content, or ethylene or carbon dioxide production rates. Various maturity-forecasting techniques have been reported using ethylene production. For example, Dilley and Dilley in Michigan (United States) showed a relationship between harvest date and the time taken to accumulate 0.5 µl/l ethylene in a sealed container (Dilley & Dilley 1985).

Determining the physiological state of the fruit by measuring fruit ethylene and respiration rates is often impractical in large-scale commercial orchards. As a result, considerable research effort has been invested in identifying simpler methods for measuring apple maturity and there are a number of commercial strategies currently applied to assess fruit physiological maturity. It is important to note that no single test can successfully determine the optimum maturity of apples for eating quality or storage. Combinations of measurements are the best approach for commercial growers. The following section summarises some of the measurements that can be used.

### Calendar date

Calendar-based harvest dates are widely used by experienced growers and they rely on a reproducible date of flowering and relatively constant growth periods from flowering to maturity. Although this model does depend on field temperatures (timing of flowering, etc.), the days between flowering (full bloom) and harvest date for each apple variety does not significantly vary between seasons or districts (Little & Holmes 2000). However, variations do occur and this method of assessing maturity should not be used in isolation of other maturity indices.

### Changes in ground colour

Changes in the ground (or background) colour have been used as a maturity measure in some nonblushed varieties (such as 'Granny Smith' and 'Golden Delicious'). But significant changes in ground colour only occur when the fruit are too mature for long-term storage. In addition. environmental growing conditions have a large impact on ground colour, independent of fruit maturity. Therefore, ground colour should not be used as a harvest guide.

### Firmness

Apples undergo flesh softening during ripening. Softening is generally an undesirable process, as firmer apples tend to be crunchier and juicer, while soft apples are more mealy and unappealing. As mentioned previously, fruit softening has been shown to be dependent on ethylene action. However a range of pre- and post-harvest factors, such as seasonal and orchard variability, tree vigour, fruit size and nutrition, also affect the rate of fruit softening during storage (Johnston *et al*. 2002, 2005).

Fruit firmness is usually measured destructively with a penetrometer; however, the ability of an 11 mm penetrometer tip to relate to sensory perception has been questioned (Harker *et al*. 2002). A range of nondestructive assessments of fruit softening (such as low-mass impact and acoustic responses) show some promise for in-line firmness management and sorting, but require more commercial evaluation (Johnson & Dover 2005).

### Soluble solids content

Sugars are an important aspect of eating quality and are the major soluble solid in fruit juice. Total soluble solids can be used as an estimate of sugar content, although other compounds such as organic acids, amino acids, phenolic compounds and soluble pectins also contribute to total soluble solids. Soluble solids content (SSC) is usually determined in a small sample of fruit juice using a refractometer. More modern nondestructive technologies such as near infrared (NIR) allow rapid SSC determination (Ventura *et al*. 1998). However, SSC is not a good indicator of apple fruit maturity, as it is strongly influenced by factors such as irrigation, nutrition, weather and the fruit position on the tree (Little & Holmes 2000).

### Starch content

Starch content is one of the main factors that affect the storage life of apples (Wills *et al*. 2007). Starch is the storage carbohydrate in apples (Figure 5.2) and is broken down into sugars as the fruit matures. A starch–iodine test is based on the reaction between starch and iodine to produce a blue-purple colour. The intensity of colour indicates the amount and distribution of starch in the fruit. The stained pattern can then be compared with a rating scale. The average rating of the sample known as a starch index is determined and helps to estimate the degree to which starch has converted to sugars.

### Integrated maturity indices

As indicated in the previous sections, fruit maturity is an integrated measure of a range of physiological attributes.

The techniques and methods described so far for assessing fruit maturity are imprecise and only measure one attribute. A range of indices and techniques has been developed to integrate these maturity measures. For example, the Streif Index was developed in Germany to combine three maturity measures (firmness, SSC and starch conversion) to estimate the optimum harvest time (Streif 1996). It is calculated as {firmness / (soluble solids content × starch index)}. This approach has been successfully applied to a range of apple varieties in many countries, but adaptations to specific cultivates in each region are needed to validate this approach (DeLong *et al*. 1999).

### Regulation of maturity and ripening by manipulating ethylene

Genetic manipulation of ethylene biosynthesis has been shown to significantly affect fruit maturity, ripening and fruit quality (Defilippi *et al*. 2004). However recent research has provided two chemical treatments that can regulate fruit maturity and ripening. These chemicals, aminoethoxyvinylglycine (AVG) and 1-methylcyclopropene (1-MCP), both work by blocking ethylene activity and as a result delay fruit ripening.

### AVG

Aminoethoxyvinylglycine is a plant growth regulator that inhibits ethylene production in plants by competitively inhibiting 1-aminocyclopropane-1-carboxylase (Halder-Doll & Bangerth 1987). The inhibition of ethylene production has some important postharvest benefits for managing apple maturity.

The preharvest application of AVG to apple trees has been shown to reduce pre-harvest fruit drop, delay ripening and maturation and reduce the loss of quality of long-term stored apples (Bramlage *et al*. 1980; Halder-Doll & Bangerth 1987; Greene 2003; Phan-Thien *et al*. 2004; Silvermann *et al*. 2004; Jobling *et al*. 2005). As a result of these benefits, AVG became commercially available in the 1980s. A commercial product is sold as ReTain™ (Valent BioSciences Pty Ltd).

Research has shown that ReTain™ applied 28 days before first harvest (where harvest is defined as the earliest possible pick for long-term storage) delays fruit maturity (Greene 2003; Phan-Thien *et al*. 2004). The delay in maturity is reported to be between five and 15 days depending on the variety and the seasonal weather conditions (Greene 2003, 2005). Research by Phan-Thien *et al*. (2004) showed that the maturity of 'Gala' apples was delayed by nine to 12 days and the maturity of 'Pink Lady™' apples was delayed by five days. This delay in fruit maturity allows growers to spread their harvest window, and this can be an important commercial management tool if there are large volumes of fruit that need harvesting at one time.

There are also postharvest benefits of the preharvest application of ReTain™. Research has shown that the application of ReTain™ delays the postharvest fruit ripening (Greene 2003). Apples treated with ReTain™ have been shown to soften more slowly than untreated fruit when stored in air or CA storage. The treatment effect was most dramatic for fruit stored in air at 0°C (Golding *et al*. 2005). Research has also shown that ReTain™ applied at seven days before harvest to 'Gala' and 'Pink Lady™' apples had little impact on the maturity indices of fruit but delayed the postharvest ripening of the fruit and reduced the rate of postharvest softening (Halder-Doll & Bangerth 1987).

The relative benefit of the application of ReTain™ has been shown to be dependent on environmental factors, the time of application, harvest date and variety (Greene 2003).

### 1-MCP

A major development in apple storage technology has been the postharvest use of 1-methyl-cyclopropene (1-MCP, SmartFresh$^{SM}$). This compound has only been available for the last decade but is not only revolutionising our understanding of fruit ripening (Blankenship & Dole 2003) but is also changing apple storage practices. 1-MCP has been successfully integrated into commercial use around the world to maintain apple fruit quality during storage.

1-MCP is applied as a gas to fruit in airtight cool rooms after harvest. It acts by irreversibly binding to ethylene receptors (Sisler & Serek 1997) where the affinity of 1-MCP for the receptor is approximately ten times greater than that of ethylene. Eventual recovery is thought to be via the synthesis of new ethylene receptors. The blocking of ethylene perception with 1-MCP has a variety of effects on apple respiration, ethylene production, volatiles production, chlorophyll degradation and other colour changes, protein and membrane changes, softening, disorders and diseases, acidity and sugars (Blankenship & Dole 2003). In general, the correct postharvest application of 1-MCP has been to shown to dramatically reduce the rate of softening in apples during storage, resulting in firmer fruit after storage (Watkins *et al*. 2000). 1-MCP has also been shown to slow the decline in acidity of the fruit during storage (Watkins *et al*. 2000). In addition, 1-MCP reduces the occurrence of some common storage disorders such as soft scald, core flush and greasiness (Fan *et al*. 1999). One of its most useful benefits is its inhibition of superficial scald. However, 1-MCP has been shown to induce 'new' or

enhanced physiological disorders on some apple varieties. The management of these is still being investigated and is yet to be resolved. It should be noted that 1-MCP is not a substitute for other correct postharvest handling, storage and transport practices. Correct temperature management is still paramount in maintaining quality fruit.

The major goal in applying research on fruit ripening such as 1-MCP is to create a healthy and pleasurable eating experience for the consumer. It is important that technologies such as 1-MCP that improve storability or any other single factor, do not negatively impact on consumer satisfaction. Aroma production in ripening fruit is generally dependent on ethylene action and therefore 1-MCP application can alter the aroma profile. In general, volatile production is lower in 1-MCP treated fruit (Kondo *et al*. 2005), but this is dependent on the timing and harvest maturity of the fruit (Mattheis *et al*. 2005). Similar results have been observed following CA storage, where CA suppresses ethylene and respiration, which in turn suppresses aroma development (Mattheis *et al*. 2005). On the other hand, when applied at the correct time and concentration 1-MCP treated apple fruit have been shown to possess a more acceptable aroma than control fruit (Lurie *et al*. 2002). Fruit quality involves integration of a range of quality and sensory parameters. In a recent study, the effects of 1-MCP on consumer acceptance related the well-known effects of 1-MCP on apple fruit (firmness, soluble solids and titratable acidity) to the sensory and organoleptic ratings (overall odour, fruit odour, sweet, sour, ripe, firm, crisp, juicy and mealy) (Pre-Aymard *et al*. 2005). They showed that consumers placed a high value on apple fruit texture and that correct 1-MCP treatment can maintain the texture characteristics that are preferred by consumers (Pre-Aymard *et al*. 2005). This relationship to the consumer is often the critical limiting step to applying our knowledge of fruit quality and ripening. Such studies are important because consumers who have a negative experience when purchasing apples are likely to change varieties, purchase less or purchase something different (Harker *et al*. 2003).

The effect of 1-MCP on other aspects of apple storage is still to be investigated. For example, there are opportunities to investigate the role of 1-MCP and ethylene in apple fruit pathology. There are conflicting reports on the role of ethylene and 1-MCP in apple storage decay.

**Sensory requirements of apples**

Fruit and vegetables are becoming increasingly valued as an important part of a healthy diet. Research in Europe has shown that the average rate of consumption of apples per person is about two to three apples per week (Peneau *et al*. 2006). However, there is also an increase in the range of choices a consumer can make when purchasing fruit and other snacks, and so it is becoming increasingly important for apple growers to understand the preferences of apple consumers (Harker *et al*. 2003).

Consumers have both emotional and sensory expectations of apples (Lund *et al*. 2006). Research suggests that consumers easily recognize the appearance of the apple varieties they prefer and the association between eating experience and variety are firmly established for regular consumers of apples (Jaeger *et al*. 1998).

In terms of the sensory quality of apples, consumer preferences are based on interactions between texture and taste (Harker *et al*. 2003; Lund *et al*. 2006). Taste, aroma and freshness are the most important attributes taken into account by consumers when choosing an apple (Peneau *et al*. 2006). Most consumers prefer apples to be crisp and juicy rather than mealy and soft. Mealiness is the degree to which the flesh breaks down to a fine lumpy mass and is a significant negative attribute of apple quality (Andani *et al*. 2001). These negative characteristics develop as fruit age during storage. Another interpretation of this change is that consumer preferences within a single apple variety are usually defined by the stage of ripeness of the fruit (Harker *et al*. 2003).

It is very difficult to objectively measure the quality attributes of apples in relation to consumer preferences. The problem is that there is a high level of variability between consumers and within a population of fruit (Harker *et al*. 2003). This means that the 95% confidence limits defining the relationship between an objective parameter and a sensory perception are often large (Harker *et al*. 2006). For example, Harker *et al*. (2006) found that samples of apples had to vary in firmness by more than 12 N puncture force (Effegi penetrometer, 11 mm tip) before consumers could perceive a difference in sensory quality. Industries often try to set grade standards based on penetrometer readings for firmness but the variability within the apple sample and the differences in consumer perception of firmness makes defining a minimum level very difficult.

A consumer's perception of "quality" is the result of a cascade of choices based on several factors including previous experience, price, perceptions of freshness and food safety (Lund *et al*. 2006). As a result sensory research is focussing on developing preference maps and other multivariate techniques to gain a better understanding of how segments of consumers have differing responses (Harker *et al*. 2006; Peneau *et al*. 2006). Specific flavour

attributes are highlighted on different parts of these maps and in most cases for apples they are closely associated with the key taste and texture attributes of the fruit.

## NUTRITIONAL VALUE AND HUMAN HEALTH

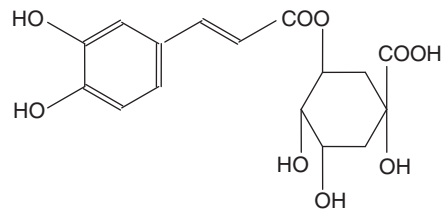
The nutritional value of fruit and vegetables are becoming a more important determinant of consumer choice. Apples are a good nutritional source of dietary fibre and Vitamin C and are very low in saturated fat, cholesterol and sodium (Wills *et al*. 2007). In addition to these standard nutritional contents, apples are becoming desirable because they are a rich source of phytochemicals, namely, phenolics (Boyer & Liu 2004). Phenolics are well-known antioxidants that have been shown to benefit human health. It has been estimated that apples contribute 22% of the American consumption of fruit phenolics (Vinson *et al*. 2001).

Phenolics are naturally occurring compounds that are derived from phenylalanine via the shikimate and phenylpropanoid pathways and are widely found in apples (Macheix *et al*. 1990). The major classes of phenolics in apple peel include phenolic acids (hydroxybenzoic acids), hydroxycinnamic acids (chlorogenic acid) and the flavonoids, for example flavans (catechin), procyanidins (condensed tannins), flavonols (quercetin glycosides), chalcones (phloretin glycoside) and anthocyanins (cyanidin glycosides) (Figure 5.5).

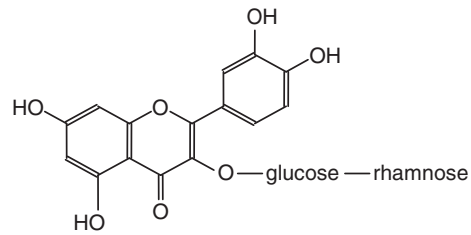
The growing human interest in apple phenolics is their role in the human diet. Epidemiological studies have linked the consumption of apples with reduced risk of some cancers, cardiovascular disease, asthma and diabetes (Boyer & Liu 2004). Apple phenolics possess significant antioxidant potential and have been shown to inhibit cancer cell proliferation, decrease lipid oxidation and lower cholesterol in laboratory tests (Boyer & Liu 2004).

The role of phenolics in the apple fruit is unclear, but they may play an important part in the physiology and metabolism. For example, phenolics act as substrates for browning enzymes, they are important antioxidants (Wills *et al*. 2007) and they have also been implicated in pathogen resistance and some physiological disorders (Macheix *et al*. 1990).

The phenolic content of apples varies by variety, environmental growing (nutrient) conditions and location within the tree (Awad *et al*. 2001, 2002). For example, lower levels of some phenolics such as catechin and chlorogenic acid are not affected by canopy position, but others such as anthocyanins are affected by tree position (Awad *et al*. 2001). Not surprisingly, significant differences in phenolic concentrations in fruit from different regions for some varieties have been reported (McGhie *et al*. 2005).




Hydrocinnamic acid derivative
5'-caffeoylquinic acid
Chlorogenic acid




Flavonol
quercetin rutinoside
Rutin

**Figure 5.5** Important apple phenolics: chlorogenic acid and rutin.

There are only relatively small changes in fruit phenolics during maturation and ripening, where their levels are relatively stable during air and CA storage for over nine months (Golding *et al*. 2001), indicating that phenolic metabolism and turnover are low during storage.

## PRE-HARVEST FACTORS AFFECTING STORAGE

It is important to remember that fruit are alive while they are on the tree and remain alive during post-harvest storage. While the fruit is attached to the tree, it is growing and accumulating carbohydrates and other nutrients. These stored reserves sustain the fruit during post-harvest storage and marketing. This means that any factor which limits the growth and accumulation of stored reserves of the fruit while it is on the tree can also affect the fruit's post-harvest storage life (Sharples 1975; Little & Holmes 2000; Stanley *et al*. 2000).

Often the effects of climate on storage life are small and only affect such things as fruit size, shape, red colour and blemish more than their storage potential (Little & Holmes 2000). However, in some instances the effect of climate, or the interaction between climate and orchard management,

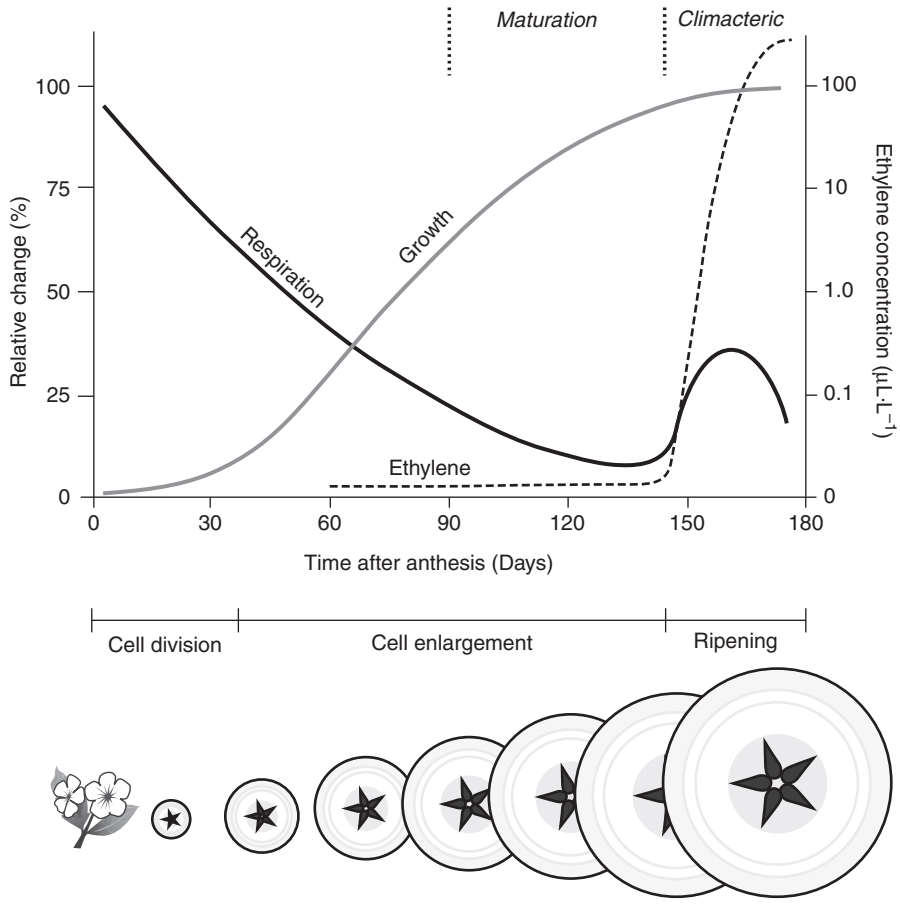



**Figure 5.6** Relative changes in physiology during growth, development, maturation and ripening in apple fruit. (Figure by Dr. Ekman, 2006.)

have a very profound effect on fruit quality, and some of these instances are described below.

### The influence of seasonal climate on fruit growth and maturity

The classic apple growth curve is illustrated in Figure 5.6, and shows the three stages of apple fruit growth; cell division, cell expansion, growth and ripening. Seasonal growing temperatures impose many effects on apple production and most obviously set limits on apple production areas (Palmer *et al*. 2003). Growing temperatures determine the length of the growing season and alter the rate of physiological processes, including cell division, growth and respiration (Palmer *et al*. 2003). Apple fruit growth is defined by an initial 35–60-day period of exponential growth following fertilisation coinciding with rapidly increasing fruit cell numbers. This period is followed by a more or less linear growth phase until harvest maturity, during which fruit size increases through cortical expansion (Figure 5.6).

Research has found that the total fruit cell number determines the potential maximum fruit size. The total number of cells in an apple is produced during the initial cell-division growth phase during the first 60 days after full bloom (DAFB) (Stanley *et al*. 2000). Given no limitations, these cells would expand to their optimum size to provide the maximum fruit weight achievable for that total cell number. A reduction in fruit weight would be expected from trees with a higher crop density (Volz *et al*. 1998) or from late thinning of the crop (McArtney *et al*. 1996) due to competition for total carbohydrate. Low temperature during the initial 60 DAFB extends the cell

division period and increases the "size potential" of the fruit by laying down more cells. However, warmer temperatures increase the rate of cell expansion and raise the actual rate of size increase (Austin *et al*. 1999; Stanley *et al*. 2000).

Research has also shown that temperatures experienced during early fruit growth affect the rate and timing of fruit ripening. There may also be an impact on fruit growth and size at maturity if the duration from bloom to harvest varies greatly. Studies have shown that fruit maturity indicators (changes in starch content, firmness, background colour, red blush and ethylene production) are accelerated by higher temperatures in the first six weeks of fruit growth (Stanley *et al*. 2000). Late-season temperatures are more likely to influence ripening physiology than fruit growth. It is important to note that there are differences in temperature response between varieties.

## THE EFFECT OF VARIETIES AND ROOTSTOCK ON QUALITY AND POST-HARVEST STORAGE

There are thousands of apple varieties available around the world with each one having specific quality characteristics (such as colour, size and flavour) and storability (Hampson & Kemp 2003). These workers reviewed the characteristics of 12 of the leading varieties around the world and showed that in general early season varieties such as 'Gala' and 'Jonathan' have shorter storage lives than late season varieties such as 'Cripps Pink' and 'Granny Smith'.

Different varieties also have different patterns of ethylene production. For example 'Gala' and 'Lady Williams' apples have typical climacteric patterns of ethylene production whereas 'Fuji' apples have a suppressed climacteric pattern (Jobling & McGlasson 1995). Research has found that the suppression of ethylene production in 'Fuji' apples is due to different expression of the genes encoding ACC synthase compared to typically climacteric varieties like 'Golden Delicious' (Sunako *et al*. 1999). As a result of the different ripening patterns, 'Fuji' apples in general have a longer post-harvest storage life than 'Gala' apples. However, even in the absence of a suppressed ethylene production rate, 'Lady Williams' has an exceptionally long storage life as it is a very hard apple at harvest and so does not soften significantly during storage (Jobling & McGlasson 1995). In terms of post-harvest storage potential, the level of ethylene produced during ripening is a guide but so too is the density of the flesh of the fruit (denser fruit have more cells and less air spaces in the cortex) and the fruit's potential to soften during storage.

Just as there is variation in the post-harvest storage potential of varieties, rootstocks also significantly influence storage life. Webster and Wertheim (2003) reviewed the range of effects that rootstocks can have on apple tree physiology and production. Fruit grown on M26 (dwarfing) rootstocks had higher levels of flesh firmness, soluble solids and higher calcium contents and also had more red blush than fruit grown on more vigorous rootstocks. The fruit on dwarfing rootstocks also matured earlier, whereas fruit grown on vigorous rootstocks such as M111 and seedling stock tend to be greener and have lower calcium levels. This is associated with the fact that the trees are vigorous with reduced light penetration. The lower light levels leads to reduced fruit red colour development and vigorous trees often have lower crop loads that reduce fruit calcium levels (Drake *et al*. 1991).

## STORAGE AND HANDLING

### Temperature

Apples are generally harvested in the late summer and autumn, but are available to consumers for the entire year. Cold storage is the basis of maintaining fruit quality over extended periods. The optimum temperature for apple fruit depends on the variety but is generally in the range of 0–3°C. Although apples are usually tolerant to these cold storage temperatures, some apples are considered susceptible to some forms of chilling injury and storage disorders such as core flush (Little & Taylor 1981). Therefore, the optimum storage conditions for every apple variety need to be determined.

Lowering the storage temperature lowers the rate of deterioration (i.e. quality is maintained and shelf life increased) and can delay onset of ripening. However, cold treatment can hasten the onset of the climacteric rise of ethylene production through enhancement of both ACC synthase and ACC oxidase activities in some apples ('Granny Smith', 'Lady Williams' and 'Fuji') (Jobling & McGlasson 1995), although this is not observed in other varieties such as 'Royal Gala' (Larrigaudiere *et al*. 1997).

The rate of cooling is an important aspect of handling harvested fruit but its importance varies according to variety, harvest maturity, nutritional status of the fruit and storage history. In most apple varieties, the lower and quicker the storage temperature is reached, the greater the retention of fruit quality (particularly firmness retention) and the longer the potential storage period. Hydrocooling is a fast way to initially cool apples, removing the field heat before they are placed in cool rooms. Bins of fruit can also be air cooled with a tunnel cooler or serpentine type airflow systems. It is important to rapidly cool apple varieties that mature in the early part of the season since they will soften

more rapidly than those that mature in the later part of the harvest season. However, for some apple varieties it is important not to cool apples so quickly as they can develop low temperature injuries such as low temperature breakdown and core flush (Little & Holmes 2000). Step-wise cooling can be used on varieties of apple that are susceptible to these disorders such as 'Jonathan' and 'Bonza'. This involves four weeks at 2°C, four weeks at 1°C then storage at 0°C. However, as expected, this technique can advance ripening and reduce storage and shelf life

**Relative humidity**

To minimise water loss and shrivel during cold storage the ideal relative humidity is around 98%. This is difficult to achieve in most cool stores that run at about 80% relative humidity. Nonetheless, under high humidity, several physiological disorders such as low temperature breakdown are enhanced (Little & Holmes 2000). In addition, storage problems associated with free water on the fruit surface such as lenticel discolouration and skin blotchiness can occur.

**Controlled atmosphere storage**

Along with temperature management, controlled atmosphere (CA) storage has been the basis of apple storage technology for the last 50 years. CA storage of apple fruit involves the regulation of the storage atmosphere at low temperatures where the level of oxygen is reduced to 1–3% and carbon dioxide is increased to 1–3%. The advantage of CA storage is a 30–40% increase in storage life over regular air storage, slower rate of fruit softening, few storage disorders (such as superficial scald and greasiness) and better shelf life following storage (Beaudry 1999; Little *et al*. 1973).

The basic principles of modifying the storage environment to increase storage life have been in practice for thousands of years. However, it was not until the 1920s and 1930s that Kidd *et al*. (1927) demonstrated the effect of reduced $O_2$ and elevated $CO_2$ in the storage environment would prolong the storage life of apple fruit. This is the basis of CA technology that is used around the world.

The physiological basis of CA relies on the reduced rate of respiration and reduction in ethylene sensitivity with the concomitant reduction in the rate of ripening and other ethylene-mediated events such as chlorophyll breakdown. Controlled atmospheres also slow down the activity of cell wall degrading enzymes involved in softening, therefore slowing the rate of firmness loss in CA. Low $O_2$ and/or high $CO_2$ atmospheres influence flavour by reducing loss of acidity, starch to sugar conversion, sugar interconversions and biosynthesis of flavour volatiles (Beaudry 1999).

Due to its sensory importance, the effect of CA on aroma production is of enormous commercial interest. The characteristic aroma production starts after the climacteric rise of ethylene production and typical flavour compounds are only produced after ripening has been initiated by ethylene. CA has been shown to suppress aroma production in apples, although with time volatile production rates return to acceptable limits (Fellman *et al*. 2000). For example the aroma levels in CA stored 'Fuji' apples decrease over time and fruit stored in ultra-low oxygen (ULO) atmospheres (1% $O_2$) show the lowest aroma production (Echeverria *et al*. 2004). This may be due to the action of $O_2$ on ethylene action, where low $O_2$ suppresses ethylene action. But this may also be likely to be via action of $O_2$ on oxidative processes including respiration where the suppression of volatiles production is a result of lowered respiration rate during CA storage via lower adenosine triphosphate (ATP) concentrations to decreased fatty acid biosynthesis (Saquet *et al*. 2003).

If the CA conditions are too severe and beyond the fruit's tolerance, it will shift from aerobic to anaerobic respiration. This is detrimental to fruit quality and causes accumulation of acetaldehyde and ethanol (Beaudry 1999). However, a nondestructive measure of chlorophyll fluorescence of the apple peel in CA storage can assist in managing low $O_2$ storage environments (DeLong *et al*. 1999). Specific responses to CA depend upon variety, maturity and ripeness stage, storage temperature and duration.

The commercial use of CA for long-term storage is the basis of year around apple marketing. Although increasing international trade will see the decline in reliance of long term CA, there will still be a need to maintain fruit quality using this well-established technology.

Cool storage and CA storage can only maintain fruit quality, they do not improve it. As a result the fruit must be in the best condition before being placed in storage. The following sections describe some of the physical, physiological and pathological disorders that can occur in storage to the detriment of fruit quality.

**Bruising**

Bruising can be a major problem in apple handling, storage and transport. Physical impacts during harvesting, sorting and packing can result in bruises that significantly reduce apple quality. Such injuries may not always be obvious immediately or even after storage, but develop during marketing and shelf life. Such injuries not only reduce returns to growers but also affect customer satisfaction and re-purchases. A thorough review of impact

damage on apples during transport and handling was conducted by Van Zeebroeck *et al*. (2007).

Apple packers have developed various methods of 'conditioning' the fruit to allow for a controlled amount of moisture to be lost by the fruit by decreasing storage humidity. This can reduce the turgor pressure within the peel cells and this has been shown to reduce bruise susceptibility. Some methods of conditioning include increasing the number of defrost cycles, opening the doors and increasing the temperature, or placing the bins in a warm room before packing. It is easy to remove a small amount of moisture from a cool room, but difficult to ensure that all fruit in a bin are affected equally (Kupferman 2006). However, Samim and Banks (1993) concluded that the potential for decreasing bruise susceptibility in 'Granny Smith' apples by manipulating fruit water status is quite limited. In addition, removing water from the cool rooms (and hence from the fruit) reduces the amount of saleable fruit and risks the potential of excessive water loss resulting in shrivel.

All apples are susceptible to bruising. It is has been a common preconception that 'Red Delicious' is more resistant to bruising. Although the external symptoms on the skin may not reveal classic bruise symptoms through the highly blushed peel, the tissue immediately under the skin often reveals classic brown bruise symptoms. Bruising is particularly an issue for light-coloured varieties such as 'Pink Lady™' and 'Golden Delicious', where the bruising symptoms are more obvious.

The most obvious method to reduce bruising is to try to reduce or eliminate impacts that occur from harvest through to packing. Careful and constant vigilance in minimising fruit impact during harvest, transfer of fruit from the field and in the packing house can significantly reduce bruising.

**Physiological disorders**

Due to their long time in cold storage, apples are renowned for developing storage disorders that are one of the major storage impediments in storing apples. Disorders are characterised by abnormal breakdown of tissue that is not caused by mechanical damage nor invasion of pathogens (Little *et al*. 1973; Wills & Scott 1981; Little & Peggie 1987). There are literally hundreds of described disorders and injuries in apples. The names and classification of these disorders are very descriptive and reflect their often indeterminate and seasonal nature.

**The influence of climate and orchard management on storage disorders**

Many storage disorders of apples are associated with interactions between seasonal climate and mineral nutrition. Often it is the imbalance between nutrients that causes the problems. For example, calcium and boron are acquired by the tree via the mass flow of water as it is drawn up through transpiration. Therefore, when the demand for water is low, such as cloudy weather, the transport of calcium is also low (Little & Holmes 2000). In contrast, other essential nutrients such as potassium and nitrogen are taken up via active transport through the phloem and uptake is influenced less by the weather (Little & Holmes 2000). This very simple example shows how seasonal weather conditions and their interaction with nutrient uptake can influence the composition of the fruit and in turn its post-harvest storability and quality.

Most calcium uptake into the fruit occurs in the first weeks of the growing season and so different timings of the water stress may cause different effects. For example, water stress late in the season will reduce the final growth and size of the fruit and may also reduce the 'dilution' of the calcium concentration. Smaller fruit have a higher concentration of calcium even though the total amount of calcium is the same (Lakso 2003). Little and Holmes (2000) detail the factors such as rootstock, crop load, pruning and variety that influence calcium status of the fruit.

Another disorder, which is known as low temperature breakdown (LTB), was the subject of one of the earliest investigations into the effects of climatic conditions on the storage life of apples, carried out by West in the 1930s using samples of 'Bramley's Seedling' apples. West found that the level of LTB was lower in fruit after warm dry weather during the four weeks immediately preceding harvest. This work also revealed that low rainfall and high temperatures during that period were both associated with reduced levels of LTB. There was, however, an interaction between cool seasons, late picking and light crops with late harvested fruit, from low cropping trees from cool seasons, being more susceptible to the disorder (Sharples 1975).

Core flush is a disorder that occurs in apples that have been harvested after a cool summer. For example, research has shown that there is a negative correlation between core flush in 'McIntosh' apples and solar radiation and temperature during the last six weeks of the growing season (Sharples 1975). It has also been shown that fruit grown under shade are more susceptible to core flush than fruit grown in full sun (Sharples 1975).

Another factor to consider for seasonal climate is water management and stress. There are often contradicting reports about the impact of water stress on post-harvest quality. This is because it is difficult to separate out the effect of water stress and its interaction with other factors (Lakso 2003). As detailed in the review by Lakso (2003),

water stress reduces fruit size, increases fruit dry matter, increases the percentage of total soluble solids and leads to earlier ethylene production. It has also been reported that the rate that fruit lose water and shrivel in storage is greater following a wet summer than after a dry one (Sharples 1975). Fruit grown with more water have a more porous skin and are more prone to shrivel in storage. These examples show how pre-harvest factors influence growth and production that in turn set the post-harvest potential storage life.

The underlying metabolic events that lead to the production of symptoms in most storage disorders are not understood. However, applied research has improved understanding of the nature and underlying biochemical and physiological mechanisms of some disorders, enabling successful control strategies. Three common potentially devastating but manageable physiological disorders are described here: superficial scald, bitter pit and flesh browning. Each example illustrates the extensive and complex pre- and post-harvest interactions of physiological disorders and also how an understanding of their underlying mechanisms can assist in their management.

## Superficial scald

Scald is a major physiological disorder that occurs during cold storage of some important apple varieties, such as 'Red Delicious' and 'Granny Smith'. Scald is characterized by brown, irregular patches that appear on the skin during cold storage (Plate 5.1). The damage is only confined to the peel and can be removed with shallow peeling (Plate 5.2). However, this amount of damage greatly downgrades fruit quality and grower returns.

The incidence of scald is affected by a number of interrelated varietal, orchard and management factors (Ingle & D'Souza 1989). Some of these include tree vigor, tree nutrition, pre-harvest temperatures, sunlight, rainfall, fruit size, and mineral content. However, the major factors influencing scald susceptibility are fruit variety (the overriding factor in the development of scald), fruit maturity (immature apples tending to scald more than more mature fruit) and seasonal conditions (fruit grown in warm, dry areas are more susceptible to scald than fruit grown in cool, moist climates). In addition, for some varieties and regions there exists an inverse relationship between the number of days below 10°C in the month before harvest and the incidence of scald. The severity of scald is also affected by storage conditions such as composition of the storage atmosphere, storage temperature, ventilation of the storage atmosphere and length of time in storage.

Scald is thought to be induced by the oxidation products of the naturally occurring fruit volatile, α-farnesene (Huelin & Coggiola 1970), when its chemical breakdown products kill the cells in the peel and cause the symptoms associated with scald. A more general oxidative stress within the peel has also been proposed to induce scald development (Whitaker *et al*. 2000).

### *Control of scald*

The simplest solution to the scald problem would be to only grow apple varieties that do not scald. However, plant breeding is a long-term solution, and many of the scald susceptible varieties have desirable commercial attributes that warrant the development of measures for controlling scald.

It was first reported in 1919 that wrapping apples in paper impregnated with mineral oil could control scald, and that ventilation of the storage room could also reduce the incidence of scald (Smock 1961). In the mid-1950s, the chemical antioxidants diphenylamine (DPA) and ethoxyquin were found to be extremely effective for controlling scald, and DPA is now routinely used in many countries to control scald as a post-harvest dip or drench, which should be applied as soon as possible after harvest.

Delaying treatment by two weeks or more greatly reduces the effectiveness of DPA. The rates of DPA application depend on variety, district and the composition of the storage atmosphere. Therefore, application rates need to be adjusted according to the variety being treated, not only to control scald but avoid DPA damage to the skin (Ingle & D'Souza 1989).

1-Methylcyclopropene (1-MCP) has also been successfully used to control scald and is registered in many countries for this purpose and to maintain fruit quality. However, as with the DPA treatment, the timing of 1-MCP treatment as soon as possible after harvest is important (Watkins & Nock 2005).

There are a growing number of potential other post-harvest treatments to control scald which are undergoing further commercial research and development. These include low oxygen storage, initial low oxygen stress and CA, application of vegetable oils, initial ethanol vapour treatment and pre-storage heat treatment (Ingle & D'Souza 1989).

## Bitter pit

Bitter pit is a nutritional disorder of apples that is caused by calcium deficiency in the fruit as it matures (Ferguson & Watkins 1989). Bitter pit can occur on fruit in trees where the tree may be adequately supplied with calcium but the fruit may be deficient. It results from a complex relationship

between climate, nutrition and tree vigour. Bitter pit symptoms often occur prior to harvest, or after long-term storage.

The disorder starts internally, but as it worsens external blemishes develop on the skin (Plate 5.3). Badly affected flesh often has a bitter taste, hence the name. Small bruise-like spots, which may be darker than the surrounding tissue, develop on the skin. As the disorder worsens the spots become brown and sunken to form pits and dry out to become tough and spongy. Spots usually develop first at the calyx end of the fruit, but highly susceptible varieties can be damaged right up to the shoulder. Even fruit with no obvious symptoms at harvest can develop skin pitting in storage, resulting in unexpected loss.

Bitter pit can be managed with pre- and post-harvest control measures (Ferguson & Watkins 1989). Calcium uptake can be influenced by several pre-harvest factors such as water availability, climatic factors, nutrition, tree vigour and crop regulation. Variety and good tree management is critical to avoid bitter pit. For example, light cropping normally promotes bitter bit by influencing the level of nutrients in the fruit but uptake is also influenced by water stress. During stress conditions, the leaves retain water at the expense of the fruit and so calcium goes to the leaves rather than the fruit (Sharples 1975). Post-harvest calcium dips are also an effective management tool to control the disorder.

**Flesh browning disorders**

There are several internal flesh browning disorders of apples and often they are variety specific. Flesh browning results from a range of pre- and post-harvest factors such as $CO_2$ injury, chilling injury, nutrient deficiency or senescent breakdown. The following are a few examples of some of the types of flesh browning storage disorders seen in apples.

Braeburn browning disorder (BBD) is an internal browning disorder related to seasonal conditions affecting fruit density that can result in $CO_2$ injury in storage (Lau 1998). Research into BBD has shown that the rapid establishment (within 2–3 days) of CA (1.2% $O_2$ and 1.0% $CO_2$) increased BBD relative to air storage after cool but not warm seasons. Another important seasonal predictor is the accumulated growing degree-days (GDD) above 10°C from full bloom to harvest. The GDD is a mathematical calculation of the number of hours per day above 10°C and this is an indication of how warm or cold a season has been, BBD develops in regions with less than 1300 GDD above 10°C from full bloom to harvest. Lau (1998) proposed that cool growing conditions may alter cellular metabolism, reduce skin and tissue diffusivity and/or increase fruit susceptibility to elevated $CO_2$ and low $O_2$.

In contrast, flesh browning in 'Fuji' apples is usually the result of $CO_2$ injury. 'Fuji' apples are more sensitive to high $CO_2$ than many other apple varieties (Volz *et al*. 1998). The susceptibility to $CO_2$ damage in 'Fuji' apples can be predicted from a sample of fruit held at 20°C at 20% $CO_2$ and then flesh browning symptoms are observed in susceptible fruit after three days. These symptoms are reported to take up to 24 days to develop in controlled atmosphere storage (Volz *et al*. 1998).

In 'Cripps Pink' apples there are three types of flesh browning disorders that represent many of the symptoms discussed earlier (Jobling *et al*. 2005; James *et al*. 2005, 2006). The first is a $CO_2$ injury that appears to be similar to $CO_2$ injury in other apple varieties. $CO_2$ injury in 'Cripps Pink' apples is aggravated by controlled atmosphere (CA) conditions with increasing levels of $CO_2$ and decreasing levels of $O_2$ causing most damage (Jobling *et al*. 2005; James *et al*. 2005). The effect of CA conditions on the incidence of $CO_2$ injury has been previously observed in other apple varieties (Park & Lee 1992; Johnson *et al*. 1998; Argenta *et al*. 2000). The second type of flesh browning is called radial flesh browning (RFB) which appears to be similar to a type of senescent or vascular breakdown described in other apple varieties (Meheriuk *et al*. 1994) and is aggravated by low seasonal temperatures, late harvest, low storage temperatures and elevated $CO_2$ in CA storage (Plate 5.4A). The third type of flesh browning is called diffuse flesh browning (DFB) and this disorder is reported to be the result of chilling injury (Plate 5.4B). Similar chilling injuries have been observed in other apple varieties such as 'Cortland' apples which have been found to be sensitive to low temperatures in storage but relatively insensitive to increased $CO_2$ in the storage atmosphere (DeEll & Prange 1998).

Interestingly, seasonal climatic conditions have also been found to influence the development of these three types of flesh browning in 'Cripps Pink' apples (James *et al*. 2005). The critical periods at this stage appear to be the first 50 DAFB with cooler seasons promoting the development to denser fruit and this can increase the risk of fruit developing RFB in storage. Seasonal accumulated GDD have also been related to the development of storage disorders of other apple varieties (Lau 1998). For 'Cripps Pink' grown in Australia, fruit in seasons or districts with accumulated GDD below 1200 appear to be susceptible to diffuse flesh browning and in areas or seasons where the accumulated GDD are between 1200 and 1500 the fruit are susceptible to radial flesh browning and all fruit are

susceptible to $CO_2$ injury if exposed to high levels of $CO_2$ in storage (James *et al*. 2005). These critical values for accumulated GDD are only guidelines as, given that there are often interacting factors promoting the induction of flesh browning symptoms in apples, it requires many seasons of data before a firm value can be set as a predictor.

These observations illustrate the range of complex pre and post-harvest interactions that develop physiological disorders characteristic of apples.

**Pathological diseases**

Fungal diseases are the main pathological diseases in apples and can cause large post-harvest losses (Snowdon 1990; Hall *et al*. 1989). Numerous pre- and post-harvest factors interact to influence the incidence of post-harvest decay. For example, the fungal spore load in the orchard or packinghouse can have enormous effect on infection pressures. In addition, the type of nutritional status, maturity and type of calyx of the apple have significant effects on susceptibility to infection. For example, apple varieties with open calyxes (open between the external calyx and the core) are more prone to rots such as mouldy core or core rot, which can enter via the calyx.

Common fungal diseases and their causative pathogens during storage of apples include alternaria rot (*Alternaria alternata* (Fr.) Keissl.), blue mould (*Penicillium* spp), grey mould (*Botrytis cinerea* (De Bary) Whetzel), anthracnose, target rot/spot (*Phlyctaema vagabunda* Desm. and others) and mucor rot (*Mucor piriformis* Scop.).

Blue mould is often the most common and important post-harvest disease of apples (Plate 5.5). It is caused by the fungus *Penicillium expansum* Link and, less often, other *Penicillium* species. The disease is found worldwide wherever these fruits are grown.

Grey mould, caused by *Botrytis cinerea*, is the most frequently encountered disease in untreated fruit stored in bins. Because *B. cinerea* frequently spreads from fruit to fruit, losses from an initial infection can be large.

Anthracnose rots have been called ripe fruit rot, lenticel rot, target rot or spot and bitter rot, and are primarily caused by the related fungi *P. vagabunda*, *Neofabraea malicorticis* H.S. Jacks. (syn. *Cryptosporiopsis malicorticis*) and *Colletotrichum gloeosporioides* Penz. Infection occurs during fruit growth and remains quiescent but can develop when the fruit becomes less resistant to disease during ripening.

Although apple pathology has been extensively studied for over 100 years, new pathogens still emerge. For example, speck rot is a relatively new post-harvest disease that has been described in Washington State (United States) and is caused by *Phacidiopycnis washingtonensis* Xiao & J.D. Rogers, sp. nov. (Kim & Xiao 2006)

***Control of post-harvest pathogens***

Disease prevention is essential to maintaining fruit quality from the packing house to the consumer. Prevention starts in the orchard where orchard sanitation (e.g. removal of diseased fruit) and using properly timed orchard fungicide sprays reduces the inoculum pressures on the fruit. The susceptibility of the fruit tissue to fungal attack is influenced by fruit maturity and the nutritional status of the fruit. It is therefore also important to harvest the fruit at optimum maturity and not create injury points for infection, such as puncture marks or fruit bruising. Fruit injury sites are ideal entry points to fungal spores such as *Penicillium* and *Mucor* (Hall *et al.* 1989; Little & Holmes 2000).

It has long been established that fruit respiration and fungal growth are both reduced at low temperatures and CA, therefore rapid cooling and establishment of CA storage help reduce the levels of storage diseases.

It is standard practice in many parts of the world to use post-harvest fungicides to control decay. There are numerous chemicals that effectively control post-harvest decay. However, good management is crucial to prevent any potential residue issues, development of fungicide resistance and to ensure the fungicide is effective. Sanitation in the packing house (including dump tank and flotation conveyors) is crucial in reducing the build-up of fungal spore populations.

The future of the control of post-harvest pathogens will involve the integration of pre- and post-harvest factors to minimise post-harvest chemicals and may include biological control (antagonists), heat and irradiation, new classes of fungicides and improved hygiene and sanitation.

## APPLE TRENDS AND CONCLUSIONS

For over a century, apples have been stored for extended periods, and this has allowed out-of-season marketing. Refrigeration, controlled atmosphere and more recently utilisation of 1-MCP all extend the shelf life and maintain fruit quality during storage. This has allowed apples to be stored for up to nine months and transported around the world. Indeed, the current world trade in apples is increasing. The whole concept of storage and transport of food is very topical. Some people are using the concept of ‘food miles’ to propose new ways of looking at the way we trade and consume food.

Food miles measure the distance that food travels from the producer to the consumer. This concept has been born

out of concern for the environment, especially in regard to greenhouse gas emissions (such as carbon dioxide) and the global warming arising from this. It is argued that the longer the transport distance, the more energy is consumed, the more fossil fuels are burned and consequently the more greenhouse gases are released into the air, and these gases are contributing to global warming. The same too can be argued for storage costs (refrigeration, CA), and this concept is receiving more attention. However, others argue that it is not the distance that should be assessed but the total energy used, from production to plate, including transport (Saunders *et al*. 2006). Apple storage in the future will be based on a diversity of technologies, and this will increase the options for apple marketing. In the future a relatively small number of apple varieties will continue to be stored, transported and marketed around the world. However, there will be a growing niche of apple producers that are successful in selling locally produced, low-input production apples to local consumers. In all cases, apples will have to satisfy the consumer and so sensory research is essential to understand the consumers' needs. Current sensory research is focusing on developing preference maps and other multivariate techniques to gain a better understanding of how market segments have differing responses (Harker *et al*. 2006; Peneau *et al*. 2006).

New apple varieties such as such as 'Jazz™' (a 'Gala' × 'Braeburn' cross from New Zealand) and 'HoneyCrisp' (released by the Minnesota Agricultural Experiment Station in 1991), offer promise of better consumer eating experiences. However, with new varieties come different post-harvest challenges. For example, 'Honeycrisp' is susceptible to the storage disorders soggy breakdown, soft scald, and bitter pit (Watkins *et al*. 2005). It is the challenge for the post-harvest researcher and apple manager to overcome these difficulties to produce high-quality fruit for the consumer.

Another problem for the apple industry is variability in eating quality among individual fruit in each consignment. Quality assurance systems based on visual quality are widely used but internal quality attributes (such as mealiness) present some limitations. Commercial nondestructive internal quality assessments are being developed and applied, but it is up to the packing house manager to ensure that excessive fruit softening and mealiness development does not occur during storage. This practical fruit management is built on a solid knowledge and application of fruit physiology and storage behaviour.

Apple fruit generally have a long storage life that is often terminated by low-temperature disorders and post-harvest disease. While some pre- and post-harvest measures can be managed to delay or reduce these storage disorders, transferring traits for tolerance or resistance by conventional breeding is slow but selection could be speeded up if molecular markers for long storage life can be identified. This also raises the issue of genetically modified food (GM food). A recent study carried out in New Zealand asked consumers about their responses to genetically modified apples. The results showed that there are two groups of consumers in relation to GM apples. One group did not accept the technology and another group accepted the technology as long as there were tangible benefits such as improved quality or health benefits (Kaye-Blake *et al*. 2005). Studies such as this will become important in the future for highlighting the concerns of consumers if genetic modification is used as a tool to transfer traits into new varieties of apple.

The post-harvest application of 1-MCP gas, particularly in combination with CA storage, has been shown to commercially maintain fruit quality and control scald during storage. There are many factors that will determine the long-term utilisation of 1-MCP into the apple supply chain. These include its cost and benefit for growers and consumers, the correct application rate of 1-MCP for maximum benefit and the marketing of treated apples in relation to the perception of quality by the consumer. Time will tell how well 1-MCP will be adapted into apple storage and marketing supply chains. The preharvest 1-MCP treatment is currently being trialled and may yet be another tool to manage fruit production and quality.

The apple industry should be able to look forward to more rapid advances in variety improvement leading to the production of fruit with more consistent flavour and improved cool storage life as the promise of genomics, proteomics and metabolomics is realised. Active apple breeding programs around the world are selecting apples with improved agronomic features, but these programs must be consumer focussed in developing apples that provide benefits to consumers.

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# 6
# Mango

*Zora Singh and Sukhvinder Pal Singh*

## INTRODUCTION

The mango (*Mangifera indica* L.) belongs to the Anacardiaceae family and is the second most important fruit crop of the tropics after banana. It is native to South Asia especially eastern India, Burma and the Malay Archipelago. It has been cultivated in this region since ancient times. However, it has spread to different parts of the world in the past few centuries. Mango tree is an arborescent evergreen, medium to large in size with rounded canopy and has a very long life span of sometimes more than 100 years. The fruit is a large, fleshy drupe with edible mesocarp, and the size and shape vary considerably depending upon the cultivar. There is a great diversity in mango cultivars distributed throughout the world. It is popularly known as 'the king of fruits' and is the choicest fruit due to its delicious taste, pleasant aroma and high nutritional value. Earlier considered as an exotic fruit, it has now become a popular fruit in the European and North American markets also. Mango is cultivated over an area of 3.87 million hectares with an annual production of 28.22 million tonnes in the world (FAO 2005). The Asian continent contributes 75% of the total world mango production followed by Africa (9.67%), North and Central America (9.04%), South America (5.99%) and a very little share from Oceania (Table 6.1). Country-wise, India is world's largest mango producing country contributing about 38% to the world production followed by China, Thailand, Pakistan, Mexico, Indonesia, Brazil and the Philippines (FAO 2005). The mango industry experienced buoyant growth in the past decade and is likely to boom further in future as its cultivation is expanding to some newer regions of the world and the trade liberalization which imparts impetus to the expansion of international trade of fresh fruits including mango, is resulting in higher volume of fruits shipped across different continents. The international trade of fresh mangoes is expanding at a faster rate as consumers in the European and North American countries are developing the taste for the fruit. A massive increase in the export and import of mango has been observed in both quantity and monetary terms during the 2000s. Mango export rose from 0.33 million tonnes (US$335 million) in 1995 to 0.9 million tonnes (US$583 million) in 2004 (FAO 2005). Despite the huge production in the Asian continent, its share in export is around 37% (FAO 2005). Mango production is located in most of the developing countries of the world where an appropriate post-harvest handling infrastructure is still in infancy. It is a highly perishable fruit but keeps well for 9–10 days if harvested at mature green stage. However, the post-harvest behaviour of mango fruit is strongly influenced by the cultivar, harvest maturity, the post-harvest treatments and storage conditions. The chilling sensitive nature of mango fruit limits its long duration storage and transportation at low temperature below 13°C. The use of controlled/modified atmosphere technology for long distance shipping has not been yet fully capitalized by the exporters. The restriction on the use of certain fumigants has narrowed the scope of post-harvest disinfestation treatments. The quarantine requirements of various importing countries to prevent the entry of exotic pests to their domestic fruits

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**Table 6.1** Area and Production of Mango in Different Parts of the World in 2005.

| Continent | Area (millions of ha) | Production (millions of tonnes) |
|---|---|---|
| Asia | 3.05 | 21.19 |
| Africa | 0.38 | 2.73 |
| North and Central America | 0.30 | 2.55 |
| South America | 0.12 | 1.69 |
| Rest of the world | 0.02 | 0.06 |
| World | 3.87 | 28.22 |

Source: FAOSTAT (2005), http://www.fao.org.

have seriously hampered the international trade. Major mango producing countries still lack commercial-scale post-harvest handling facilities for cooling, cold storage, quarantine treatments and other cutting-edge technologies developed for mango. This chapter will focus on the maturity indices, ripening changes, post-harvest handling and storage, disorders, post-harvest insect pest disinfestations and disease management of mango fruit.

## MATURITY INDICES

Harvesting at optimum maturity is a critical step which determines the potential storage life, flavour and consumer acceptance of mango fruit (Medlicott *et al*. 1988, Seymour *et al*. 1990). Immature fruit are more prone to mechanical damage (Chonhenchob & Singh 2003) and of inferior quality when ripe (Medlicott *et al*. 1988). These are also more susceptible to certain post-harvest maladies like chilling injury in addition to their uneven ripening behaviour with less skin colour development (Ledger 1995). However, more delay in picking the fruit may result in aggravation of physiological disorders like internal breakdown (Lee *et al*. 1998). The advanced maturation of mango on the tree results in better aroma quality (Bender *et al*. 2000a), lower sugar acid ratio (Lakshminarayana, 1975) and reduces the storage potential (Seymour *et al*. 1990). Optimum harvest maturity determines the suitability of fruit for post-harvest treatments like vapour heat or hot-water treatments in order to meet the quarantine requirements (Jacobi *et al*. 2001a; Jacobi & Wong, 1992) Immature fruit subjected to hot-water treatment show severe heat injury in the form of skin scald, while fruit at advanced maturity are more tolerant (Jacobi *et al*. 2001a). If fruit are not harvested at an appropriate stage of maturation, the characteristic flavour and aroma fail to develop. But, harvesting decisions by growers and contractors are generally biased towards achieving more shelf life by harvesting fruit prior to the appropriate maturity stage. The determination of optimum harvest maturity remains a debatable question. There is a plethora of maturity indices which can be applied to judge the fruit maturation. The suggested maturity indices for mango include morphological changes (skin colour, shape), computational methods (days from full bloom, days from fruit set, heat units), chemical attributes (soluble solids content (SSC), acidity, SSC: acidity, starch index, phenolics), physical attributes (specific gravity) and some non-invasive methods such as near-infrared spectroscopy and ultrasonic waves (Table 6.2).

Mango fruit are mainly picked at mature unripe stage for better storage life and long distance transportation. Visual assessment is the most commonly followed subjective method to determine harvest maturity in mango. It requires a plentiful past experience about the maturation and ripening behaviour of a particular cultivar at a location. Visible skin colour change from dark green to light green is a very common maturity index, but not always accurate. Some cultivars such as 'Harumanis' 'Katchamita' (Lizada, 1993) and 'Langra' retain green colour even if physiologically mature and ripe. Another conspicuous change in the morphology of maturing mango is rising of shoulders and sunken stem end; it is also referred to as the fullness of cheeks. Fully mature mango fruit have raised shoulders (Wang & Shiesh 1990). But this index may fail to judge the maturity of certain cultivars having no or less prominent shoulders; for example, 'Totapari'. 'Kensington Pride' mangoes can be considered fully mature and ready to pick when flesh colour is almost all yellow and the fruit shape is filled out around the beak (Holmes *et al*. 1990).

The use of computational methods to ascertain harvest maturity is widely studied and practised (Burondkar *et al*. 2000; Del Mundo *et al*. 1984; Kalra & Tandon 1983; Kasantikul 1983; Kudachikar *et al*. 2003; Lechaudel & Joas 2006; Mendoza *et al*. 1972; Obasi 2004; Shinde *et al*. 2001; Wang & Shiesh 1990). Number of days from full bloom (DFFB) or fruit set (DFFS) to reach physiological maturity varies among cultivars and locations and thus, cannot serve as a good guide. Therefore, the recommendation of DFFB or DFFS for a cultivar should be restricted over a small geographical area. The total heat units can also serve as a reliable alternative to other computational methods. For example, in 'Alphonso' mango, the number of days from fruit set to maturity varies at two locations, but the heat units remaining the same constitute a good calculative maturity index (Burondkar *et al*. 2000; Shinde *et al*. 2001). Since mango is a crop of subtropical and tropical regions,

**Table 6.2** Maturity Indices of Mango Used in Different Parts of the World.

| Maturity Index | Cultivar | Description | Country | Reference |
|---|---|---|---|---|
| *A. Morphological changes* | | | | |
| 1. Colour changes | Kensington Pride | Yellow pulp | Australia | Holmes *et al*. 1990 |
| | Williard | Light green skin | Sri Lanka | Amarakoon *et al*. 1999 |
| 2. Shoulders outgrowth | Irwin | Fullness of cheeks | Taiwan | Wang and Shiesh, 1990 |
| | Williard | | Sri Lanka | Amarakoon *et al*. 1999 |
| | Karuthacolomban | | Sri Lanka | |
| | Velleicolomban | | Sri Lanka | |
| *B. Computational methods* | | | | |
| 1. Days from flower induction | Carabao | 116 days | Philippines | Del Mundo *et al*. 1984 |
| 2. Days from full bloom | Cogshall | 133 days | Reunion | Lechaudel and Joas, 2006 |
| | Irwin | 90 days | Taiwan | Wang and Shiesh, 1990 |
| 3. Day from fruit set | Alphonso | 103.33 days (Location 1) | India | Shinde *et al*. 2001 |
| | | 80 days (Location 2) | India | Shinde *et al*. 2001 |
| | | 110 days | India | Kudochikar *et al*. 2003 |
| | Dashehari | 85 days | India | Kalra and Tandon, 1983 |
| | Harumanis | 90–100 days | Malaysia | Tarmizi *et al*. 1988 |
| | Julie | 100 days | Nigeria | Obasi, 2004 |
| | Kesar | 110.00 days (Location 1) | India | Shinde *et al*. 2001 |
| | | 86 days (Location 2) | India | Shinde *et al*. 2001 |
| | Neelum | 110 days | India | Kudachikar *et al*. 2001 |
| | Peter | 117 days | Nigeria | Obasi, 2004 |
| | Ratna | 118 days (Location 1) | India | Shinde *et al*. 2001 |
| | | 97.5 days (Location 2) | India | Shinde *et al*. 2001 |
| 4. Heat units | Alphonso | 701–718 | India | Burondkar *et al*. 2000 |
| | | 752–803 | India | Shinde *et al*. 2001 |
| | Carabao | 1000 | Philippines | Mendoza and Suriyapananont, 1984 |
| | Kesar | 773–799 | India | Burondkar *et al*. 2000 |
| | | 843–898 | India | Shinde *et al*. 2001 |
| | Ratna | 849–866 | India | Burondkar *et al*. 2000 |
| | | 932–977 | India | Shinde *et al*. 2001 |
| *C. Specific gravity* | Alphonso | 1.0 | India | Kudachikar *et al*. 2003 |
| | Baneshan | >1.0 | India | Narayana *et al*. 1999 |
| | Chiin Hwang | 1.01 | China | Lee *et al*. 1998 |
| | Kesar | 1–1.02 | India | Kapse and Katrodia, 1997 |
| | Nam Dorkmai | 1.03–1.04 | Thailand | Kasantikul, 1983 |
| *D. Chemical attributes* | | | | |
| 1. Soluble solids content (SSC) | Carabao | 6.25° Brix | Philippines | Mendoza *et al*. 1972 |
| 2. Titratable acidity (TA) | Carabao | 2.94% | Philippines | Del Mundo *et al*. 1984 |
| 3. SSC: TA ratio | Alphonso | 2.7–3.0 | India | Kudachikar *et al*. 2003 |

**Table 6.2** *Continued*

| Maturity Index | Cultivar | Description | Country | Reference |
|---|---|---|---|---|
| 4. Starch content | Tommy Atkins | | Brazil | Rocha *et al*. 2001 |
| 5. Starch: acidity ratio | Langra | ≥4.0 | India | Teotia *et al*. 1968 |
| 6. Phenolics | – | – | India | Lakshminarayana, 1980 |
| *E. Nondestructive methods* | | | | |
| Acoustic resonance spectroscopy | Neelum | | India | Raju *et al*. 2006 |
| Near-infrared (NIR) spectroscopy | – | – | Japan | Saranwong *et al*. 2003 |
| Ultrasonic waves | – | – | Israel | Mizrach *et al*. 1999 |

so the extremely high temperatures prevailing in some regions may limit the use of heat units as maturity indices. Specific gravity as a maturity index is also widely acknowledged in mango. In mature mango, the specific gravity is equal to or more than 1.0 (Kapse & Katrodia 1997). However, in some cultivars specific gravity may reach 1.0 before the fruit is completely mature (Lam *et al*. 1982; Obasi 2004). As the maturation progresses, there is a constant increase in total solids, dry matter and decrease in titratable acidity and phenolics (Lakshminarayana 1980; Rocha *et al*. 2001; Teaotia *et al*. 1968). The use of chemical attributes such as SSC, acidity, SSC: acidity ratio, phenolics and starch content has limited application because the changes in these parameters during the later phase of maturation (near harvest) are little (Del Mundo *et al*. 1984; Lam *et al*. 1982; Mendoza *et al*. 1972). The development of some non-destructive techniques like acoustic resonance spectroscopy (Raju *et al*. 2006), near-infrared spectroscopy (Saranwong *et al*. 2003) and ultrasonic waves (Mizrach *et al*. 1999) in evaluation of maturity status is still in nascent stage. These methods are also based on the dry matter and starch content in fruit. It is difficult to reach any consensus on a single maturity index for a particular cultivar. Therefore, the use of multiple maturity indices to determine harvest maturity may be more appropriate.

## CHANGES DURING RIPENING

### Respiration and ethylene

Mango is a climacteric fruit and exhibits a burst in the respiratory activity and ethylene production during normal course of ripening (Akamine & Goo 1973; Biale & Young 1981; Mattoo & Modi 1969). The post-harvest techniques aim at minimizing the rate of respiration of fruit to the lowest possible level without any anaerobiosis and also to reduce the biosynthesis and action of ethylene. The rise in the rates of respiration and ethylene production during ripening symbolises normal ripening behaviour of mango fruit. The absence of such an upsurge in the respiration and ethylene production is generally associated with uneven ripening leading to inferior quality of ripe fruit. The respiratory patterns of mango are influenced by several factors such as cultivar, harvest maturity, ethylene, post-harvest handling conditions such as storage temperature and atmosphere, disease incidence, heat treatments (Cua & Lizada 1990; Esguerra & Lizada 1990; Lalel *et al*. 2005; Mitcham & McDonald 1993; Nair & Singh 2003; Nair *et al*. 2004b). 'Kensington' mangoes harvested at mature green stage showed a respiratory peak on day 3 of ripening at 21°C with a concomitant increase in the ethylene production on the same day (Lalel *et al*. 2003f). Interestingly, the cyanide (CN) insensitive respiration pathway operates in mango fruit during ripening (Considine *et al*. 2001; Cruz-Hernandez & Gomez-Lim 1995; Kumar *et al*. 1990). As a consequence of CN pathway operation, there is a drastic increase in the internal fruit temperature from 29°C to 38.9°C during ripening (Kumar *et al*. 1990). The CN respiration contributes 80% of the total respiration during the climacteric phase of fruit ripening (Kumar *et al*. 1990). The alternative oxidase (Aox) responsible for CN insensitive respiration during ripening of mango is differentially expressed (Cruz-Hernandez & Gomez-Lim 1995). The accumulation pattern of cytochrome proteins during ripening suggested their role in facilitating the climacteric burst of respiration and that the alternative oxidase (Aox) and uncoupling proteins (Ucp) may play a role in post-climacteric senescent processes. Both messages and

proteins for the Aox and Ucp increased in a similar pattern which suggested that their expression was not controlled in a reciprocal manner but may be active simultaneously (Considine *et al*. 2001).

During the maturation process, ethylene production decreases and becomes undetectable for a short span of time and then reappears upon ripening (Akamine & Goo 1973). Ethylene biosynthesis is an essential feature of mango fruit ripening. The ethylene peak may precede, coincide or lag behind the respiratory peak during mango fruit ripening. According to Burg and Burg (1962), ethylene peak may precede or coincide with the respiratory peak. While Biale and Young (1981) categorised mangoes among the fruits in which ethylene rises after the respiratory peak. The temporal variation in the respiratory and ethylene peaks is a very complex phenomenon and still remains unfolded. Ethylene production is peaked at the onset of climacteric phase of fruit ripening and the small amount of ethylene present in the fruit at harvest is sufficient to initiate ripening (Burg & Burg 1962; Mattoo & Modi 1969). Ethylene is either directly or indirectly involved in ripening associated changes. Post-harvest handling conditions such as storage at chilling temperatures impair the capacity of fruit to produce sufficient ethylene to initiate normal ripening (Nair *et al*. 2004b). The skin and pulp tissue of mango fruit also behave differently with regard to ethylene production. The pulp tissue is found to produce only about one eighth of the ethylene and responded much less to exogenously applied ACC than skin tissue in 'Keitt' mango during low temperature storage (Lederman *et al*. 1997). The successful manipulation of respiration and ethylene production rates to delay ripening constitutes the hub of the post-harvest management of mango fruit.

**Softening**

Mango fruit undergoes extensive textural changes during ripening. Fruit softening involves the degradation or modifications of cell wall polymers by the synergistic action of various cell wall hydrolases. Cell wall polymers such as pectin, cellulose and hemicellulose undergo substantial transformation and solubilization during ripening of fruit which result in cell wall disintegration and cause softening of fruit. There is a rapid increase in water soluble pectin (WSP), chelator-soluble polyuronides, chelator soluble carbohydrates and a decrease in total polyuronides in mango during ripening (Ali *et al*. 2004; Chaurasia *et al*. 2006). The cell wall hydrolases implicated in pectin depolymerization in mango are polygalacturonases (PG), pectinesterases (PE), β-1,4-glucanases, β-galactosidases, galactanases, arabinanases and pectin lyases (PL) (Abu-Sarra & Abu-Goukh 1992; Ali *et al*. 1995; 2004; Ashraf *et al*. 1981; Chaurasia *et al*. 2006; Mitcham & McDonald 1992; Prasanna *et al*. 2003, 2005; Roe & Bruemmer 1981). PG can exist in two forms either as exo-PG or endo-PG. In mango, mainly exo-PG seems to act and the activity of exo-PG increases as the fruit ripening proceeds (Abu-Sarra & Abu-Goukh 1992; Ali *et al*. 2004; Mitcham & McDonald 1992; Prasanna *et al*. 2003; Roe & Bruemmer 1981). The differential rate of fruit softening in mango is mainly due to the higher PG activity in the inner mesocarp than the outer tissue (Mitcham & McDonald 1992). However, there are some contradictory reports which suggested weak correlation between PG activity and fruit softening (Abu-Sarra & Abu-Goukh 1992; Lazan *et al*. 1986). Pectin esterases (PE) activity shows either a declining or constant trend during ripening (Ali *et al*. 2004; Ashraf *et al*. 1981; El-Zoghbi 1994; Prasanna *et al*. 2003; Roe & Bruemmer 1981). Contrarily, an increase in PE activity during ripening of African mango 'Irvingiagabonensis' has also been reported (Aina & Oladunjoye 1993). The role of PE in softening of mango fruit is still not well defined and understood. Despite high pectin solubilization during softening of fruit, the changes in the activities of PG and PE are not much higher in mango unlike other fruits. Therefore, the implication of other hydrolases in excessive softening cannot be ruled out. Cellulases also show enhanced activities during ripening (Abu-Sarra & Abu-Goukh 1992; El-Zoghbi 1994; Lazan *et al*. 1986; Prasanna *et al*. 2003; Roe & Bruemmer 1981). The role of other hydrolases such as β-galactosidases, galactanases, arabinanases (Ali *et al*. 2004; Lazan & Ali 1993; Prasanna *et al*. 2003, 2005) in mango fruit softening has also been observed. The activity of β-galactosidase increases seven fold during ripening of mango (Ali *et al*. 2004). Recently, the role of pectin lyase in ethylene-induced softening in mango has also been established at the gene level (Chaurasia *et al*. 2006). It is, therefore, the concerted action of various hydrolases which bring about mass scale changes in the content and properties of the cell wall components. The fruit texture is an integral component of quality and determines the consumer acceptance. For extension of shelf life the post-harvest approaches should be focused on maintaining the activities of these enzymes at the lowest possible levels. The role of cell wall hydrolases in other growth and developmental processes cannot be denied. It further requires a deeper understanding of the sequence of events in the cell wall disassembly of mango fruit so that some genetic engineering approaches can be applied to have desirable genotypes.

**Carbohydrates and organic acids**

During fruit maturation, starch is accumulated in mango fruit (Fuchs *et al*. 1980). With the onset of ripening, there is a metabolic flux in the system which brings about drastic changes in the carbohydrates and organic acids. In general, there is an increase in total sugars and decrease in the organic acid content during ripening. There is a tremendous increase in the total soluble solids (TSS) from harvest to ripe stage. TSS increased from 7.0% to 15.0% in 'Alphonso' (Thomas 1975), from 4.9% to 11.6% in 'Keitt' (Medlicott & Thompson 1985) and from 6.2% to about 14.0% in 'Kensington Pride' mangoes (O'Hare 1995). Among sugars, sucrose is the predominant sugar in ripe mango followed by fructose and glucose (Castrillo *et al*. 1992; Hubbard *et al*. 1991; Medlicott & Thompson 1985; Yashoda *et al*. 2006). However, the proportion of sugars varies among cultivars and also depends upon the extent of interconversion of sugars. There is an increase in the ratio of fructose to glucose during the ripening period (Hubbard *et al*. 1991; Medlicott & Thompson 1985). In 'Keitt' mango, the concentrations of sucrose, fructose and glucose are 57%, 28% and 15%, respectively (Medlicott & Thompson 1985).

There are basically two mechanisms responsible for increase in total sugars during ripening of mango. First, degradation of starch into soluble sugars by the action of amylases (Fuchs *et al*. 1980; Subramanayam *et al*. 1976) and secondly, the biosynthesis of sucrose during the ripening phase (Castrillo *et al*. 1992; Hubbard *et al*. 1991). The activity of α-amylase increases during ripening with a concomitant decrease in the starch content of fruit (Fuchs *et al*. 1980). It has been shown that starch degradation alone cannot account for the large increase in the sugar content during ripening (Hubbard *et al*. 1991). So there may be some other sources of carbon involved and some of them are as yet unknown. In addition to hydrolysis of starch, there is increase in sucrose biosynthesis in mango fruit during ripening. The activity of sucrose phosphate synthase increases several folds during mango ripening while sucrose synthase activity undergoes little change (Castrillo *et al*. 1992; Hubbard *et al*. 1991). The balance of sucrose synthesis and breakdown during ripening decides the accumulation of sucrose in the fruit (Castrillo *et al*. 1992). The active role of gluconeogenesis in the carbohydrate metabolism has also been reported (Selvaraj & Kumar 1994; Yashoda *et al*. 2006). Most of the gluconeogenic enzymes also increase significantly during ripening, exhibiting highest activities at the ripe stage (Yashoda *et al*. 2006).

During ripening, there is drastic decrease in the organic acids content. Citric acid and malic acid have been found as predominant organic acids in 'Keitt' mango, whilst tartaric, ascorbic, oxalic and α-ketoglutaric acids have been reported to be present at low concentrations (Medlicott & Thompson 1985). The ratio of citric acid to malic acid changes during ripening without any particular trend, but the fully ripe 'Keitt' and 'Tommy Atkins' mangoes have values more than one (Medlicott *et al*. 1986b; Medlicott & Thompson 1985). Mango flavour perception by the consumer is strongly influenced by the ratio of sugars and acids (Malundo *et al*. 2001). Thus, a decline in organic acids during ripening favours the development of optimum flavour quality in fruit.

**Colour**

Skin colour is the most conspicuous visible change associated with the ripening of mango fruit and is an important factor in the consumer acceptance of the fruit. The skin colour changes from dark green to greenish yellow, yellow, orange yellow and red depending upon the cultivar. The degradation of chlorophyll pigments in the skin with a simultaneous increase in the carotenoid pigments takes place during ripening. β-Carotene, xanthophyll esters and xanthophylls are the principal carotenoids in the peel of mango fruit (Lizada 1993). The carotenoid level in skin increases during ripening with a gradual decrease in the anthocyanin in 'Tommy Atkins' mangoes (Medlicott *et al*. 1986a). Anthocyanidin hexoside, quantified as peonidin-3-O-glucoside, has been tentatively identified as a major anthocyanin in skin of red coloured mango cultivars (Berardini *et al*. 2005) which is in contrast to peonidin-3-galactoside reported previously (Proctor & Creasy 1969). The presence of cyanidin 3-O-galactoside in mango skin has also been reported for the first time (Berardini *et al*. 2005). The total anthocyanin contents in the skin of some red-coloured mango cultivars are summarised in Table 6.3.

Parallel to skin colour changes, there is accumulation of carotenoids in the pulp tissue during ripening. A typical carotenoid profile of ripe mango pulp contains *all-trans*-violaxanthin, 9-*cis*-violaxanthin and β-carotene as the principal carotenoid compounds as shown in Table 6.4 (Mercadante & Rodriguez-Amaya 1998; Mercadante *et al*. 1997). Carotenoids are mainly deposited in the plastoglobular substructures of the mango chromoplasts. An ultrastructural study has shown that pigment carrying plastoglobuli were observed in the chromoplasts irrespective of the ripening stage which led to the assumption of earlier differentiation of chloroplast into chromoplasts (Vasquez-Caicedo *et al*. 2006). Accumulation of β-carotene in mango fruit has been emphasized in terms

**Table 6.3** Anthocyanin Levels (μg/kg Dry Matter) in the Skin of Red-coloured Mango Cultivars.

| Cultivar | Cyanidin 3- O-galactoside[a] | Anthocyanidin hexoside[b] | Total content |
|---|---|---|---|
| Tommy Atkins | 234 ± 15 | 3485 ± 290 | 3719 ± 291 |
| R2E2 | ND | 211 ± 7 | 211 ± 7 |
| Kent | 85 ± 4 | 422 ± 2 | 507 ± 5 |
| Josẻ | 4 ± 2 | 279 ± 20 | 283 ± 20 |
| Haden | 206 ± 10 | 1488 ± 15 | 1694 ± 18 |
| Heidi | 1165 ± 99 | 1755 ± 90 | 2920 ± 13 |

[a] Quantified as cyanidin 3- O-glucoside.
[b] Quantified as peonidin 3- O-glucoside.
[c] ND: not detected.
Source: From Berardini *et al*. (2005) with permission.

**Table 6.4** Carotenoid Composition and Vitamin A Values of Ripe Mango cv. Keitt from Two Locations in Brazil.

| Carotenoid | Keitt | |
|---|---|---|
| | São Paulo Location | Bahia Location |
| *all-trans*-β-carotene[a] | 6.7 ± 1.6 | 15.1 ± 1.5 |
| unidentified | 0.2 ± 0.0 | 0.2 ± 0.0 |
| *cis*-β-cryptoxanthin | tr-0.1 | tr-0.1 |
| *all-trans*-β-cryptoxanthin | 0.2 ± 0.0 | 0.3 ± 0.0 |
| *all-trans*-zeaxanthin | 0.8 ± 0.3 | 0.8 ± 0.2 |
| luteoxanthin isomers | 2.7 ± 0.2 | 3.8 ± 0.6 |
| *all-trans*-violaxanthin | 18.0 ± 4.0 | 21.1 ± 2.9 |
| 9-*cis*-violaxanthin | 7.2 ± 1.4 | 10.1 ± 1.0 |
| 13-*cis*- violaxanthin[b] | ND-tr | 1.4 ± 0.1 |
| *cis*-neoxanthin | 0.3 ± 0.2 | tr-0.2 |
| *all-trans*-neoxanthin | 1.9 ± 0.9 | 2.1 ± 1.3 |
| Total | 38.0 ± 7.7 | 55.0 ± 5.0 |
| Vitamin A value (RE[c]/100 g) | 112 ± 27 | 251 ± 26 |

[a] Mean and standard deviation. ND: not detected. Tr: trace.
[b] Location of *cis* double bond tentative.
[c] RE: retinol equivalent
Source: Mercadante and Rodriguez-Amaya (1998) and Mercadante *et al*. (1997).

of interrelationships with flesh colour and resulting vitamin A values. β-Carotene exists in mango fruit in both forms, *cis* and *trans* while *trans* form predominates (Vasquez-Caicedo *et al*. 2006). In fully ripe 'Tommy Atkins' mango, the relative proportion of all-*trans,* 13-*cis* and 9-*cis* forms of β-carotene is 1970 ± 7, 312 ± 2 and 237 ± 2 μg/100g on dry weight basis, respectively (Vasquez-Caicedo *et al*. 2006). The climatic factors play a vital role in determination of the accumulation of carotenoids. In Brazil, ripe 'Keitt' mango from Bahia (hot climate) had more than twice the β-carotene than those from São Paulo (moderate climate) (Table 6.4) (Mercadante & Rodriguez-Amaya 1998; Mercadante *et al*. 1997). Thus, hot climate favours the accumulation of carotenoid pigments in mango fruit. The synthesis of carotenoids in skin or pulp tissue is also regulated by the storage and ripening temperature. It seems that ripening temperature plays a very crucial role in the optimum colour development of fruit. Certain post-harvest treatments such as hot water or hot air enhance the rate of degradation of chlorophyll and promote the carotenoid biosynthesis in the skin and pulp. It warrants further research to determine the factors influencing the relative proportion of *cis* and *trans* isomers of β-carotene in ripe mango as the latter has more biological activity in terms of the pro-vitamin A.

**Aroma**

Aroma is an integral component of fruit flavour which influences consumer perception. Mango aroma is very complex as it is contributed to by a multitude of volatile compounds. A plethora of factors influence the aroma biogenesis in mango such as cultivar, harvest maturity, ripening conditions, chilling injury, post-harvest treatments, growth regulators (ethylene and jasmonates) and storage conditions (Lalel 2002; Lalel & Singh 2006; Lalel *et al*. 2001, 2003a, 2003b, 2003c, 2003d, 2003e, 2003f, 2004a,

2004b; Nair *et al*. 2003; Singh *et al*. 2004). The effect of other factors on aroma volatile production in mango, which include rootstock, polyamines, hot-water and fungicide treatments (Dang *et al*. 2008b), and edible coatings (Dang *et al*. 2008a), have been recently investigated by our research group. Among major volatile compounds, terpenes are the most abundant group of compounds followed by esters, ketones and lactones. Most of the fatty acids increased during fruit ripening. In a study on 'Kensington Pride' mango, sixty-one aroma volatile compounds were identified, of which 35 compounds have not been reported previously in this cultivar (Lalel *et al*. 2003a). (+)-Spathulenol and β-maaliene were reported for the first time in mango fruit. The most abundant group of volatile compounds was hydrocarbons, accounting for about 59% of the total identified compounds, followed by esters (20%). α-Terpinolene was the major compound during the first 7 days of ripening and later ethyl octanoate became the major compound. Except for car-3-ene, the concentration of major monoterpenes increased for the first 3 or 4 days and decreased afterwards. Most of the major sesquiterpenes were intensively synthesised in the early part of the ripening process. The production of three major esters increased quite sharply during fruit ripening. It appeared that production of terpenes was parallel with production of ethylene, whilst production of esters appeared to be associated with production of fatty acids (Lalel *et al*. 2003a). The extensive data available on the aroma volatile compounds in different cultivars under various conditions may be used to build an aroma digital library or database which can serve as a benchmark for designing and developing electronic sensory devices. Such data would also be of utmost importance for the preparation of aroma descriptors that can be used by sensory panels. The volatile compounds emitted during different stages of ripening can serve as markers to develop biosensors which can be incorporated in the intelligent packaging system to allow the importer or consumer to judge the degree of ripeness of fruit just by looking at the package label. Such a versatile utility of aroma research in the proposed direction can be instrumental in promoting the international trade of mango fruit.

### Lipids and phenols

Lipid components in mangoes, though found in minor quantities, are presumed to contribute to the characteristic aroma and flavour of mangoes. Total lipids, as well as glycerides of the fruit pulp, increased during ripening of 'Alphonso' mango accompanied by a rapid change in fatty acid composition, particularly with respect to the ratio of palmitic acid to palmitoleic acid, and fruit aroma (Bandyopadhyay & Gholap 1973a). The ripening conditions strongly influence the total fatty acid content in ripe mango fruit. With the increase in ripening temperature up to 30°C, the total fatty acid content increased during ripening of 'Kensington' mango. Except palmitic, palmitoelic and linolenic acids, all other major fatty acids increased during ripening (Lalel *et al*. 2004b). The fatty acid composition in fruit pulp has direct relationship with the aroma and flavour of mango fruit (Bandyopadhyay & Gholap 1973b). A relation between aroma and flavour of the fruit and the ratio of palmitic acid to palmitoleic has been proposed. If the ratio was less than 1, the fruit had a strong aroma and if more than 1, the fruit had a mild aroma (Bandyopadhyay & Gholap 1973b). An unusual fatty acid, named mangiferic acid (*cis*-9, *cis*-15-octadecadienoic acid), has been identified in the pulp of mango fruit which constitutes 5.4% of total acyl groups in the pulp lipids; whereas a common octadecadienoic acid, linoleic acid, is a minor component (1.1%) in the same lipids (Shibahara *et al*. 1993).

The total phenol content is higher in skin than pulp during all developmental stages of mango fruit (Kondo *et al*. 2005). The reduction of polyphenolics in the skin during ripening might be responsible for reduced disease resistance. Simultaneously, the total phenols in pulp decreases, which is responsible for removal of astringency in the fruit. Characterization of polyphenolics of mango (cv. 'Tommy Atkins') showed that there are 18 gallotannins and five benzophenone derivatives in skin which are tentatively identified as galloylated maclurin and iriflophenone glucosides; no benzophenone derivatives and eight gallotannins are present in the pulp (Berardini *et al*. 2004). Gallotannins quantified by the rhodanine assay amounted to 1.4 mg/g dm in the skin (expressed as gallic acid), while only small amounts (0.2 mg/g dm) are detected in the pulp (Berardini *et al*. 2004).

## RIPENING CONDITIONS

The ripening process of mango fruit involves numerous biochemical changes including increased respiration, ethylene production, fruit softening, chlorophyll degradation, carotenoid synthesis and several other metabolic activities leading to changes in carbohydrates, organic acids, lipids, phenolics and volatile compounds (Gomez-Lim 1993). The ripening process takes place within 4 to 8 days post-harvest at ambient temperature depending on cultivar and harvest maturity. The conditions during fruit ripening influence the rate of ripening and the quality of the ripe fruit. The optimum ripening temperature may vary among

mango cultivars. The optimum ripening temperatures for different cultivars as suggested by various workers are 25°C for 'Alphonso' (Thomas 1975), 22°C for 'Tommy Atkins' (Medlicott *et al*. 1986b), 20–22°C for 'Haden', 'Irwin', 'Keitt', 'Kent' (Vazquez-Salinas & Lakshminarayana 1985) and 18–23°C with optimum of 20°C for 'Kensington Pride' (Lalel 2002, O'Hare 1995) mangoes. Ripening temperatures below or higher than optimum result in retention of more acids, less sugars, reduced carotenoid development in skin and pulp, poor aroma and flavour quality in ripe fruit (Lalel 2002; Medlicott *et al*. 1986b; O'Hare 1995; Singh & Janes 2001; Thomas 1975; Vazquez-Salinas & Lakshminarayana 1985). Thus, optimum ripening conditions in a temperature range of 20–23°C are congenial for the eventual appearance and flavour quality of mango fruit.

### Regulation of ripening

Ethylene, a ripening hormone, is directly involved in the onset of ripening in climacteric fruits such as mango. Even traces of ethylene in the storage environment can induce the autocatalytic production of ethylene and promote ripening. Thus, the ripening process can be regulated either with exogenous application of ethylene or by inhibiting the biosynthesis and action of ethylene in mango fruit.

#### *Promoting ripening*

The promotion of ripening is usually carried out keeping in view the market demand and fruit supply. Special ripening treatments are also required after long term storage at low temperature either in ambient air or controlled atmospheres. Mango fruit harvested at commercial maturity can be ripened artificially with ethylene treatment. Exogenous application of ethylene in the form of ethrel (200 to 2000 ppm) stimulates the biosynthesis of ethylene and triggers respiration, carotenoid synthesis and chlorophyll degradation in mango (Kulkarni *et al*. 2004; Medlicott *et al*. 1987; Nair & Singh 2003; Pal 1998a, 1998b; Singh & Janes 2001). The ethrel-treated fruit ripen uniformly with good colour development and flavour and better overall sensory scores. Ethrel treatment not only accelerates the ripening process but also alleviates chilling injury and improves the fruit quality (Nair & Singh 2003; Nair *et al*. 2004b). Dipping fruit in ethrel solution is the most common method of exogenous application of ethylene. But the exposure of fruit to ethylene released from ethrel in alkaline medium has been found more advantageous than aqueous dip as it is more effective and reduces an extra step in post-harvest operations (Mohamed & Abou-Goukh 2003). Depending on concentration and cultivar, ripening was 1–3 days faster in fruits dipped in 500 and 1000 ppm ethrel and 1 to 5 days earlier in fruits treated with 250, 500 and 1000 ppm ethylene released from ethrel, compared with untreated fruits (Mohamed & Abou-Goukh 2003). The Queensland Department of Primary Industries, Australia recommended the exposure of 'Kensington Pride' and 'R2E2' mangoes to ethylene concentration of either 10 ppm (trickle system) or 100 ppm (shot system) for 2–3 days at 18–20°C coupled with high humidity 85% to obtain completely uniform ripe fruit.

#### *Ethylene biosynthesis and action inhibitors*

Aminoethoxyvinylglycine (AVG) is a potent inhibitor of 1-aminocyclopropane-1-carboxylic acid (ACC) synthase activity, a key enzyme in the ethylene biosynthesis pathway. The post-harvest application of AVG (100, 500 and 1000 ppm) inhibited the biosynthesis of ethylene in a dose-dependent manner and also reduced the respiratory activity of mango fruit during ripening under ambient conditions (Lalel *et al*. 2003e). However, the aroma volatile production of AVG-treated fruit is affected as ethylene influences the metabolic pathways inducing volatile compounds production (Lalel *et al*. 2003e). The use of 1-methylcyclopropene (1-MCP), an ethylene action inhibitor, blocks the ethylene receptors irreversibly and thus delays ripening. In mango, the post-harvest application of 1-MCP to delay ripening has been reported by many researchers (Hofman *et al*. 2001; Jiang & Joyce 2000; Lalel *et al*. 2003e; Penchaiya *et al*. 2006). The treatment of mangoes with 1-MCP at 100 µl $L^{-1}$ for 12 hours delayed the fruit softness and skin colour changes (Jiang & Joyce 2000). The post-harvest application of 1-MCP at 25 µl $L^{-1}$ for 6 or 14 hours reduced the rate of ethylene production drastically and delayed ripening by 5.1 days in 'Kensington' mangoes (Hofman *et al*. 2001; Lalel *et al*. 2003e). The application of 1-MCP in mango also retarded the biosynthesis of aroma volatile compounds leading to lower aroma quality in ripe fruit (Lalel *et al*. 2003e). The post-harvest life of 'Nam Dokmai' mangoes treated with 1-MCP (1 µl $L^{-1}$) for 24 hours could be extended to 15 days at 20°C (Penchaiya *et al*. 2006). A significant variation has been observed among results from 1-MCP treatments at differing doses and exposure durations in mango. To achieve success of 1-MCP on commercial scale in mango, cultivar and harvest maturity specific investigations are required.

## POST-HARVEST HANDLING AND STORAGE

### Cool storage

Mango is a seasonal tropical fruit unlike many other tropical fruits that are available throughout the year. Its sea freight to importing countries may involve the transit

period of two weeks followed by a period in the wholesale and retail markets at different temperatures (Mohammed & Brecht 2002). However, in some cases, for example during export from Australia to Europe, the transit period may be as long as 4–6 weeks. Therefore, storage at low temperature becomes imperative to prolong its green life followed by ripening to provide consumers with the best quality fruit. Mango, being a fruit crop of tropical origin, is highly sensitive to chilling temperatures (Medlicott *et al*. 1990b; Nair 2002; Nair *et al*. 2003, 2004a, 2004b; O'Hare & Prasad 1993; Pesis *et al*. 1997). A wide range of storage temperatures has been described in various investigations on the storage of mango, but the most common safe storage temperature for mango is 12–13°C for 2–3 weeks storage (Kader 1992; Kalra & Tandon 1983; Malik & Singh 2005; Medlicott *et al*. 1990b; Mohammed & Brecht 2002; Thomas & Oke 1983). The predominant factors affecting storage of mango include genotype (Farooqui *et al*. 1985), developmental stage, and season of harvest (Medlicott *et al*. 1988, 1990b; Seymour *et al*. 1990). 'Tommy Atkins' and 'Keitt' can be stored for three weeks at 13°C (Medlicott *et al*. 1990b). Other varieties such as 'Alphonso'(Thomas & Oke 1983), 'Kensington Pride' (O'Hare & Prasad 1993), 'Kent' (Veloz *et al*. 1977) and 'Samar Bahisht' (Farooqui *et al*. 1985) can also be stored at 13°C up to about three weeks. The ripe fruit can tolerate lower temperatures while mature green unripe fruit are generally more sensitive to chilling conditions (Cheema *et al*. 1950). Tree-ripe 'Keitt' and 'Tommy Atkins' mangoes can be stored for two weeks at 5°C without chilling injury development followed by five days at 20°C (Bender 1996; Bender *et al*. 2000a). According to Medlicott *et al*. (1990b), fruit from mid- and late harvest stored better at 10°C than 12°C with no apparent signs of chilling injury. Certain pre-storage treatments such as ethrel dip (Nair & Singh 2003), low-temperature preconditioning (Pesis *et al*. 1997; Thomas & Oke 1983), hot air (McCollum *et al*. 1993; Pesis *et al*. 1997), hot-water treatment (Jacobi & Wong 1992), ethanol vapours and low oxygen (Pesis *et al*. 1997) can positively modulate the response of mango to chilling storage temperatures. Pre-conditioning of 'Tommy Atkins' and 'Keitt' mangoes by decreasing the temperature from 20°C to 17°C or 14°C for two days facilitated their safe storage at 9°C for three weeks (Pesis *et al*. 1997). However, low-temperature storage for 2–3 weeks is not sufficient to achieve the supply chain goals in mango and, therefore, needs further extension using other strategies.

Storage temperature and duration have great influence on the sensory and nutritional quality of ripe mangoes. Aroma, an integral component of flavour, influences the consumer acceptability of mango. Storage at low temperature (5–15°C) resulted in significant reduction of total aroma volatile compounds in 'Kensington Pride' mango (Nair *et al*. 2003). The storage of mature green or tree-ripe 'Irwin' mangoes at 5°C for 20 or 30 days, respectively, led to the development of off-flavours in pulp due to presence of aldehydes (Shivashankara *et al*. 2006). Development of typical aroma and flavour of 'Alphonso' mangoes stored for 14 days at <20°C was suppressed during ripening (Thomas 1975), whilst, ripe chill-injured 'Alphonso' mangoes after 30 days at 10°C had poor flavour and carotenoid development (Thomas & Oke 1983). Thus, cold storage of mango at safe temperature is indispensable to assure the acceptable flavour and nutritional quality of fruit.

**Controlled atmosphere (CA) storage**

The international trade of fresh mangoes is limited due to its highly perishable nature and susceptibility to chilling injury when stored below 13°C. Low temperature storage of mango at 12–13°C is successful only for 2–3 weeks accompanied by substantial losses of fruit quality. Controlled atmosphere (CA) in combination with an optimum storage temperature has been reported to prolong the shelf life and maintain fruit quality in mango. However, the application of CA for mango is limited on a commercial scale. There are several serious issues related to CA induced physiological and biochemical changes which adversely affect fruit quality. The research on CA storage of mango began about seven decades ago when Singh *et al*. (1937) reported that mango can be stored in CA containing 9.2% $O_2$ to prolong their ripening period. Various researchers have tried to optimise CA conditions for different cultivars of the world (Table 6.5). The CA requirements of mangoes vary among cultivars and also depend upon the harvest maturity. A slight variation in CA from its optimum may result into the development of poor flavour quality of mango. A very low $O_2$ and/or high $CO_2$ shift the equilibrium from aerobic to anaerobic metabolism. Respiratory quotient (RQ) and ethanol concentration can serve as good indicators of anaerobic metabolism. A linear relationship exists between RQ and ethanol content (Beaudry *et al*. 1993). The tolerance of mango to a low $O_2$ and/or a high $CO_2$ level has been evaluated (Bender *et al*. 1994, 2000b; Lalel *et al*. 2005; Yahia and Hernandez 1993; Yahia *et al*. 1989). Mango is tolerant to high $CO_2$ concentrations for a short period (Yahia & Hernandez 1993; Yahia *et al*. 1989) which warrant the use of high $CO_2$ for insect disinfestation purposes. Mature-green New World mango cultivars can tolerate 25% $CO_2$ for 3 weeks at 12°C (Bender *et al*. 1994). Atmospheres with $CO_2$ concentrations higher than 25%

**Table 6.5** Controlled Atmospheres (CA) Requirements for Various Cultivars of Mango.

| | CA Conditions | | | | |
|---|---|---|---|---|---|
| Cultivar(s) | $O_2$ (%) | $CO_2$ (%) | Temp. (°C) | Storage Period (days) | Reference(s) |
| Kensington Pride | 2–4 | 4 | 13 | 30 | McLauchlan and Barker 1992 |
| | 2 | 6 | 13 | 35 | Lalel *et al*. 2001, 2004a |
| Tommy Atkins | 3 | 20 or 30 | 13 | 28 | Abdulah and Basiouny 2000 |
| | 3 | 0 | 12–15 | 21 | Bender *et al*. 2000b |
| | 5 | 5 | 12–13 | 31 | Lizana and Ochagavia, 1997 |
| Delta R2E2 | 3 | 6 | 13 | 34 | Lalel *et al*. 2005, Lalel and Singh 2006 |
| Kent | 5 | 10 | 12–13 | 29 | Lizana and Ochagavia 1997 |
| Alphonso | 0 | 7.5 | 8.3–10 | 35 | Kapur *et al.* 1962 |
| Ameli | 5 | 5 | 10–12 | 28 | Kane and Marcellin 1979 |
| Raspuri | 0 | 7.5 | 5.5–7.2 | 49 | Kapur *et al.,* 1962 |
| Irwin | 5 | 5 | 8–12 | 28 | Maekawa 1990 |
| Haden | 6 | 10 | 8 | 30 | Bleinroth *et al*. 1977 |
| Carlota, Jasmin, Sao Quirino | 6 | 10 | 8 | 35 | Bleinroth *et al*. 1977 |
| Keitt | 5 | 5 | 13 | – | Spalding and Reeder 1977 |
| | 10 | 5 | 12 | 21 | Pesis *et al*. 2000 |
| South-East Asia grown cultivars | 5 | 5 | 13 | | Kader 1993 |
| Rad | 6 | 4 | 13 | 25 | Noomhorn and Tiasuwan 1995 |
| Chok Anan | 2 or 5 | 0 | 15 | 28 | Shukor *et al*. 2000 |

result in elevated ethanol production and damage to skin colour development of the mangoes. Low $O_2$ concentrations below 2% resulted in the accumulation of ethanol and thus impaired the flavour quality of 'Tommy Atkins' (Bender *et al*. 2000a) and 'Delta R2E2' mangoes (Lalel & Singh 2006). The extent of ripeness also determines the tolerance of mango to low $O_2$ concentration. 'Haden' mangoes when stored for two weeks at the onset of the climacteric peak produced ten times more ethanol than pre-climacteric mangoes of the same cultivar (Bender *et al*. 2000a).

The earlier research on CA storage of mango was aimed at maximising the storage life of mature green fruit with less attention to flavour quality. Currently, due to stiff competition in the international market and a need to fulfil consumer indulgences, the research priorities have been refocused more towards flavour and aroma quality of fruit (Lalel & Singh, 2006; Lalel *et al*. 2004a). CA storage of 'Kensington' mangoes in atmospheres containing >6% $CO_2$ increased the concentration of total fatty acids as well as palmitic acid, palmitoleic acid, stearic acid and linoleic acid (Lalel *et al*. 2004a). CA storage comprising 2% $O_2$ and 3% $CO_2$ or 3% $O_2$ in combination with 6% $CO_2$ at 13°C seems to be promising for extending the shelf life of the 'Kensington Pride' mango while still maintaining a high concentration of the major volatile compounds responsible for the aroma of ripe mangoes. Another approach is to subject the tree ripe fruit to CA storage which can yield the storage life of 2–3 weeks that is generally considered enough for sea freight and distribution of fruit at the destination market (Brecht *et al*. 2003). The applications of CA in preventing chilling injury and insect disinfestation are both discussed in detail in later sections.

**Low-pressure storage (LPS)**

Low-pressure storage (LPS), also known as hypobaric storage, has been found useful for long-term storage of mangoes (Burg 2004). The storage life of 'Haden' mangoes was enhanced to 8 and 13 days at room temperature when these were stored in LPS at a pressure of 200 and 150 mmHg, respectively (Burg & Burg 1966). With the reduction of pressure to 76 or 152 mm Hg at 13°C for three weeks, 'Irwin', 'Tommy Atkins' and 'Kent' mangoes exhibited 3–5 days delay in softening during ripening upon removal to ambient atmosphere (Spalding & Reeder 1977). Anthracnose and stem-end rot diseases were also

suppressed greatly in LP-stored fruit as compared to those stored in normal air. The LPS at 80 mmHg at 10°C for four weeks also alleviated chilling injury in 'Irwin', 'Kent', 'Keitt', 'Haden' and 'Tommy Atkins' mangoes. A study conducted in Israel showed that the ripening process was delayed to 25 and 35 days in fruit stored at 100 and 75 mmHg pressures, respectively, while it was set in control fruit stored at 760 mmHg after 16 days at 13°C (Apelbaum *et al*. 1977). LPS of mangoes at pressures more than 250 mmHg did not influence ripening process and a marked reduction in pressure to less than 50 mmHg caused fruit desiccation. The coloured varieties such as 'Haden' and 'Maya' that had been stored in LP failed to develop their characteristic fruit colour. The improvement in the storage life and quality of 'Okrang' mangoes has also been reported (Ilangantileke & Salokhe 1989) when these were first hydrocooled to 15°C, dipped in wax and then stored at 13°C either at 60 or 100 mm Hg for four weeks.

Burg (2004, p. 388), in his book, described some unpublished reports highlighting the successful application of LPS in mango. Mango could be stored at very low pressure of 15 mm Hg (= 0.1% $O_2$) at 10°C with no indication of low $O_2$ injury or off-flavours (Davenport & Burg 2002 unpublished, cited in Burg 2004). The tolerance of mango to such a low level of $O_2$ demonstrated the effectiveness of low pressure in enhancing $O_2$ diffusion in the fruit. LP might have improved the mango's gas exchange properties by opening its stomates (Burg 2004). Similarly, the late season harvested fully mature 'Keitt' mangoes were stored at 13.3°C (98%RH) either in normal atmosphere or in LP at 20 mmHg for 45 days. These fruit ripened with little increase in decay although they were heavily infected with anthracnose at the beginning of experiment (Davenport & Burg 2002 unpublished). Decay development in mango is a very serious problem paralysing the long-term storage and distant distribution of mango in the world market and thus posing a great hindrance in its commercialisation. These investigations provided evidence in favour of LPS to overcome this problem and it may prove a big leap if LPS commercialisation takes place.

**Modified atmosphere packaging (MAP)**

MAP involves the use of polymeric films to create a modified atmosphere (MA) that is high in $CO_2$ and low in $O_2$. The major contributing factors towards the success of MAP in delaying ripening of mango are increased $CO_2$ and low $O_2$ levels which reduce the respiration rate and inhibit ethylene biosynthesis, and a plastic film barrier which prevents water loss from fruit. Despite the success of MAP in mango at laboratory scale (Castro *et al*. 2005; Illeperuma & Jayasuriya 2002; Macnish *et al*. 1997; Miller *et al*. 1983; Pesis *et al*. 2000; Rodov *et al*. 1997; Singh & Janes 2001; Singh *et al*. 2001; Srinivasa *et al*. 2002; Yuen *et al*. 1993), it is still not a commercial practice in post-harvest handling and shipment of mangoes. There is a large range of polymeric films available in the market. The selection of a suitable packaging film for a cultivar depends upon several factors such as ripeness stage of fruit, weight and volume, thickness of film, perforation, permeability to water vapours, $O_2$, $CO_2$ and $C_2H_4$ and temperature conditions in the supply chain. Individual sealed packaging of 'Tommy Atkins' mangoes in heat-shrinkable plastic films showed less weight loss, but the firmness and decay development were not affected to a large extent compared with unwrapped fruits (Miller *et al*. 1983). Yuen *et al*. (1993) observed that shrink wrapping or sealed packaging using polyethylene, for 'Kensington' mango, caused the undesirable retention of green skin colour after 30 days at 20°C. Shrink wrapping possibly depletes the internal $O_2$ to such an extent that there is anaerobiosis in fruit tissue leading to accumulation of anaerobic metabolites such as ethanol, acetaldehyde and ethyl acetate which impart strong off-flavour. Therefore, micro-perforated film could prove more beneficial for mango packaging, as it prevented the accumulation of high levels of $CO_2$ that can lead to off-flavours (Rodov *et al*. 1997). The high decay level and off-flavour development are major hurdles to commercial acceptance of individual shrink-wrapping technology for mango.

'Tommy Atkins' and 'Keitt' fruits could be stored for three weeks at 12°C when these were packed in 4 kg film-lined cartons by using microperforated polyethylene (PE) or Xtend® film (XF). XF film was found to be very effective in reducing chilling injury and lowering the level of condensation inside the package due to lower relative humidity in the XF film (~ 90%) as compared to PE (~99%) (Pesis *et al*. 2000). The packaging of 'Karuthacolomban' mango in 0.05 mm LDPE bags of 1:1 surface area to weight ratio ($cm^2g^{-1}$) with 50 ml of saturated potassium permanganate absorbed onto suitable porous matrices and 2 g of activated granular charcoal could be recommended to increase storage life at 13°C for 21 days (Illeperuma & Jayasuriya 2002). The plastic films used for MAP result in environmental hazards. Today, many environment protection agencies discourage their use. There is therefore a quest for alternatives which should be cost-effective, biodegradable and safe for consumers. The application of biodegradable films for MAP of fruits is gaining momentum slowly. 'Alphonso' mangoes stored in chitosan-covered wax-lined cartons showed an extension of shelf life of up to 20 days under ambient conditions

(27± 1°C; 65% RH) and without any microbial growth and off-flavour (Srinivasa *et al*. 2002). Being biodegradable and eco-friendly, chitosan-based films can serve as an alternative to synthetic packaging films in the storage of freshly harvested mangoes.

**Edible coatings**

The growing demand by consumers for eco-friendly and safe packages has driven researchers to develop new systems of packaging. One of the most popular alternatives in the last few years is edible coating – a transparent film that covers the fruit, imparts gloss and acts as a barrier to water and gases ($O_2$ and $CO_2$). Edible coatings increase a fruit's skin resistance to gas diffusion, modify its internal atmosphere composition and depress its respiration rate (Banks *et al*. 1993). These coatings can also be used as a carrier of some other preservatives which can have a synergistic effect on the post-harvest life of fruit. Semi-permeable coatings can create a modified atmosphere (MA) similar to CA storage, but the concentrations of $O_2$ and $CO_2$ can change in response to environmental conditions such as temperature and humidity (Baldwin 1994; Baldwin *et al*. 1999). A variety of coating materials have been tested on mangoes including carnauba wax, shellac, zein, cellulose derivatives, chitosan and its derivatives and other composite mixtures containing sucrose esters of fatty acids and a sodium salt of carboxymethylcellulose. Results obtained were variable (Baldwin *et al*. 1999; Carrillo-Lopez *et al*. 2000; Dhalla & Hanson 1988; Diaz-Sobac *et al*. 1997, 1996, 2000; Hoa *et al*. 2002; Kittur *et al*. 2001). This variation in results may arise due to different coating materials, concentrations, methods of application and maturity stages of fruit selected for experimentation. The application of different coating formulations containing carnauba wax, shellac, zein and cellulose derivatives reduced the respiration rate, development of external and internal colour and delayed fruit ripening in 'Kent', 'Tommy Atkins' and 'Lirfa' mangoes (Hoa *et al*. 2002). Shellac and carnauba based coatings led to the higher levels of ethanol, although they did not affect the flavour quality. Another study by Carrillo-Lopez *et al*. (2000) showed that coating of 'Haden' mangoes with different concentrations of 'Semperfresh' resulted in higher acidity, firmness and green colour and reduced weight loss in coated fruits compared to non-coated ones, while decay development was not influenced by the coating treatments. Baldwin *et al*. (1999) tested polysaccharide-cellulose and carnauba based coatings for their effects on external and internal mango atmospheres and quality during storage at 10–15°C with 90–99%RH followed by simulated marketing conditions of 20°C with 56% RH. They observed that both types of coatings modified atmospheres, reduced decay, weight loss and improved appearance by imparting a subtle shine. Polysaccharide based coating delayed ripening and increased concentrations of flavour volatiles in mango (Baldwin *et al*. 1999). The activities of softening related enzymes such as pectinesterase (PE), polygalacturonase (PG) and cellulase were also suppressed in pre-climacteric 'Manila' mangoes coated with a composite mixture containing maltodextrins, carboxymethylcellulose, propyleneglycol and a mixture of sorbitan esters (Diaz-Sobac *et al*. 1997).

The use of petroleum based waxes on fresh produce has been banned by some countries. Therefore, there is a growing interest and scope for commercialisation of natural edible coatings in fresh mangoes. A few consumers may be allergic to some edible waxes containing wheat gluten, which may be an obstacle to their popularity. Another issue is the permeability characteristics of these edible coatings which may alter with the environmental conditions (Baldwin *et al*. 1999) and may lead to off-flavour in fruit. Despite the complexities of the interaction between fruits and surface coatings, there is no doubt great scope for exploiting this technology in mango.

**Irradiation**

The use of ionizing radiations for achieving increased shelf life, insect disinfestation and reducing microbial load in mango is widely studied and reviewed. Several reports on irradiation have shown good response of mango to irradiation treatment. The response of mango fruit to irradiation depends upon cultivar, maturity status and post-harvest handling system (Akamine & Moy 1983; Boag *et al*. 1990; Gonzalez-Aguilar *et al*. 2001; Janave & Sharma 2005; Moreno *et al*. 2006; Spalding & Von Windeguth 1988; Thomas 1986; Thomas & Janave 1975; Uthairatanakij *et al*. 2006). Irradiation of mature green 'Alphonso' mangoes with a dose of 250 Gy delayed ripening to 16 days against 10 days in control as evidenced by fruit texture and skin colour (Dharkar *et al*. 1966). Deleterious effects on the skin, such as lenticel spotting and darkening, were observed with higher doses of irradiation (500 to 2000 Gy), but these could be negated by equilibrating the fruit in nitrogen for 3 hours before treatment followed by irradiation in the same atmosphere (Dharkar *et al*. 1966). Similarly, irradiation with ≥250 Gy increased skin scald and internal breakdown in mature green 'Keitt' and 'Tommy Atkins' mangoes. 'Tommy Atkins' fruit were relatively more tolerant to higher doses than 'Keitt' (Spalding & Von Windeguth 1988). A higher dose causing

skin and flesh discolouration was correlated with the irradiation-induced increased polyphenoloxidase activity in mango (Thomas & Janave 1973). Mature green pre-climacteric 'Kensington Pride' mangoes irradiated with a dose of 75 Gy showed delayed ripening, but higher dose levels of 300 and 600 Gy caused lenticel damage and minor losses of vitamin C (McLauchlan *et al*. 1990). However, a recent study has shown that skin and flesh colours of 'Nam Dokmai' and 'Chok Anan' mangoes were not affected by gamma irradiation at a dose level of 400 to 600 Gy (Uthairatanakij *et al*. 2006). Recently, it has been reported that 'Tommy Atkins' mangoes can be irradiated with electron beam at 1 k Gy dose without having any adverse effect on biochemical and sensory attributes (Moreno *et al*. 2006). The stage of maturation of mango fruit decides the rate of success as partially ripe fruit and those in their climacteric phase are largely unaffected by irradiation (Boag *et al*. 1990). Although, ripe fruit are more tolerant to higher doses of irradiation with regard to appearance of external injury symptoms, their limited shelf life may not allow much time for marketing and distribution. Therefore, treating mature green pre-climacteric fruit with lower doses of radiation is the appropriate alternative for maximising the benefits. In addition to lenticel damage and skin scald, higher doses of irradiation may also result in excessive softening of fruit (Moreno *et al*. 2006; Uthairatanakij *et al*. 2006). Utthairatanakij *et al*. (2006) also reported varietal variation in the response of mango to irradiation and found that higher doses of irradiation (400 or 600 Gy) resulted in more softening of 'Chok Anan' than 'Nam Dokmai' mangoes harvested at either 70% or 90% maturity.

Irradiation influences respiratory behaviour of mangoes (Boag *et al*. 1990; Dharkar *et al*. 1966). Thomas (1993) reported that there was a transient increase in the respiration rate of mangoes immediately after irradiation which could possibly be an implication of stress response. However, the actual respiratory climacteric was delayed as well as suppressed by the irradiation treatment in mangoes (Boag *et al*. 1990; Dubery *et al*. 1984). Irradiation treatment of 'Haden' mangoes with a 750 Gy dose suppressed the respiratory climacteric to a greater extent and also reduced the peak activity of malic enzyme during ripening (Dubery *et al*. 1984). Similarly, 'Kensington Pride' mangoes had reduced respiratory activity when these were treated with a 200 Gy dose of gamma irradiation (Boag *et al*. 1990). The application of other sources of radiation like UV-C in enhancing the storage life and quality has also gained momentum in fresh fruits including mango. The exposure of ripe 'Tommy Atkins' fruit to UV-C irradiation for 10 min was most effective in suppressing the decay symptoms and maintaining firmness during storage at 5°C or 20°C for 14 days and did not affect sugars and organic acids levels (Gonzalez-Aguilar *et al*. 2001). Irradiation did not have much detrimental effect on nutritional quality of mangoes. The changes in carotenoids, sugars, acids and vitamin C were more strongly influenced by the post-irradiation storage conditions than irradiation dose (Thomas 1993). Moy and Wong (2002) found that 'Haden' mangoes irradiated with 750 Gy did not differ from non-irradiated fruit with regard to TSS, titratable acidity, ascorbic acid and firmness. However, a minor decrease in ascorbic acid was observed when mangoes were irradiated with a generic irradiation dose of 150 Gy (Bustos *et al*. 2004). It is evident from the literature that the results of various studies were often contradictory with regard to optimum irradiation doses and their resulting effects in mango. The major factors that might have influenced the results included genotype, ripeness stage, time interval between harvesting and irradiation and post-treatment storage conditions. In conclusion, mango fruit showed delayed ripening if irradiated with the optimum dose and at the right stage of maturity.

**Post-harvest application of calcium**

Calcium (Ca), an important mineral nutrient, has a profound effect on the post-harvest life and physiological disorders in fresh fruits (Poovaiah *et al*. 1988). Low levels of Ca have been associated with poor textural quality, short post-harvest life and high incidence of physiological disorders in many fruits including mango (Poovaiah *et al*. 1988; Wainwright & Burbage 1989). Therefore, post-harvest application of Ca is of special interest in mango as it undergoes accelerated softening during post-harvest handling and storage. In order to increase Ca content in fruit, pre-harvest sprays (Singh *et al*. 1993), post-harvest dipping (Mootoo 1991; Santos *et al*. 2004; Singh *et al*. 2000; Yuniarti & Suhardi 1992) and vacuum infiltration (Joyce *et al*. 2001; Shorter & Joyce 1998; Tirmazi & Wills 1981; Yuen *et al*. 1993) of calcium salts, mainly $CaCl_2$, have been investigated by several researchers on mango. Two consecutive sprays of 0.6% $Ca^{2+}$ as $CaCl_2$, 20 and 10 days before commercial harvesting of 'Dashehari' mangoes resulted into higher Ca levels in skin and flesh of fruit and also reduced weight loss and restricted ripening changes during storage under ambient conditions for 10 days (Singh *et al*. 1993). Post-harvest $CaCl_2$ dips in either 4% (Tarmizi *et al*. 1988) or 8% (Mootoo 1991; Santos *et al*. 2004; Singh *et al*. 2000; Yuniarti & Suhardi 1992) have been found to delay ripening in mature green mangoes. Calcium treatment suppressed the respiration of mango fruit (Joyce *et al*. 2001; Mootoo 1991; Singh *et al*. 1993) which resulted

in delayed ripening of fruit. There are some contradictory reports on the usefulness of Ca treatment in extending the shelf life and on the penetration patterns and distribution of Ca in different parts of fruit. Yuen *et al*. (1993) found that the ripening in 'Kensington' mangoes can be delayed by 12 and 8 days at 20°C when they were either pressure (115 kPa for 2 min) or vacuum infiltrated (−32 kPa), respectively, with $CaCl_2$ solution (2–8%). However, Joyce *et al*. (2001) did not obtain any extension in shelf life of four cultivars viz., 'Kensington', 'Sensation, 'Irwin' and 'Palmer' when these were vacuum infiltrated (−33 kPa) with 4% (w/v) $CaCl_2$ which was in contrast to findings of Tirmazi and Wills (1981), Mootoo (1991) and Yuen *et al*. (1993). They observed that Ca level in flesh tissue was not affected by vacuum infiltration into any of the cultivars harvested at different maturities. Calcium concentration of 4g $Ca^{2+}$/L should be considered the upper limit as higher concentration may lead to skin injury (Shorter & Joyce 1998; Tirmazi & Wills 1981). Fruit infiltrated with the optimum dose at very low partial pressures (−66 and −99 kPa) exhibited injuries which included exacerbated lenticel blackening and anaerobic off-odour and lacked respiratory climacteric and normal ripening (Shorter & Joyce 1998). Calcium uptake was not influenced by the maturity factor in mango (Joyce *et al*. 2001) as in some other temperate fruits. Most of the applied $Ca^{2+}$ remained localised in the skin and outer flesh of fruit and hardly penetrated into the inner mesocarp and caused skin injury (Joyce *et al*. 2001). However, Ca uptake can be improved by the use of some surfactants like Tween-80 (0.01%) before dipping in $CaCl_2$ solution (Singh *et al*. 2000). The combination of post-harvest Ca treatment along with waxing (Bringas-Taddei *et al*. 2005) and MAP (Singh *et al*. 2000; Yuen *et al*. 1993) have also shown synergistic effects on post-harvest life, firmness and quality of mangoes. It is still inconclusive from the literature whether it would be beneficial to adopt post-harvest treatment of calcium as there a risk of skin injury coupled with limited benefit of delayed fruit ripening.

### Plant growth regulators and other chemicals

The use of plant growth regulators both as pre-harvest and post-harvest treatments has been studied in mango and found successful in delaying ripening and maintaining quality during storage and ripening. Post-harvest treatment with gibberellic acid ($GA_3$) at 200 ppm has been found highly effective in retarding ripening of 'Mallika', 'Alphonso' and 'Kesar' mangoes (Khader 1988; Krishnamurthy & Gopalakrishna Rao 1982; Parmar & Chundawat 1988). $GA_3$ treatment retarded the total loss in weight, chlorophyll and ascorbic acid content, and reduced amylase and peroxidase activity during ripening (Khader 1988). Similarly, pre-harvest application of $GA_3$ also influenced the post-harvest ripening behaviour of mango fruit (Khader 1991). The post-harvest dip treatment of 'Alphonso' mango with cycocel, alar and menadione bisulphite at 500 ppm significantly retarded ripening process (Krishnamurthy & Gopalakrishna Rao 1982). The application of polyamines as a pre-storage treatment significantly affected mango fruit quality parameters. Dipping of 'Kensington Pride' mangoes in 0.01 mM spermine solution for 6 min prior to storage at 13°C for three or four weeks resulted in retarded fruit softening during storage while putrescine (1mM) was effective in maintaining higher fruit firmness and ascorbic acid in ripe fruits (Malik & Singh 2005; Malik *et al*. 2003).

## POST-HARVEST DISORDERS

### Chilling injury

Mango fruit is highly chilling sensitive and cannot be stored below 13°C (Chaplin *et al*. 1991; Kane *et al*. 1982; Malik & Singh 2005; Medlicott *et al*. 1986b; O'Hare & Prasad 1993). The severity of chilling injury (CI) depends upon the storage temperature, duration of exposure, maturation stage, cultivar and pre-storage conditions (Medlicott *et al*. 1990a; Mohammed & Brecht 2002; Nair *et al*. 2004a, 2004b; Phakawatmongkol *et al*. 2004; Wang 1993). The fruit at pre-climacteric stage were more susceptible to CI than at post-climacteric (Cheema *et al*. 1950; Medlicott *et al*. 1990a; Mohammed & Brecht 2002). The symptoms of CI in mango include pitting or sunken lesions, skin discolouration, lenticel spotting, flesh browning, uneven ripening, reduction in carotenoid development, insipid flavour and increased susceptibility to decay (Chaplin *et al*. 1991; Chhatpar *et al*. 1971; Han *et al*. 2006; Kane *et al*. 1982; Medlicott *et al*. 1990b; Mohammed & Brecht 2002; Nair & Singh 2003; Nair *et al*. 2004b; Pesis *et al*. 2000; Phakawatmongkol *et al*. 2004). Most of the CI symptoms appear only after the fruit are transferred to ambient conditions for ripening. The increased tolerance to chilling in chilling-sensitive tissues or delayed development of chilling injury symptoms would lead to the possibility of storing these commodities at lower temperatures with a minimum rate of deterioration in quality (Nair & Singh 2003). Chilling-induced damage to cell membranes disrupts a cascade of metabolic reactions in mango including ethylene production, causes increased respiration, interference in energy production, accumulation of toxic compounds such as ethanol and acetaldehyde,

and disruption of cellular and subcellular structures, leading to uneven ripening and poor fruit quality (Chaplin *et al*. 1991; Chhatpar *et al*. 1971; Han *et al*. 2006; Lederman *et al*. 1997; McCollum *et al*. 1993; Medlicott *et al*. 1990b; Nair *et al*. 2003, 2004a, 2004b; Phakawatmongkol *et al*. 2004; Zauberman *et al*. 1988; Zhao *et al*. 2006). The cell wall components and cuticle structure of mango are adversely affected by chilling injury (Han *et al*. 2006; Ketsa *et al*. 1999b). The texture of chill injured mango fruit remained firm which was mainly due to the inhibitory effect of chilling on the activities of polygalacturonase and β-galactosidase (Ketsa *et al*. 1999b). The cell wall contents of chilled fruit contained less water-soluble pectin, more ammonium oxalate-soluble pectin and less alkali-soluble pectin than nonchilled fruit (Ketsa *et al*. 1999b). The treatment of mango with methyl salicylate (0.1mM) prior to storage at 5°C for 35 days resulted in a decrease in the incidence and severity of CI by positive modulation of the cell wall components and ultrastructural changes in the cuticular waxes (Han *et al*. 2006). CI adversely affected the activities of ACC synthase and ACC oxidase leading to reduced ethylene biosynthesis in fruit resulting in failure to ripen (Nair *et al*. 2004b). Exogenous application of ethrel prior to storage alleviated the chilling injury development in 'Kensington' mangoes at 5°C for 28 days (Nair & Singh 2003) which suggested that reduced ethylene biosynthesis was associated with CI development. Polyamines also play an important role in chilling stress tolerance in mango (Malik & Singh 2005; Malik *et al*. 2003; Nair *et al*. 2004a). CI promoted the accumulation of putrescine in mango peel and reduced the levels of spermidine and spermine in skin and pulp of fruit (Nair *et al*. 2004a). To replenish the depleted spermidine and spermine contents in mango fruit during chilling, the pre-storage exogenous application of spermine (0.50 mM) was found to be the most effective method to impart chilling tolerance in mango (Nair *et al*. 2004a). The role of methyl jasmonate (MJ) in preventing CI in mango has also been documented (Gonzalez-Aguilar *et al*. 2000, 2001; Kondo *et al*. 2005). Exposure of 'Tommy Atkins' mangoes to methyl jasmonate (MJ) vapours ($10^{-4}$M) for 24 h at 25°C reduced chilling injury during subsequent storage for 21 days at 7°C and after 5 days of shelf life at 20°C. The chilling tolerance induced by MJ was positively correlated with the reduction in electrolyte leakage of fruit tissue and with improvement in fruit quality in terms of colour and total soluble solids (Gonzalez-Aguilar *et al*. 2000, 2001). The treatment of 'Choke Anan' mangoes with n-propyl dihydrojasmonate (PDJ) solution at a concentration of 0.39 mM for 15 min reduced and delayed the CI development during subsequent storage at 6°C (Kondo *et al*. 2005). CA/MA has also been found helpful in alleviation of CI in mango (O'Hare & Prasad 1993; Pesis *et al*. 2000, 1997). CA at 5–10% $CO_2$ alleviated chilling symptoms in 'Kensington' mangoes stored at <10°C, but higher concentrations of $CO_2$ were injurious (O'Hare & Prasad 1993). Short treatments of 'Tommy Atkins' fruit with low $O_2$ induced higher $CO_2$ levels and were effective in reduction of CI symptoms at 5°C (Pesis *et al*. 1997). A modified atmosphere (~5% $CO_2$ and ~10% $O_2$) created by microperforated polyethylene (PE) or Xtend® film (XF) or in CA chambers, alleviated CI in mango during storage at 12°C for three weeks plus 1 week at 20°C (Pesis *et al*. 2000). Coating of mangoes with carnauba natural wax (0.1%) was found to be effective in preventing the development of CI in 'Kensington' mangoes stored at 5°C for 28 days (Nair 2002). Individual shrink film wrapping of 'Banganpalli' and 'Alphonso' mangoes using Cryovac® films alleviated the CI symptoms during storage at 8°C for one month followed by normal ripening under ambient conditions (Sudhakar Rao & Shivashankara 2004). The use of low temperature conditioning for alleviating chilling injury has recently been studied as an alternative to other approaches (Zhao *et al*. 2006). The low temperature conditioning of 'Wacheng' mangoes at 0°C for 4 hours followed by storage at 2°C for 12 days showed that CI index was lower in fruit subjected to cold-shock than control. The cold-shock treatment invigorated the antioxidant defence mechanism of fruit as evidenced by the increased activities of catalase, ascorbate peroxidase and higher contents of glutathione and phenolic compounds during storage. The reduced levels of malondialdehyde and ion leakage indicated better membrane integrity in conditioned fruit (Zhao *et al*. 2006). Therefore, CI in mango is possibly an oxidative stress phenomenon and can be related to the failure of antioxidant defence machinery. Pre-conditioning of 'Tommy Atkins' and 'Keitt' mangoes by decreasing the temperature from 20°C to 17°C or 14°C for two days facilitated their safe storage at 9°C for three weeks (Pesis *et al*. 1997). Pre-storage heat treatment also inhibits the development of CI symptoms during storage. Hot-water treatment (HWT) at 55°C for 3 or 5 min induced chilling tolerance in mangoes. At least 12 h of hot-air treatment (HAT) at 38°C was needed to achieve similar results (Zhu *et al*. 2003). 'Keitt' mangoes kept at 38°C for 24 or 48 hours before storage at 5°C for 11 days showed less CI symptoms upon transfer to 21°C for 9 days (McCollum *et al*. 1993). Pre-storage heating also reduced the respiration and ethylene production rates without adverse effects on firmness. As discussed above, there is a plethora of strategies that can be

adopted to alleviate the adverse chilling effects. However, the adoption of a strategy depends upon the availability of necessary facilities and resources.

## Skin disorders

### *Sapburn*

Mango, being a member of Anacardiaceae family, has an extensive resin duct system in fruit and stem; there is no continuity between the fruit and stem ducts (Jole 1981). When fruit is detached from the stem, the sap or latex bursts out with a considerable pressure and smears over the fruit surface, damaging the skin with symptoms ranging from small dark spots to dark sunken blotches (Bagshaw & Brown 1989; Brown *et al*. 1986; O'Hare 1994; O'Hare *et al*. 1999). The fruit sap contains both aqueous and non-aqueous (oil) phases (Loveys *et al*. 1992). The non-aqueous phase contains terpinolene which is responsible for skin burn while aqueous components are harmless (Loveys *et al*. 1992; O'Hare *et al*. 1999). However, the ratio of the aqueous phase to the non-aqueous phase varies among cultivars. For example, among Indian mango cultivars, 'Seedling' and 'Totapuri' had non-aqueous to aqueous ratios of about 1:2, and 'Mallika' and 'Alphonso' had about 1:3 and 1:4, respectively, indicating the presence of relatively large amounts of non-aqueous phase in these cultivars. Whereas, 'Malgoa', 'Banganapalli' and 'Raspuri' cultivars yielded very little non-aqueous phase with ratios of 1:13, 1:11 and 1:7, respectively (Saby John *et al*. 1999). The extent of sap injury was regulated by several factors including total sap flow, oil content in sap and lenticel distribution (Loveys *et al*. 1992; O'Hare 1994). 'Kensington' mangoes are highly prone to sapburn because their latex contains very high levels of terpinolene as compared to 'Irwin' (Loveys *et al*. 1992). The latex levels in some Thai mango cultivars with less sapburn susceptibility are in the range of 0.16–0.48 ml/fruit, while it is 1.67 ml/fruit in 'Kensington' mangoes (O'Hare 1994). The mechanism of sapburn injury involves the complex interaction among terpenoid components of sap, polyphenol oxidase, peroxidase, and polyphenols of the skin (Saby John *et al*. 2002, 2003). Limonene, ocimene and β-myrcene, the major terpenoids identified in saps of Indian varieties, caused sapburn injury. The skin of 'Totapuri' cultivar had very low level of polyphenol oxidase, peroxidase and polyphenols compared to other varieties and was found highly resistant to sapburn (Saby John *et al*. 2002). Sapburn seriously impairs the visual quality of fruit which leads to lower consumer acceptance (O'Hare *et al*. 1999). The damage to skin also encourages some pathogens to grow, perpetuate and cause rotting.

Desapping is a post-harvest operation which involves draining of latex from the fruit so as to avoid or reduce the incidence and severity of sapburn. Different post-harvest techniques can be applied to avoid the damage. The common handling practice involves harvesting fruit with a long stem attached and transporting the fruit to the packing shed in plastic crates (Holmes *et al*. 1993). The approaches to reduce the sapburn include placing destemmed fruit on a conveyer or rack under a water spray for 20 to 30 minutes, destemming of fruit immersed in a calcium hydroxide solution (1% w/v), spray or dipping in a detergent solution (0.1%) just before destemming, applying surface coating prior to desapping, washing with 1% aluminium potassium sulphate, and packing with short stems (Brown *et al*. 1986; Holmes *et al*. 1993; Ledger 1991; O'Hare 1994; O'Hare *et al*. 1999; O'Hare & Prasad 1992; Shorter & Joyce 1994). The use of manual harvesting aids reduces the incidence and severity of sapburn in addition to saving labour costs due to elimination of the desapping operation (Holmes *et al*. 1993). Using harvest aids, mangoes are picked with long poles or by hand without stems and dropped onto a sloping canvas catching device soaked with a detergent solution. The fruit are then conveyed through a detergent dip or spray and placed into field crates and sent to the packing shed (Holmes *et al*. 1993).

### *Etch browning*

Apart from sapburn, a number of forms of blemish have been identified and collectively grouped under the term 'etch' which consists of numerous small brown flecks, which when viewed from a distance give the appearance of a brown blemish (O'Hare *et al*. 1999; Underhill *et al*. 1996). The etch symptoms are scattered all over the fruit surface but more at contact points among fruit and towards the stem end (O'Hare *et al*. 1999). The presence of etch similar to sapburn also reduces the consumer acceptability of fruit. A detailed study on characterization of 'etch browning' revealed that mango sap appears to be a greater etch inducing agent than detergents and that the problem can be reduced by minimising the wet contact times in the harvest and handling operations (O'Hare *et al*. 1999).

## Internal breakdown

Internal breakdown (IB) is a common term used to describe disorders of mango fruit mesocarp related to premature and uneven ripening. However, it is an umbrella term which covers many disorders such as spongy tissue, soft nose, jelly seed and stem-end cavity. The attempts made to clearly distinguish these disorders and use appropriate terminologies in literature have not so far been successful.

**Spongy tissue**

Spongy tissue is a disorder specific to 'Alphonso' mango, and the term has been interchangeably used with internal breakdown (Krishnamurthy 1981; Subramanayam *et al*. 1971). Spongy tissue is characterised by the yellowish white corky patches with or without air pockets in the mesocarp tissue and is observed at or after the onset of ripening. Spongy tissue disorder is under genetic control and restricted to only a few cultivars. 'Alphonso' mango in India suffers from this order to the extent of 35% to 55% (Vasanthaiah *et al*. 2006). Numerous factors have been associated with the incidence and severity of this disorder such as pre-harvest heating of fruit in the field due to convection, post-harvest heating during handling and storage, low calcium content, nutrient imbalances, late harvesting, low fruit transpiration, large fruit size, internal $O_2$ and $CO_2$ concentrations in response to CA or MAP and oxidative stress (Katrodia *et al*. 1989; Katrodia & Sheth 1989; Krishnamurthy 1981; Leon *et al*. 2000; Lima *et al*. 2000; Shivashankara & Mathai 1999; Vasanthaiah *et al*. 2006). But there is no consensus among researchers about the actual cause. The affected pulp tissue contains high starch content and total pectin, low soluble pectin, low reducing and nonreducing sugars, low $\beta$-carotene, low Ca and K, higher P, low pH and low ascorbic acid contents. The biochemical and metabolic disturbances in the affected tissue result in increased or decreased activities of certain enzymes associated with the development of symptoms. The reduced activities of $\alpha$-amylase, invertase, polygalacturonase and pectin methylesterase are associated with the high starch and low-soluble pectin contents in the spongy tissue (Katrodia *et al*. 1989; Lima *et al*. 2001). The activities of certain enzymes such as peroxidase, polyphenoloxidase (PPO) and phenylalanine ammonia-lyase (PAL) are triggered in the disordered tissue (Lima *et al*. 1999).

Harvesting of mangoes before full maturity can reduce the spongy tissue and seems to be the most economical and adoptable strategy (Subramanayam *et al*. 1971). High humidity prevailing inside the tree canopy or in the atmosphere causes poor uptake of nutrients due to lower transpiration pull; it ultimately leads to higher incidence of spongy tissue (Shivashankara & Mathai 1999). The proper training and pruning practices, sod culture (Katrodia & Sheth 1989) and pre-harvest and post-harvest application of Ca (Gunjate *et al*. 1979; Hermoso *et al*. 1997; Krishnamurthy 1981) have been reported to ameliorate the symptoms of spongy tissue. The long term storage of fruit in an optimum CA or MAP should be practised to control this malady. The possible measures to mitigate post-harvest oxidative stress in the fruit need further investigations. The detection of spongy tissue in the fruit with X-ray imaging can be used for elimination of affected fruits on the packing line (Thomas *et al*. 1993).

There is also confusion between soft nose, jelly seed and stem-end cavity (SEC) disorders which are completely different from each other (Raymond *et al*. 1998). The observations of flesh breakdown symptoms at an advanced stage of mature or ripe fruit make it difficult to differentiate among different disorders. Raymond *et al*. (1998) described the symptomology of jelly seed, soft nose and SEC and classified them as separate disorders under the common terminology of IB.

*Soft nose* can be described as the breakdown of flesh at the distal end of the fruit (Young 1957). This causes the premature softening of the mesocarp at the distal end of the fruit with little external sign of the developing disorder. Raymond *et al*. (1998) defined it as an incomplete ripening of the mesocarp tissue at the distal end of the fruit, which in early stages results in a defined yellow area between the apex of the stone and the exocarp. The non-uniform distribution of calcium in the fruit has been observed as the causal factor for soft nose. The Ca concentration in the stem end portion of the fruit is high and decreased to the least at the distal end (Burdon *et al*. 1991). After tissue breakdown, Ca redistribution results in high Ca concentration in affected tissue. The accumulation of calcium in the disordered tissue may assist in the spread of the breakdown by depleting the mineral content of the adjacent mesocarp (Burdon *et al*. 1991). Cultivar plays a considerable role in the development of this disorder as some Indian cultivars are more susceptible (Young 1957).

*Jelly seed* is localised all around the endocarp resulting in the intense yellow colour of the inner mesocarp which eventually becomes brown and softens to the consistency of jelly, so called jelly seed (Raymond *et al*. 1998).

*Stem-end cavity* (SEC) is characterized by the formation of a cavity in the proximal area of the fruit resulting from the deterioration of the vascular tissues between the proximal end of the stone and the fruit peduncle (Raymond *et al*. 1998). However, there is no cavity, air pocket, gap or tissue necrosis developed in fruit affected with jelly seed and soft nose. Jelly seed and SEC are observed first after 8 weeks of fruit set whereas soft nose symptoms are only observed in fully mature fruit (Raymond *et al*. 1998). These disorders are either under genetic control or mainly caused by the nutrient imbalances. The causes of these disorders warrant further investigations.

## POST-HARVEST INSECT PEST DISINFESTATION

The insect pests of mango have remarkably retarded the growth and expansion of world trade of fresh fruit. Mango fruit is the host of many species of Tephritidae fruit flies distributed in a particular geographical region of production. The major fruit fly species infesting mangoes in different parts of world include the Mexican fruit fly (*Anastrepha ludens*, Loew), West Indian fruit fly (*Anastrepha obliqua*, Macquart), the Queensland fruit fly (*Bactrocera tryoni*, Froggatt), the Mediterranean fruit fly (*Ceratitis capitata*, Wiedemann), the papaya fruit fly (*B. papayae*, Drew and Hancock), the Oriental fruit fly (*B. dorsalis*, Hendel) and the Zapote fruit fly ( *A. serpentina*, Wiedemann) (Hallman 1999; Heather *et al*. 1997; Sharp 1986; Sharp *et al*. 1988, 1989). There are very strict quarantine regulations which demand post-harvest treatments to eliminate the risk of entry of a new pest into the importing country. Due to these legal restrictions, the world's largest mango producing country, India, could not have access to US in the past and Japanese markets. Quarantine treatments against fruit flies are not mandatory for fruit entering the European Union and Canada because fruit flies have not been perceived as a threat due to freezing winter temperatures prevailing in these countries (Johnson *et al*. 1997). Moreover, the use of fumigants such as ethyl dibromide (EDB) and methyl bromide, for insect disinfestations has already been phased out by many countries. This necessitated the quest for chemical free and biologically safe alternatives to achieve post-harvest insect disinfestation in order to have wider access to international markets. In this section, the application of heat treatments, irradiation and insecticidal controlled atmospheres (ICA) for post-harvest insect pests is reviewed.

### Heat treatments

There has been growing interest in the use of post-harvest heat treatments to control insect pests in order to meet quarantine requirements. There are mainly three methods in use to heat the commodities; hot air, hot water and vapour heat (Lurie 1998). All these three methods have been in use for mangoes in different parts of world (Jacobi *et al*. 2001b). The heat treatments must ensure a prescribed degree of statistical probability that over 99.9968% insect mortality is achieved; this is called Probit 9 security level of insect control. In the United States, the Probit value implies that no more than 3.2 individuals survive out of a population of 100 000 at the 95% confidence level after the quarantine treatment (McGuire 1991). However, in Japan, there should not be any survivor from a treated population of 30 000 target pests to meet Probit security level of treatment (Paull & Armstrong 1994). Jacobi *et al*. (2001b) presented a comprehensive review on heat treatments in mango and described the methods used to heat treat mango varieties for insect disinfestation.

#### *Forced hot-air treatment (FHAT)*

Hot and humidified air is circulated over the fruit surface to raise the temperature of fruit core to a desired level (Jacobi *et al*. 2001b, Lurie 1998). The speed of air circulation is precisely controlled at a specified temperature. Forced hot-air treatment will heat the fruit faster than a regular heating chamber (Lurie 1998). The control of relative humidity during FHAT is essential to prevent fruit weight loss and shrivelling (Mangan & Ingle 1992). The application of FHAT has been found to be useful as a quarantine treatment in mango (Mangan & Ingle 1992) but it also causes accelerated softening, yellowing of skin colour, peel pitting (McGuire 1991, Miller *et al*. 1991) and enhanced rate of respiration (Mitcham & McDonald 1993). Miller *et al*. (1991) observed that FHAT at 51.5°C for 125 min caused skin pitting and accelerated fruit softening in 'Tommy Atkins' mangoes. A parallel work by McGuire (1991) showed that FHAT at 47°C for 3.25 h or 48°C for 2.5 h resulted in uniform yellow skin colour in addition to fruit softening in three mango cultivars 'Tommy Atkins', 'Keitt' and 'Palmer'(Sharp 1992).

#### *Hot-water immersion treatment (HWT)*

Hot-water immersion involves submerging of fruits in a hot-water bath at a specified temperature for a specified time based on the fruit tolerance to heat and the target pests' mortality (Jacobi *et al*. 2001b). It is currently being used to treat mangoes in various parts of world with the prime objective of providing an assurance to the importing countries that the fruit is free of target pests. The use of hot-water immersion treatments has been found to be satisfactory for meeting quarantine requirements for most of the species of fruit flies infesting mangoes (Sharp 1986; Sharp *et al*. 1988, 1989; Sharp & Spalding 1984). The water serves as a better heat transfer medium than air and, therefore, the rate of heating of skin is considerably faster when fruit are immersed in hot water than when the same temperature of air is passed over the fruit in FHAT (Couey 1989). Jacobi *et al*. (2001b) reviewed the status of commercial scale adoption of HWT in different parts of world. The use of HWT has been more widespread in the United States and Central America; but in Australia, the commercial use of HWT technology has not been adopted because

the high temperatures necessary to kill all stages of the life cycles of fruit fly species have been found to be injurious to the fruit (Jacobi & Wong 1992). However, the HWT technology is a more cost effective alternative to vapour heat treatment which is presently in use in Australia. The HWT also offers certain additional advantages, such as ease- of-use less time consuming, reliable, and it gives fruit surface sanitation to exclude plant debris and disease control (Couey 1989, Jacobi *et al*. 2001b). Disinfestation protocols approved for use in mango consist of immersing fruit in hot water held at 43–46°C for 65–90 min depending upon the fruit size and shape whereas temperatures above 46°C may cause excessive damage to fruit (Sharp 1986; Sharp *et al*. 1988, 1989; Sharp & Spalding 1984). For large-size mangoes weighing up to 900 g, HWT at 46.1°C for 110 minutes provided Probit 9 level quarantine security against Mexican fruit fly (*Anastrepha ludens* Loew) without adversely affecting fruit quality (Shellie & Mangan 2002). However, certain pests such as the stone weevil *Sternochetus mangiferae* (Fabricius) were not killed by hot-water immersion treatment at 48–52°C for up to 90 min and 54–70°C for up to 5 min (Shukla & Tandon 1985).

### *Vapour heat treatment (VHT)*

Vapour heat treatment involves the use of heated air saturated with water vapour to heat the fruit to a specified temperature and hold that temperature for a specified period to ensure that all target pests are destroyed (Jacobi *et al*. 2001b). The temperature of mango fruit at or below the dew point causes the condensation of air moisture on the fruit surface and thus heat transfer takes place by conduction. Vapour heat has proven to be a very effective quarantine treatment in mango. It has been adopted on a large scale in many countries like Australia, Japan, Philippines, Thailand and the United States (Jacobi *et al*. 2001b). However, disinfestation protocol requirements depend upon the cultivar and the importing country. Vapour heat treatment of 'Kensington' mangoes to a core temperature of 47°C maintained for 15 min has been shown to exceed the Probit 9 security level for a quarantine disinfestation treatment against major species of fruit flies in Australia (Heather *et al*. 1997). The 47°C schedule is the requirement for Australian mangoes to enter Japan. Jacobi and Giles (1997) treated 'Kensington' mangoes with vapour heat at 47°C for 15 min or a HWT at 53°C for 5 min prior to VHT combined with either storage at 10°C for 5 days followed by 22°C for 5 days or storage at 22°C for 10 days. The HW-VHT combination with continuous storage at 22°C produced better quality fruit with better skin colour and sensory ratings. According to Mitcham and McDonald (1997), there is differential response of mango fruit tissue to VHT with inner mesocarp tissue affected more than the outer tissue when the fruit were treated either at 46°C for 160, 220 or 280 min or at 50°C for 120, 180 or 240 min. Colour development and softening were reduced more in inner than in outer mesocarp tissue. Although VHT is an established quarantine treatment for mangoes it needs further modifications to reduce the heat damage with minimal effects on the ripening process. The retardation of heat promoted fruit ripening is a challenging area of research and needs some basic investigations to elucidate the underlying mechanisms.

### Heat treatments and fruit physiology

Ethylene biosynthesis is reversibly inhibited by the heat treatments in mangoes (Ketsa *et al*. 1999a; Mitcham & McDonald 1997). The heat treatment of mangoes (cv. Nam Dokmai) at 38°C for 3 days suppressed and delayed the ethylene peak by 5 days compared to control during ripening at 25°C. There was a partial recovery of ACC synthase activity during ripening while ACC oxidase recovered fully following heat treatment. However, sufficient ethylene synthesis was recorded to cause fruit ripening (Ketsa *et al*. 1999a). Respiratory metabolism is also strongly influenced by heat treatments in mangoes. Mitcham and McDonald (1993) observed 3.5- and fivefold increases in respiration rates of mangoes during heat treatment at 46°C for 3 or 4 h and 48°C for 5 h, respectively. However, respiration rates fell below that of control fruit after a subsequent 4 or 6 days at 20°C. This transient increase in respiration during and after heat treatment could be related to heat-induced stress (Mitcham & McDonald 1993).

### Heat treatments and fruit quality

The development of an effective quarantine treatment is a very difficult task with dual goals of achieving insect mortality without adversely affecting the fruit quality. The heat tolerance in mango fruit is governed by several factors such as cultivar, harvest maturity, fruit size, pre-harvest factors, method of heat application and pre-heat treatment conditioning, etc. (Jacobi *et al*. 2001b). However, heat treatments are known to accelerate the fruit ripening processes which leads to uniform and better skin colour development and softening in mangoes (Esguerra & Lizada 1990; Jacobi & Wong 1992; McGuire 1991; Mitcham & McDonald 1993; Pesis *et al*. 1997; Spalding *et al*. 1988). There is always a potential risk of heat injury in mango fruit when subjected to heat treatments. The symptoms of heat injury included peel pitting, lenticel darkening, skin scalding, uneven skin colour development, starch retention

in ripened mesocarp, internal cavities, and sometimes fermented odours also (Jacobi & Wong 1992; Jacobi *et al*. 1995b; Miller *et al*. 1991; Mitcham & McDonald 1993; Spalding *et al*. 1988). To reduce the heat damage to fruit, hot air conditioning has been strongly recommended (Jacobi *et al*. 1995a, 2000; Joyce & Shorter 1994). Conditioning of 'Kensington' mangoes at 40°C for 8 hours prior to a hot-water treatment of 47°C for 15 min was very effective in alleviating heat-induced damage. Conditioning temperatures of 40°C accelerated the process of ripening and resulted in elevated sugar levels in tissue which helped the fruit to withstand high heat stress during HWT (Jacobi *et al*. 2000).

A hot-water treatment of 'Kensington' mangoes where fruit core temperature was held for 15 min at 47°C increased weight loss (50%), fruit softness (15%), disrupted starch hydrolysis and reduced the skin yellowness (40–51%) of early harvested fruit (Jacobi *et al*. 2001a). Immature fruit were found to be more susceptible to hot-water treatment-induced skin scalding, starch layer and starch spot injuries. Thus, harvest maturity is a key factor affecting the heat tolerance in mango. Despite appreciable differences in fruit quality during heat treatments, only minor differences in antioxidant phytochemicals were observed in heated mangoes (Talcott *et al*. 2005). There is a paucity of information on the effects of heat treatments on nutritional and phytochemical contents in mangoes.

**Irradiation**

Irradiation is an ideal technology for developing generic quarantine treatments because it is effective against most insect pests at dose levels that do not affect the fruit quality (Follett 2004). Irradiation can provide quarantine security for a broad range of pests. Hallman (1999) reported that most of the tephritid fruit fly species which act as quarantine barriers for international trade of mangoes can be controlled by irradiation treatment with a dose ranging between 150–250 Gy and emphasized that even lower dose levels should be tried to avoid quality losses in fruits. The use of irradiation of mango for quarantine purposes is restricted to Hawaii and the US mainland. Hawaii has become the first place in the world to use irradiation as a quarantine treatment for fruits (Moy & Wong 2002). Irradiation treatments have been found to be very effective against most of the tephritid fruit fly species in mango (Bustos *et al*. 1992, 2004; Heather *et al*. 1991; Von Windeguth 1986). Bustos *et al*. (2004) recommended a dose of 150 Gy as a generic quarantine treatment against potential infestation of the Mexican fruit fly (*Anastrepha ludens*), the West Indies fruit fly (*A. obliqua*), the sapote fruit fly (*A. serpentina*) and the Mediterranean fruit fly (*Ceratitis capitata*) in mangoes. Irradiating 'Kensington' mangoes with a dose of 74–101 Gy resulted in disinfestation of eggs and larvae of Queensland fruit fly in Australia (Heather *et al*. 1991). However, irradiation is not an approved quarantine treatment in Australia (Heather *et al*. 1997). Moreover, the results of studies on efficacy of irradiation in killing stone weevil are not consistent (Seo *et al*. 1974; Shukla & Tandon 1985). According to Shukla and Tandon (1985), 'Alphonso' mangoes could not be disinfested of seed weevil with a dose of 500 Gy while Seo *et al*. (1974) observed that irradiation doses less than 500 Gy (206 and 329 Gy) killed mango weevils in Hawaiian mangoes. The irradiation of mangoes provides additional benefits of extension of shelf life as discussed earlier in this chapter.

**Insecticidal controlled atmospheres (ICA)**

Insecticidal controlled atmospheres (ICA) involve the short-term exposure of a commodity to very low $O_2$ (<1%) and/or very high $CO_2$ (50–80%) at low or high temperature to achieve insect disinfestation (Yahia 2006). The possible detrimental effects of ICA may include low-$O_2$ and/or high-$CO_2$ injury along with off-flavour due to fermentation in tissue. The application of ICA in mango for achieving insect disinfestation against various tephritid fruit fly species has proven successful (Ortega-Zaleta & Yahia 2000; Yahia 1993; Yahia & Hernandez 1993; Yahia *et al*. 1989; Yahia & Ortega-Zaleta 2000; Yahia & Vazquez-Moreno 1993). Mango is the most suitable fruit for ICA treatments as it is quite tolerant to high $CO_2$ (Yahia 2006). 'Keitt' mangoes could tolerate extreme atmospheres containing $\leq$0.5 kPa $O_2$ (= 0.5%) and/or $\geq$50 kPa $CO_2$ (=50%) for up to 5 days at 20°C (Yahia 1993; Yahia & Hernandez 1993; Yahia & Vazquez-Moreno 1993). The ICA treatments not only serve as a possible means of insect disinfestation but also delay ripening as shown by suppressed respiration, flesh firmness and colour development (Yahia & Hernandez 1993; Yahia & Vazquez-Moreno 1993). On the basis of these studies, it is clear that 'Keitt' mango is highly tolerant to ICA. Any quarantine treatment should be completed in the shortest possible period to avoid delay in the transportation and distribution of the fruit to destination market. To promote the efficacy of ICA in terms of insect mortality in a shorter period, treatment temperature can be elevated to room or high temperatures (44–45°C) (Ke & Kader 1992). Yahia & Ortega-Zaleta (2000) reported that dry hot air at $\geq$44°C and 50% RH in CA (0 kPa $O_2$ + 50 kPa $CO_2$), for 160 min or longer, is effective in increasing *in vitro* mortality of eggs and third instar

larvae of *A. ludens* and *A. obliqua*. 'Manila' mangoes exposed to ICA (0 kPa $O_2$ + 50 kPa $CO_2$) could tolerate up to 43°C for 160 min without showing any external or internal injury (Ortega-Zaleta & Yahia 2000). Recently, the effectiveness of low pressure storage treatment in killing the various tephritid fruit fly species has also been reported (Davenport *et al*. 2006). Caribbean fruit fly eggs and larvae, if exposed to simulated hypobaric conditions for shipment of mangoes (15 and 20 mm Hg, at 13°C, ≥98% RH), were killed by 11 days with a predicted kill of 99.999% of the eggs by 9.4 days in 15 mm Hg and 10.6 days in 20 mm Hg LP (based on Probit 9 statistical analysis). Thus, shipment of fresh mangoes using this technology seems promising as a means to provide quarantine control while preserving the freshness of fruit. However, further *in vivo* investigations are needed to prove the technology's ability to achieve insect disinfestation in mango. The approval of ICA as quarantine treatment and its commercial adoption are still awaited.

## POST-HARVEST DISEASES

Mango fruit is highly susceptible to many post-harvest diseases. The susceptibility to post-harvest diseases increases during storage after harvest due to physiological changes and senescence favouring pathogen development (Prusky *et al*. 2002). Anthracnose, stem-end rot and *Alternaria* rot are the major post-harvest diseases which limit the long term storage of the fruit. Mango is a host of several other fungal and bacterial pathogens but these are either restricted to only a few regions or not of much economic importance. The wide scale prevalence of anthracnose and stem-end rot in humid tropical areas causes heavy losses in mango fruit (Arauz 2000; McGuire & Campbell 1993; Pelser & Lesar 1990; Rappel *et al*. 1991, 1986). Alternaria rot or black spot is the major post-harvest disease of dry regions, for example, Israel (Prusky *et al*. 1983, 1999, 2002). The type and strength of post-harvest treatments for the control of post-harvest diseases in mango should depend on the relative quiescent infection levels (Prusky *et al*. 2002), but most of the post-harvest disease control treatments are applied independent of these levels. If the use of mild chemicals can give effective disease control, there is no need to give uniform fungicide treatment to the fruits harvested from different locations with variable quiescent infections. The determination of quiescent infection level in the fruit with a diagnostic kit may prove useful for post-harvest handlers to decide which type of treatment, mild or severe, should be given to fruit.

### Integrated post-harvest disease management

In a complex post-harvest handling system of mango, cultural practices during growth, optimal use of safer synthetic fungicides, biological antagonists and physical treatments are integrated to manage post-harvest diseases. The greatest challenge is to substitute the use of synthetic fungicides with the safer alternatives to provide the consumer with chemical residue-free fresh fruit with highest quality. There is no consensus among the importing countries about the post-harvest use of chemicals. Certain chemicals permitted by EU countries may be banned in North America or vice versa. The rising awareness among consumers about the deleterious effects of synthetic fungicides prompts the consumption of organic food and the research on non-chemical solutions for post-harvest diseases. Integrated anthracnose management practices in mango at pre- and post-harvest stages have been excellently reviewed by Arauz (2000).

### Cultural control

In most of the post-harvest diseases, developing fruit are infected in the field, but infection remains quiescent until the onset of ripening (Figure 6.1). The development of anthracnose is dependent upon wetness or high relative humidity and the entire disease cycle is shown in Figure 6.1. Therefore, regulation of flowering in such a way that the flowering, fruit set and maturation is completed in the dry season is an ideal cultural practice to control post-harvest anthracnose (Arauz 2000). There are some viable options for regulation of flowering in mango. Sanitation in the orchard can also reduce the incidence of anthracnose and stem-end rot (Saaiman 1997a). The removal of mummified fruit, affected twigs, and dried panicles can reduce the inoculum load on the tree. The bagging of developing mango fruit in the paper bags resulted in reduced anthracnose severity, but it also reduced the red colour development, which may affect the consumer acceptability (Hofman *et al*. 1997). The longstanding need for breeding disease resistant cultivars in mango is still unfulfilled.

### Post-harvest chemical control

The selection of a fungicide for post-harvest disease control depends upon the type of fungicide used in the field sprays and also the destination market for the fruit. A chemical registered for use in one country may not be permitted in another country. Benomyl and prochloraz give good after-infection control of mango anthracnose, but prochloraz is the only fungicide registered for post-harvest use (Arauz 2000). Benzimidazole fungicides such as benomyl and thiobendazole are effective for control of stem-end rot and anthracnose as well. Benomyl was used in the past as a post-harvest dip at rates varying from 500 to 1000 ppm, but its use is no longer permitted. Thiobendazole (1000 to 2000 ppm)

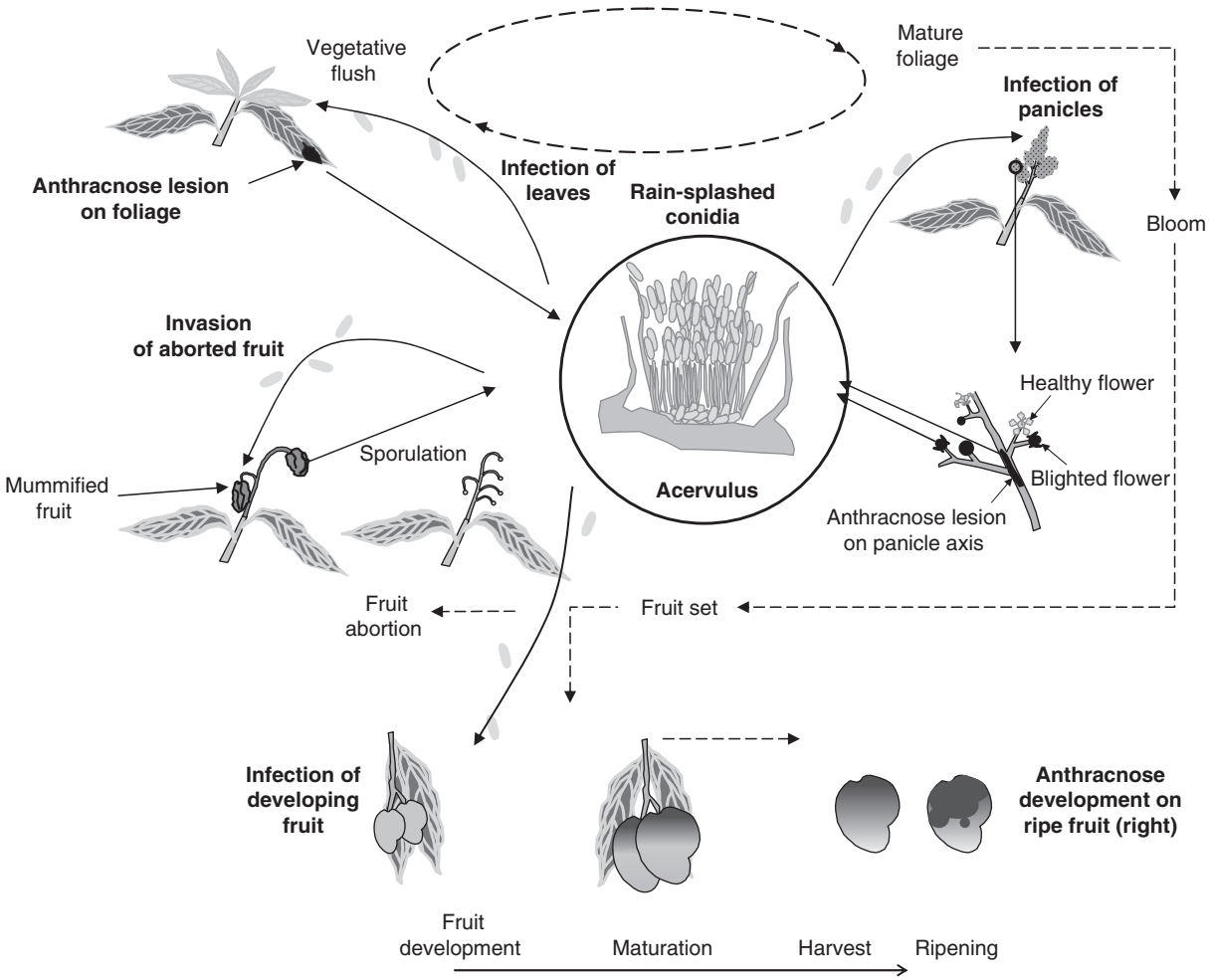


**Figure 6.1** Anthracnose cycle in mango. Solid lines represent disease cycle. Dotted lines represent mango phenology. (Adapted with permission from Arauz, L.F. (2000) Mango anthracnose: economic impact and current options for integrated management. *Plant Disease*, **84**, 600–611.)

is also effective and its registration is still questionable. Prochloraz can be used at rates up to 1000 ppm in fruit shipped to European Union. Efficacy of this fungicide varies from 65% at very high disease pressure to 94% under moderate disease pressure (Arauz 2000). The post-harvest application of fungicides at ambient conditions requires higher concentrations and does not give effective disease control under high disease pressure situation (Arauz 1995, 2000).

### Heat treatments

Heat treatments can serve as alternatives to chemical treatments as they eliminate any residue on the fruit. Heat treatment is a prerequisite for mangoes entering into United States and Japan in view of post-harvest insect disinfestation. Heat has both insecticidal and fungicidal properties. Therefore, heat treatment can give dual control of insect pests and diseases. To fulfil the quarantine requirements, fruit is immersed in water at 46°C for 90 to 120 min, depending upon the variety and fruit size. This treatment also controls between 60% and 85% anthracnose (McGuire 1991). Hot water treatment at 55°C for 5 min is the most common recommendation for control of post-harvest diseases (Pelser & Lesar 1990; Rappel *et al*. 1991, 1986; Sopee & Sangchote 2005). Vapour heat treatment (VHT) of 'Kensington' mangoes where core temperature is held at 47°C for 15 min reduces the incidence of anthracnose as well as stem-end rot, compared to hot-water treatment

(Jacobi & Wong 1992). A hot-water brushing (HWB) technique developed by Fallik and co-workers in Israel is an improvement of a hot-water immersion technique in which higher temperatures (56–64°C) can be used without any adverse on the fruit quality (Prusky *et al*. 1999). In mango, HWB treatment for 15–20 s at 56–64°C is effective in reducing the incidence of black spot caused by *Alternaria alternata* (Prusky *et al*. 1999). The efficacy of HWB in controlling anthracnose and stem-end rot warrants further investigations. Heat treatments give only partial disease control and need supplementation with fungicides.

**Combination of heat and chemicals**

A combination of hot-water treatment and fungicide is the best commercial post-harvest treatment to control post-harvest diseases. Both rate of fungicide and duration of exposure to hot water are lower, and efficacy is higher than with either treatment applied separately (Arauz 2000). Hot water and fungicides can be applied sequentially or together. Prochloraz is the best fungicide for control of anthracnose in mango when applied in combination with hot water (Arauz 1995, 2000; Oosthuyse 1997; Rappel *et al*. 1991; Swart & Broekhuizen 2004). The combination of hot-water dip at 52–53°C for 3–5 min with 500 ppm prochloraz gives excellent control of anthracnose disease and a partial control of stem-end rot, which is the second most important post-harvest disease (Arauz 1995; Rappel *et al*. 1991). The substitution of prochloraz with benomyl can effectively control both the diseases (Rappel *et al*. 1991), but the latter is now obsolete. Higher doses of hot prochloraz at 50°C can effectively control stem-end rot and these doses conform to the maximum residue limit of 5 ppm in the European Union (Swart & Broekhuizen 2004). Post-harvest development of alternaria rot in mango fruit during storage is usually prevented by a combination of hot-water brushing with prochloraz at 225 ppm (Prusky *et al*. 1999). Recently, Prusky *et al*. (2006) showed that application of a combination of HWB for 15–20 s, followed by spraying with 50 mM HCl effectively controlled alternaria rot in stored mangoes. The acid treatment alone was as effective as the combination of acidified prochloraz and HWB (Prusky *et al*. 2006).

**Biological control**

Biological control using microbial antagonists is a relatively new approach that can be used as a part of an integrated post-harvest disease management strategy to reduce the use of synthetic fungicides. The efficacy of biological control agents can be improved if applied with the recommended fungicide, used at a lower concentration. The trial of a commercial formulation 'Mangogreen' containing the biocontrol agent *Bacillus licheniformis*, under semi-commercial conditions in South Africa showed that the incorporation of this agent with a hot-water dip at 45°C for 5 min followed by a quarter strength of prochloraz dip reduced the incidence of anthracnose and stem-end rot in 'Keitt' mangoes (Govender *et al*. 2005). Another example of effective biocontrol of anthracnose in mango is the post-harvest application of isolate 558 of *Pseudomonas fluorescens* where the bacterial antagonist reduced the anthracnose development compared with the control (Koomen & Jeffries 1993). The success of a commercial biocontrol formulation in South Africa opens new vistas of research in other countries also. The efficacy and stability of biocontrol formulations under various post-harvest handling systems deserve more attention of researchers before their release for large scale use by the mango industry.

**Other approaches**

As the use of post-harvest fungicides is becoming more and more limited, the development of new approaches that exploit natural or induced fruit resistance represent a feasible approach to reduce the reliance on the chemicals for the control of post-harvest diseases. Induction of host resistance is a good strategy to control post-harvest diseases. The use of various chemical, physical and biological elicitors can artificially induce host resistance (Wilson *et al*. 1994). The exogenous application of salicylic acid (SA), which is involved in the disease resistance in plants, has been demonstrated to be effective in enhancing the disease resistance in mango fruit (Zainuri *et al*. 2001; Zeng *et al*. 2006). The post-harvest application of SA at 2000 ppm concentration in 'Kensington' mangoes reduced the severity of anthracnose, but doses up to 1000 ppm were not very effective (Zainuri *et al*. 2001). The vacuum infiltration of 1 mmoll$^{-1}$ SA in 'Matisu' mango also enhanced the disease resistance against anthracnose by increasing the activities of phenylalanine ammonia lyase (PAL) and $\beta$-1,3-glucanase in SA-treated fruit (Zeng *et al*. 2006). The use of 2, 4-dichlorophenoxyacetic acid (2, 4-D) may be helpful in strengthening the abscission zone and thus preventing its breach by the stem-end rot pathogen. A treatment of hot-water brushing and prochloraz followed by 2,4-D at 75 to 175 µg ml$^{-1}$ diluted in wax reduces the stem-end rot and side rot diseases in mango by 50–70% during prolonged storage (Kobiler *et al*. 2001). The exposure of mango fruit to UV-C and infrared (IR) for 3–5 min also reduced the incidence of anthracnose, but did not control stem-end rot and brown rot (Duvenhage 2000). The exposure to IR radiation in controlling anthracnose

was as effective as hot-water treatment (Saaiman 1997b). The exposure to gamma radiations also reduced the decay incidence in mango (Uthairatanakij *et al*. 2006). The use of surface coating, which contained maltodextrin, carboxymethylcellulose, propylene glycol and sorbitan esters reduces the incidence of anthracnose by 70% in stored mangoes (Diaz-Sobac *et al*. 2000). This comprehensive review enumerates various options for controlling post-harvest diseases in mango. The role of heat in post-harvest handling of mango seems the crux of the system which must be integrated to achieve dual goals of insect and disease disinfestation. The successful post-harvest disease management in mango demands the integration of various cultural, physical, chemical and biological methods so that the use of synthetic fungicides can be minimised in favour of consumer satisfaction and environmental safety.

## FUTURE RESEARCH

Mango fruit is known for its delicious taste, unique flavour and nutritional value. The mango industry is expected to continue present trends in growth and boom further. Due to the fruit's highly perishable nature, delicate skin, chilling sensitivity and high disease susceptibility, providing a consistent supply of high-quality fresh and safe fruit to the consumer poses a great challenge for post-harvest biologists and technologists. The adoption of total quality management systems covering production practices, harvesting, post-harvest handling, storage, transportation and distribution can assure the consumer about the fruit safety aspects. Furthermore, the insect-pests of mango hinder the wider distribution due to strict quarantine restrictions imposed by various countries. More research is still needed to develop nondestructive maturity assessment, quality evaluation methods and machinery. Controlled atmosphere storage technology can play a vital role in the wider distribution of fruit across different continents. The cultivar-specific information available on the use of CA/MA in mango is still inconclusive. Maximising the beneficial effects of CA/MA with the least negative impact on fruit flavour and quality warrants further research. The alternative application of CA to achieve insect pest disinfestation in mango might prove a commercial practice if approved by the quarantine regulatory authorities. It seems a promising proposition to eliminate post-harvest fumigants and heat treatments which otherwise may affect the consumer health and fruit flavour, respectively. Recent studies on the post-harvest disease management in mango through the natural or induced systemic disease resistance and use of biocontrol agents offer attractive alternatives to reduce the use of fungicides. The molecular and conventional breeding approaches to regulate fruit ripening and improve shelf life have not resulted in substantial success. Therefore, the development of post-harvest technologies based on eco-friendly, biologically safe and nonchemical approaches holds a key towards the sustainable post-harvest management practices in mango.

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# 7
# Pineapple

*Nimal Adikaram and Charmalie Abayasekara*

## INTRODUCTION

The pineapple (*Ananas comosus* L. Merril.) is the leading member of the Family Bromeliaceae native to Southern Brazil and Paraguay where wild relatives occur. The pineapple was apparently domesticated by the Indians. The plant was carried through Southern and Central Americas to Mexico and the West Indies long before the arrival of the Europeans. Pineapples are grown in Australia, Brazil, China, Hawaii, Kenya, Malaysia, Mexico, Philippines, Thailand, South Africa, Sri Lanka and West Indies. Brazil, China, Philippines and Thailand are the main pineapple producers in the world supplying nearly 50 % of the total output (FAO 2004). Total production of pineapple was 14 million tons in 2003 (FAO 2004). Nearly 70% of the pineapple is consumed as fresh fruit in producing countries.

The pineapple is a xerophytic, succulent, herbaceous plant (Bartholomew and Malezieux 1994). The plant is a perennial, flowers only once and dies after fruiting; a side root then takes over. There are genetically diverse groups of pineapple: the Cayenne group, Queen group, Red Spanish, Abacaxi group and Maipure group (Leal and Soule 1977; Grazia *et al*. 1980). The commercial varieties are classified into three groups, the Cayenne group, Queen group and Red Spanish, based on their morphological characters. Smooth Cayenne is the world's most grown and largest commercial group (Grazia *et al*. 1980) used in processing and fresh fruit trade. Cayenne has spineless leaves and bigger plants, and produces fruits with shallow eyes and very sweet taste. Queen has spiny leaves and somewhat smaller plants and produces very sweet fruits with deep eyes. Spanish group plants have spiny leaves and produce medium-sized fruits with an acidic taste.

Pineapple is a collective fruit made up of berry-like fruitlets developed from a whole inflorescence. The fruit is made up of 100 to 200 fruitlets which are fused together on a central axis or core. The fruit has a conical shape with larger fruitlets at the base and smaller ones at the top. Flesh of fresh or canned fruit is eaten as a dessert, and the juice has a growing demand as a beverage. The pineapple has long been one of the most popular of the noncitrus tropical and subtropical fruits, largely because of its attractive flavour and refreshing sugar–acid balance.

## FRUIT COMPOSITION

The mature pineapple fruit contains 80–86% water and is a good source of carbohydrates. The sugars are not distributed evenly throughout the fruit; the bottom portion has more sugars than the top crown end because it is composed of more mature fruitlets (Sinclair 1993). The fruit has 0.5–2% acids. Consumption of 100 g edible portion provides 218 KJ of energy (Wenkam 1990). The fruit also has fibre. Potassium is the most prominent mineral, followed by calcium (Table 7.1). Pineapple juice contains S-sinapyl-L-cysteine, N-L-γ-glutamyl-S-sinapyl-L-cysteine and S-sinapylglutathione in substantial concentrations (Wen *et al*. 1999).

Twenty-nine odour-active compounds were detected in an aroma distillate prepared from fresh pineapple, and five of these were key odorants in fresh pineapple flavour: 4-hydroxy-2,5-dimethyl-3(2H)-furanone (HDF; sweet, pineapple-like, caramel-like), ethyl 2-methylpropanoate

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**Table 7.1** Composition of Pineapple Fruit.

| Nutrient | Amount per 100 g edible portion | Nutrient | Amount per 100 g edible portion |
|---|---|---|---|
| Water | 80–86 g | Ascorbic acid | 10.00 mg |
| Energy | 218 KJ | Vitamin B12 | 0.09 mg |
| Protein | 0.2 g | Vitamin B6 | 50 IU |
| Lipid | 0.2 g | Vitamin A, IU | 53 IU |
| Carbohydrate | 13.5 g | Vitamin A, RE | 1.0 |
| Acids | 0.5–2 g | α Tocopherol | 0.16 mg |
| Total sugars | 8 g | Riboflavin | 0.4 mg |
| Fibre | 0.5 g | Folate (Total) | 11 mcg |
| Ash | 0.3 g | Thiamin | 0.9 mg |
| Calcium | 18 mg | Cryptoxanthene | 0 mg |
| Iron | 0.3 mg | Niacin | 0.036 mg |
| Magnesium | 12 mg | Pantothenic acid | 0.42 mg |
| Phosphorus | 12 mg | Potassium | 98 mg |
| α Carotene | 31 mcg | Brix | 10.8–17.5 |
| Sodium | 1 mg | Titratable acidity | 0.6–1.62 |

Source: Dull (1971) and Wenkam (1990).

(fruity), ethyl 2-methylbutanoate (fruity) followed by methyl 2-methylbutanoate (fruity, apple-like) and 1-(E,Z)-3,5-undecatriene (fresh, pineapple-like) (Tokitomo *et al*. 2005).

The proteolytic enzyme, bromelain, obtained from the juice or mature plant stem (Nakasone & Paull 1998) is used for tenderizing meat and chill proofing beer, is added to gelatine to increase its solubility for drinking and has been used for stabilizing latex paints and in the leather tanning process. In modern therapy, bromelain is used as a digestive and for its anti-inflammatory action after surgery (Nakasone & Paull 1998). Bromelain, is believed to cause soreness and discomfort of the mouth when excessive amount of fresh pineapple is consumed. The presence of bromelain in pineapple juice also prevents gelatinization if the juice is used as an ingredient for gelatin. Therefore, commercial pineapple juice has to be pasteurized to inactivate the enzyme. Bromelain FA2, the main proteinase component of the juice of pineapple fruit, has been purified and characterized, the molecular weight being 31 000 Daltons and the isoelectric point pH 4.6 (Yamada *et al*. 1976).

## FRUIT DEVELOPMENT AND PHYSIOLOGY

### Fruit development

Pineapples can initiate flowers only after reaching a minimum weight (about 500 g for Smooth Cayenne). However, plants at this minimum weight will produce only very small flowers. Ethylene is believed to be the chemical which causes natural initiation of flowering. Plants can be artificially induced to flower at any time by applying ethylene-producing chemicals (Sinclair 1993). In pineapple, and other bromeliads, it has been proposed that flowering is triggered by a small burst of ethylene production in the meristem in response to environmental cues (Trusov & Botella 2006). Flowering dynamics studies revealed significant differences in flowering behaviour, with transgenic plants that exhibited the silencing ACACS2 (1-amino-cyclopropane-1-carboxylate synthase) gene showing a marked delay in flowering when compared with nonsilenced transgenic plants and control nontransformed plants. It appears that the ACACS2 gene is one of the key contributors towards triggering 'natural flowering' in mature pineapples under commercial field conditions (Trusov & Botella 2006).

It takes approximately four months from the end of the last open flower to fruit maturity and the total time required from flower initiation to harvest is between six and seven months (Nakasone & Paull 1998). During maturation, the fruit size, weight, soluble solids and acidity in the flesh are increased. During ripening, the shell of the pineapple loses chlorophyll rapidly, starting at the fruit base, the pulp soluble solids increase dramatically and the fruit attains the maximum eating quality.

**Physiology**

Pineapple, like most other succulents, fixes 40% to 100% of its carbon in the dark via phosphoenolpyruvate carboxylase, storing the carbon as malic acid. The $CO_2$ is released from the malic acid in the light and is then fixed via conventional C3 photosynthesis, a process referred to as Crassulacean acid metabolism (CAM). Pineapple is one of the typical PCK-CAM plants (Hong *et al*. 2004) which have significant activities of PCK (pyruvate carboxykinase) with lower levels of malic enzyme (ME) (Winter & Smith 1996). Malate decarboxylation is a very important metabolism in plant mitochondria, especially in CAM plants in which malate is accumulated in the vacuoles at night and released into the cytoplasm during the day. Based on malate metabolism, CAM plants are divided into ME-CAM and PCK-CAM. ME-CAM plants have significant activities of malic enzyme without PCK, and they use ME to decarboxylate malate, generating pyruvate and $CO_2$ (Cuevas & Podestá 2000).

Pineapple is a nonclimacteric fruit but does produce ethylene gas. When ethylene gas levels ranging from 0.01 to 1000 µl/l were applied to fruit just at the start of ripening, no respiration or chemical changes were induced (Dull *et al*. 1967) showing that external application of ethylene does not affect ripening.

Two key enzymes involved in the ethylene biosynthesis pathway, 1-aminocyclopropane-1-carboxylate (ACC) synthase (acacc-1) and 1-aminocyclo- propane-1-carboxylate (ACC) oxidase (acaco-1), have been isolated from pineapple fruit and characterized (Cazzonelli *et al*. 1998). These two enzymes catalyse the last two steps in the ethylene biosynthesis pathway (Yang & Hoffman 1984). Both enzymes have been proven to be important in the overall regulation of ethylene biosynthesis; however, ACC synthase is established as the limiting enzyme in the pathway (Kende 1993). Southern blot analysis suggested the presence of only one copy of acacc-1 and one or two copies of acaco-1 in the pineapple genome. Expression of some acacc-1 was detected in green pineapples and there was a 16-fold increase in the level of acacc-1 in ripe fruit tissue. Unwounded leaf tissue did not show any detectable levels of acacc-1, whilst wounded tissue showed low levels of expression. Northern blot analyses have shown the expression of acaco-1 to be highly induced in wounded pineapple leaf tissue and to a lesser extent in ripening fruit tissue. The accumulation of ACC synthase and ACC oxidase mRNAs during pineapple fruit ripening raises new questions about the putative role of ethylene during nonclimacteric fruit ripening (Cazzonelli *et al*. 1998).

The nonclimacteric pineapple fruit produces around 22 ml $CO_2$ $kg^{-1}$ $h^{-1}$ at 23°C, with no dramatic respiratory or biochemical changes during ripening (Dull *et al*. 1967). A decrease in the oxygen concentration to 2.5% resulted in a decrease in respiratory rate. In contrast an increase in the carbon dioxide concentration up to 10% had no detectable effect on the respiration rate (Dull *et al*. 1967). Measurement of carbon dioxide exchange and acid levels in detached pineapple leaves indicated the presence of photorespiration in pineapple (Moradshahi *et al*. 1977).

Presence of preformed chitinase activity, which is usually considered to be an antifungal or anti-pest defence mechanism, was shown in pineapple using chitinase activity gel and immunoblot analysis by Taira *et al*. (2005a). Of the three chitinases, Type A (acidic class III) was found to exist in all tissues, while type B (weakly basic class I, which has strong antifungal activity) and type C (acidic class I) are localized mainly in the leaf and stem. In a pericarp, Type A exists at all stages during fruit development, while type B and type C exist only at the early stage. Synthesis of type A is induced by ethylene, while that of types B and C is not affected by it. These results suggest that the physiological roles of these three types of chitinase in pineapple are different. At low ionic strength, PL Chi-B exhibits strong antifungal activity toward *Trichoderma viride* while the others do not. At high ionic strength, PL Chi-B and -C exhibit strong and weak antifungal activity respectively. PL Chi-A does not have antifungal activity (Taira *et al*. 2005b).

**POST-HARVEST HANDLING**

Changes in maturation stage are evident when peel colour turns from green to yellow at the base of the fruit. Harvesting maturity is often when the base of the fruit has changed from green to yellow colour. Generally when 30–50% eyes have turned yellow from the base, the fruit becomes ready to harvest. Harvesting maturity of pineapple may also vary depending on purpose and market destination. For remote markets it is best to harvest slightly early when at the 10–20% yellow stage or even 100% green but mature stage, just before these striking colour changes begin. External colour of pineapple is an important trait in consumer preference. Consumers judge fruit quality by skin colour and aroma. A minimal content of soluble solids of 12% and a maximal acidity of 1% ensure a minimal level of consumer acceptance along with size and texture uniformity, absence of rotting, sunburns cracks, bruises, internal breakdown, endogenous brown spot and damage by insects. A SSC:TA ratio of 0.9 to 1.3 is normally recommended (Soler 1992). Immature fruit should not be shipped, since they do not

develop good flavour, have low brix and are more prone to chilling injury (Rohrbach & Paull 1982). Fully ripe, yellow fruit are also unsuitable for transporting to distant markets, therefore slightly less mature fruit are selected for this purpose (Akamine 1963; Cancel 1974). Being a non-climacteric fruit, only a few compositional changes such as decrease in acidity and de-greening may occur after harvest. Fruits harvested very early will not develop the characteristic flavour and shell colour.

Pineapples for the fresh market are hand harvested, with pickers being directed as to stage or stages (shell colour) of ripeness required (Rohrbach & Schmitt 1994). Fruit is either packed in the field or at a central packing shed. In Hawaii, pickers walk in the space between rows and place the fruit on a conveyer belt, which transfers the fruit to a truck field bin. Fruits are also harvested by pickers carrying large baskets on their backs. When the fruits arrive at the packing shed, it is unloaded by hand, by submerging the bin in water or by sliding the fruit out of the field bin into water. Fruit with high translucency are separated at this step (Rohrbach & Schmitt 1994).

Fruits are best harvested between first light and 8.00 A.M. Fruits harvested at midday or mid-afternoon have poor keeping quality. Harvesting is done by cutting the stalk with the help of a sharp knife leaving the stalk about 6–8 inches long. The stalk must not be separated from the stem end of the fruit to prevent entry of spoilage organisms into the fruit during storage or transit. Harvested fruits must not be exposed to sun, but instead they should be collected in a shady place.

Harvested fruits must be carefully cleaned with a soft brush to remove any insects and debris. Stalks must be trimmed to about 1.0–1.5 inches. Knives used for harvesting and stalk trimming must be cleaned at regular intervals by dipping the knife blade in a disinfectant solution. The cut end of the stalks should be dipped in a suitable fungicide solution to prevent any fungal infection. A wax treatment may be included at this stage to reduce physiological disorders and improve visual quality. Rough handling must be avoided at all stages of harvest, collection, packing and transport.

Pineapples are graded by the degree of skin colouration, size (weight), absence of defects and disease, and uniformity of these characteristics before packing. Other characteristics include maturity, firmness, nice shape, flat eyes and well-cured broken stem (peduncle). Crown size is a crucial grade component, with a minimum size, and ratio of crown:fruit length (0.33 to 1.5) for higher grades. Crowns developed during the summer tend to be larger and may require gouging (removal of the crown center) at harvest to meet the standard.

**Nondestructive methods for assessing pineapple quality**

Guthrie and Walsh (1997) have developed a non-invasive method for measurement of pineapple fruit quality based on near-infrared (NIR) spectroscopy. A remote reflectance fibre optic probe, placed in contact with the fruit skin surface in a light-proof box, was used to deliver monochromic light to the fruit, and to collect NIR reflectance spectra (760–2500 nm). The NIR spectral attributes were correlated with pineapple juice Brix (Guthrie & Walsh 1997). Resonant frequency, firmness and soluble solids were evaluated for pineapple classification using artificial neutral networks (ANNs) as the analytical tool. A sample of 149 pineapples was classified based on their internal qualities into five classes: unripe, partially ripe, ripe, partially overripe and completely overripe. The developed ANN model successfully classified pineapples into merely three classes as unripe, ripe and completely overripe. The classification accuracy was more than 83% for all three classes.

Acoustic methods using "tapping" on the fruit showed 100% accuracy in sorting good quality of Smooth Cayenne pineapple cv. '*Pattavia*'. Fresh fruit is graded based on eating quality of the flesh, the flavour score and TSS/acid ratio and this correlated well with "tapping" sound. X-ray computed tomography (CT) has been used to produce a precise internal image of the fruit electronically (Sornsrivichai *et al*. 2000) and the intensity of X-ray CT images and CT numbers show significant correlation with the ripeness and translucency of flesh which reflects the taste quality. The technique could identify other internal defects such as bruise damage and porosity as well as identify the inferior fruit with nonsymmetrical shape. Thus, X-ray CT can be an effective nondestructive tool for internal quality evaluation and following the internal change of each fruit during storage (Sornsrivichai *et al*. 2000).

**Storage conditions for whole and cut fruit**

Temperatures of 7°C to 12°C are recommended for storage of pineapples for 14 to 20 days, provided fruit are at the colour break stage (Paull 1993). A relative humidity (RH) of 85–95% is recommended; a high RH significantly reduces water loss. Ripe fruit can be held at 7.2°C for about 7 to 10 days. Pineapples may be stored at 0–4°C for weeks, but upon removal, fruit fail to continue ripening and show severe chilling injury. Quarter-yellow fruit at harvest gain about one additional week of storage for every 6°C decrease in storage temperature (Dull 1971). The maximum storage life at 7°C is about 4 weeks (Paull & Rohrbach 1985). However, when removed, chilling injury-induced internal browning develops within 2 to 3 days.

Temperature was also the main factor affecting post-cutting life of fresh cut pineapples which ranged from 4 days at 10°C to over 14 days at 2.2 and 0°C (Marrero & Kader 2006). The end of post-cutting life was signalled by a sharp increase in $CO_2$ production followed by an increase in ethylene production. The main effect of reduced $O_2$ levels was better retention of the yellow colour of the pulp pieces whereas elevated $CO_2$ levels led to a reduction in browning. Modified atmosphere packaging allowed conservation of pulp pieces for over 2 weeks at 5°C or lower without undesirable changes in quality parameters (Marrero & Kader 2006). Modified Atmosphere Storage (MAP) of minimally processed pineapple in a gas mixture, 4% $O_2$, 10% $CO_2$ and 86% $N_2$, increases the shelf life compared to storage in 100% $O_2$, or under vacuum (Martinez-Ferrer *et al*. 2002). Sample preparation consisted of hand peeling, dicing, blanching, dipping in ascorbic acid and packaging.

## POST-HARVEST DISEASES AND DISORDERS

Most pests and disease of pineapple are universally distributed, as vegetative germplasm has been transported around the world since the 1800s. The Smooth Cayenne is relatively resistant to most diseases (Rohrbach 1994).

The etiologies of fruit diseases have been difficult to determine because of the wide range of microorganisms found on the surface of the inflorescence and inside the fruitlet and because of the sporadic occurrence of these diseases. Diseases/disorders of pineapple fruit can be classified as: (1) pre- flower infections that begin at the floret before the flower opens including fruitlet core rot and leathery pocket disease, (2) flower infections beginning after the flower opens and caused by bacterial complexes including pink disease and marbling disease, (3) wound infections caused most frequently by *Thielaviopsis paradoxa* that begin in wounds during harvesting resulting in black rot and (4) physiological disorders, the most common of which is internal browning or black heart caused by chilling injury (Rohrbach & Phillips 1990). Black rot and internal browning have been of sufficient economic importance and occurrence to warrant control practices.

Fruit diseases generally begin following harvest and occur in pineapple markets throughout the world. However, other post-harvest diseases which begin prior to pineapple harvest also cause economic problems (Rohrbach & Phillips 1990). Care is necessary at all stages of the post-harvest handling chain to prevent injury, and packaging has to be well designed to prevent the sharp 'crown' leaves from piercing adjacent fruits (Snowdon 1990).

A single blemish in one fruitlet of the fruit cylinder may downgrade the entire slice from a fancy whole slice to chunks or crush and require additional labour to remove the blemish (Rohrbach & Schmitt 1994). Severely infected fruit are discarded, whereas low to moderate blemish levels, which must be removed from fruit cylinders prior to or following slicing, increase labour costs and downgrade the remaining product, especially in canneries.

### Black rot

Black rot of pineapples, also known as *Thielaviopsis* fruit rot, water blister, soft rot, water rot and stem-end rot, is caused by *Ceratocystis paradoxa* (Syn. *Chalara paradoxa*; anamorph *Thielaviopsis paradoxa*).

Black rot is a major post-harvest disease of pineapples, widespread and most common during warm, wet weather (Pegg 1993). The disease has been responsible for serious losses in the fresh fruit industry (Snowdon 1990; Nakasone & Paull 1998). The disease occurs in all major pineapple producing countries, Ivory Coast, India, the Philippines, Malaysia, Australia, Hawaii, Cuba, Puerto Rico, Nigeria, South Africa (Snowdon 1990) and Sri Lanka (Damunupola & Adikaram 2000; Abeygunawardena 1969).

The pathogen enters through wounds and shell bruises that occur during harvesting, or through natural growth cracks (Pegg *et al*. 1995). The main point of entry is through the broken fruit stalks, but any bruised region can be invaded. Infection occurs within 8–12 h following wounding. The disease is most severe during wet weather (Pegg *et al*. 1995). There is evidence that the pathogen infects the fruit in the field and remains quiescent. Infection can also occur in the harvested fruit. In both situations, the symptoms of black rot are developed during storage or marketing several days after fruit harvest. Therefore the disease is seldom seen by the grower. Fresh fruit is marketed with the crowns intact, which eliminates a major entry point for the fungus (Pegg *et al*. 1995).

The disease develops as a soft, watery rot in the fruit flesh (Plate 7.1) with the overlying skin glassy, water-soaked and brittle (Sinclair 1993). Eventually, the skin, flesh and core disintegrate and the juice leaks through the shell. Diseased tissue darkens as the dark-coloured mycelium and chlamydospores of the causal fungus form. In advanced stages, the rot leaves a fruit shell containing only a few black fibres. This shell collapses under the slightest pressure (Pegg *et al*. 1995). The severity of the problem is dependent on the degree of bruising or wounding during harvesting and packing, the level of inoculum on the fruit and the storage temperature during transportation and marketing (Rohrbach & Schmitt 1994). *C. paradoxa* also occasionally infects the upper portion of the pineapple crown and produces a black, charcoal like rot. The advancing area is of

a pale colour and water-soaked. Base rot and butt rot of pineapple plant are also caused by the same fungus especially where drainage is poor.

***Control***

Black rot is commercially controlled in fresh fruit by minimizing bruising of fruit during harvest and handling, by refrigeration and with fungicides (Nakasone & Paull 1998). The fruit should be carefully handled to avoid mechanical damage as invasion of the fungus can occur through minute fractures. As sunburnt and damaged fruit could have minor skin cracks that are readily infected, these should be rejected. Susceptibility varies with the cultivar, Red Spanish types being more resistant than Smooth Cayenne (Rohrbach & Schmitt 1994; Nakasone & Paull 1998). Removal of pineapple refuse and rejected fruit in packing areas and at the market is important to reduce inoculum and infection (Pegg *et al*. 1995).

The base of the fruit can be dipped in a recommended fungicide within 4–5 hours of harvesting, especially for fruit harvested during warm, wet weather (Pegg 1993). Wax treatment at a post-harvest level has been proved effective against the disease (Wijeratnam *et al*. 2006). Hot water treatment at 54°C for 3 minutes controls disease when stored at 10°C for 21 days followed by 48 h at ambient temperature (28 ± 2°C) and also at 28 ± 2°C for 6 days (Wijeratnam *et al*. 2005).

Complete inhibition of spore germination of *C. paradoxa* has been observed with 2% acetic acid (AA) (v/v) and radial mycelial growth of the organism showed inhibition at 3% AA. Black rot of Mauritius (Queen) pineapples was shown to be minimal after a 7-day storage period at 28 ± 2°C when fruits were subjected to a three minute dip at either 4% or 5% AA (Wijeratnam *et al*. 2006).

The use of microbial antagonists as agents of biological control, such as *Pichia guilliermondii* or a yeast mixture has also proved to be successful. The use of *Pichia* or the yeast mixture was comparable with current industry practice of holding fruit at a low temperature (8–10°C) and fungicide (Reyes *et al*. 2004).

**Fruitlet core rot, leathery pocket and interfruitlet corking**

Fruitlet core rot (FCR), black spot, fruitlet brown rot and eye rot are terms that have been used to describe brown to black diseased centres of individual pineapple fruitlets. Leathery pocket (LP) and interfruitlet corking (IFC) are additional symptoms that develop as FCR continues to develop.

The fungi *Penicillium funiculosum* and *Fusarium guttiforme* (formerly *Fusarium moniliforme*), the round yeast *Candida guilliermondii*, the pineapple fruit mite, *Steneotarsoneumu ananas* (Tryon), and the pineapple red mite, *Dolichotetranychus floridanus* (Banks), are associated with FCR (Rohrbach & Schmitt 1994; O'Donnell *et al*. 1998). The condition has been reported from all major pineapple producing countries (Snowdon 1990), but it is sporadic (Pegg *et al*. 1995) and rarely occurs at epidemic levels. Low-acid cultivars (Rohrbach & Schmitt 1994) and rough leaf pineapples grown commercially are the more susceptible than Smooth Cayenne (Pegg *et al*. 1995). The disease is more common in fruit maturing during the winter or spring.

Both *P. funiculosum* and *F. guttiforme* are involved in flower infections, but there is no cause-and-effect relationship established for the yeast, *C. guilliermondii*. The importance of *P. funiculosum* and *F. guttiforme* varies among different production areas. In Brazil, *F. guttiforme* is the predominant cause of FCR, whereas *P. funiculosum* is the most common cause of FCR and LP in South Africa (Rohrbach 1980; Rohrbach & Taniguchi 1984). In Hawaii, both *P. funiculosum* and *F. guttiforme* cause FCR symptoms, while only *P. funiculosum* causes IFC and LP (Rohrbach & Schmitt 2003). *P. funiculosum* was consistently isolated from pineapple fruitlets with black spot symptoms.

The pineapple fruit mite, *S. ananas* Tryon associated with the disease seems to enhance the pathogenesis of *P. funiculosum* but does not act as a vector (Rohrbach & Apt 1986). *S. ananas* is light brown and the adult male is oval with an average length of 0.2 mm and width of 0.10 mm (Petty 1975, 1978). *D. floridanus* is a large phytophagous mite found on pineapple, and is conspicuous because of its bright orange to red colour. The adult mite is 0.3–0.4 mm long and 0.1 mm wide (Petty 1975, 1978).

*P. funiculosum* builds up on mite-damaged trichomes on the basal parts of heart leaves, and on the bracts and sepals of flowers. The fungus can also infect unopened flowers and on developing flowers 1–2 weeks before anthesis (Pegg e*t al*. 1995). On unopened flowers, *P. funiculosum* initially causes necrosis of the anthers and pistil, blue green sporulation on ovules and locule walls cork formation on the locules. As the disease progresses, septa between locules become dark to medium brown, and the discolouration may extend into adjacent noncapillary tissues (Rohrbach & Schmitt 2003). Further corking of locules as fruit matures results in LP (Rohrbach & Schmitt 1994). LP disease was formally attributed to mite damage (Le Grice & Mark 1970) but it has now been established that *P. funiculosum* is the primary cause (Lim & Rohrbach 1980). IFC develops on the fruit surface between affected fruitlets which do not enlarge rapidly as healthy fruitlets. This results in distortion of affected fruitlets (Hepton & Anderson 1968).

*F. guttiforme* causes a light to dark brown discolouration of septa that may extend down the entire fruitlet core. White to pinkish mycelium and sporulation of the pathogen occur in locules. The optimum temperature for infection is 16–20°C and temperatures higher than 20°C inhibit disease development. Rainfall is needed for the fungus to build up in damaged leaf hairs, but not needed for infection to occur (Rohrbach & Taniguchi 1984). *F. guttiforme* enters the fruit through open flowers or injuries on the fruit. The risk of FCR due to *F. guttiforme* is higher when flowers are initiated and fruit mature under warm conditions (21–27°C) (Pegg *et al*. 1995).

The degree to which these symptoms develop appears to depend on the time of infection, the pathogen or mixture of pathogens that is present, the cultivar and the environmental conditions (Rohrbach & Schmitt 1994). Smooth Cayenne fruits do not show any external symptoms, therefore the disease is undetectable. However, the Queen group may produce fruitlets which fail to colour, a condition often referred to as 'green eye'.

A global analysis of the data showed that average ascorbic acid content in fruits at harvest is negatively linked with the percentage fruits affected with FCR (*P. funiculosum*). The nutritional status of the plants, especially low levels of calcium and magnesium, and/or high levels of nitrogen and climatic conditions before harvest are significant factors that favour the development of the disease (Marie *et al*. 2000).

### *Control*

Fungicides have not been effective except when applied directly into the opening of the terminal leaves that is created by the emerging inflorescence. No control measures for fruitlet core rot caused by *F. guttiforme* have been developed (Rohrbach & Schmitt 2003). Miticide sprays help disease control. Integrated control with the pink pineapple mealybug, *D. brevipes*, the pineapple fruit mite, *S. ananas* and a fungicide application programme, from one week before to 11 weeks after flower induction controls the disease and allows 14 days storage at ambient temperature (Petty *et al*. 2006). The sporadic nature of this disease makes chemical control impractical and uneconomical in Queensland, Australia (Pegg *et al*. 1995).

## Green fruit rot

Green fruit rot is caused by *Phytophthora cinnamomi*. Serious losses generally follow heavy rains when phytophthora root rot has caused plants to lodge (Pegg *et al*. 1995). Green fruit in contact with the soil are liable to be infected. Initially a water-soaked rot develops behind affected fruitlets, with no external symptoms. There is a risk that infected fruit with no visible symptoms will be harvested and sent to the market, where breakdown will become evident. When conditions favour development of the disease, samples of fresh market fruit should be cut and examined carefully for internal rotting. As the disease progresses, a general, water-soaked rot of green fruit with a distinct brown margin develops (Pegg *et al*. 1995).

### *Control*

Green fruit rot is primarily controlled through application of registered fungicides for root and heart rot control.

## Pink disease

Pink disease of pineapple fruit is characterized by the brownish-pink pigmentation of the fruit tissue when heated during canning (Rohrbach & Pfeiffer 1976). The disease may be caused by strains of *Erwinia herbicola*, *Gluconobacter oxydans*, *Acetobacter aceti* and *Pantoea citrea*. Depending on the species and strains involved and the severity of infection, browning symptoms may appear in the fruit flesh before cooking (Rohrbach and Pfeiffer 1976), or a pinkish discolouration and wilted appearance may be detectable in the whole fruit in the field before harvest (Rohrbach 1989). This causes losses to fresh pineapple. Most often affected fruits do not show any external symptoms even when fully ripe. Internally the flesh may be water-soaked or light pink (Plate 7.2) and have an aromatic odour (may smell like cantaloupe melons), but none of these symptoms may be immediately obvious. In some fruit, only one or a few fruitlets may be infected. In highly translucent, low-sugar fruit the entire cylinder can be invaded (Pegg *et al*. 1995). The production of 2,5-diketogluconate by *P. citrea* appears to be responsible for the dark colour characteristic of the pink disease in pineapple (Pujol & Kado 2000). The fruit can be infected by certain strains without producing symptoms, and the discolouration occurs only when the fruit is sterilized, causing problems in the canning industry (Rohrbach & Pfeiffer 1976). The disease is therefore of considerable importance in processing, where great care is needed to ensure that infected tissue does not enter the canned product.

The disease has been encountered in Hawaii, the Philippines, Australia and Mexico (Snowdon 1990). The incidence of pink disease is usually low. Outbreaks in Australia are very infrequent and scattered, often affecting only one or two flushes of fruit on just a few properties. Occasional economically significant epidemics have been reported in Hawaii and Taiwan from February to April and in the Philippines from August to September (Hine 1976; Rohrbach & Schmitt 1994).

The bacteria enter through the open flowers during cool weather. They are carried to the flowers by nectar feeding insects (Pegg *et al*. 1995). Nectar is probably an energy source for the bacteria. Once inside the flower, they remain latent in the nectary gland or stylar canal and locule until the fruit matures, sugar concentrations increase and translucence occurs (Rohrbach and Schmitt 1994). Drought before flowering, followed by rainfall during flowering, increases disease incidence.

The bacteria are thought to be part of a group of organisms that habitually live on the surface of the pineapple plant, and which are carried by insects and mites to the open flowers from infected rotting fruit. High temperatures kill the bacteria (Pegg *et al*. 1995). The disease appears to be limited to pineapple production areas where fruit develops under cooler conditions since the disease rarely occurs in the lowland tropics. Pink disease bacteria cannot survive fruit temperatures greater than 38°C. Thus pink disease only occurs when flowering occurs during cool weather or a rainy season (around 18°C) and fruit mature during periods when air temperatures do not exceed 29°C (Rohrbach 1989).

### *Control*

Controlling the vectors with insecticides is the primary means of managing pink disease. Applications, starting at the red-bud stage and followed by three additional applications at 5-day intervals (throughout flowering), have resulted in the highest level of control. The disease has been controlled in the Philippines by applying insecticides during flowering (Kontaxis 1978). Susceptibility to the disease can be reduced by the use of potash fertilizer. Cultivars and hybrids vary from highly resistant to very susceptible. Growing of relatively resistant groups such as Smooth Cayenne, provides control of the disease (Rohrbach & Schmitt 1994). Control is not warranted in Queensland, Australia (Pegg *et al*. 1995).

## Marbling

Strains of the bacteria, *Acetobacter peroxydans*, *Acetobacter* sp. and *Erwinia herbicola* var. ananas are the causative organisms of this disease (Pegg *et al*. 1995).

Though the disease occurs in all pineapple growing countries, it is serious only in countries where pineapples are produced under lowland tropical conditions, where temperatures remain above 21°C (Rohrbach & Schmitt 1994). In Thailand, 5–20% of the slices in canneries are marbled, and high incidences in October and November can even stop canning operations. In Hawaii, the highest levels of marbling occur in April and May (Rohrbach & Schmitt 1994).

Infection usually occurs through the open flower, but may also occur through fruit surface growth cracks during the latter stages of fruit development. Bacteria may be vectored to the flowers by insects. Application of surfactants prior to and during flowering significantly increases disease in Hawaii, indicating that the bacteria are ubiquitous on the plant. The bacteria remain quiescent in the flower and developing fruit until approximately one month before fruit maturity. Low fruit acid and sugars are associated with high levels of the disease (Rohrbach & Schmitt 1994).

The most common symptom is a yellowish to reddish brown to very dark, dull brown discolouration of fruit tissue internally (Plate 7.3). Infected tissues generally become hardened, granular, brittle and speckled with colour variations with a woody consistency. External symptoms are not seen in the affected fruit, however, severely infected fruit may be identified by a ‘woody’ sound when tapped (Rohrbach & Schmitt 1994). The disease may affect multiple fruitlets or the entire fruit, but occasionally only single fruitlets are involved. Frequently, the speckled appearance will occur in vascular tissue to the core of the fruit. Symptoms develop during the last month of fruit maturation (Rohrbach and Schmitt 1994).

Marbling disease is similar to pink disease but is characterized by a brown granular appearance and consistency of infected fruit tissue without sterilization. In contrast to pink disease, marbling occurs when fruit are initiated, flower, and mature under warm conditions (>21–27°C). While moisture does not appear to be critical for infection, disease is enhanced with rainfall during flowering and when fruit matures under dry hot conditions followed by rainfall during the last 6–8 weeks of development (Rohrbach 1989).

### *Control*

No practical control measures are known. Affected fruit having clearly visible symptoms at harvest are readily eliminated during processing (Pegg *et al*. 1995). Processing costs can be reduced by excluding diseased fruit from the cannery operation. Infected fruit can he detected by examining the external appearance and by testing fruit firmness. Differences in cultivar susceptibility have also been noted; Smooth Cayenne is moderately resistant (Rohrbach & Schmitt 1994).

## Yeasty rot

Several fungi in the genus *Saccharomyces* cause yeasty rot. The disease is widespread and associated with ripe fruits, and observed mainly during spring in overripe or damaged fruit (Pegg *et al*. 1995). In spring, rapid changes in fruit growth resulting from the shift from cold, dry to warm, wet

weather can cause basal cracking between fruitlets. Fruit affected by even minor frost damage are prone to cracking as they ripen in spring. Juice weeping from wounds is immediately invaded by yeasts, and these fruit are severely damaged or destroyed as they ripen. The disease may occur in the plantation or as a post-harvest problem (Pegg *et al*. 1995).

Yeasts are among the most common organisms found in nature. In damaged and overripe fruit, and in fruit with interfruitlet cracking already present, yeasts start growing and dividing or new yeasts invade (Paull 1997). In warm temperature, they infect and grow in sugar solutions causing fermentation (conversion of sugar to alcohol), releasing carbon dioxide gas. Early symptoms of yeast rot include the appearance of bubbles of gas and juice through cracks or points of injury where infection occurs (Pegg *et al*. 1995). The skin turns brown and leathery (Paull 1997). With the leakage of juice, the fruit becomes spongy. Internally, the decaying flesh is bright yellow with large gas cavities. Finally, the shell is left surrounding a mass of spongy fibrous tissue (Pegg *et al*. 1995). Some yeasts do not produce gas but cause a glassy spoilage with a distinctive aroma (Snowdon 1990).

### *Control*

Fruit that will ripen in spring in frost-prone areas must be protected against damage, by covering young, developing fruit with paper bags (Pegg *et al*. 1995). Fruits should also be protected from sunburn and mechanical damage. Fruit showing even minor interfruitlet cracking should not be consigned to the market. Any fruit showing fractures between fruitlets should be picked at the earliest stages of fruit maturity to minimize losses from yeasty rot (Pegg *et al*. 1995).

## Internal browning of fruit

Internal browning is a physiological disorder in pineapple also known as black heart and endogenous brown spot (EBS). Pineapple is a chilling sensitive fruit and when the harvested fruit is exposed to low temperature 8–15°C during storage, transport or when the developing fruit is exposed to cool winter periods in the field, development of internal browning occurs (Wills *et al*. 1985). Internal browning is induced in ripening fruit when field temperatures fall below 21°C for several days, followed by a return to warmer temperatures (Teisson 1979; Rohrbach & Paull 1982; Smith & Glennie 1987). In subtropical Queensland, summer crops of Smooth Cayenne produce fruits with excellent characteristics, but fruit grown in the winter months (May–September) are particularly susceptible to the internal browning disorder (Teisson 1979).

The characteristic symptoms of this disorder are initially the formation of translucent, water-soaked spots at the base of the fruitlets and these areas become brown at later stages (Abdullah *et al*. 1985; Akamine 1976). The individual spots may enlarge and coalesce to form a dark brown to black colour tissue mass along the core in the entire centre of the fruit. The browning may expand both inwards and outwards from the periphery of the core, more into the flesh, as brown water-soaked areas. The pattern and extent of development of internal browning symptoms may vary with the variety. In cultivar ‘Mauritius’ (Queen) (Plate 7.4) the initial symptoms appear within 7–10 days of cold storage at 10°C and the intensity increases on prolonged cold storage (Plate 7.5). The symptoms could be seen in both core and flesh tissue covering over 75% of the fruit stored for 3 weeks. The internal browning symptoms develop rather slowly in certain varieties such as ‘Kew’ (Smooth Cayenne) (Plate 7.4) where initial symptoms appear following 2 weeks of storage at 10°C (Plate 7.5) and the browning is mostly confined to the flesh tissue as isolated patches. Internal browning symptoms are observed in the flesh of Smooth Cayenne fruit chilled at 10°C and the symptoms were progressively less at lower temperatures, with no symptoms observed in the flesh of fruit stored at 0°C (Stewart *et al*. 2002).

Because there are no obvious external symptoms, affected fruit is often not detected until it is sliced after purchase, resulting in considerable customer dissatisfaction (Stewart *et al*. 2002). This also restricts processing and leads to significant wastage during processing of pineapple. The disorder is reported from many pineapple growing regions in the world and several commercial cultivars. In countries like Australia field-induced internal browning is found to be most prevalent (Swete-kelly & Bagshaw 1993).

Internal browning is a result of both cellular damage and enzymatic browning. Pulp tissues of pineapple affected by internal browning leak out greater amount of electrolytes than unaffected tissues (Weerahewa & Adikaram 2005a) and this might be due to alteration of membrane structure.

The disorder is induced by chilling and results in browning of the flesh and core of the fruit due to the oxidation of phenolic substances by the enzyme polyphenol oxidase (PPO) (Stewart *et al*. 2001), a copper containing enzyme which catalyses conversion of *o*-dihydroxyphenols to *o*-quinones (Van Lelyveld & De Bruynm 1977). The browning of most plant tissues is a result of oxidation of colourless monophenolic compounds first to *o*-dihydroxy phenol and *o*-dihydroxy phenolic substances to *o*-quinones by polyphenol oxidase (Mayer & Harel 1979; Walker & Ferrar 1998). The *o*-quinones react with amino acids,

proteins and other phenolic compounds to form complex brown polymers. The brown or black colour of the affected tissue is due to the formation of these compounds. The phenolic substrates for PPO are located in the vacuole, and therefore the enzymic browning reaction only occurs when sub-cellular compartmentalization is altered. The *p*-coumaric acid, ferulic acid, caffeic acid and sinapic acid are identified as the major phenolic compounds in pineapple (Van Lelyveld & De Bruynm 1977) and it has been confirmed that the concentration of coumaric acid and sinapic acid and the activity of polyphenol oxidase are higher in the tissue undergoing internal browning (Teisson *et al*. 1979). In fruit affected by the chill-induced internal browning disorder, PPO activity was tenfold higher than in unaffected fruit, and there was a direct correlation between PPO activity and the severity of internal browning symptoms (Stewart *et al*. 2001). Southern blot analysis suggested the presence of at least four PPO genes in pineapple. The chilling induces the *de novo* synthesis of PPO in Smooth Cayenne pineapples (Stewart *et al*. 2001).

PPO activity of pineapple cv. Mauritius (Queen) under prolonged cold (10°C) storage increases progressively in parallel to the increase in the intensity of internal browning. The increase of PPO activity coincided with the initiation of internal browning. The level of PPO activity in relatively resistant cultivars (e.g. 'Kew') was low throughout the period of cold storage (Weerahewa & Adikaram 2005a). An increase of PPO activity in pineapple fruit Smooth Cayenne was related to the incidence of internal browning symptoms both temporally and spatially (Zhou *et al*. 2003). The effect of maturity on susceptibility to internal browning was highly correlated to the response of PPO activity to chilling.

Weerahewa and Adikaram (2005a) studied physico-chemical and biochemical differences between two varieties having varied responses to chilling injury by internal browning development. The study revealed greater increase in rate of respiration, higher total soluble solids, build-up of acidity and higher PPO and peroxidase activity in the more susceptible variety 'Mauritius' (Queen) during cold storage than 'Kew' (Smooth Cayenne). Graham *et al*. (1998), however, found that peroxidase activity remained unaltered during the induction of internal browning while PPO activity increased tenfold.

Numerous factors affect the development of internal browning disorder in pineapple. Fruits harvested at more mature stage are more susceptible to chilling injury and internal browning than less mature fruit (Wang 1982; Weerahewa & Adikaram 2005a). Fruit size (Hoffman & Smith 1993), crown size and ascorbic acid content (Teisson *et al*. 1979) affect the expression of internal browning. Relative to Smooth Cayenne Queensland clone13, the intergroup hybrids 73–50 and 53–116 have been found to show some level of field resistance to internal browning after storage at 10°C for 14 days followed by 20°C for 8 days. The ascorbic acid levels were not consistent with relative resistance suggesting that factors other than ascorbic acid play a role in resistance to internal browning (Sanewski & Giles 1997).

### *Control*

Field application of certain fertilizers has been found effective in reducing internal browning. Application of $CaCl_2$ and fused magnesium phosphate (Selvarajah *et al*. 1998) to soil reduced internal browning of harvested pineapple. Combined treatment of pre-harvest $CaCl_2$ fruit spray (1.3 g per fruit) followed by post-harvest wax treatment showed 80% good fruit with no black heart symptoms after low-temperature storage at 10°C for 17 days followed by 2 days at ambient temperature of 28 ± 2°C. Both core and flesh regions of pineapples subjected to pre-harvest fruit spray treatment showed higher total calcium levels compared to controls (Hewajulige *et al*. 2006). There is a correlation between the calcium content in the pineapple tissue and incidence of internal browning (Hewajulige *et al*. 2003). The calcium concentrations in the fruit were significantly higher in variety Kew (Smooth Cayenne) than Mauritius (Queen) pineapple. The difference corresponded to a significantly lower incidence of chilling injury in the former. The calcium concentration in both cultivars was significantly higher in the shell than the core. Internal browning symptoms are associated with the core and the flesh adjacent to the core, where the calcium content is low (Hewajulige *et al*. 2003).

Harvesting fruits at immature, green stage tends to limit the development of internal browning, but this fruit is generally of poorer eating quality than fully ripe fruit. While the above methods have been used with some success, they are not completely effective in reducing the incidence of the disorder (Stewart *et al*. 2002). Fruits containing high ascorbic acid developed only slight browning, but fruits containing low ascorbic acid showed severe browning.

Post-harvest attempts to control internal browning include waxing of fruit to restrict the availability of oxygen (Rohrbach & Paull 1982), storing fruit in modified atmospheres (Abdullah *et al*. 1985) and rapid marketing strategies designed to deliver the fruit to the consumer before browning symptoms become evident (Swete-kelly & Bagshaw 1993). Waxing the fruit and the crown of fresh pineapple with a 20% v/v paraffin–polyethylene:water mixture reduced the incidence and severity of internal browning (Rohrbach & Paull 1982).

Post-harvest heat treatment, in the form of a hot water dip, induced pineapple cv. Mauritius fruit tolerance to cold injury and, in turn, reduced internal browning during prolonged low-temperature storage (Weerahewa & Adikaram 2005b). Several temperature–time combinations were found effective, but the best was 38°C for 60 minutes. The results indicated that an internal tissue temperature of 38°C is a prerequisite for the induction of cold tolerance. Heat treatment, however, slowed down fruit ripening and increased water loss. Wrapping heat-treated fruits in polythene exposing only the crown, prior to cold storage reduced internal browning further and also the water loss giving the fruit a better appearance (Weerahewa & Adikaram 2005b). Akamine (1976) also found that exposure of fruits to hot air at 37.2°C and 33% humidity reduced internal browning. Heat treatment after refrigeration was found more effective than before refrigeration.

More recently, treatment with 1-methylcyclopropane (1-MCP), an inhibitor of the ethylene receptor, has been reported to effectively control internal browning of pineapple (Selvarajah *et al*. 2001). 1-MCP has delayed the decline of ascorbic acid and acted as an inhibitor of ethylene receptors in pineapple (Selvarajah *et al*. 2001).

The use of breeding to develop resistant cultivars of pineapple provides an attractive alternative to the costly and often inefficient post-harvest treatments used to control the disorder. The major challenge facing the pineapple breeders is to produce cultivars that not only show resistance to the disorder, but also retain desirable agronomic and eating quality characteristics (Stewart *et al*. 2002).

Control of internal browning (blackheart) was attempted by inhibiting the expression of PPO in genetically engineered pineapple plants (Graham *et al*. 1998). A transformation technique for the introduction of transgenes to control blackheart by particle bombardment has been developed for Smooth Cayenne pineapple. Leaf callus cultures capable of high frequency organogenesis with a short regeneration time were used as explant material (Ko *et al*. 2006).

**Fruit translucency**

Translucence or water-soaking of the flesh is a problem in fresh fruit market. The condition occurs before fruit harvest and does not increase after harvest (Rohrbach & Paull 1982). Chen and Paull (2001) found that pineapple fruit translucency begins to appear 2–4 weeks before harvest. The basal flesh is the first to show translucence, and in severe cases the whole fruit is affected. The translucence has been regarded as being due to premature ripening (Soler 1994) of the flesh, irrespective of skin colour (Py *et al*. 1987). The condition appears more often in large fruit (Teisson 1979). The condition in Hawaii has been associated with cultivar, high nitrogen, large vigorous plants, winter- and spring-ripened fruit, treatment with fruit enlarging growth regulators, irrigation rate and planting density (Paull & Reyes 1996).

Affected fruit is more susceptible to pre-harvest sunburn (Keetch 1977) and more prone to mechanical damage after harvest, and the fruit has poor flavour due to low acids and low esters (Bowden 1969). Impact damage of translucent fruit is characterized by leaking of juice from the damaged area (Paull & Reyes 1996). Leakage could lead to bacterial and yeast development and may also play a role in some fungal diseases of harvested fruit (Paull & Reyes 1996).

Detection of pineapple fruit translucency using X-ray images was investigated. Ninety-two pineapples were imaged with X-ray and after imaging, each pineapple was cut open to determine the true level of the disorder and rated on a scale from 1 (no translucency) to 5 (extremely translucent). There was a high correlation ($R^{-2} = 0.96$) between the likelihood of a sample being rated as good and the actual level of translucency observed. Samples with no translucency were correctly identified 95% of the time, while those with extreme translucency were correctly identified 86% of the time. The results indicate that X-ray imaging is a useful nondestructive method for industry for selecting pineapples that are most likely to be free of translucency or extremely translucent (Haff *et al*. 2006).

Crown removal either at an early or late stage of fruit development did not have any significant effect on fruit weight or translucency occurrence (Chen & Paull 2001). Waxing does not influence the increase of translucency of less mature fruit after harvest, but did reduce the severity in more mature fruit stored at 8°C for 2–3 weeks (Rohrbach & Paull 1982).

**Knobbiness**

Knobbiness, a formation of knobs in the base of fruits, is a result of genetic off type (Soler 1992). This is not a very common disorder, and observed occasionally in a small number of plants. However, if the plants are used for propagation, the incidence of knobby fruit will increase (Pegg *et al*. 1995). Therefore culling of the crowns of these fruits is recommended. Knobs usually occur on the base of fruit in off types. These fruits are not marketed, since trimming generally breaks the fruit skin and allows rots to develop (Pegg *et al*. 1995).

Plants showing knobbiness should be culled from the field or separated from planting material. Knobby fruit

should not be sent to the fresh market, as they are unattractive and also prone to disease, due to trimming. Knobby fruits are best used for the canning industry (Pegg *et al*. 1995).

**Multiple crowns**

Crown abnormalities occur frequently in pineapple. The condition, multiple crowns, is a common condition of pineapple, caused by a genetic aberration. When two or more crowns develop on each fruit, there is a tendency for fruit to flatten and fruit cores to thicken (Pegg *et al*. 1995).

***Control***

Careful selection of planting material is essential for its control. Plants showing this disorder should be culled from the field or separated from planting material. Multiple crowns need to be trimmed if fruit are destined for the fresh market. However, the appearance of the trimmed top reduces the visual appeal of the fruit. The preferred (but sometimes impractical) option is to send only single crown fruit to the fresh market (Pegg *et al*. 1995).

**Prickly eye**

Prickly eye, a malformation, is caused by cold weather during flowering and during the early stages of fruit development (Pegg *et al*. 1995). Malformations, or pineapple fruit with pronounced eyes or fruitlets, are normally not acceptable in fancy grades of fruit, and the thicker skin results in lower flesh recovery (Lim 1985).

The condition occurs when cold weather prevails during flowering and early fruit development. Fruit harvested in southern and central Queensland, Australia, during the months of November and December often show typical symptoms of prickly eye. Fruit harvested in north Queensland rarely show this problem and command a fresh market price premium at this time. The north Queensland crop harvest schedule is aimed at taking advantage of this (Pegg *et al*. 1995).

Pronounced fruitlets or 'eyes' appear instead of being flat. Each eye is quite conical. Affected fruit are reported to be more susceptible to fruit blemish. Internally the flesh is not as juicy as normal and prominent cavities appear in the fruitlets. Fruit size is smaller than normal. Apart from the skin symptom, the fruit is quite edible. When processed, affected fruit have a low flesh recovery, as a thick skin slice is required to remove the defect (Pegg *et al*. 1995).

Some Spanish varieties are susceptible to broken core, in which the central core has a transverse break leading to the upper part of the fruit ripening ahead of the bottom resulting in another form of malformation of pineapple (Lim 1985).

***Control***

Planting should be planned to avoid cold weather during flowering and early fruit development. In southern and central Queensland, fruits should not be induced in late summer (March–April). If fruits are induced during this period, prickly eye can be reduced by covering the fruit with paper bags. However, this must be completed as soon as the flowers appear and before the petals open (Pegg *et al*. 1995).

**Sunburn**

Sunburn, also called 'sunscald', is caused by high fruit temperatures resulting in injury and death of fruit tissue (Pegg *et al*. 1995). Sunburn can cause major losses, especially when fruit is maturing during hot months (> 35°C) of the year (Keetch & Balldorf 1979), when the fruit is not shaded by leaves and especially in ratoon crops, and is more prevalent in the outer rows and when fruit is lodged (Nakasone & Paull 1998). Ratoon fruit are especially susceptible. Much of this fruit falls over (lodged), exposing its sides to the full force of the sun. Plant crop is less susceptible, as it is generally standing upright. However, fruit shoulders can still be damaged during very hot weather, especially on western slopes and around the edge of the field (Pegg *et al*. 1995). The dark green skin of the fruit contributes to the problem, as it absorbs a lot of heat from the sun. Sunburn damage is much more likely to occur on calm days (Pegg *et al*. 1995). Affected fruits soon rot and become infested with pests.

Mild fruit sunburn simply shows as a bleached yellow area on the exposed side of the fruit, which turns pale grey and brown, with damage to the flesh underneath. More severe injury causes the development of a sunken, spongy, brown skin lesion in the centre of the bleached area. Interfruitlet cracks in the brown area allow drying out of fruit tissue, and entry of disease causing organisms. Tissue underneath this area could be extensively damaged. These damaged areas are more susceptible to disease organisms, particularly yeasts and bacteria (Nakasone & Paull 1998).

***Control***

Adjusting the ratoon crop cycle to ensure that the fruits do not mature during hot summer months will provide some control. Treating cannery fruit maturing during the hot months with a reflective, clay-based sun screen is also recommended. The unattractive residue of these treatments precludes its use on fresh market pineapples. Some fresh fruit consumers are aware of its nonharmful nature, but treated fruit is generally in poor demand (Pegg *et al*. 1995). Care should be taken to control lodging or leaning. Dry grass, straw or brown paper sleeves may be placed over

fruits maturing to prevent sunburn. The effected fruits must be cut as soon as noticed and safely disposed of in order to prevent contamination of other fruits.

### Boiled fruit

Hot conditions can also cause premature flesh translucency in developing fruit, commonly referred to as 'boiled fruit'. Boiled fruit is soft and very juicy, with an insipid flavour. Boiled fruits are particularly prevalent among fruit that have developed during winter, and then are subjected to very hot spring conditions during maturation (Pegg *et al*. 1995).

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# 8
# Avocado

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## INTRODUCTION

Avocado is a dicotyledonous plant from the Ranales order and the Lauraceae family. It was classified as *Persea gratissima* by Gaertner, and *Persea americana* by Miller. *P. americana* developed subspecies due to geographical isolation that finally originated different botanical types. The avocado tree (*Persea americana* Mill.) belongs to the family *Lauraceae* and is one of the few commercially significant members of the genus *Persea*. The fruit is called 'Ahuacatl' by the Aztecs and from there derived the term 'avocado', 'aguacate' (in Spanish), 'avocat' (in French) and 'abacate' (in Portuguese). The Aztecs considered avocados an aphrodisiac and called it *huacatl*, meaning testicles, referring to the fruit's shape and the way they hang from the tree. The fruit is also called 'palta' in Chile, Ecuador and Peru, and also has been referred to as alligator pear, vegetable butter, butter pear and midshipman's butter.

The avocado originated in Central America and southern Mexico. Based on archaeological evidence found in Tehuacán, Puebla (Mexico), it is believed that it appeared approximately 12 000 years ago. It has been determined that the centre of origin of this fruit is the central part of Mexico, passing through Guatemala to Central America. In this region, the natural gene stock can be found, which can be useful to the biotechnological improvement of the species. As evidence for this theory, primitive avocado trees have been found in the 'Oriental Sierra Madre' along from the State of Nuevo León (Mexico) to Costa Rica. From this region avocado dispersed to the south-eastern part of the United States, the West Indies, to a large part of South America (Colombia, Venezuela, Brazil, Ecuador, Peru, Bolivia and Chile) (Rodríguez Suppo 1992).

The avocado is botanically classified into three races: (1) West Indian (WI), *Persea americana* Mill. var. *americana* (*P. gratissima* Gaertn.), tropical with large variably shaped fruit and lower oil content; (2) Mexican (MX), *P. americana* Mill. var. *drymifolia* Blake (*P. drymifolia* Schlecht.& Cham.), semi-tropical with smaller elongated thin-skinned fruit and higher oil content; and (3) Guatemalan (G), *P. nubigena* var. *guatemalensis* L. Wms., subtropical with mostly round thick-skinned fruit and intermediate oil content (Bergh & Lahav 1996). The Mexican race, which originated in the mountains of México and Central America, is characterized by relatively small fruit, ranging from 75 to 300 g, with a thin, smooth skin. Fruit of the Guatemalan race are native to the highlands of Central America and are not as resistant to low temperatures as those of the Mexican race, characterized by large fruit, averaging 500–600 g, and thick brittle skin. The West Indian race is native to the lowlands of Central America and northern South America, characterized by intermediate fruit size, with smooth, leathery and sometimes glossy skin. There are differences in fruit maturity and oil content between the different races (Biale & Yo 1971). Generally, West Indian avocado trees are the most cold sensitive and are damaged by temperatures below 1.2°C (Joubert & Bredell 1982). While racial ancestry was identified as the most important factor influencing susceptibility to cold, other factors such as tree size, age and vigour, crop load, and cultural practices were also shown to

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influence cold damage (Malo *et al*. 1977). Mature trees of the Mexican race are capable of withstanding temperatures as low as –4°C without damage (Joubert & Bredell 1982). Mexican cultivars are well adapted to cool climates of the tropics and subtropics and are the most cold tolerant of the three races. The West Indian cultivars are best adapted to lowland tropical conditions of high temperature and humidity. The Guatemalan cultivars are intermediate between these two cultivars with respect to climatic adaptation. Mexican race fruit have mostly green skin (the natural seedling 'criollo' is black skin), the pulp is green in colour with very high oil content (up to 30% in weight), while fruit of the Guatemalan race is characterized by thick peel, high oil content and nutty flavour pulp (Storey 1988).

Systematic studies have classified more than 500 varieties; however, many are not commercial, because of productivity problems (production time, amount of fruit), quality (protein and fat content), and commercial handling problems (such as resistance to transportation). Many of the commercial cultivars are hybrids of the three races. There is great variability in fruit traits not only between races but also between cultivars within a race. One of the most distinct differences between cultivars is the peel colour when ripe. The peel of some cultivars changes from green to black or purple with increasing maturity or ripening. 'Hass', a G-MX hybrid, is a black-skinned (when ripe), ovate cultivar whose fruit weighs 140 to 300 gm (Plate 8.1). 'Hass' accounts for about 75% of the production in Mexico and California, and is also important in other countries. In Mexico, 'Hass' is harvested all year but the main season is from October to May. The main Florida cultivars (West Indian and Guatemalan races and hybrids) are 'Simmonds', 'Nadir', 'Booth 8', 'Choquette' and 'Lula'. Some other commercial cultivars include 'Bacon', 'Fuerte', 'Gwen', 'Lamb Hass', 'Pinkerton', 'Reed' and 'Zutano'. With the exception of 'Reed,' which is believed to be entirely of the G race, the other cultivars are considered to be primarily G-MX hybrids. 'Sharwil' is a MX-G cross and represents more than 57% of the commercial acreage in Hawaii, its green-skinned fruit weigh 220 to 560 gm, matures in winter and spring, has small seeds and greenish-yellow flesh with a rich, nutty flavour.

About 349 000 ha are dedicated to the production of avocado in about 60 countries, producing more than 2.6 million tons annually, with average yield of about 7.40 tons per ha. Mexico is the leading producer, accounting for about 36% of the total production, with other important producing countries including the United States (8%), Colombia (5.5%), Indonesia (5%), Dominican Republic (4.3%), Chile (4.2%), Brazil (3.5%) and Israel (3.3%).

**Table 8.1** Consumption of Avocado in Different Countries in 1998–2000.

| Ranking | Volume (ton) | Country |
|---|---|---|
| 1 | 815 749 | Mexico |
| 2 | 228 310 | United States |
| 3 | 128 447 | Indonesia |
| 4 | 127 697 | Colombia |
| 5 | 85 598 | Brazil |
| 6 | 79 298 | Dominican Republic |
| 7 | 79 020 | France |
| 8 | 76 355 | Peru |
| 9 | 63 667 | China |
| 10 | 49 000 | Cameroon |
| 11 | 45 000 | Haiti |
| 12 | 39 145 | Venezuela |
| 13 | 32 662 | Chile |
| 14 | 32 446 | Israel |
| 15 | 32 079 | South Africa |
| | 2 288 208 | World Total |

Source: FAOSTAT (2002) and Tubello and Piccolo (2001).

**Table 8.2** Consumption of Avocado in the European Union in 1999.

| Country | Kg/person/ year | Country | kg/habitant/ year |
|---|---|---|---|
| Austria | 0.160 | Ireland | 0.194 |
| Bel-Lux | 0.899 | Italy | 0.033 |
| Denmark | 0.580 | Netherlands | 1.128 |
| Finland | 0.150 | Portugal | 0.035 |
| France | 1.420 | Spain | 0.596 |
| Germany | 0.157 | Sweden | 0.610 |
| Greece | 0.228 | United Kingdom | 0.315 |

Source: Tubello and Piccolo (2001).

The avocado fruit can be round, pear shaped, or oblong, and the skin of the fruit may vary in texture and colour. The skin may be pliable to woody, smooth to rough, and green-yellow, reddish-purple, purple or black in colour. The flesh of the fruit is greenish yellow to bright yellow when ripe and buttery in consistency, but inferior varieties may be fibrous. The avocado fruit has one large seed which makes up to 10–25% of the fruit weight. The fruit of different avocado varieties vary in moisture and oil content, from less than 5% to more than 30% oil.

Avocado consumption (Tables 8.1 and 8.2) is concentrated in the major producing areas. US per capita consumption

of fresh avocados increased from 0.18 kg in 1970 to 0.68–1.0 kg in the late 1980s, which is equivalent to nectarines and comparable to pineapples (0.77 kg), but considerably lower than bananas (11 kg), apples (8.7 kg) and oranges (6.6 kg). Avocado is consumed as a fresh fruit, besides its use in the oil, cosmetic, soap, and shampoo industries. Unlike many fruits that typically have a sweet or acidic taste, avocados have a smooth, buttery consistency and a rich flavour. A popular use is as a salad fruit, but avocados are also processed into guacamole and can be used in sandwich spreads. Avocado paste with flavour extracts and skimmed milk can also be used to make ice cream. Oil extracted from avocados can be used for cooking and preparation of salads, sauces and marinades. Avocado oil also can be used for skin care products such as sunscreen lotions, cleansing creams and moisturizers, or for hair conditioners and makeup bases. Several more uses have been added around the world. For example, in Mexico and Brazil, it is added to ice creams and sorbets; in Japan it is eaten in sushi rolls; in Cuba the pulp is mixed with capers, green olives, lemon juice and olive oil to make a sauce which is served with steamed fish; and in Nicaragua it is stuffed with cheese, fried and baked. In other countries such as Taiwan, it is eaten with milk and sugar; in Korea it is mixed with milk and used as a facial cream and body lotion; in Indonesia it is mixed with coffee, rum and milk to make a refreshing beverage; in the Caribbean it is mixed with salt, garlic, and coconut and served as an entrée; in the Philippines the avocado purée is mixed with sugar and milk to make a beverage which is served as dessert (Yahia 2003).

## FRUIT DEVELOPMENT

The pericarp, which is the fruit tissue proper excluding the seed, comprises the rind (exocarp), the fleshy edible portion (mesocarp) and a thin layer next to the seed coat (endocarp) (Biale & Young 1971). The large seed of the avocado consists of two fleshy cotyledons, plumule, hypocotyl, radicle and two seed coats adhering to each other. The endosperm disappears in the course of development. The cotyledons consist of parenchyma tissue interspersed with idioblasts and contain starch as the main storage material (Biale & Young 1971). The avocado fruit is unusual in that cell division in the mesocarp is not restricted to the initial period of growth but also continues during fruit development and even occurs in the mature fruit attached to the tree (Van Den Dool & Wolstenholme 1983; Lewis 1978). In some cases, cell enlargement stops when the fruit reaches about 50% of its size at full maturity, while cell division accounts for the continued growth (Cummings & Schroeder 1942).

### Hormonal control of fruit development

Two important endogenous factors affecting the physiology of fruit growth include hormones and nutrients (Bower & Cutting 1988; Cutting *et al*. 1986b, 1986c). At all stages of fruit development, it was observed that the mesocarp contained lower levels of the auxin, indole acetic acid (IAA) than the seed and testa (Cutting et al., 1985). Auxin increased the skin strength of the fruit and regulated endosperm development. There is strong evidence that ethylene is involved in the abscission of young avocado fruitlets. Davenport and Manners (1982) observed that an increase in ethylene did not occur in fruit that failed to abscise. The prevention of the ethylene peak and associated fruitlet abscission could, therefore, be under the control of other plant growth substances such as cytokinins, which showed a strong peak during this period. Blumenfeld and Gazit (1970) found high levels of cytokinins in both the cotyledons and testa of avocado, which decreased with development. The high levels of cytokinin activity in the young seed served to increase the sink strength of the fruit for nutrients and other metabolites. The high cytokinin levels detected in young fruitlets may actively assist in increasing the sink strength of the fruit, and therefore promote fruit growth (Bower & Cutting 1988). Stress-induced increases in abscisic acid (ABA) caused an irreversible loss in fruit growth, and the physiological mechanism associated with ABA-induced retardation of 'Hass' avocado fruit growth appeared to be inextricably linked to a decline in cytokinin content and included: diminution of mesocarp and seed coat plasmodesmatal branching, gating of mesocarp and seed coat plasmodesmatal by deposition of electron dense material in the neck region, abolishment of the electrochemical gradient between mesocarp and seed coat parenchyma, and arrest of cell-to-cell chemical communication (Moore-Gordon *et al*. 1998). Adato and Gazit (1976) were unable to elicit initiation of fruit ripening, except with a very high dose of IAA. IAA decreases to low levels in all parts of the fruit with the onset of maturity (Wolstenholme *et al*. 1985). A direct role of auxins in the initiation and development of the ripening response is not clear. Gazit and Blumenfeld (1970a) showed low levels of cytokinin activity in the mesocarp by the time the fruit was mature. Cutting *et al*. (1986a) were unable to confirm the role of cytokinins in avocado fruit ripening, although there were indications that the interaction with ABA may occur, as suggested by Letham and Palni (1983). Lieberman *et al*. (1977) found that exogenous addition of gibberellins had little effect on avocado ripening. They showed an increase in ethylene and ripening following application of ABA before the

climacteric peak, but depressed evolution if applied after the peak, concluding that ABA accelerates ageing. Gazit and Blumenfeld (1972) reported little change in ABA level during fruit development, but once ripening started, a considerable increase occurred. They have also reported that the increase in ABA closely followed the ethylene curve with peaks at the same time. Bower *et al*. (1986) found that the free ABA content in ripening avocados increased with fruit softening, with the peak at approximately the same degree of softness at which the maximum ethylene peak occurred, and declined thereafter. Factors other than water stress can also affect both ABA levels and ripening rate.

**Effect of minerals on fruit development**

Yields of avocado on a tree-by-tree basis are extremely variable (Jones *et al*. 1957), which could be due to the alternate bearing nature of the avocado and its susceptibility to root rot. Nitrogen, phosphorus and potassium are largely mobilized from the leaf prior to leaf abscission. In contrast calcium, magnesium and iron are not mobilized from the leaf and it is estimated that up to 60% of the total tree calcium can be lost each year (Cameron *et al*. 1952). Addition of phosphorus and potassium in a 3-year trial did not significantly increase yield (Lynch & Goldweber 1956). In contrast nitrogen, and calcium levels markedly affect yield, fruit size and post-harvest quality, and it appears that there is considerable interaction between these two elements in controlling vegetative reproductive balance in the avocado tree (Bower & Cutting 1988). Witney *et al*. (1986) found that 'Fuerte' and 'Hass' fruit from non vigorous trees accumulated more calcium during development than the fruit from vigorous trees. Calcium is known to affect fruit ripening to a considerable extent (Tingwa & Young, 1974). Infiltration of calcium can delay the overall softening process during ripening, reducing the ethylene peak and respiratory rise (Davenport 1984; Wills & Tirmanzi 1982). Tingwa and Young (1974) found that avocados with higher endogenous levels of calcium had slower rates of ripening.

**Fruit softening during ripening**

During avocado fruit ripening, it was found that the middle lamella of cell walls begins to disappear, with pectin removal from the matrix of the cell walls. Later, a loss of organization and density in the walls occurs and during the post climacteric the walls almost completely disappeared (Platt-Aloia *et al*. 1980; Platt-Aloia & Thomson 1981). Scott *et al*. (1963) reported cellulose as the major constituent of avocado cell walls. Huber (1983) considers the avocado to be the fruit most representative of those in which cellulases are of primary importance. Pesis *et al*. (1978) found a rapid increase in this enzyme accompanying softening, which was closely correlated with the respiratory climacteric and ethylene. Application of ethylene in the air surrounding fruit for 48 hours after harvest also caused an increase in cellulase activity, which led Pesis *et al*. (1978) to conclude that ethylene plays a role in controlling cellulase activity. Tucker and Laties (1984) showed the possibility of ethylene causing gene transcription of cellulase. The early stages of softening in the avocado appear to be due to cellulase, controlled at least in part by ethylene, with polygalacturonase responsible for final softening (Bower & Cutting 1988).

**Respiration and ethylene production**

The avocado is a climacteric fruit, with a marked rise in respiration rate at the onset of ripening, followed by a decline (Zauberman & Schffman-Nadel 1972). Respiration rate of avocado fruit is relatively high compared to many other fruits; about 20 to 50 mg $CO_2$ $kg^{-1}$ $h^{-1}$ at 5°C, 50 to 160 at 10°C, and 80 to 300 at 20°C (Kader & Arpaia 2001). Rates of ethylene production are generally low for unripe avocados, <0.1 µL $kg^{-1}$ $h^{-1}$ at 20°C, but increase rapidly after harvest up to levels >100 µL $kg^{-1}$ $h^{-1}$ at 20°C when fully ripe. Therefore, ripe avocados should not be stored with commodities that are sensitive to ethylene damage. Unripe avocados are sensitive to ethylene, and therefore should not be stored near ripe fruit or other fresh produce that produce more than trace ethylene. Ethylene exposure during storage accelerates ripening/softening and can increase incidence and severity of internal chilling injury and decay. Exogenous applications of ethylene after harvest cause an earlier climacteric with consequent ripening (Eaks 1978). Although, other factors initiate the respiratory rise, alter sensitivity to ethylene, or control its increase, the autocatalytic production of ethylene is of vital importance to normal avocado ripening. Any factors affecting this process could be expected to alter the fruit ripening pattern.

## COMPOSITIONAL CHANGES DURING FRUIT DEVELOPMENT, AND THE NUTRITIONAL AND HEALTH VALUE OF AVOCADO FRUIT

Avocado fruit is a high fat fruit, contains rare sugars of high carbon number and is relatively rich in certain vitamins, dietary fibre, minerals and nitrogenous substances (Tables 8.3, 8.4 and 8.5). It has a high oil content with a wide range (3–30%) and low sugar (about 1%); hence it is recommended as a high energy food for diabetics (Salunkhe &

**Table 8.3** Avocado Fruit Composition.

| Component | Quantity |
|---|---|
| Water (%) | 74.4 |
| Lipids (%) | 20.6 |
| Proteins (%) | 1.8 |
| Fibre (%) | 1.4 |
| Ash (%) | 1.2 |
| Sugars (%) | |
| Glucose | 0.30 |
| Fructose | 0.10 |
| Sucrose | 0.10 |
| Organic acids (%) | |
| Malic acid | 0.32 |
| Citric acid | 0.05 |
| Oxalic acid | 0.03 |
| Vitamins (mg/100g) | |
| Ascorbic acid | 11.0 |
| Thiamine | 0.07 |
| Riboflavin | 0.12 |
| Nicotinic acid | 1.9 |
| Vitamin B6 | 0.62 |
| Folic acid | 0.04 |
| Biotin | 0.006 |
| Carotenoids (mg/100g) | |
| α-carotene | 0.29 |
| β-carotene | 0.03 |
| Criptoxanthin | 0.16 |
| Minerals (mg/100g) | |
| Potassium | 480 |
| Phosphorus | 27.0 |
| Calcium | 14.0 |
| Magnesium | 23.0 |
| Sodium | 2.0 |
| Iron | 0.7 |
| Zinc | 0.5 |

Desai 1984). It is a rich source of potassium; containing 1.6 times as much as bananas. A 100 gm serving has about 177 calories, contains no cholesterol, and has about 17 gm of fat, which is primarily mono-unsaturated type. Oil content is a key part of the sensory quality of the fruit. Oil quality is very similar to that of olive oil with a high proportion of the oil being approximately 75% mono-unsaturated, 15% saturated and 10% polyunsaturated fatty acids. However, there is variation with race, cultivar, growing region and season. The high mono- and poly-unsaturation, and low saturated content makes it a 'healthy' oil in terms of effect on heart disease (Lerman *et al*. 1994). Mono-unsaturated fats in avocados have been shown to reduce blood cholesterol while preserving the level of high-density lipoproteins. In addition, avocado oil contains a range of other health promoting compounds such as chlorophyll, carotenoids, α-tocopherol and ß-sitosterol. The edible portion of the fruit is rich in oleic, palmitic, linoleic and palmitoleic acids, while stearic acid is present only in trace amounts. Changes in fatty acid distribution of the lipids were demonstrated to be associated with fruit development. Linolenic acid remained unchanged throughout the development period, palmitic, palmitoleic and linoleic acids increased slightly while the major change was a large increase in oleic acid. The fatty acid composition of the lipids of avocado fruit and avocado oil differs greatly with cultivar, stage of ripening, anatomical region of the fruit and geographic location (Itoh *et al*. 1975). However, the major fatty acid is always oleic followed by palmitic and linoleic acids, while the fatty acids present in trace amounts are myristic, stearic, linolenic and arachidonic (Gutfinger & Letan 1974; Itoh *et al*. 1975; Tango *et al*. 1972; Mazliak 1971; Swisher 1984). The cuticular wax contains C20 to C27 long-chain fatty acids (Mazliak 1971).

Avocados are rich in vitamin B6 (3.9–6.1 µg/g pyridoxine) and contain lesser amounts of biotin, folic acid, thiamin, riboflavin (Hall *et al*. 1955), calciferol (vitamin D), α-tocopherol (vitamin E) and 2-methyl-1, 4-naphthoquinone (vitamin K) (Kadam & Salunkhe 1995).

**Table 8.4** Nutritional Content (g/100 g) of Some Avocado Varieties Grown in Mexico.

| Variety | Moisture | Ash | Fat | Protein | Carbohydrates | Total fibre |
|---|---|---|---|---|---|---|
| Pellejo | 1.10 | 1.37 | 1.37 | 1.37 | 3.70 | 3.73 |
| Grande | 0.50 | 1.37 | 1.37 | 1.37 | 4.82 | 2.25 |
| Verde | 1.10 | 1.81 | 1.81 | 1.81 | 5.89 | 0.40 |
| Hass | 1.30 | 1.60 | 1.60 | 1.60 | 5.60 | — |

Source: Ortiz *et al*. (2003).

**Table 8.5** Vitamin Content (mg/100g) in Three Avocado Cultivars.

| Vitamins | 'Fuerte' | 'Hass' | 'Anaheim' |
|---|---|---|---|
| Thiamine | 0.12 | 0.09 | 0.08 |
| Riboflavin | 0.22 | 0.23 | 0.21 |
| Niacin | 1.45 | 2.16 | 1.56 |
| Pantoteic acid | 0.90 | 1.14 | 1.11 |
| Pyridoxine* | 0.61 | 0.62 | 0.39 |
| Folic acid | 0.03 | 0.04 | 0.018 |
| Biotin | 0.005 | 0.006 | 0.0034 |

*Including pyridoxal y pyridoxamine.

Besides being a source of energy and vitamins, avocados also contain several phytochemicals that are thought to be beneficial for health. Therefore, avocado is considered by some as 'functional food' (Mazza 1998). Some nutraceutical ingredients that have been found in avocado pulp are antioxidants, such as tocopherols (about 4.3 UI/100 g) and glutathion (18 mg/100g). It has also been reported that avocado is a source of lutein (contain up to 248 mg/100g). The amount of β-sitosterol in this fruit is comparable to that found in soy and olives. An avocado-enriched diet produced a significant reduction in low-density lipoproteins and total cholesterol in patients with high-cholesterol levels, while diets enriched with soy and sunflower did not change the total cholesterol concentrations (Carranza *et al*. 1997). Pigments are important contributors to the appearance and healthful properties of both avocado fruit and oil. Ashton *et al*. (2006) identified in the skin, flesh, and oil of avocado fruit lutein, α-carotene, β-carotene, neoxanthin, violaxanthin, zeaxanthin, antheraxanthin, chlorophylls a and b, and pheophytins a and b with the highest concentrations of all pigments in the skin. Chlorophyllides a and b were identified in the skin and flesh tissues only. As the fruit ripened and softened, the skin changed from green to purple/black. The levels of carotenoids and chlorophylls did not change significantly during ripening. As fruit ripened, the total chlorophyll level in the oil from the flesh sections remained constant but declined in the oil extracted from the skin. Skin of 'Hass' avocados changes colour from green to purple/black as fruit ripen. This colour change is important as an indicator of ripeness. Colour change in 'Hass' avocados from green to purple, then black, results from an initial decrease in chlorophyll content, followed by an increase in the levels of the anthocyanin, cyanidin 3-O-glucoside (Cox *et al*. 2004). Total anthocyanins in skin tissue increased during ripening, but this increase was due almost entirely to a single anthocyanin; cyanidin 3-O-glucoside (Cox *et al*. 2004).

## QUALITY COMPONENTS AND INDICES

The major quality criteria used for avocado fruit are size, skin colour, firmness and freedom from wounds, blemishes, insect damage, residues and other contaminants. When ripe, the key quality indices are absence of diseases, physiological disorders, and physical damage. Many of these quality factors are cultivar-dependent and consumer preference for size, shape and colour can vary from region to region. There are significant differences in size, texture, and flavour between the different cultivars.

Freshly harvested avocados tend to have 'green' skins, although 'Hass' fruit that are harvested late in the season may have some skin darkening at harvest. The peel of ripe 'Hass' and 'Lamb Hass' avocados should have a dark, purple-black or black skin while green-skinned cultivars remain green when ripe. Pulp colour, texture and flavour when ripe are cultivar-specific.

California avocados are graded as No. 1 or No. 2. Florida avocados are graded as U.S. No. 1, U.S. No. 2 and U.S. Combination. However, only some Florida varieties are graded, while the others are marketed as unclassified. In California, fruit are weight sized into the following categories: 20 (532 to 624 g), 24 (447 to 532 g), 28 (390 to 447 g), 32 (333 to 397 g), 36 (298 to 354 g), 40 (269 to 326 g), 48 (213 to 269 g), 60 (177 to 213 g), 70 (135 to 177 g) and 84 (106 to 135 g), indicating the count for 11 kg packs, and half these values for flats (or single layer trays). Florida fruit are packed by count. Regulations specify that the pack shall be at least fairly tight and that the weight of the smallest fruit in any container shall not be less than 75% by weight of the largest fruit in the container. Commonly used counts for Florida packages are 6, 7, 8, 9, 10, 12, 14, 16, 18, 20 and 24 counts.

Food safety has become an important issue with strict guidelines now being set by the food industry. The major retailer chains invest heavily into promoting brand names and avoid adverse publicity that might arise from product exceeding the legal limits set for pesticide residues.

## MAJOR CAUSES OF POST-HARVEST LOSSES

Coursey (1971) reported that the post-harvest losses of avocado were estimated as 43%, and smooth skin varieties are more prone to physical injuries during handling and transport than the rough skin varieties. Some of the most important causes of post-harvest losses in avocado include mechanical damage, physiological disorders especially chilling injury (CI), decay and insects. Avocado is a subtropical fruit sensitive to CI (Pesis *et al*. 1994). The main symptoms are black stains in the epidermis and a grey or brown discolouration in the mesocarp. Morris (1982)

reported another symptom as alteration of internal metabolism, which leads to an increase in anaerobic respiration and, as a consequence, of abnormal metabolites, resulting in the development of foul taste and odour. Anthracnose (caused by *Colletotrichum gloeosporioides*) is the most important disease in avocado that reduces fruit quality after harvest. Friction damage, which is characterized by an oxidation of the tissue that later inclines downward and becomes necrotic, is one of the most frequent problems during fruit harvest and handling. Mechanical damage accelerates water loss and disrupts the superficial arrangement of the tissue allowing a faster gas exchange. Cuts break completely the protective layer of the fruit and expose the tissue directly to the environment. The damage is more serious due to inadequate packaging processes.

## PHYSIOLOGICAL DISORDERS AND THEIR CONTROL

A range of physiological disorders affect avocado fruit and most of these occur following long storage periods (2–4 weeks) (Zentmyer 1984). The key disorders are flesh greying, vascular browning and pulp spot, which are all symptoms of internal CI (Eaks 1976). When fruit are stored for excessively long periods the flesh may fail to ripen evenly, and become increasingly susceptible to pathogens. The timing of expression of internal CI and its severity depends on temperature management, initial ripeness, cultivar, production area and fruit maturity. External CI may occur if fruit are stored at low temperatures (0°C to 3°C) or for long periods (>6 weeks) at standard storage temperatures. Skin pitting, scalding and blackening are the main external CI symptoms on mature-green avocado kept at 0–2°C for more than 7 days before transfer to ripening temperatures. Avocados exposed to 3–5°C for more than two weeks may exhibit internal flesh browning (grey pulp, pulp spot and vascular browning), failure to ripen and increased susceptibility to pathogen attack. The timing of CI development and its severity depend on cultivar, production area, and maturity-ripeness stage. Hatton *et al*. (1965) observed CI characterized by a grey-brown discolouration of the vascular system in addition to uneven ripening and development of off-flavours in avocado fruits. Florissen *et al*. (1996) reported symptoms as mesocarp discolouration, hardening of vascular strands and 'off flavours'. Chaplin *et al*. (1982) and Couey (1982) reported symptoms as grey or dark discolouration of the mesocarp. Engelbrech and Koster (1986) found that storage for longer than 5 days at 5.5°C caused abnormalities in subsequent respiratory patterns during ripening at 18°C. Kosiyachinda and Young (1976) found that lower temperatures were tolerated during the post-climacteric phase. Internal CI is manifested as a greyish-brown discolouration of the flesh, particularly at the base of the fruit around the seed. This can be associated with vascular browning which starts at the base of the fruit (rather than at the stem end, which is often associated with stem end rots). In 'Hass' avocado fruit, internal CI tends to occur after about 4 or more weeks storage at about 6°C, depending on maturity and growing conditions. Calcium content in the fruit might be a possible reason for differences in internal CI (Chaplin & Scott 1980). Internal CI is the key limiting factor to long-term storage of avocados, generally associated with softening of fruit during storage, and is increased by the presence of ethylene (Chaplin *et al*. 1983). External CI occurs as irregular patches of blackening on the skin and can be observed during storage, but generally increases slightly in intensity after removal from cold storage. The damage is first seen in inner cell layers of the exocarp and then the outer layers of the skin (Woolf 1997). In cultivars that naturally darken during ripening, such as 'Hass', the damage will be less apparent after ripening, but may be discriminated as brown, corky skin tissue in ripe fruit. External CI is generally induced by temperatures lower than 3°C, but fruit become less sensitive with increasing maturity, and ripe fruit are less affected. Fruit exposed to low temperatures may be of poor internal quality when ripe with a high incidence of rots and softening disorders (Woolf *et al*. 1995), but will have lower incidence of internal CI (greying). For 'Hass' fruit stored for long periods at standard storage temperatures (6 to 7 weeks at about 6°C), a form of external CI is expressed which is of a very similar appearance to that observed at low temperature, which can sometimes be seen in fruit that are quite soft (nearly ripe) at the point of removal from storage. 'Pulp spot', a low-temperature disorder, is commonly observed in 'Fuerte' fruit as small dark spots in the flesh, and blackening of a region surrounding cut vascular bundles. Swarts (1984) reported the incidence to be higher early in the season. Mesocarp discolouration results in an overall grey to brown flesh discoloration, usually most intense in the distal half of the fruit, and the symptom is more predominant towards the end of the season. Both disorders involve browning reactions implicating particularly the enzyme polyphenol oxidase (PPO) (Kahn 1975) and phenolics (Kahn 1977). Application of exogenous ethylene, irrespective of the method of application, caused intensification of mesocarp discolouration in the fruit of several avocado cultivars during cold storage (Pesis *et al*. 2002). 'Ettinger' fruit treated with Ethrel (2-chloroethyl phosphonic acid) (a chemical that

releases ethylene) prior to packing and storage developed severe CI symptoms, expressed as mesocarp discolouration after 3 weeks at 5°C. 'Fuerte' fruit treated with ethylene gas (100 µl $l^{-1}$) for 24 h at 20°C prior to storage at 5°C exhibited mesocarp discolouration, which increased dramatically during shelf life at 20°C. 'Fuerte' fruit treated in cold storage with a continuous low-ethylene dose (4 µl $l^{-1}$) developed severe browning in the fruit pulp after 3 weeks at 5°C. 'Hass' fruit treated with 50 µl $l^{-1}$ ethylene, for 12, 24 or 48 h at 5°C showed a gradual increase in mesocarp discolouration after 3 weeks in cold storage plus shelf life; the 48 h ethylene-treated fruit exhibited the most severe pulp browning. Use of absorbent sachets that removed ethylene from modified atmosphere (MA) packages reduced mesocarp discolouration and decay development in 'Hass' fruit after 5 weeks storage at 5°C. Application of 1-methylcyclopropene (1-MCP), which inhibits ethylene effects by competitive binding to ethylene receptors, reduced mesocarp discolouration, decay development and polyphenol oxidase (PPO) activity, whereas this enzyme activity was induced in ethylene-treated fruit that were cold stored for 4 weeks. 1-MCP (50–1000 nl $l^{-1}$) treated fruit were firmer following storage for 4 to 7 weeks at 5.5°C and 6–24 h, at 6 or 15°C, had reduced skin colouration (purpling) at removal from storage, increased time to softening, and reduced physiological disorders associated with long-term storage (Woolf *et al*. 2005). Fruit conditioned at temperatures of 4, 6, 8, 10, 12 and 15 °C for a period of 0, 1, 2, 3, 4 or 5 days before 3 weeks storage at 0°C, had reduced skin damage. The optimum temperature/time combinations were 6 or 8°C for 3–5 days prior to 0°C storage (Woolf *et al*. 2003).

## DISEASES

Post-harvest diseases of avocados, an important problem of this crop, are commonly developed during the latter stages of fruit ripening, with symptoms first appearing when fruit are minimally ripe but often becoming quite severe before the fruit are over soft. Fruit ripened at 20°C and assessed at the same stage of ripeness, just before the flesh becomes over soft, had fewer post-harvest rots if they had been previously stored at 4°C or 6°C, than if they had been stored at either lower or higher temperatures. Diseases of avocados are divided into two categories on the basis of their location (Snowdon 1990). Stem end rots enter the fruit at the stem, or peduncle end of the fruit and move down the fruit resulting in discoloured flesh, often with associated browning of the vascular strands (Johnson & Kotze 1994). Body rots invade through the skin and are generally manifested as circular brown to black spots that may be covered with spore masses in the later stages of infection. Decay penetrates through the flesh resulting in discrete areas of discoloured flesh. In cultivars that darken when ripe (such as Hass), rots may be less obvious externally. The most prevalent fungi responsible for post-harvest diseases of avocado fruit are *Colletotrichum acutatum*, *C. gloeosporioides*, *Botryosphaeria parva*, *B. dothidea* and *Phomopsis* (Hartill 1991). Apart from *Phomopsis*, which is almost exclusively isolated from stem end rots, these fungi can cause both stem end rots and anthracnose (a disease usually characterised by necrotic lesions on the body of the fruit) on 'Hass' avocados. *Botryosphaeria* spp. is generally isolated in greater numbers from rots of avocados than are any of the other fungi.

The most important post-harvest decays of avocados are caused by the fungi *C. gloeosporides*, which causes anthracnose or black spot decay, and *Diplodia natalensis*. Also important are *Phomopsis* spp. and *Dothiorella* spp. which cause stem-end rot (Ahmed & Barmore 1980). Infection with *C. gloeosporides* occurs while the fruit is developing on the tree. Fruit spot disease caused by *C. gloeosporioides* is the most commonly occurring disease of avocado. Infection of avocado fruits by *Fusarium solani* and *F. sambucinum* causes accelerated softening of fruits. Other diseases of avocados are cercospora spot (*Cercospora purpurea*) and scab (*Sphaceloma perseae*), which attack leaves as well as fruits (Kadam & Salunkhe 1995). Anthracnose, caused by *Glomerella cingulata,* of which the conidial state is *Colletotrichum gloeosporioides,* is found in the United States, Israel (Prusky *et al*. 1983), Argentina (Oste & Ramallo 1974), Australia (Peterson & Inch 1980), New Zealand (Hartill 1991), India, South Africa (Rowell 1983) and Puerto Rico (Nolla 1926). Infection studies have identified *Colletotrichum gloeosporioides* as a weak pathogen. Anthracnose appears as the fruit begins to soften as circular black spots covered with pinkish spore masses in later stages. Decay can penetrate through the flesh and induce browning and rancid flavour. Infection is enhanced by wounding, artificially and by the fruit spotting bug (Fitzell 1987). On the tree during the season, spores of this fungus have been shown to germinate, form an appressoria and a short infection peg which penetrates about 1.5 µm into the skin (Coates *et al*. 1993). The fungus then remains quiescent until harvest, when antifungal dienes in the skin of avocado fruit break down due to degradation by lipoxygenase activity (Karni *et al*. 1989; Prusky *et al*. 1988), the fungus resumes growth and invades the avocado fruit to cause post-harvest rots (Prusky *et al*. 1988, 1984, 1983, 1990, 1991; Adikaram *et al*. 1992; Neeman *et al*. 1970; Sivanathan & Adikaram

1989). Breakdown of the antifungal dienes was delayed by $CO_2$ (Prusky *et al*. 1991), hypobaric pressure (Prusky *et al*. 1984) and treatment with antioxidants (Prusky *et al*. 1995).

Cercospora spot of avocados, caused by *Pseudocercospora purpurea* causes spots on fruit, which at first form small greenish-white dots that expand into slightly sunken irregular brown blotches. Mature lesions are rarely larger than 0.5 cm, but the cracks and lesions formed provide entry for other fungi, particularly anthracnose (Snowden 1990). This disease is found in Brazil (Albuquerque 1962), South Africa (Darvas 1982), Cameroon (Gaillard 1971), Japan (Hino & Tokeshi 1976), Mexico (Fucikovsky & Luna 1987) and the United States (Nagy & Shaw 1980). Up to 69% pre-harvest fruit loss on some orchards in South Africa has been attributed to infection with this fungus (Darvas & Kotze 1987). Dothiorella rot, caused by *Botryosphaeria ribis*, of which the conidial state is *Dothiorella gregaria* is found in Israel, South Africa (Labuschagne & Rowell 1983), the United States (Stevens & Piper 1941), and parts of South America (Zentmyer 1961). In New Zealand this disease is caused by *Botryosphaeria parva* (Hartill *et al*. 1986) or *Botryosphaeria dothidea* (Hartill 1991) and in Australia by *Dothiorella aromatica* (Muirhead *et al*. 1982). This disease can invade avocados through the body of the fruit or through the cut stem end (Snowden 1990). Symptoms usually only appear as fruit begin to soften after harvest, although this fungus has been isolated from lesions on hard unripe Californian avocados (Snowden 1990). Stem end rot, generally caused by *Botryodiplodia theobromae* in Australia (Peterson 1978), South Africa (Darvas *et al*. 1987), the Ivory Coast (Frossard 1964) and the United States (Stevens & Piper 1941). *Dothiorella* spp., *Phomopsis perseae* (Peterson 1978) and *Thyronectria pseudotrichia* (Darvas *et al*. 1987) have also been implicated in stem end rots. *Dothiorella* spp. and *Phomopsis* spp. can cause latent infection in developing fruit (Peterson 1978). However, *Botryodiplodia* is a wound parasite, and most infections with this fungus probably take place at harvest. In New Zealand, *Botryosphaeria dothidea, B. parva*, *Colletotrichum gloeosporioides, C. acutatum* and *Phompsis* spp. have all been associated with stem end rot (Hartill 1991). This appears as dark-brown to black discolouration which begins at the stem and advances toward the blossom end, finally covering the entire fruit. *Dothiorella gregaria* is another cause of stem-end rot in ripe avocados. Scab, caused by *Spaceloma perseae*, affects young developing fruit. Raised corky brown spots are produced on the skin which mars the cosmetic appearance of the fruit. Wound pathogens can gain entry to the fruit through lesions caused by this fungus (Ramallo 1969). Scab occurs in North, Central and South America, in the West Indies (Jenkins 1934), in New Zealand (Hartill 1991), and in South Africa and the Philipines (Snowden 1990). Some other fungi that can cause post-harvest diseases of avocado worldwide, but are rare in occurrence and are not perceived to be important include *Alternaria* sp. in Israel (Zauberman *et al*. 1975), *Penicillium expansum* in the United States and the West Indies (Horne 1934; Wardlaw 1934), *Fusarium* spp. in Israel (Zauberman & Schiffmann-Nadel 1979), South Africa (Darvas & Kotze 1987), the United States (Horne 1934) and the West Indies (Wardlaw 1934), *Pestalotiopsis versicolor* in South Africa (Darvas & Kotze 1987), *Phytophthora citricola* which attacks fruit near the ground in Mexico (Fucikovsky & Luna 1987) and the United States (Koike *et al*. 1987), *Trichothecium roseum* in the United States (Horne 1934), and *Rhizopus stolonifer* in South Africa, the United States and Israel (Darvas & Kotze 1987; Zentmyer *et al*. 1965). In New Zealand species of *Fusarium* have also been isolated from anthracnose (Hartill 1991). In New Zealand *Colletotrichum acutatum* has been isolated from both stem end rots and anthracnose of 'Hass' avocados (Hartill 1991). *Colletotrichum acutatum* spores released from infected dead twigs and fruit in the canopy, or possibly on the orchard floor, seem to infect avocado fruit while hanging in the tree. Most infections are probably initiated from within the avocado tree, and the influence of shelter belt infections does not seem to be important, and timing of infection appears to be random throughout the year (Everett 1994). *C. acutatum* may be a wound pathogen, as only a few fruit became infected when unwounded fruit were artificially inoculated throughout the season in the orchard (Everett & Hallett 1994). Damage caused by grading equipment was insufficient to aid infection.

Avocado blight, caused by *Sphaceloma perseae* (Myriangiales: Elsinoeaceae), found in Michoacán (Mexico), Florida, Puerto Rico, Brazil, Africa, Peru, Cuba, Haiti and California, attacks the fruit (in all stages), leaves, and young branches. The affected fruit present brown lesions of corky aspect with round or irregular shapes at first. When these lesions grow they can cover a large part of the fruit or the whole fruit, and cause fissuring in leaves and branches. In the fruit, the damages are exclusive of the exocarp, while the rest of the fruit remain healthy. However, the lesions can be an entry point for other organisms (Gallegos 1983). The *S. perseae* fungus requires a high relative humidity and high temperatures for its proper development. The most susceptible stage of the fruit is when it reaches one-third or one-half its normal size. Damage to the fruit caused

by insects, rodents or mechanically, allow the entrance of the pest, which produces spores on the attacked tissue. Among all the cultivars grown in Mexico, 'Fuerte' is the most susceptible to this disease. 'Hass' can also be severely affected if the pest is not prevented. 'Booth 1', 'Pollock', and 'Waldin' are considered slightly susceptible. The Mexican local hybrids (Criollos) are also likely to be affected by the fungus, although the incidence is lower because fruit from these trees ripens in the spring (Gallegos 1983).

**Control measures**

Darvas *et al*. (1990) showed less stem end rots and more anthracnose due to snap picking 'Fuerte' avocado fruit, and that removing the pedicel delayed ripening, which may account for the increase in anthracnose rots. Tingwa and Young (1975) showed that removing the pedicel increased the rate of ripening in avocados in California. More rots resulted in snap picked fruit in 'Hass' fruit in New Zealand (Hartill & Sale 1991).

In order to minimise post-harvest diseases of avocados an integrated disease management needs to be implemented. Both pre-harvest and post-harvest protocols and procedures are important for their control. A basic understanding of the infection processes and the periods of highest risk for infection to take place are required, in order to more effectively use control procedures. Development of prediction models in the orchard for calculation of periods of infection risk is a valuable tool, to enable growers to more effectively target spray applications and thus reduce costs, and reduce the risk of resistance to chemicals. Post-harvest handling, especially temperature and ripening control should be optimised. Sanitation in the pack house is necessary. Pre-harvest control methods for post-harvest fungal decay include good orchard sanitation (removal of mummified fruit and dead wood) and effective pre-harvest fungicide application such as copper which is widely used in some countries where humid growing conditions prevail. Harvesting should not be carried out in the rain or when fruit are wet, and careful handling to minimize skin damage helps to reduce rots. Snap picking of fruit can reduce stem end rot incidence in dry periods but it can result in increased rots in humid growing environments or when harvested in wet conditions.

The most important post-harvest factor for reducing rots is that of maintaining optimum temperature during handling, storage, transport, and ripening. It is also critical not to store fruit for long periods. Ripening fruit at lower temperatures (15 to 20°C) can lead to significant reduction in rots compared with higher temperatures (Hopkirk *et al*. 1994). Post-harvest fungicides (prochloraz, benlate/benomyl and thiabendazole) are used in some countries, but these are not registered for use in the United States (Darvas *et al*. 1990).

Control methods include good orchard sanitation, effective pre-harvest fungicide application, careful handling to minimize physical injuries, prompt cooling to optimum temperature for the cultivar and maintaining that temperature during marketing. Pre-harvest sprays with copper have been shown to significantly reduce post-harvest diseases (Hartill *et al*. 1990a). Four sprays during the season were insufficient to reduce post-harvest rots, and 12 sprays were required before significant differences were obtained. Pre-harvest Benlate application has been shown to reduce disease significantly when three sprays were applied during the season (Hartill *et al*. 1990b). Post-harvest dipping with Sportak$^{R}$ appears to be unreliable. It appears that there may be a curing effect, or alternatively an infection period immediately after harvest that is not halted by a delayed application of prochloraz. Hartill *et al*. (1986) found no difference in rots if prochloraz was applied within 24 hours of picking. Everett and Korsten (1996) have demonstrated the effectiveness of applying prochloraz either in wax or as an ultra low-volume spray. Wax by itself also seemed to reduce levels of stem end rots, however waxing has been reported to increase the incidence of all post-harvest diseases on 'Fuerte' avocados (Darvas *et al*. 1990). Waxing probably increases the humidity next to the skin of the fruit, and also the production of ethylene, both can promote the growth of anthracnose fungi (Darvas *et al*. 1990; Flaishman *et al*. 1995). However, Darvas *et al*. (1990) have shown that wax extended the shelf life of 'Fuerte' avocados. Fruit treated with prochloraz cannot be exported to Asia, the United States and some countries in Europe.

Post-harvest temperature control is effective in reducing the incidence of diseases (Truter & Eksteen 1987; Young & Kosiyachinda 1975; Fitzell & Muirhead 1983). However, optimum temperatures are specific for different cultivars and in different regions. For example, New Zealand 'Hass' avocados stored under appropriate South African recommendations (Hass from KwaZulu/Natal) were affected by more rots than the standard New Zealand post-harvest temperature regime (Hopkirk *et al*. 1994). Storage in 2% $O_2$ and 5% $CO_2$ extended the effective storage of 'Hass' avocados to 4 weeks, but rots were severe (Hopkirk *et al*. 1994). High concentrations of $CO_2$ (10%) prevented development of anthracnose for 3–4 weeks in 'Fuchs' and 'Waldin' fruit stored at 7.2°C (Spalding & Reeder 1975).

## INSECT PESTS

Johansen *et al*. (1999) published a taxonomic study of 41 Mexican insect species of Thysanoptera inhabiting *Persea americana* Mill floral and foliar structures. They reported that a total of 38 species are phytophagous, whereas only three are predators. Only six phytophagous species can be considered as primary pests for the young fruit or foliar structures, and the other 32 can be considered as incidental visitors. The three predatory species live in both natural ecosystems and avocado agricultural ecosystems. The cacao thrips (*Selenothrips rubrocinctus*) and greenhouse thrips (*Helipthrips haemorrhoidalis*) are the most common and relevant for avocado in the world. The damage produced by these pests can result in up to 50% crop loss (Adame 1994; Gallegos 1983). Even though 31 species of insects are potentially harmful to Chilean avocado (Prado 1991), only 9 species are considered as economically important. Gallegos (1983) reported 46, and Coria (1993) listed 11 species in the state of Michoacán, Mexico. However, as is the case in Chile, only a few pest species are economically important for avocado crops. Avocado pests in Mexico have been estimated to affect 14% of avocado production and diminish 10% of fruit quality, increasing the cost by 23% (Vidales-Fernández & Alcántar-Rocillo 1999).

Thrips, of the species, *Liothrips persea* Watson, *Scirtothrips aceri* Moulton, *Frankiniella cephalica, Heliothrips haemorrhoidalis* (Insecta:Thysanoptera: Thriphidae) are found in Florida, California, Mexico, Central and South America, Argentina and Chile, but their damage is reduced in avocado cultivated between 1900 and 2400 m of altitude. Thrips are one of the most relevant pests for avocado cultivars in Mexico. They can cause malformation of the fruit and premature falling from the tree and damage the vegetative tissue when feeding, producing lesions that become entry points for micro organisms such as *Sphaceloma perseae* (González-Hernández *et al*. 1999). The major damage is caused when the thrips feed on young fruits, producing crest-shaped malformations of the exocarp, which are more evident in ripe fruit. A natural biological control exists when wasps (*Desycapus pariopennis* Gaham, Trichogramatidae family) parasitise the thrips eggs. There are other predators such as *Leptothrips*, *Franlinothrips* and *Watsoniella*. An important cultural control is the elimination of weed, and keeping the orchard clean. This is a pest easily controlled by chemical pesticides, such as Malathion and parathion. For severe attacks, pyrethrines such as fluvalinates are recommended (Adame 1994; Gallegos 1983). Chemical pesticides should be applied when 10% and 100% of flowers appear, and when fruits are in bud stage.

Small seed weevil, of the species *Conotrachelus perseae* Barber (Coleoptera: Curculiondae: Cryptorhynchinae), is found in the eastern central region of Mexico and northern parts of Central America, Guatemala and Panama. They tunnel, forming a gallery throughout the pulp until they arrive at the seed, which is usually destroyed. Highly infected areas can affect up to 85% of the fruit, destroy the seeds and notably affect the production, since this situation induces the falling of the fruit from buds to maturity (Martinez & Adame 1987). An integrated management is required in order to control the pest, including cultural labours, chemical and legal control, since that this is a pest covered by quarantine regulations in several countries. Cultural control consists in the destruction of infested fruits, together with soil labour to destroy the pupa. Chemical control is carried out using methylic parathion or Malathion in powder (2% to 3%) applied to the soil during the emergence of adults, or as a spray at doses of 1 to 2 L / 1000 L of water every 10 days while adults are present. Legal control includes the establishment of campaigns for prevention in free zones and quarantines to avoid dispersion (Bravo *et al*. 1988; Martínez & Adame 1987). The large seed weevil, *Heilipus lauri* Boheman (Coleptera: Curculionidae: Hylobiinae), is found in the western central region of Mexico, but not in the avocado cultivars of Michoacán. Other species of this weevil are *H. sguanosus* found in Florida and California, the West Indies, and in the Virgin Islands; *H. pihieri* in Central America; *H. cartagraphus* and *H. montei* in Brazil; and *H. persea* in Panama. Females lay 1 to 2 oval-shaped eggs in a previously made cavity under the epidermis of the fruit, which at first are green in colour and later become darkened. They tunnel through the flesh of the fruit, forming a gallery that extends to the seed, which is usually destroyed. Furthermore, they produce secondary rotting of the flesh and the seed. The pupae develop inside the fruit after 14 to 16 days. This pest can destroy the flesh, seeds, and cause a premature falling of the fruits (Bravo *et al*. 1988; Gallegos 1983). Optimum control of this pest is achieved when combining chemical and cultural controls. The spraying of the foliage every 8 to 10 days after adult appearance is recommended, using phosphate-containing chemicals such as methylic parathion, Malathion and ethylic gustathion at doses of 1–2 L in 1000 L of water. As a cultural control, it is important not to leave fruit on the tree after harvest, to gather all fallen fruits and destroy them. A biological control that gives 20% efficiency can be achieved with *Bracon* sp (Bravo *et al*. 1988; Gallegos 1983).

Seed moth, caused by *Stenoma catenifer* Walsingham (Lepidoptera: Stenomidae), is one of the most widely distributed avocado pests in Mexico, being found in the east and coastal zones of the country. It is also found in Guatemala, Costa Rica, Panama, Colombia, Venezuela, Peru, Bolivia, Ecuador, Brazil and Argentina. The eggs are deposited on or near the fruit, and also on tender branches. Upon hatching, whitish larvae emerge and penetrate the fruit forming galleries which extend to the seed, and in branches extend to the central cylinder. Seed moths can penetrate fruits of any size and destroy the seed completely (Bravo *et al*. 1988; Gallegos 1983). A combination of chemical and cultural control is needed. The cultural control consists of pruning the affected branches, gathering the fallen fruit and burying or incinerating it. Chemical control can be used for adult insects by spraying phosphate-pesticides, carbamate, or piretroid pesticides, such as Malathion, gustathion, sevin and permetrines in commercial doses. Phosphate-containing pesticide in powder form can also be applied at 2% to the soil when the fruit begins to fall during the emergence of adults (Bravo *et al*. 1988; Gallegos 1983).

### Control measures

In order to establish a good strategy for integral pest control, thresholds and levels of economical damage need to be determined. This can help to reduce the frequency of fumigation, lower the crop handling costs, as well as to increase the production. In Mexico, only four pesticide products are recommended for chemical control: (1) parafinic petroleum oil, (2) Malathion CE 47, (3) Methylic parathion and (4) Permetrine. In Chile, the presence of a large fauna of biological controllers has helped to contain potential avocado pests. However, there is no doubt that the use of pesticides in the orchards contribute to maintain this situation. Different pests that sometimes need to be restrained can be handled with selective pesticides that do not interfere significantly with biological controllers. In other cases, spraying specific sectors of the orchard help to maintain the beneficial fauna. In the same way, the establishments of reservoirs for biological controllers, together with cultural practices such as the elimination of low branches, removal of branches that constitute the origin of infections, and the maintenance of vegetation that feed beneficial fauna in adult stage, are also biological control practices. Finally, the artificial introduction of biological controls through the development and release method can help where the beneficial fauna is not efficient enough or does not colonize the orchard on time (López-Laport 1999).

## QUARANTINE TREATMENTS

Avocados grown in fruit fly infested areas require quarantine treatments to be marketed in certain countries. Methyl bromide (MBr) treatment is an APHIS approved treatment for Mediterranean fruit fly, but can result in a significant reduction in fruit quality. Avocado fruit treated with MBr can exhibit some external damage, ripening 2 to 4 days earlier than the non-fumigated controls. Pitting and other visual damage caused by fumigation is commonly masked in the case of cultivars with purple or black fruit when the fruit ripen and achieve a dark colour. The cultivars with least damage are those with purple or black skin. MBr fumigation does not affect the flesh as much as the skin. Flesh colour and flavour are commonly acceptable in most cultivars and the former is usually equal to that of the controls in appearance. Fumigated fruit, however, commonly show more internal browning in certain cultivars with visibly affected vascular fibre throughout the flesh (Ito & Hamilton 1980).

Low-temperature disinfestations can be used, but can also result in fruit damage. Tolerance to temperatures which can be used for low temperature disinfestations can be imparted by pre-treatments at 38°C (Sanxter *et al*. 1994; Woolf *et al*. 1995: Roman & Yahia 2000a, 2000b) or low temperature conditioning (Woolf *et al*. 2002). Commercial disinfestations treatment in use for Queensland fruit fly in 'Hass' avocados is at 6°C to 8°C for 3 to 5 days followed by 16 days at <1°C (Hofman *et al*. 2002). However, this low-temperature disinfesting treatment may not be effective for all fruit fly species because of tolerance differences in insects and also of different avocado cultivars. The potential for hot water treatment (HWT) to improve quality of 'Hass' avocado following cold disinfestations for fruit flies was investigated by Hofman *et al*. (2002). HWT at 38–42°C for 20–60 min significantly reduced skin damage caused by cold disinfestations, with 40°C for 30 min, 41°C for 20–30 min and 42°C for 25–30 min resulting in the greatest reduction (Hofman *et al*. 2002). HWT also reduced body rots in ripe fruit, with 40°C and 41°C for 30 min being consistently the most effective. Treatment at 42°C increased body rots compared to the other HWTs in one season, and there was no benefit of HWT times longer than 30 min. The severity of vascular browning (VB) and mesocarp discolouration (MD) in ripe fruit was generally low, and increased following cold disinfestations. Hot water treatments reduced VB severity but had no effect on MD. Treatment at 41°C for 25–30 min and 42°C for 25 min increased the percentage of externally acceptable fruit (less than 5% of the skin area with defects) from 0% to about 80% 3 days after removal from disinfestations. The same

treatment also increased the percentage of ripe fruit with acceptable flesh quality (less than 5% of the flesh with rots or disorders) from 0% to 16–20%, due mainly to reduced body rots. These results indicate the commercial potential of HWTs of about 41°C for 25–30 min, or 42°C for 25 min to improve avocado external and internal fruit quality following cold disinfestations. The effects of a transient (warming) temperature spike on efficacy of an APHIS approved quarantine cold treatment, T107 (a), against Mediterranean fruit fly, *Ceratitis capitata*, was tested on Hawaii grown 'Sharwil' avocados (Jang *et al*. 2001). Avocados infested with late stage eggs were subjected to a warming temperature spike (*ca*. 4.2°C for 1 h) at 6–9 days into the treatment and subsequently allowed to resume the treatment until conclusion (12 days at <1.1°C, 14 days at <1.67°C or 16 days at <2.2°C). Insertion of a *ca*. 4.2°C temperature spike into the treatment at 6–9 days had no effect on the efficacy of the quarantine cold treatment when fruit were allowed to resume the treatment to completion. Infested fruit which did not receive a 'heat shock' treatment (recommended to improve fruit quality) and subjected to cold treatment for 6–16 days at fruit centre temperature of <1.1, <1.67 or <2.2°C had no survivors in the fruit by the ninth day of cold treatment. Infested avocados subjected to a 'heat shock' treatment for 10–12 h at 38°C prior to cold treatment had no survivors in the fruit by the 8th day of cold treatment. Therefore, the T107 (a) cold treatment (as stated in the APHIS treatment manual) seems to be effective against Mediterranean fruit fly eggs in 'Sharwil' avocados, and that use of a 'heat shock' to prevent CI during the cold treatment do not extend survivorship of fruit fly eggs. The potential for low temperature conditioning (LTC) treatments, either alone or in combination with HWT, to improve the quality of 'Hass' avocado fruit following cold disinfestations of Queensland fruit flies, was investigated by Hoffman *et al*. (2003). LTC at 4°C for 4 days or at 6–8°C for 3–4 days increased the percentage of fruit with acceptable external appearance (less than 5% of the fruit with discrete dark patches on the skin, and skin spotting combined) after disinfestations from 0% to 100% due to the effective elimination of discrete patches on the skin. Disinfestations alone increased body rots and diffuse flesh discolouration severity in ripe fruit, while LTC before disinfestations reduced severity of these disorders to similar levels as those in non-disinfested, non-stored fruit. LTC before disinfestations reduced discrete patches severity and improved flesh quality more than HWT. Combined treatments of HWT and LTC before disinfestations were no more beneficial compared with LTC alone. Conditioning of fruit at 6°C for 3 days followed by disinfestations resulted in no survivors from 50 748 third instars of Queensland fruit fly (*Bactrocera tryoni* Froggatt). LTC efficacy was verified commercially by conditioning fruit at 6°C for 3 days followed by disinfestations and airfreight to New Zealand. External fruit appearance and internal ripe fruit quality after disinfestations were found to be high. Therefore, LTC before cold disinfestations could effectively eliminate skin damage and improve flesh quality of ripe 'Hass' avocado fruit, with no negative effect on Queensland fruit fly disinfestations efficacy. 'Hass' avocados have been reported to be sensitive to hot air treatments (Yahia 1997a, 1997b, 2001).

Pre-treatment at moderate temperatures applied immediately prior to the high or low temperature treatments can reduce skin damage to avocados. A hot-air pre-treatment (38 °C for 6 h) applied prior to storage at 0°C for 3 weeks with intervening delays of 1–4 days at 20°C, showed a large reduction in CI as a result of the pre-treatment but that this was progressively lost with increasing delay to storage (Woolf *et al*. 2004). Hot water pre-treatment (38 °C for 0, 5, 20 and 60 min) increasingly reduced chilling damage at 0°C and heat damage from a HWT at 50°C for 10 min. With delays of up to 3–24 h prior to the HWT, heat damage was reduced for the 5 and 20 min pre-treatments. However, delays up to 5 days between pre-treatment and HWT, loss of heat tolerance was observed. For delays of between 1 and 5 days there was a clear loss of chilling tolerance which was more rapid than the increase in CI in control treatments for the same delays. However, the effect of delays <24 h was less clear for the 5 and 20 min treatments. Heat shock proteins (hsp) 17 and 70 homologous RNA levels were induced by heat pre-treatment and delays lead to first an increase in RNA levels (maximum induction at 6 h), which paralleled the induced tolerance, and then a decline which was less closely associated with loss in tolerance. Thus, delayed time between thermo tolerance inducing pre-treatment and high or low temperatures may lead to a general reduction in tolerance, and can be exploited in the application of temperature treatments.

## MATURITY AND HARVESTING INDICES

Avocado differs from most other fruits in that ripening does not normally take place on the tree, but only after picking (Schroeder 1953). Avocado is characterized by great natural variability. The question of when to start harvesting avocado fruit is of great commercial importance. Harvesting of the fruit before reaching an optimal stage can lead to deficient ripening and quality. On the other hand, when the harvest of the fruit is carried out after the

optimal point, its post-harvest life could be diminished. In order to determine this optimal harvest point some indices are used; the most important are two quantitative indices: oil and dry matter content. However, other complementary indices can be considered, such as flesh softening and change of skin colour from green to black in some cultivars such as 'Hass'. Determining when to harvest avocados requires experience. Slight changes in skin colour, loss of glossiness or a brown seed coat are signs of maturity.

Oil content is an important factor in the taste of avocado fruit. Percent of dry matter is highly correlated with oil content and is used as a maturity index in most avocado production areas (Lee *et al*. 1983). Minimum dry matter content required ranges from 17% to 25%, depending on cultivar. In California, the minimum percentage of dry matter at harvest for the major cultivars are Bacon (17.7%), Fuerte (19.0%), Gwen (24.2%), Hass (20.8%), Pinkerton (21.6%), Reed (18.7%) and Zutano (18.7%). In California, fruit are also released onto the market at predetermined dates based on dry matter and size for each cultivar. For example, the size/release dates for 'Hass' are Size 40 and greater, November 28; Size 48, December 12; Size 60, January 2; and Size 70 or smaller, January 16. Based on the experiences obtained in Mexico for export fruit, it can be established that avocados should have an average of 22% of dry matter, and the lowest value of a sample should not be under 20%. The California regulation defined minimum maturity of avocado fruit as containing 21% dry matter content. In 1983, dry matter content has become an index of maturity for the California avocado industry and has been followed by the Mexican avocado growers (Kurlaender 1996). In order to have a high-quality product, a 25% dry matter content in the fruit is required. This also equates to about 13% oil content. Although harvesting of the fruit for fresh market starts when the dry matter reaches 21%, it is not yet suitable for processing. This is due to lack of the typical nutty flavour; the colour of the pulp would be pale green and the viscosity of the product would be too low (runny) (Kurlaender 1996). Florida (West Indian) avocados have lower oil content (3 to 15% oil) and are generally harvested at a specified calendar date (days after full bloom) and weight or size (Ahmed & Barmore 1980).

Dry matter is measured by placing approximately 10 g of thin slices of avocado pulp into Petri dishes. The uncovered dishes are placed in a microwave oven and cooked until constant weight (from 5 to 15 min) (Clark *et al*. 2003).

Some attempts have been tried to determine fruit maturity nondestructively, on the tree, before harvest, such as with the use of near-infrared (NIR) technology (Brown & Sarig 1994).

**Figure 8.1** Avocado harvesting. Courtesy of Dr Mary Lu Arpaia, University of California, Riverside, CA.

## HARVESTING

Fruit are commonly hand-harvested when mature, using an array of picking aids, such as the use of ladders, telescopic poles fitted with a cutting blade and catch bag, hand clippers, etc. In some extended orchards, trees are sometimes harvested with the aid of hydraulic ladders (cherry pickers) while in smaller orchards picking poles are used to reach the fruit. In flat areas in California, man-positioning machines are used to lift the pickers. Fruit are picked into large bins usually mounted on trailers to facilitate their movement to the packing shed (Figure 8.1). The fruit is removed from the tree by either clipping or snapping the stem at the base of the fruit. For most cultivars, fruit needs to be clipped with a 'button' retained on the pedicle end. This reduces the chance of bruising and puncturing adjacent fruit once they are placed in containers (Ahmed & Barmore 1980), and the risk of stem-end rot invading the fruit as it ripens. The lack of stem end 'button' was shown to promote fungi spores to grow and discolour the interior of the fruit after ripening (Kurlaender 1996). The effectiveness of snap harvesting is dependent upon fruit maturity, growing conditions (rain) and cultivar (Arpaia & Hofshi 1998). Damage could be caused by improper harvesting, like pulling or plucking the avocados, instead of clipping the stem flush with the fruit surface.

It is important to keep the fruit out of direct sunlight after picking to prevent it from heating. It has been reported that exposure of the fruit to direct sunlight can result in temperatures in excess of 15°C above the ambient air temperature (Ferguson *et al*. 1998). However, fruit exposed to the sun before harvest have been reported to have higher

tolerance to post-harvest heat (50°C hot water) and cold (0°C storage) treatments than shaded fruit. These temperatures may be responsible for the variability observed in post-harvest responses. Thus, it appears that pre-harvest temperature experienced by avocado fruit affects their post-harvest behaviour in manners similar to post-harvest heat treatments (Woolf *et al*. 1999). High pre-harvest temperatures due to exposure to the sun dramatically affect a range of post-harvest response in several avocado cultivars such as 'Ettinger', 'Fuerte', 'Hass', 'Horshim' and 'Pinkerton'. The accumulation of heat shock proteins in the exposed fruit was an indication of their response to the stress. The shaded fruit exhibited more extensive and faster development of inoculated *C. gloeosporioides* than the sun exposed fruit.

## POST-HARVEST HANDLING

Post-harvest practices are aimed at prolonging fruit storage by delaying the senescence process and controlling the ripening of fruit picked at the mature but unripe stage. This can be achieved by lowering their temperature or changing the gas composition of the storage environment by decreasing the oxygen and ethylene concentrations and increasing the $CO_2$ concentration. Fruit respiration is often used to monitor the efficiency of these controls (Blanke 1991). Harvesting, handling and transportation to the packinghouse and all operations must be done carefully, in order not to cause mechanical damage. Any injuries can accelerate ripening and negatively affect the appearance of the peel causing blemishes and browning during and after storage. Generally, avocados are very susceptible to bruising during softening (Arpaia *et al*. 1987), and thus should be handled carefully during transport and display. Any means of minimizing 'squeezing' by customers will slow quality deterioration. Since quality can decrease rapidly during softening, it is best to check avocado ripeness every day and to display or use the ripest fruit first. If possible, ripe, or near-ripe fruit should be held at lower temperatures at 1°C to 6°C (Young & Kosiyachinda 1976) to reduce the proportion of fruit that become over-ripe, with concomitant increase in rots and other disorders. Avocados should not receive a water sprinkle or top ice during display.

## PACKING AND PACKAGING

Fruit are unloaded from the trucks, received and weighed. In Mexico, fruit arrives in boxes of different colours to identify its final destination (domestic market, export, organic fruit etc). Avocados are commonly graded by hand and then sized by weight devices. Inspection grades are based mainly on variety characteristics, shape, colour, maturity, trimming of stems, defects and decay (Nogalingam 1993).

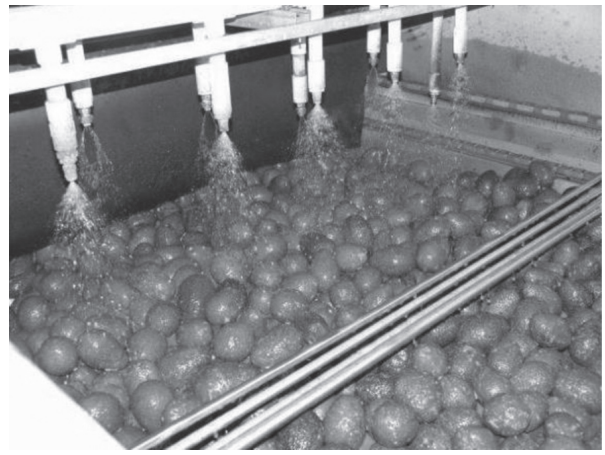

**Figure 8.2** Avocado washing. Courtesy of Dr Mary Lu Arpaia, University of California, Riverside, CA.

**Figure 8.3** Avocado packing line showing brushes. Courtesy of Dr Mary Lu Arpaia, University of California, Riverside, CA.

In the pack house, the boxes are unloaded unto a reception conveyor that twist them over, and takes the fruit to a classification machine to separate small avocados. Then the fruit is cleaned with rotating brushes (Figures 8.2 and 8.3). The selection and grading can be carried out manually or with the help of machines, and considering the shape, size and sanitary characteristics of the fruit, as well as all the defects caused by insects, rodents, mechanical mishandling and diseases. The selection criteria also depend on the final destination of the fruit. Mechanical sizers can be of expanding aperture type or cup weighers. The weighing system


**Figure 8.4** Packed avocado. Courtesy of Dr Mary Lu Arpaia, University of California, Riverside, CA.


**Figure 8.5** Avocado in consumer packages. Courtesy of Dr Mary Lu Arpaia, University of California, Riverside, CA.

can be more accurate for uniform package and presentation in the market place, but requires higher capital cost. The calibre is the number of fruit that can be packed in a single box. Once the fruit size is selected, and the defects have been discarded, it is packed. The packaging material varies according to the origin and the destination market, being cardboard, plastic or wood (wood is not used in Europe). The most common containers used for avocado are single wall corrugated fibreboard (Figure 8.4) or wooden boxes. The first usually have a capacity of 4 kg with one layer of fruit, while the second usually contain 10 kg, and the fruit is placed in bulk. In California, avocados are packed in a single layer of 5.6 kg flats or trays, or a double layer of a total of 11.3 kg lugs and 11.3 kg volume-fill boxes. Returnable plastic containers (RPCs) are being increasing used in parts of the United States and Europe. In some European supermarkets 100% of the avocado is delivered in RPCs. There is also increased usage of pre-packed units such as polyethylene containers (clam shells) (Figure 8.5) or mesh bags. For Florida avocados, the common packages used are: single-layer, 6.1 kg flats; two-layer, 12.5 kg lugs; 15.9 kg cartons and 4.5 kg natural packs.

Individual boxes are then palleted, where boxes are stowed and tied together. Pallets should comply with the measurements established by the containers they will be carried in. The number of boxes per pallet varies, but is commonly 264 boxes of 4 kg each and less number of boxes when package weight is 6 kg, with a total of 5280 boxes (4 kg) per container. Pallets are then immediately pre-cooled, and then refrigerated until they are loaded into the transport containers.

## COOLING AND STORAGE

### Pre-cooling

Pre-cooling soon after harvest is recommended to remove field heat. Removal of excess heat prior to, or immediately after packing reduces the refrigeration required during shipment to maintain fruit at recommended temperatures and to provide better control of the ripening process. This is critical where long storage periods or long transport shipments are required or where field temperatures are high (>25°C). Pre-cooling diminishes or slows down the metabolic rate, ethylene synthesis and its action on the fruit, loss of texture, fruit ripening, and fungal infections. Ideally, there should not be more than six hours from harvest to pre-cooling, and when this is not possible, the harvested fruit should not be allowed to reach an internal temperature higher than 26°C in the field and during transportation to the packinghouse.

Forced-air cooling is the method best suited for avocado pre-cooling. It is carried out until the temperature in the fruit reaches 6–7°C for 'Fuerte' and 'Hass' avocados. The time required to achieve these temperatures varies according to the initial temperature of the fruit, temperature and velocity of the air, and the final temperature of the fruit. Hydro-cooling of 'Hass' is also used commercially. It is of prime importance to assure that temperature will not be lower than that established for the fruit, otherwise CI can occur.

### Refrigeration

Temperature is no doubt the single most important factor in fruit storage. All biological processes are controlled by temperature, including fruit quality and ripening. The rate

**Table 8.6** Post-harvest Life of Some Avocado Cultivars at Optimum Temperature and Relative Humidity (RH).

| Cultivar | Temperature (°C) | RH (%) | Post harvest life (wks) |
|---|---|---|---|
| 'Hass' | 3–7 | 85–90 | 2–4 |
| 'Fuerte' | 3–7 | 85–90 | 2–4 |
| 'Fuchs' | 13 | 85–90 | 2 |
| 'Pollock' | 13 | 85–90 | 2 |
| 'Lula' | 4 | 90–95 | 4–8 |
| 'Booth 1' | 4 | 90–95 | 4–8 |

of ripening depends on temperature of storage (Eaks 1978). The response of avocado to storage temperatures varies according to temperature range and fruit type (race), variety, growing conditions, time in the season, maturity stage and length of storage required. Recommended optimum storage conditions vary according to the avocado variety (Table 8.6). All West Indian cultivars are chilling sensitive and stored best at 12.8–13°C for a maximum period of 2 weeks, and Guatemalan and Mexican cultivars are commonly maintained at 4°C and 8°C, respectively (Hatton *et al*. 1965; Zauberman *et al*. 1973). Chilling tolerant cultivars such as 'Lula', 'Booth 8' and 'Taylor' are stored best at 4.4°C; while a few cultivars such as 'Fuerte', 'Hass' and 'Booth 7' are intermediate in sensitivity to CI and store best at 7.2°C. Optimum storage temperatures for 'Hass' are 5°C to 7°C for early season fruit and 4°C to 5.5°C for late season fruit. After 3 to 4 weeks storage, 'Hass' fruit quality is reduced, and storing fruit for >6 weeks remains a challenge. Storage temperature should be maintained with a maximum variation of 1°C. It is important to avoid temperature fluctuations during transport and storage. Optimum relative humidity is 85% to 95% RH. Temperatures above 30°C cause adverse effects on avocado quality and ripening (Erickson & Takaake 1964; Zauberman *et al*. 1977). From 10°C to 25°C the avocado fruit commonly softens faster as storage temperature increases. From 5°C to 8°C softening is usually controlled, but will occur if the fruit is transferred to higher temperatures. From 0°C to 4°C, softening at these temperatures is limited by time, due to the risk of CI. 'Step-down' temperatures (Vorster *et al*. 1987), where temperatures are typically decreased 1°C to 2°C each week during shipping, with the final temperature not <3.5°C, with progressively lower initial temperatures as fruit maturity increases, are temperature regimes that have been developed and have resulted in a protocol for each cultivar for differing times in the season and growing region.

## PRE-STORAGE TREATMENTS

Some pre-storage treatments have been reported to delay ripening and prolong storage life of avocado fruit. Waxing can be regarded as a cosmetic treatment, as it imparts glossiness, but it also has pronounced physiological effects, especially on the internal atmosphere and weight loss of the fruit (Durand *et al*. 1984). A gain of 1 or 2 days of shelf-life may be achieved, but in some cases at the expense of development of some fruit rots. Waxing was found to cause a considerable reduction in moisture loss, in addition to modify the internal atmosphere of the fruit tissue, decreasing the internal oxygen and increasing carbon dioxide concentrations (Durand *et al*. 1984). Acclimation (temperature management) is being used successfully in South Africa, where temperature is reduced gradually (Vorster *et al*. 1990). Low-oxygen atmosphere pre-storage treatments (3% oxygen and 97% nitrogen) for 24 h reduced CI symptoms and softening in 'Fuerte' avocado fruit after 3 weeks of storage at 2°C (Pesis *et al*. 1994). Carbon dioxide shock pre-treatment (25% in air, for 3 days) was reported as a promising treatment (Bower *et al*. 1989). Prusky et al. (1995) suggested that a post-harvest dip or spray of avocado fruit with the antioxidant butylated hydroxyanisol might reduce post-harvest decay in avocado by modulating the natural fruit resistance.

## MODIFIED (MA) AND CONTROLLED ATMOSPHERES (CA)

Optimum MA and CA (2–5% $O_2$ and 3–10% $CO_2$) delay softening and skin colour changes and reduce respiration, ethylene production rates, and CI of avocado fruit (Yahia 1998). Mature-green 'Hass' avocado can be kept at 5–7°C in 2% $O_2$ and 3–5% $CO_2$ for 9 weeks, then ripen in air at 20°C to good quality. Exclusion and/or removal of ethylene from CA storage are recommended. Elevated (>10%) $CO_2$ levels may increase skin and flesh discoloration and off-flavour development, especially when $O_2$ is <1% (Table 8.7).

**Table 8.7** Some Reported Effects on Avocado Fruit in Different Conditions of Modified and Controlled Atmospheres.

| Variety | $\%O_2$ | $\%CO_2$ | Temperature °C | Remarks |
|---|---|---|---|---|
| Hass | 2–10 | 4–10 | 7 | Storage time of 7–9 weeks |
| Lula, Booth 8, Fuchs | 2 | 10 | 7.5 | Increase shelf life twofold |
| Fuerte, Edranol, Hass | 2 | 10 | — | Reduces internal disorders |
| Nonspecific | — | 25 | — | Reduces disorders and increases anthracnose |
| Fuerte | — | 25 | — | Delays maturation |
| Fuerte | 2 | 10 | 5.5 | Less dark spots in the pulp |
| Fuerte | — | 25 | 5.5 | Less dark spots in the pulp |
| Fuerte | 3 | 0 | 24 h at 17°C | After this treatment, fruit can be stored at 2°C for 3 weeks |
| Booth 8, Lula | 2 | 10 | 4–7 | Storage time of 8 weeks |
| Fuerte, Anaheim | 6 | 10 | 7 | Storage time of 38 days |
| Waldin, Fuchs | 2 | 10 | 7 | Storage of 4 weeks, prevents anthracnose and CI |
| Hass | 2 | 5 | — | Storage time of up to 60 days |

Source: Yahia (2003).

Very early research by Overholser (1928) reported that the storage life of 'Fuerte' avocados was prolonged one month when fruit was held in an atmosphere of 4 to 5% $O_2$ and 4 to 5% $CO_2$ at 7.5°C compared to air storage. Brooks *et al*. (1936) reported that fruit could be held in atmospheres containing 20–50% $CO_2$ at 5–7.5°C for 2 days without causing any injury. Atmospheres with $CO_2$ levels below 3% prolonged the storage life of Florida avocados at all temperatures, and reduced the development of brown discoloration of the skin (Stahl & Cain 1940). Extensive work was later done also with 'Fuerte' avocado, and concluded that the time for the fruit to reach the climacteric is extended in proportion to the decrease in $O_2$ concentration from 21% to 2.5% (Biale 1942, 1946). In later years Young *et al*. (1962) demonstrated that the delay of the climacteric could also be achieved by 10% $CO_2$ in air, and the combination of low $O_2$ and high $CO_2$ suppresses further the intensity of fruit respiration. Hatton and Reeder (1965, 1969b, 1972) and Spalding and Reeder (1972; 1974) found that a CA of 2% $O_2$ and 10% $CO_2$ at 7.5°C doubled the storage life of the cultivars 'Lula', 'Fuch', and 'Booth 8'. The percentage of acceptable fruit after storage was increased by absorption of ethylene during CA storage (Hatton & Spalding 1974). 'Reed' and 'Hass' avocados were reported to be stored for up to 3, and 2 months, respectively, in CA (Sive & Resnizky 1989a). Jordan and Smith (1993) reported that 'Hass' avocados remained firm and unripe for 7 to 9 weeks in CA of 2–10% $O_2$ and 4–10% $CO_2$ at 7°C. Below 4% $CO_2$ storage life was 5-6 weeks. Truter and Eksteen (1987a, 1987b) reported that a mixture of 2% $O_2$ and 10% $CO_2$ extended the shelf life and reduced the grey pulp and virtually eliminated pulp spot of 'Fuerte', 'Edranol' and 'Hass', but an increase in anthracnose was observed. Truter and Eksteen (1987b) found that a 25% $CO_2$ shock treatment applied one day after harvest reduced physiological disorders without any increase in anthracnose. Allwood and Wolstenholme (1995) were able to delay ripening of 'Fuerte' fruit using a 25% $CO_2$ shock treatment applied in pulses 3 times every 24 hours. Marcellin and Chavez (1983) reported that intermittent exposure to 20% $CO_2$ of 'Hass' avocados stored in air delayed senescence at 12°C, reduced CI at 4°C and controlled decay at both temperatures.

CA delays the softening process, and thus maintains the resistance of the fruit to fungal development (Spalding & Reeder 1975). In addition, Prusky *et al*. (1991, 1993) reported that 30% $CO_2$ (with 15% $O_2$) for 24 hours increased the levels of the antifungal compound 1-acetoxy-2-hydroxy-4-oxo-heneicosa-12,15-diene in the peel and flesh of unripe avocado fruits, and delayed decay development. This diene has been suggested as the basis for decay resistance in unripe avocados (Prusky *et al*. 1982, 1988, 1991). 20% $CO_2$ can be tolerated by thick-skinned avocados such as 'Hass' and 'Lula', but causes browning of the skin in thin-skinned varieties such as 'Ettinger'

(Collin 1984). High concentration of CO (5 to 10%) added to CA can reduce decay development (El-Goorani & Sommer 1981). Moderately high concentrations of $CO_2$ (up to 10%) were shown to ameliorate CI in 'Taylor' avocados (Vakis *et al*. 1973). Spalding and Reeder (1972) found less internal and external CI in CA than in air storage of 'Booth 8' and 'Lula' avocados. Intermittent high $CO_2$ treatment (3 treatments during 21 days) reduced CI symptoms (Marcellin & Chaves 1983). 'Fuerte' avocados had less pulp spot and blackening of cut vascular bundles after storage in 2% $O_2$ and 10% $O_2$ at 5.5°C for 28 days, or after a 'shock' treatment of 25% at 5.5°C for 3 days and an additional 28 days at normal atmosphere at 5.5°C (Bower *et al*. 1990). Spalding (1977a) concluded that the $CO_2$ must be kept below 15% to prevent other fruit injury. Pre-storage of 'Fuerte' avocados in 3% $O_2$ (balance $N_2$) atmosphere for 24 hours at 17°C significantly reduced CI symptoms after storage at 2°C for 3 weeks (Pesis *et al*. 1993, 1994). Fruit pre-stored in 97% $N_2$ had lower respiration and ethylene production, lower ion leakage, higher reducing power (expressed as SH groups, mainly cysteine and glutathione), and longer shelf life than the untreated fruit.

'Booth 8' and 'Lula' avocados were reported to be held successfully for up to 8 weeks in a CA of 2% $O_2$ with 10% $CO_2$ at 4–7°C and 98-100 RH, and removal of ethylene further improved the keeping quality of the 'Lula' fruits (Spalding & Reeder 1972). Fruits of 'Booth 8' had slight CI at 4.5°C. 'Fuerte' and 'Anaheim' fruits were stored in Brazil for up to 38 days in 6% $O_2$ and 10% $CO_2$ at 7°C, but only for 12 days in air (Bleinroth *et al*. 1977a). Storage of 'Waldin' and 'Fuchs' avocados in 2% $O_2$ and 10% $CO_2$ for up to 4 weeks at 7°C was also reported to prevent development of anthracnose and CI (Spalding & Reeder 1974, 1975). 'Hass' avocado was reported to be stored for up to 60 days in atmospheres of 2% $O_2$ and 5% $CO_2$ (Faubian *et al*. 1992; Jordan & Barker 1992; McLauchlan *et al*. 1992). Four commercial CA rooms were constructed in Florida in the season of 1972/73 for storage of 'Lula' avocados in bulk bins (Spalding & Reeder 1974). The rooms were run at 2% $O_2$ and 10% $CO_2$ at 7.2°C and 95% RH, and fruits were reported to be marketed in excellent conditions after 5 weeks of storage, except for some fruits with rind discoloration (CI) where temperature dropped below 4.4°C. In South Africa, Bower *et al*. (1989) suggested that even though fruit stored in CA (2% $O_2$ and 10% $CO_2$) were superior than in other storage systems the economic and logistical realities were not significant. Oudit and Scott (1973) reported a considerable extension in the storage life of 'Hass' avocados sealed in polyethylene bags. 'Hass' avocados sealed in polyethylene bags (0.015 to 0.66 mm) ranging in permeability from 111 to 605 cc $O_2/m^2$.hr.atm., and from 0.167 to 0.246 gr $H_2O/m^2$.hr.atm. and stored at 5°C for up to 4 weeks lost less weight and firmness compared with unsealed fruits (Gonzalez *et al*. 1990; González-Aguilar *et al*. 1997; Yahia & Gonzalez 1998).

Low-pressure atmosphere (LP), especially below 100 mm Hg, markedly prolonged the storage life of 'Hass' avocados (Apelbaum *et al*. 1977). Optimum conditions for LP storage of Florida avocados were suggested to be 20 mm Hg at 4.5°C (Spalding & Reeder 1976a; Spalding 1977a). Fruit held in these conditions for up to 3 weeks were firmer, and had less decay and CI than fruit held in 76 or 760 mm Hg, however, gases such as $CO_2$ and CO, can not be added when LP system is used. $CO_2$ is considered to be essential for control of decay and to ameliorate CI in avocados. 'Hass' avocados maintained in MA (0.1–0.44% $O_2$, 50–75% $CO_2$, balance $N_2$) for up to 5 days at 20°C had higher $CO_2$ production compared to fruit stored in air, most likely reflecting anaerobiosis (Carrillo-Lopez & Yahia 1990; Carrillo-Lopez & Yahia 1991; Yahia 1993b; Yahia and Carrillo-Lopez 1993; Rivera and Yahia 1994; Rivera *et al*. 1993). Fruit stored in this MA and then ripened in air had mesocarp and exocarp injury after 2 days. On the basis of these results Yahia (1993b) and Yahia and Carrillo-Lopez (1993) concluded that 'Hass' avocado fruit is very sensitive to insecticidal atmospheres, tolerating only one day at 20°C. These findings were confirmed by Yahia and Kader (1991) and Ke *et al*. (1995). 'Hass' avocados kept in 0.25% $O_2$ alone or in combination with 80% $CO_2$ for 3 days at 20°C, had higher concentrations of acetaldehyde and ethanol (Ke *et al*. 1995).

MA and CA are commonly used for transporting avocado fruit by sea to distant markets in refrigerated shipping containers (Yahia 1998). The atmosphere used and technology for controlling the atmosphere vary between shipping companies. Generally $O_2$ levels of 2–5% and 3–10% $CO_2$ are commonly used.

Low $O_2$ injury may appear as irregular brown to dark brown patches on the skin and may additionally cause diffuse browning of flesh beneath affected skin (Yahia, 1997a; Carrillo-Lopez and Yahia 1991; El-Mir *et al*. 2001; Loulakakis *et al*. 2006; Yahia & Rivera 1994). $CO_2$ atmospheres above 10% can be detrimental by leading to discoloration of the skin and development of off-flavour, particularly when the $O_2$ concentration is less than 1%.

Reducing ethylene levels to $<1\ \mu L\ L^{-1}$ by using ethylene scrubbers during CA storage may provide additional benefits for retarding ripening and decreasing the development of internal CI (Faubion *et al*. 1992).

## RIPENING

Avocados can be held on the tree for few weeks after they are physiologically mature, and will ripen after harvest, but time to ripen decreases with increasing time on the tree. Market research has shown that more avocados are sold if they are offered to the consumer in a ready-to-eat condition. This has led to a system of pre-ripening fruit prior to stocking. Fruit is treated with ethylene and held at 21°C before retailing. Fruit ethylene production begins after harvest and increases greatly with ripening to >100µl $C_2H_4$/kg·hr at 20°C. Treatment with 100 ppm ethylene at 20°C for 48 hours (early-season fruits), 24 hours (mid-season fruits) or 12 hours (late-season fruits) induces avocados to ripen in 3-6 days, depending on cultivar and maturity at harvest. There is an increasing move at the retail level toward 'ripe for tonight' programs that generally result in significant increases in sales. This is achieved by treating avocados with 10 to 100 ppm ethylene at 17°C to 20°C for approximately 48 to 72 (early-season), 24 to 48 (mid-season) or 12 to 24 h (late-season). This significantly reduces both the time to ripen (to 3 to 6 days, depending on cultivar and maturity), and also fruit to fruit variability in ripening (Gazit & Blumenfeld 1972). If fruit are stored prior to ethylene treatment, the duration of treatment required to achieve maximum rate of ripening is reduced. For 'Hass' avocado, after 3 to 4 weeks of storage there may be relatively little benefit of ethylene treatment (particularly for later season fruit) since the time to ripen decreases during storage. Heat production of avocados is much greater than many other fruit crops, and therefore careful attention should be paid to air flow and temperature management during ethylene treatment and subsequent ripening. Palletized fruit may reach temperatures of more than 30°C, with negative effects on ripe fruit quality. For this reason, ethylene treatment of palletized fruit should be carried out under forced-air conditions. Ripening rate depends on physiological maturity of the fruit, temperature and humidity, oxygen and carbon dioxide levels (Kurlaender 1996). During ethylene treatment, $CO_2$ levels should be maintained at less than 1% to 2% by either continual venting of the atmosphere, or full venting and ethylene re-injection if 'shot' systems are used. Avocados are best ripened at 15°C to 20°C (Hopkirk *et al*. 1994). The ripening rate at <15°C is relatively slow, and ripening at >25°C may result in increased decay, uneven ripening of the flesh and off-flavours. Avocado fruit fails to ripen properly at 30°C, even at 25°C, the level of post-harvest disorders was greater than in fruit ripened at 20°C, and best final quality was obtained with fruit stored at 6°C and then ripened at 15°C. However, if fruit are to be ripened at 25°C, then final quality was better if the fruit were not refrigerated but held at a temperature closer to the final ripening temperature. Following ripening, fruit should be pre-cooled to 5°C. Many consumers have trouble identifying ripe ready-to-eat avocados, especially green-skinned cultivars, and therefore stickers are now placed on ethylene gas-ripened avocados in retail outlets to help consumers select ripe fruits. Ripe (soft) avocados require care in handling to minimize physical damage.

### Effects of 1-methylcyclopropene (1-MCP)

Some experimental evidence have suggested that 1-MCP, an ethylene action inhibitor, delays ripening and reduces internal CI (flesh greying, vascular browning) which is associated with ripening during storage where storage times are long, or temperature management is poor (Pesis *et al*. 2002; Jeong *et al*. 2002). The optimum treatment conditions are 50 to 100 nL $L^{-1}$ at about 6°C for 18 to 24 h. 1-MCP treatments for 'Hass' can be effective at >4 weeks, however, for other cultivars it may cause higher levels of internal CI at even short storage times. Higher concentrations may result in excessive delays to softening and ripening which are likely to in turn increase disease incidence. 1-MCP does not reduce external CI (skin blackening) of 'Hass' avocados. 1-MCP-treated 'Ettinger' and 'Pinkerton' avocado fruit stored at 5°C for 3.5 weeks maintained a greener peel colour, lower chlorophyllase activity and less chlorophyll breakdown, reduced CI symptoms (expressed as mesocarp discoloration) and reduced PPO and peroxidase (POD) activities (Hershkovitz *et al*. 2005). Adkins *et al*. (2005) investigated the potential of 1-MCP to manipulate ripening of nonstored 'Hass' avocado fruit by treatment before or after ethylene and at different times during ripening, and found that ripening of fruit exposed to 100 ppm ethylene for 24 h at 20°C could be delayed by up to 3.3 days by applying 1-MCP. However, once the fruit started to soften there was little effect of 1-MCP, compared with no 1-MCP treated fruit. 1-MCP treatment was associated with increased severity of rots, caused mainly by *Colletotrichum* spp. and *Dothiorella* spp. Significant differences in disease severity were found between orchards, with replicates with low disease severity being less affected by 1-MCP treatment. These results indicate that 1-MCP can delay ripening, but careful sourcing of fruit is required to reduce the risk of diseases in ripe fruit, and there is some capacity to delay ripening using 1-MCP after ethylene. There is little potential to control ripening using ethylene after treatment with 500 nL $L^{-1}$ 1-MCP,

but lower concentrations may be more effective. 1-MCP and wax significantly delayed the ripening of 'Tower II' avocado stored at 20°C (Jeong *et al*. 2003). Fruit treated with both 1-MCP and wax had better retention of green peel colour and fruit firmness, and delayed climacteric ethylene evolution and respiration rates compared with other treatments. Waxing alone reduced weight loss and delayed softening, but did not delay climacteric ethylene evolution and respiration rates. Whereas firmness of control fruit decreased from >100 to 20 N over a 7-day period at 20 °C, fruit treated with both 1-MCP and wax required more than 11 days at 20°C to soften to 20 N. The firmness of waxed 'Booth 7' avocados declined from >170 to 15 N during 19 days storage at 13°C whereas fruit treated with both 1-MCP and wax required nearly 5 weeks to reach firmness values of 25 N. 1-MCP works by attaching to a site (receptor) in fruit tissues that normally binds to ethylene, preventing ethylene binding, and therefore causing the fruit to ripen and soften more slowly. 1-MCP was sorbed faster and in greater amounts by 'Hass' avocado fruit and avocado oil than by 'Cox' apple fruit and water, respectively (Daunya *et al*. 2003), which may have an influence on 1-MCP efficacy as a ripening inhibitor and should be considered when prescribing commercial 1-MCP application strategies. At the time of writing (2008) the application of 1-MCP is not commercially used yet for avocado fruit.

## IRRADIATION

Extension of shelf life by gamma irradiation has been successful for some fruits, but appears to hold little prospect for avocado. Akamine and Goo (1971) found avocado fruit to show surface and internal damage at 5 Krad. At this dosage and lower, the climacteric respiration occurred earlier than that for controls, thus giving no storage advantage. Smith and Jansen (1983) found 2.5 Krad to be the maximum safe dosage, but without significant advantage. Young (1965) studied the effect of gamma radiation on respiration, ethylene production and ripening of 'Fuerte' avocados, and reported that irradiation in the pre-climacteric phase at 5 and 10 krads caused an immediate doubling of respiration and a small ethylene production, 100 krads caused a doubling of respiration and small ethylene production, but severe injury and fruit did not ripen. Irradiation after the climacteric has been initiated or in the post-climacteric phase had no effect on ethylene production or respiration, nor was there any effect on the appearance or quality of the fruit. Doses in excess of 20 Krad seem to cause brown discoloration in the mesocarp; 10 Krad resulted in extension of storage life of 'Fuerte' avocados by 4–5 days at 20°C, but fruit irradiated at 50 Krad did not ripen, the tissue remained hard and turned brown (Nogalingam 1993).

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# 9
# Grapes

*Christian Chervin, Julia Aked and Carlos H. Crisosto*

## INTRODUCTION, BOTANY, CULTIVATION AND PRODUCT STATISTICS

### Introduction

The grape was one of the first fruits to be cultivated by man. Since the dawn of civilisation, the fermented product of grapes, wine, has probably been an important way of consuming grapes (McGovern *et al*. 1995). Wine residues have been identified in 7000-year-old jars in Iran (McGovern *et al*. 1996). However, consumption of the fresh and dried fruit has probably always been popular where the vines grew wild.

This chapter provides some basic information about the cultivation of grapes (this section) before looking at the physiology and biochemistry of the developing and mature grape berry. The final three sections of the chapter deal with post-harvest aspects of grapes pertaining to the three main product types: beverages (wine and juice), fresh fruit (table grapes) and dried fruit (sultanas, raisins and currants). Although today most grapes are converted to wine, the development of the post-harvest technology for grapes has concentrated on the fresh fruit. This is because all the eating-quality parameters (appearance, texture and taste) must be high in the commercial product. The quality of grapes for wine, drying or for other grape products is primarily dependent on harvesting the right varieties at the right time and preventing unwanted chemical changes during processing. The topic of wine production is so huge that this chapter describes only the quality factors required in the harvested grape as the basis of a good wine. Details of processing are omitted but references are given for further reading on this topic. There is relatively little published on the specific post-harvest requirements for grapes used for drying. In the section entitled 'Post-harvest technology for dried grapes', a summary of the basic processing and product preservation is provided.

### Botany

The grape plant is a vigorous vine of the family Vitidaceae Juss. (syn. Ampelidaceae; Vitacae) (Watson & Dallwitz 1991, 1992). The European grape *Vitis vinifera* (L.) is hermaphrodite whereas some native North American *Vitis* species are monoecious. Multiple buds are produced laterally on the previous season's cane and flowers are wind pollinated. The fruit clusters mature about 5–7 months after bud burst. The main cultivars in commercial production are described in the product sections below.

### Cultivation

Grape is one of the world's most widely grown fruit crops in relatively warm temperate-zone climates (see product statistics below). It is not well adapted to subtropical or tropical areas although special management allows dessert grapes to be harvested 2–4 times per year in tropical countries such as Thailand and Indonesia. Heat accumulation determines the type of grape that can be successfully grown. Between 950°C day and 1500°C day wine production predominates; above 1500°C day table grapes and fortified wines can be produced and above 1950°C day table grapes and dried fruit are dominant (Jackson & Looney 1999).

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*V. vinifera* is the dominant species for wine, fresh fruit or drying. This species is thought to originate in the Caucasus Mountains. Of the N. American species, some are used for juicing, some for rootstock and some interspecific hybrids for wine or dessert usage (Jackson & Looney 1999). The selection of sports and hybridisation has traditionally been the only methods of breeding *V. vinifera*, but they are slow because the grape has a long life cycle and high inbreeding depression (Gray *et al*. 1992). Over the past decade, a wide variety of molecular techniques have been developed to improve the identification, breeding and the study of genetic relationships among cultivars (Lefort & Roubelakis-Angelakis 2000; Reisch *et al*. 2000) and the grape genome sequencing (Jaillon *et al*. 2007) is leading to intense works in the grape research community.

The vine has deep roots and is drought tolerant although irrigation is necessary in some production areas. It is also tolerant of many soil types provided they are deep and well drained. Over-fertilisation, especially with nitrogen can lead to too vigorous growth (which may adversely affect wine quality). The vine and developing fruits are susceptible to a number of pests and diseases (Pearson & Goheen, 1988). Some recent concerns have emerged about salt concentrations rising in soils of irrigated vineyards, and their effects regarding the choice of rootstocks and fruit quality have been studied (Walker *et al*. 2007). In Europe and the United States, it is normal to use root stock resistant against the aphid *Phylloxera vastarix* which has caused large losses in these regions. Nematode-resistant root stock is also recommended. Fungal diseases can dramatically affect production. During wet weather, grey mould (*Botrytis cinerea*), downy mildew (*Plasmopora viticola*), anthracnose (*Elsinoë ampelina*) and phomopsis (*Phomopsis viticola*) can be serious. Powdery mildew (*Uncinula necator syn. Erysiphe necator*) can occur in both wet and dry regions. Crown gall (*Agrobacterium* spp.) is the most serious bacterial disease, and there are a number of viruses that damage the vine (Jackson & Looney 1999; Patil *et al*. 1995).

Classic texts on vine cultivation include Winkler *et al*. (1974) and Mullins *et al*. (1992). Other textbooks include Huglin and Schneider (1998), Jackson and Looney (1999), Reynier (1999) and Jackson (2000).

### Product statistics

World production of grapes in 2009 was estimated to be about 68 million metric tonnes (MT). The main producer countries were, in order of decreasing production volumes, Italy, China, the United States, France, Spain, Turkey, Chile, Argentina and India (FAO 2009).

Approximately half of the grapes are transformed into wine. The world production of wine was about 27 MT (representing around 36 MT of grapes) with the main producer countries being (in order of decreasing productivity): Italy, France, Spain, the United States, China, Argentina, Australia, South Africa, Chile, Germany and Portugal (FAO 2009). Of this production, about a quarter is exported. Leading exporters were: France, Italy, Spain, Chile, Australia, the United States, Germany, Portugal and South Africa. Only 0.5 million MT of unfermented grape juice was exported world-wide, with the main exporters being Italy, the United States, France, Spain, Argentina, Germany, South Africa and Chile (FAO 2002).

The remaining 32 MT of grapes are either table grapes or raisins (detail unknown). World export volumes of table grapes were in the order of 2.73 million MT with the main exporter countries being Chile, Italy, the United States, South Africa, Mexico, the Netherlands, Greece and Turkey (FAO 2002).

World export volumes of raisins were in the order of 0.6 million MT. The main exporters are Turkey, Iran, the United States, Greece, Chile and South Africa (FAO 2002).

## MORPHOLOGY AND PHYSIOLOGY

### Introduction

Grape berry physiology and biochemistry was last reviewed in detail by Conde *et al*. (2007) and formerly by Ollat *et al*. (2002). The mature grape berry is a nonclimacteric fruit with a low rate of post-harvest physiological activity. Grapes must therefore be harvested after they have reached optimum levels of colour development and of important solutes such as sugars and acids. Ripening changes occur in a relatively dramatic fashion during the development of the berry on the vine. These changes resemble, in a number of respects, those seen in climacteric fruit after harvest (see section on 'Berry development').

In the last decade, there has been considerable research on the molecular biology of berry development and maturation (Robinson & Davies 2000). The biochemical changes and their control systems that underpin fruit ripening, and thus final fruit quality are gradually being elucidated.

### Fruit morphology

Grape fruit develop as clusters (bunches) with each berry attached to the bunch stem (rachis and branches) via a pedicel which contains vascular bundles (also known as the cap stem). There is much variation between cultivars in stem structure (i.e. length of parts, toughness and adherence to berries) (Winkler *et al*. 1974). Impact or shaking of

bunches may cause the loss of berries, leaving an unsightly spray of vascular strands (brush).

Each berry consists of a multi-layered pericarp and may contain up to four seeds, although a number of cultivars for fresh consumption are seedless. The cells of grape berries are tightly packed with an internal gas volume of about 1.2 ml/100 g (Zosangliana & Narasimham 1993). The pericarp can be divided into the exocarp (skin), mesocarp (pulp) and endocarp. The pulp makes up most of the berry weight and cells are highly vacuolated, containing high levels of sugars and other soluble compounds (see below). The seeds contain high levels of tannins (5-8%), oil (10–20%) and phyto-hormones (Winkler *et al*. 1974). The pericarp contains plastids throughout berry development although their morphology changes at around anthesis and lipid-like globules form within (Hardie *et al*. 1996).

Two layers can be distinguished in the exocarp or skin, that is, the epidermis (6.5–10 µm) and the hypodermis (107–246 µm) (Alleweldt *et al*. 1981). The mature epidermis is covered with a cuticle about 3 µm thick which includes an outer 0.5 µm wax layer (Casado & Heredia 2001) and contains stomata which by maturity are not thought to be functional. Just after anthesis, the stomata density was approximately 7±2 stomata per berry for the cultivar Cabernet Sauvignon (Palliotti & Cartechini 2001). The nonliving layers give the grape its 'bloom' which is an important visual quality factor. The thickness and toughness of the skin differ among varieties and can affect the suitability of a cultivar for particular post-harvest uses (Winkler *et al*. 1974). The thickness of the epidermal cell walls is the only parameter showing a positive correlation with resistance to physical stress (Considine 1981). Thus the thickness and toughness of the skin contributes to the resistance of grapes to handling injury. Furthermore, the skin is the main location of the compounds that give the grape its colour, aroma and flavour (see below) (Winkler *et al*. 1974). Despite the stomata present in the epidermis, cuticular transport is thought to be the main route for water loss (Blanke & Leyhe 1987).

A recently described *in situ* fixation method, that better preserves the membrane integrity, should allow new information to emerge on the internal compartmentation of grape berry cells (Diakou & Carde 2001).

## Berry development

### *Pattern of development*

Ollat *et al*. (2002) and Kanellis and Roubellakis-Angelakis (1993) describe the division of the berry development into three stages based on research by a number of researchers, such as Alleweldt (1977) and Coombe (1992). Stage I is a period of very rapid cell division followed by marked cell enlargement. Stage II, the lag phase is a period of slow growth during which the embryos reach their final size, chlorophyll starts to be lost and acidity reaches its highest level. The start of stage III is called 'veraison' and is marked by a rapid acceleration in growth, softening of the berries, an increase in sugars and amino acids and the activity of some enzymes and anthocyanin accumulation in coloured cultivars. Acidity, chlorophyll and ammonia levels and respiration rates all decrease during this stage.

The individual berries within a bunch do not ripen synchronously (Coombe 1992). The variability that this causes has constrained studies of the underlying biochemistry and has commercial implications for fruit quality at harvest (Robinson & Davies 2000). Methods have been developed to extract RNA from grape fruit at different stages of development (Franke *et al*. 1995). Northern blot analysis has shown that some genes are expressed only in berries and only during ripening, whereas others are expressed in a range of grape tissues but are up-regulated during ripening. By homology with known genes, it appears that these grape genes fall into two groups: those that encode proteins involved in cell wall function and structure and those whose products appear in plants under applied stress (Davies & Robinson 2000). Further understanding of the coordination of development at a biochemical level will come as research continues into changing gene expression (Robinson & Davies 2000). The generation of Expressed Sequence Tags (ESTs) has been the basis of microarray analyses (Waters *et al*. 2005; Terrier *et al*. 2005) that many teams are now using, and the development of 'omics networks' (Grimplet *et al*. 2009; Zamboni *et al*. 2010) will speed up research on genes, proteins and metabolisms in the near future.

The recent characterisation of a fruit specific promoter should further help the design of experiments targeted towards study of berry ripening (Burger *et al*. 2006). Another recent study dedicated to a mutation of grapevine leading to fleshless berries will advance our understanding of the genetic and developmental processes involved in the differentiation of an ovary into a fruit (Fernandez *et al*. 2005).

### *Respiration and photosynthesis*

The respiratory rate of the average single grape berry is high early in stage I and then declines rapidly; it then shows a rise at veraison (between stage 2 and 3), with more $CO_2$ produced than $O_2$ consumed (Saulnier-Blache & Bruzeau 1967). The rate of gross photosynthesis on a dry weight basis peaks during the early part of stage I and then declines rapidly; on a single berry basis it shows peaks in

the later part of stage I and early part of stage III. Fully ripe berries show practically no photosynthetic activity (Koch & Alleweldt 1978; Niimi & Torikata 1979). Using the cultivar Cabernet Sauvignon, Ollat *et al*. (2000) found that during the whole growth period, the grape berry imported 12 mmoles of carbon. Respiration accounted for 18% of the imported carbon and fruit photosynthesis supplied 10% of the carbon required for fruit development. When fruit of the Pusa seedless variety were harvested at maturity and stored at 1°C, respiration rate declined for 30 days and rose thereafter (Rao *et al*. 1975).

### *Solute accumulation*

#### *Sugars and minerals*

The accumulation of sugars is the most important quality change in the ripening fruit. It is these sugars which are converted into alcohol during wine making and which give the sweetness desired in both fresh and dried fruit and fruit juice. It is not therefore surprising that there is considerable interest in understanding the processes that control the production and accumulation of sugars.

From anthesis to veraison, imported carbon (in the form of sucrose) is almost equally partitioned between pericarp, seed growth and respiration. At veraison, carbon imports increase. Then the carbon is mainly allocated to the pericarp and stored as the hexoses, glucose and fructose (Ollat *et al*. 2000). These two sugars are the main carbohydrates of the mature berry pulp. They are present in approximately equal amounts (total sugars = 12–27% fresh weight) although the actual ratio varies between cultivars. Cultivars with more fructose than glucose can be harvested earlier due to the greater sweetness of this sugar compared to glucose. As the fruit become over-mature, the fructose to glucose ratio increases (Winkler *et al*. 1974).

Up to veraison, water is imported mainly through the xylem. At the onset of ripening, the contribution of xylem water is reduced by embolism blockage (Coombe 1992). At this stage, carbon import increases fivefold due to a stimulation of water flow through the phloem.

The back-flow, water movement from the berry to the parent vine, may be an important component of berry weight loss at maturity in some cultivars, such as Shiraz (Tyerman *et al*. 2004). Mineral transport is related to the pathway of water import. Calcium is translocated during early berry growth while potassium is translocated during ripening (Ollat & Gaudillere 1997). Although it has been suggested that berry sink strength increases substantially at the onset of ripening, the factors that control the massive sugar import into the berries and the pathways of assimilate transport are still poorly understood. It is possible that an increase in berry alcohol dehydrogenase activity is linked to fruit ripening (Tesniere & Verries 2000) and that *Adh 2* expression depends upon ethylene signalling (Tesniere *et al*. 2004). There are no clear physiological means to explain these inductions yet. There is also evidence that sucrose transporters may play a role in sugar accumulation (Davies *et al*. 1999). A hexose transporter gene (Vvht1) has been cloned and shows a first peak of expression at anthesis, and a second peak about 5 weeks after veraison. The Vvht1 promoter sequence contains several potential regulating cis elements, including ethylene-, abscisic acid-, and sugar-responsive boxes (Fillion *et al*. 1999).

The effects of hormones on sucrose accumulation and metabolism at different developmental stages (I, II, veraison and III) were investigated by Xia *et al*. (2000). Gibberellic acid (GA), indoleacetic acid (IAA) and abscisic acid (ABA) all significantly facilitated $^{14}$C-sucrose import into the berries at all stages studied but caused differing effects on the subsequent transformation of the sucrose. For example, the transformation of $^{14}$C-sucrose to reducing sugars was enhanced by IAA whereas GA increased the accumulation of fructose. Recently, ethylene has been proved to regulate the sucrose transport into berries (Chervin *et al*. 2006).

#### *Acids*

The acidity level is a very important quality factor in both table grapes and those used for wine production. Consumer acceptance of table grapes and grape juice is strongly influenced by the sweetness to acid balance (Winkler *et al*. 1974). Acidity also determines the suitability of the fruit for wine making. Excessive tartness correlates with low sugar levels which give poor-quality wine (Ruffner 1982). However, in warm climates, grapes with a low pH and high acidity levels are generally desired for table wines. The brilliance and red intensity of coloured grapes is greater at moderate to high acidity and low pH. With low acidity and high pH, they tend to be bluish and dull (Winkler *et al*. 1974).

A review article gives details about the biochemistry of the acidity variations in grape berries (Terrier & Romieu 2001). Tartaric and malic acids constitute over 90% of total acids (% fresh weight); however, the ratio between the two acids varies considerably depending on the grape cultivar. Both acids accumulate before veraison although they show distinct patterns of accumulation (Ruffner 1982). Tartaric acid is thought to be stored both as insoluble calcium tartrates and as the free acid in the vacuole. A recent study demonstrated that ascorbic acid is the precursor of the tartaric acid (DeBolt *et al*.

2006). Malic acid is a very active intermediate in grape metabolism. At veraison acid levels start to go down. The decline in malic acid content is very rapid and is thought to be due to respiration via oxidative phosphorylation. The reduction in acidity is quicker under warm growing conditions (Kanellis & Roubellakis-Angelakis 1993). After veraison, two vacuolar proton pumps have been detected that create a positive membrane potential across the tonoplast resulting in the accumulation of organic acids inside the vacuole. The activity of these pumps increased in parallel during the period of sugar storage, while malic acid content decreased (Terrier & Romieu 2001). IAA, GA and ABA promoted the transformation of $^{14}$C-sucrose into organic acid at stage I, significantly inhibiting transformation at stage II (Xia *et al*. 2000).

*Phenolic components*

Tannins (proanthocyanidins) are the most abundant class of phenolics in grape berries and are the predominant determinants of astringency in red wines (Souquet *et al*. 1996; Cheynier *et al*. 1997). Other major phenolic compounds in grapes include anthocyanins, benzoic acids, cinnamic acids and flavonols (Flanzy 1998). Berry skins contain more hydroxycinnamic tartrates than the flesh, while the latter has more flavan-3-ols and procyanidins. The composition of grape skin proanthocyanidins at different stages of berry development has also been described by Kennedy *et al*. (2001). The seeds have high amounts of phenolics which form a significant proportion of wine tannins and contribute significantly to oxidative browning of grape juice. There has been considerable interest in the chemical properties of grapevine polyphenols, including nonflavonoids (stilbenes, phenolic acid derivatives) and flavonoids (flavanols, flavonols and anthocyanins), and their biological and pharmacological activities (Vitrac *et al*. 2004). A recent work has been published about the expression of different flavonol synthases in grape vines and berries (Fujita *et al*. 2006).

Anthocyanins give rise to the red and purple colouration of certain grape cultivars and are thus important quality factors in table grapes and wine. The malvidin derivatives are generally the most abundant anthocyanins in grapes. Interesting reviews have been published recently about anthocyanin content in wine grapes (Mazza 1995) and table grapes (Carreño *et al*. 1997). During the last 20 years, there have been several studies on the gene expression of anthocyanins summarised by Holton and Cornish (1995). In grapes, the cloning of various genes of the anthocyanin pathway was performed by Sparvoli *et al*. (1994). They found that most of them were induced by light in grape seedlings. The induction of the main genes involved in the anthocyanin pathway is probably resulting from complex interactions between various signals such as light, sugar, abscisic acid and ethylene among others (Mol *et al*.1996). Boss *et al*. (1996a) observed the expression of these genes in white and red grapes, the non-expression of some of these genes being correlated to the absence of anthocyanins. The transcription of most of these genes was clearly induced at veraison (Boss *et al*. 1996b). The UDP-flavonoid glycosyl transferase plays an important role in the redness of the berry tissues (Boss *et al*. 1996a; Kobayashi *et al*. 2004 and refs herein), catalyzing a step that is known to stabilise the anthocyanins (Piffaut *et al*. 1994). A recent study points out the role of a transcription factor involved in phenylpropanoid pathways (Deluc *et al*. 2006). Plant hormones like auxin and abscisic acid may play a role on the expression of these genes (Davies *et al*. 1997). From a physiological point of view, some competition between the anthocyanin and stilbene synthesis has been highlighted (Jeandet *et al*. 1995).

Some recent advances in anthocyanin analysis by electrospray ionisation mass spectrometry have been reported (Sarni-Manchado *et al*. 1997). In the last decade, some studies have focussed on the antioxidant properties of the grape anthocyanins and associated variations between red and white, young and old wines (Tubaro *et al*. 1999).

*Aromatic compounds*

The aroma of grapes is attributed to over a hundred different compounds, mostly located in the skin. Some cultivars from the species *V. labrusca* and *V. rotundifolia* have very distinct aromas, as do the Muscat types of *V. vinifera* although other cultivars of this species are not highly aromatic. Some aroma compounds are isoprenoid secondary metabolites such as monoterpenes and damascenone (Jackson 2000). It has been suggested that their synthesis is linked to the formation of lipid-like globules in plastids found in the pericarp (Hardie *et al*. 1996). Some other aroma precursors are present in a glycosylated form (Williams *et al*. 1995).

## Hormonal changes

The hormonal changes from anthesis to maturation of the berry are well summarised in the review by Kanellis and Roubellakis-Angelakis (1993). Very little is known about the post-harvest role of phyto-hormones in grapes.

### *Gibberellic acids*

The size of mature berries correlates well with the number of seeds and parthenocarpic or stenospermocarpic cultivars

generally have small fruit unless treated artificially with growth hormones. The seeds have high levels of hormones such as abscisic acid and gibberellic acid-like compounds. Girdling of certain cultivars such as the parthenocarpic black Corinth is known to increase gibberellic acids (GAs) in the fruit and increase the size of the berries. GAs are sprayed on the developing grape bunch to control bunch shape and berry size (Lynn & Jensen 1966). Transcripts potentially involved in seedlessness have been described recently (Costenaro-da-Silva *et al*. 2010).

### *Ethylene*

Grapes have been classified as nonclimacteric fruit as their ripening phase was apparently not triggered by ethylene and not associated with a respiratory burst. In fact ethylene levels are very low in grapes, within the range of pmoles. $g^{-1}_{FW}$, however the use of a specific inhibitor of ethylene receptors has shown that ethylene signalling is involved in some ripening metabolisms such as the increase of the berry volume during the second growth phase and the anthocyanin accumulation (Chervin *et al*. 2004). Indeed the ethylene signalling modulates the berry expansion, via the transcription regulation of many genes, among which xyloglucan endotransglucosylases and aquaporins seem critical (Chervin *et al*. 2008) and changes occur in transcripts related to ethylene signals (Chervin & Deluc 2010). Wounding and water deficit have been shown to induce ethylene emission by grapevines, but the influence on fruit ripening was not assessed (Boschetti *et al*. 1997). Goldschmidt (1998) has published a review about the possible involvement of ethylene in the ripening of nonclimacteric fruit.

It has been suggested that the levels of ethylene and abscisic acid (ABA) act synergistically to promote pre-harvest ripening (Coombe & Hale 1973). The grape industry has already adopted the use of an ethylene precursor (2-chloroethylphosphonic acid), also known as ethephon, whose spray applications around veraison enhance colour development, in pigmented cultivars, with a concomitant fall in acid levels and sometimes a rise in sugar levels (Weaver & Montgomery 1974; Shulman *et al*. 1985). The impact on anthocyanin accumulation may be due to ethylene effects on several enzymes involved in anthocyanin synthesis, among which the UDP glucose-flavonoid 3-O-gucoslyltransferase (El-Kereamy *et al*. 2003). Ethephon also stimulates abscission and is used to chemically thin just after full bloom and to improve berry removal during mechanical harvesting for wine production (Szyjewicz 1984).

### *Abscisic acid and auxins*

Abscisic acid (ABA) levels increase in the maturing fruit and are thought to induce *de novo* synthesis of gluconeogenic enzymes (Palejwala *et al*. 1985). ABA-specific binding sites have been located in the endomembranes of grape berry mesocarp with maximum binding values coinciding with development phase II and dropping off at veraison (Zhang *et al*. 1999).

The abscisic acid is involved in the grapevine response to partial root zone drying (Stoll *et al*. 2000), a method that consists in boosting grape ripening by altering the irrigation schedule, thus creating a stress beneficial to grape quality when well managed.

On the contrary, auxins act primarily in the young berry formation, thus the conjugation of auxin to amino acid leading to low auxin levels in the berry may be part of the ripening induction (Bottcher *et al*. 2010).

### *Jasmonates*

There is an increasing interest in the study of jasmonate roles in grape berry physiology. Their levels seem related to the presence of seeds (i.e. more jasmonates in seeded berries), and they seem to follow an accumulation kinetic that resembles the ethylene one (Kondo & Fukuda 2001; Chervin *et al*. 2004). They are also known to stimulate stilbene accumulation, with a more pronounced effect on leaves (Larronde *et al*., 2003).

### *Brassinosteroids*

A novel series of compounds has been determined as potential grape hormones, brassinosteroids are indeed produced at relatively high level at the onset of berry ripening and stimulated this berry developmental process (Symons *et al*. 2006).

## Defence mechanisms

Immature fruit of all plant species contain preformed and/or inducible defence systems (production of phytoalexins). Usually however, these systems become less effective as the fruit ripens. This appears to be true in grape berries for the best studied grape phytoalexin, a stilbene called resveratrol (Jeandet *et al*. 1991). Maximum levels of resveratrol were shown to be induced by UV light from 1–5 weeks post-flowering, dramatically declining in maturing berries sampled from 10–16 weeks post-flowering. It was suggested that this might be a major factor in the increasing susceptibility of ripening grape berries to *Botrytis cinerea* infection (Bais *et al*. 2000). On the other hand, a study has shown that levels of defence-related protein, basic chitinase and a thaumatin-like protein (grape osmotin) rise proportionally with fruit reducing sugar content (Derckel *et al*.

1998; Salzman *et al*. 1998). The timing of the accumulation of grape osmotin correlates with the inability of the fungal pathogen powdery mildew (*Uncinula necator*) to initiate new infections of the berry (Tattersall *et al*. 1997). Loulalakis (1997) showed that an osmotin-like gene was expressed in grape cell cultures exposed to ethylene.

### Soluble proteins

Proteins in the fruit pulp contribute to clouding of juice and wine. Recently some authors have described the proteome of berry skin (Deytieux *et al*. 2007). The major soluble proteins appear to be the pathogenesis-related chitinases as described previously (Pocock *et al*. 2000). Polyphenol oxidase (PPO) activity in grapes has been well characterised (Okuda *et al*. 1999; Yokotsuka *et al*. 1988). The role of PPO in berry and juice browning is discussed further in sections on wine and juice grapes and on table grapes respectively. There is evidence of only one PPO gene in grape with high levels of expression in young developing berries, leaves and roots, but little expression in mature tissues (Dry & Robinson 1994). The compartmentation of a number of key enzymes in grape berries during development is described by Famiani *et al*. (2000).

### Cell wall changes

Grape cell walls are composed of about 90% polysaccharide and less than 10% protein. The two main types of polysaccharides, cellulose and polygalacturonans show considerable varietal differences in their relative abundance (Nunan *et al*. 1997). The firmness of table grapes is an important quality attribute. Grape berries begin to soften at veraison and the degree of softening at maturity is determined largely by cultivar. Although most post-harvest berry softening has been attributed to loss of water (Nelson 1979), the softening associated with ripening is considered to result from changes in the composition of the cell walls (Robinson & Davies 2000). During softening, depolymerization of pectin and xyloglucan molecules and a decrease in the amount of hemicellulose and cellulose have been detected (Yakushiji *et al*. 2001). Large changes in protein composition also occur (Nunan *et al*. 1998). There is a steady decrease in total pectin substances during grape ripening and a decrease in methyl-esterification of insoluble pectins (Barnavon *et al*. 2001). Furthermore levels of calcium, a mineral which stabilises plant cell walls, decrease during berry ripening (Cabanne & Doneche 2001). Soluble pectic polymers from mesocarp activity in juices (also named musts) may play a detrimental role in white wine making by restricting juice extraction (Robertson *et al*. 1980) and delaying must clarification (Saulnier & Brillouet 1988). The expression patterns of cell wall modifying enzymes during berry development have been described by Nunan *et al*. (2001).

## POST-HARVEST TECHNOLOGY FOR WINE AND JUICE GRAPES

### Introduction

Wine grapes have not been the subject of much post-harvest research so far. This may change in the future with trends towards longer transport times of grapes to wineries, more mechanically harvested grapes that are more exposed to post-harvest deterioration and the increasing need to preserve very delicate fruit flavours. The production of wine is a complex process which transforms the grape berries into an alcoholic beverage. Recent books published on the science of wine making include Jackson (2000) for North America, Rankine (1997) for Australia and New Zealand and Ribéreau-Gayon *et al*. (1998) and Flanzy (1998) for France. A quite comprehensive and practical book about most laboratory analyses has been published by Australian academics (Iland *et al*. 2000). A book listing the OIV official methods for must and wine analyses is also available (Anonymous 1999).

Fewer than 30 cultivars provide the world's classic quality wines, all from *V. vinifera*. Hundreds more are used to a limited extent. Some important cultivars are: red: pinot noir, merlot, cabernet sauvignon, shiraz, grenache and tempranillo; and white: chardonnay, riesling, sauvignon blanc, chenin blanc, muller thurgau, chasselas, Semillon and palomino (Galet 2002). There might be interesting aromas to be gained from the use of some other Vitis species.

### Harvest maturity requirements

The timing of wine grape harvest is very critical. Too early and the grapes are too acid. Too late and they may lack acidity or suffer reduced yields from bird damage or rots. The berries must contain the correct balance of flavour and aromatic compounds. The typical maturation levels of sugars should lie between 16% and 24% and acid between 0.6% and 1%. The yield of juice depends primarily on the cultivar's degree of pulpiness. Other factors influence yield such as the stage of ripeness, size of berries, seediness, thoroughness of fermentation and efficiency of crushing, pressing and other operations (Winkler *et al*. 1974).

#### *Sampling*

The most important source of variation is in the individual vine (Rankine 1997). A detailed set of precautions is given by Rankine to enable the most representative sample to be

achieved. Various effects of freezing and homogenising the sample with various durations and tools has been reported recently (Cynkar *et al*. 2004).

***Sugars***

Sugar level at harvest depends on the region of production. For classical dry wines, a global figure of 200 g of reducing sugars/kg of fresh grapes can be given (Jackson 2000), this will roughly give a 12% alcohol wine. But cool climate areas will produce grapes which are usually less sweet than warmer and sunnier areas. Moreover the type of desired wine will also influence the date of harvest (thus the sugar level), for example late harvested grapes (with sugar levels above 300 g / kg) will be used to produce sweet wines. An optimal harvest date is critical to achieving the right sugar level.

There are pre- or post-harvest practices known to increase the sugar levels like leaving the grapes on the vines for one or two months beyond the optimal harvest date, thus leading to natural sugar enrichment by berry desiccation. The vineyard has to be in a suitable climatic area (dry afternoons avoiding strong rot development).

***Acids***

The acid level varies according to the region and type of wine, but as described in *Berry Development* (acidity) it is inversely proportional to the sugar level i.e. as the acid content drops, the sugar content increases. To give an idea of the range of acidity found in musts, one can cite average acidity of Cabernet Sauvignon in Bordeaux over 20 years: 100 ± 20 g of meq. / L (Ribéreau-Gayon *et al*. 1998). Jackson (2000) states that must pH should be below 3.3 for whites and 3.5 for reds. The acid content is important in various ways: it affects sulphur dioxide efficiency, the freshness of the taste and the ability of the wine store well, among other factors. An optimal harvest date is critical to achieving the right acid level.

***Polyphenols***

Polyphenols are of great importance to wine quality and can be assessed using various methods (see *Berry Development*: *phenolic components*). However, rapid and accurate measurement of polyphenol berry content is still difficult (Jackson 2000), and a matter for further research. An optimal harvest date and good post-harvest management are critical to achieving and preserving the polyphenol content. There are very few studies on the polyphenol changes over the post-harvest period; one report least shows a global decrease of most of them during this period (Borsa & Di Stephano 2000), but an ethylene postharvest treatment was shown recently to increase polyphenols in wine grapes (Botondi *et al*. 2011); this effect was associated to a partial dehydration. Furthermore, polyphenolics are substrates of enzymes that may alter wine quality (Flanzy 1998). Another aspect, linked to the food science, is the optimisation of polyphenol extraction in the case of red wines using various processes that will not be detailed here.

***Aroma potential***

Aroma potential depends on several compounds which vary according to the grape cultivar. Jackson (2000) cited the terpenes and the glycosyl-glucose contents, as being among the markers for aroma potential which have received attention. Their assessment by simple means is still a matter for research and development (Flanzy 1998). A suitable harvest date and good postharvest management are critical to optimise this potential (see 'Harvesting and post-harvest management; below). Some other aromatic componds, like methoxypyrazines that are typical of green pepper, are already present in grape berry tissues in the aromatic form (Allen *et al*. 1990), but rarely desired in the resulting wines. However, in white wines, there are also some aromas produced during the fermentation, that are derived from precursors, whose levels in grape depend on cultivation conditions as some volatile thiols in Sauvignon blanc (Gachons *et al*. 2005).

***Phytopathogens***

One of the main post-harvest problems due to grape moulds and *Botrytis cinerea* in particular is the oxidative action of fungal laccase (Nair & Hill 1992; Jackson 2000). This extracellular enzyme induces browning of white musts by oxidising polyphenols and causes off-flavours in red wines (Rankine 1997). Laccase activity in musts can be assessed by various automated systems which are already in use in many wineries (Ribéreau-Gayon *et al*. 1998). Good pre-harvest and post-harvest control of fungal infections is critical to managing this problem. Laccase has been used as a marker for successful disease control in grapes (Dubos *et al*. 1996). Recent efforts have been made for the assessment of gluconic acid as an indicator of rotten grapes (Crachereau 2004).

***Waxes***

Waxes from the berry epidermis are the primary source of waxes in wine and may contribute to colloidal turbidity of wines (Rosenquist & Morrison, 1988). The waxes offer anchoring points for large numbers of spores of various microorganisms (Zahavi *et al*. 2000) that will influence the post-harvest life of the berries and the wine quality.

### Harvesting and post-harvest management

#### *Temperature control*

The temperature of freshly picked grapes should be as low as possible to limit biochemical alteration processes (Rankine 1997). Grapes are often picked at night with mechanical harvesters and transported in refrigerated trucks when long distance trips are necessary. Solid carbon dioxide ($CO_2$) or dry ice is sometimes used to cool harvested grapes (see below).

#### *Oxidation control*

Some antioxidants (ascorbic acid, sulphur dioxide) are sometimes introduced into the transport bin just after harvest, but $SO_2$ addition is not recommended before de-stemming as it favours the extraction of compounds with a grassy taste (Ribéreau-Gayon *et al*. 1998). Limiting oxygen access to the grapes after mechanical harvest can also help to minimise unwanted oxidative changes (Flanzy 1998) and inert gases ($CO_2$, $N_2$) have been tested during transport.

Before pressing grapes used for white wines, $CO_2$ is sometimes added to protect the grapes from oxidation and cool them down (for example using solid $CO_2$). On-line addition of $CO_2$ gas in the must as an antioxidant is sometimes set-up between the hopper and the storage tank, or the pre-fermenting vat.

#### *Sorting*

Sorting is a crucial step to get the best of hand-harvested grapes, and may limit the quantity of rotten bunches to be sent to a given tank, thus increasing the must quality and limiting the amount of sulphur dioxide required. Ideally sorting is carried out in the vineyard or it can be done on arrival in the winery. For mechanically harvested grapes, systems separating stems from juice are recommended to avoid a grassy taste (Ribéreau-Gayon 1998).

#### *Drying*

Natural drying on shelves or on the ground, for example as carried out in Jerez, Spain, is another post-harvest step aiming to concentrate the sugars and obtain a higher alcohol degree. The yield in juice is usually very low, as little as 300 L / ton of grapes (Ribéreau-Gayon *et al*. 1998). The vineyard has to be in a suitable climatic area (at least dry autumn afternoons to avoid strong rot developments). Alternatively, artificial drying using forced warm air may be used. The association of partial dehydration and changes in protein patterns has been studied recently (Di Carli *et al*. 2010).

### Juice and jelly production

Juice is an important product in some countries (see section *Product statistics*). For white grapes, the juice is extracted from the crushed fruits using a basket press. The juice is filtered through cloth and bottled. It may be preserved either by adding $SO_2$, sodium benzoate or by pasteurisation. Although the flavour of the juice is better from cold-pressed fruits, hot pressing can increase yields by as much as 20%. Coloured grapes need to be heated for 10–15 min at 60–63°C in order to extract the coloured anthocyanins treatment (Patil *et al*. 1995).

Browning is one of the most important quality changes in grape juice, especially from white grapes (Yokotsuka *et al*. 1988). Intensity of browning depends on the activity of polyphenol oxidase and the type and concentration of certain phenolic compounds in the juice (Sapis *et al*. 1983a). Soluble proteins can cause haze and sediments in the final product and levels are exacerbated by damage to the fruit caused by mechanical harvesting and long distant transport which delays pressing (Pocock *et al*. 1998). Sediments in the juices can be removed by clarification with kaoline or bentonite treatment, freezing or enzyme treatment (Patil *et al*. 1995).

Some grape juice is clarified for use in blended juices. The prevention of 'wine stone' or the crystallisation of tartrate is a problem for long-term storage of the juice. Exchanging sodium for potassium in the juice by ion exchange will change the relatively insoluble potassium hydrogen tartrate for the more soluble sodium salt (Arthey & Ashurst 2001).

In the United States, about 30% of juice produced is used to make jelly. The most important cultivar in the United States for juice and jelly production is Concord (Patil *et al*. 1995). Grape juice is occasionally concentrated following de-acidification and removal of water usually by evaporation under a partial vacuum. Concentrated grape juice can have a sugar precipitate if it is concentrated above about 55° Brix but this will quickly re-dissolve on dilution (Arthey & Ashurst).

## POST-HARVEST TECHNOLOGY FOR DRIED GRAPES

### Introduction

The main dried products of grapes are raisins, sultanas and currants. Raisins are the second most important product of the grape vine after wine (Shanmugavelue 1989).

### Cultivars

The main grape types used for commercial drying are all *V. vinifera* cultivars (Jackson and Looney 1999). Currants

are universally produced from the small dark seedless Zante type grape (known as Black Corinth in California) although other grapes (e.g. the Australian Carina are used; Arthey & Ashurst 2001). In Australia both Thompson's seedless and Sultana grapes are used to make sultanas. In California, Thompson's seedless are used to make raisins. In both California and Europe, Sultanas are used to make sultanas. Muscat raisins are known as such in Europe and America, while in Australia, they are known simply as raisins. These raisins are sweeter than other types. The Muscat grapes have large berries with seeds which may or may not be removed after drying (Arthey & Ashurst 2001).

### Harvest maturity indices

A high-quality dried product depends on the harvest quality. This is determined by the berry size, the uniformity and brilliance of the berry colour, the texture of the skin and pulp, the moisture content, chemical composition and presence of decay and foreign matter. There is evidence that the timing of harvest can be critical to final quality, not just in terms of berry sugar content but that it affects other parameters such as product colour (Uhlig & Clingeleffer 1998).

### Harvesting

Grapes for drying are usually hand-picked. Generally, machine harvesting causes too much berry damage but the canes can be pruned mechanically with the bunches still attached and hung to dry on the vine (Jackson & Looney 1999).

### Drying technology

A review of raisin production is given by Arthey and Ashurst (2001), Patil *et al*. (1995) and Waskar (1993). For efficient drying, grapes should have a high sugar content of 20–24° Brix. The grapes may be dried naturally (common in California, Iran and the USSR) or they may be pre-treated to speed up the drying process. A solar drier that is substantially more efficient than natural drying for grapes has been described by Fuller *et al*. (1990). The moisture reduces from about 70% to about 15%. Differences in the thickness and toughness of the skin between varieties influence the rate of water loss in raisin making (Winkler *et al*. 1974). The raisins are then winnowed mechanically to remove the capstem, leaves and stem pieces. After washing and grading, the raisins are filled into packs ranging in size from a few grams to bulk packs of about 12.5 kg for other food manufacturers to use.

For some products it is normal to dip the grapes before drying in a solution of potassium carbonate (2.5–4.5%) containing a 'dipping' oil. Other dips include sodium hydroxide (NaOH), citric acid or a mixture such as an alkaline, oil-in water emulsion. There may be benefits to combining alkali dipping with a microwave pre-treatment to reduce total drying time (Kostaropoulos & Saravacos 1995).

It appears that the dip changes the structure of the waxy bloom making it more permeable to water (Rojchev & Botiyanski 1998). It also seems that it makes the grape more transparent to infrared rays, allowing a better radiant heat uptake. It can speed up the drying process by several weeks (from 4–5 weeks to 8–14 days). Pre-treatments such as NaOH and citric acid have been shown to cause a substantial reduction in cell wall pectins (Femenia *et al*. 1998).

Muscat grapes are usually alkaline treated due to their larger size. Those that are not treated are carefully handled so as not to damage the bloom. The resulting dried fruits are used for high-class outlets such as health food stores (Arthey & Ashurst 2001). To optimise quality, various combinations of pre-treatments may need to be evaluated for particular cultivars and under local conditions (Gowda 2000).

### Improving product quality

A light colour for dried grape products is considered highly desirable. The extent of browning in the dried product is determined amongst other things by the activity of polyphenol oxidase (PPO) particularly in the skin of the berry. Cultivars with a naturally low level of PPO dry to a lighter colour than others (Rathien & Robinson 1992). Low (<21° Brix) or very high sugar levels (>23° Brix) can increase browning in the dried fruit (Uhlig & Clingeleffer 1998). Berries exposed to the sun before harvest tend to produce darker dried product than shaded fruits (Uhlig 1998).

In some countries, sultanas and occasionally raisin grapes are treated with sulphur dioxide to bleach the fruit and give a more golden colour. The fruits are placed in purpose-built fumigation chambers (houses). Sulphur is then burned in a draught channel under the chamber, the gas enters the chamber and treats the fruit. Residues up to 2000 mg/kg are permitted. The fruits are then dried by one of the methods described above.

Some products may be given a light coating of mineral oil to improve handling and prevent stickiness and clumping when packaged.

### Problems of dried grapes

An important quality problem of dried grapes is the migration and crystallisation of sugars on the outside known as sugaring. Skin characteristics influence the degree of sugaring of natural raisins during storage. The delicate skin of Monukka raisins renders them susceptible to sugaring,

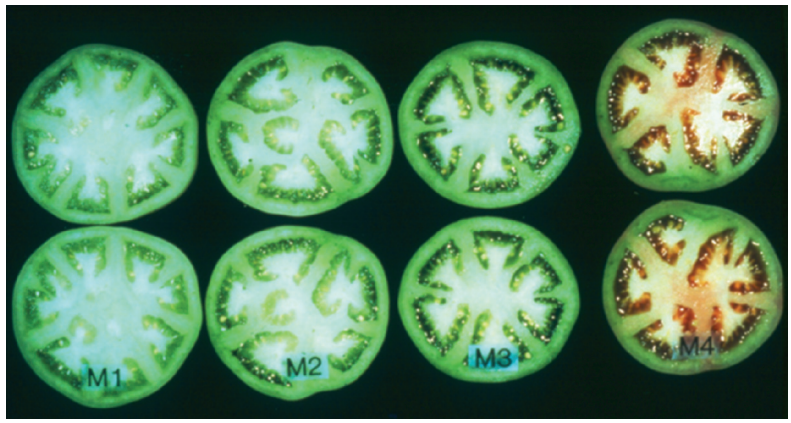


**Plate 2.1** Internal development of green tomato fruit. From left to right: M1 locular tissue is still intact and seed coats have not hardened; M2 has one or more locules containing gel and seeds with hardened coats; M3 is mature green with gel in all locules and autocatalytic ethylene production initiated; M4 has internal red color while remaining green externally. Photo credit: J.K. Brecht, University of Florida.

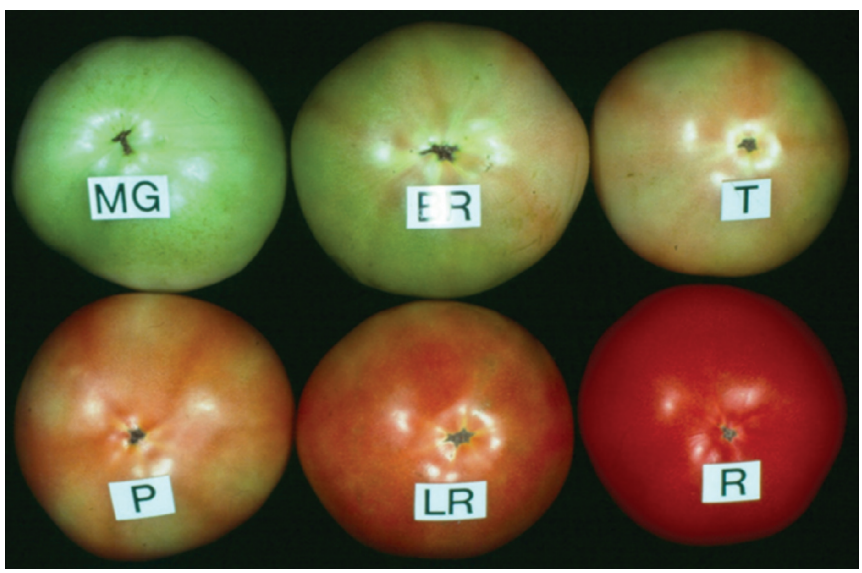


**Plate 2.2** Ripening stages of tomato. From top left: MG = mature green, incipient ripening; BR = breaker, with red color development at the distal or blossom end of the fruit; T = turning, with red color on 10–30% of the fruit surface; P = pink, with red color on 30–60% of the fruit surface; LR = light red, with 60–90% of the fruit surface red in color; R = red, fully ripe and ready to eat. Photo credit: J.K. Brecht, University of Florida.

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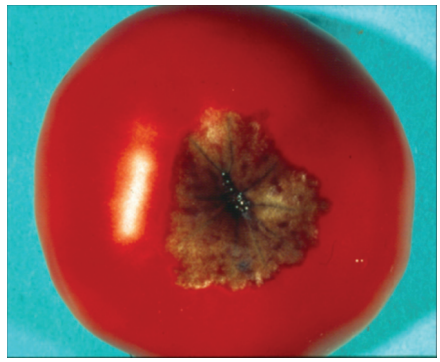

**Plate 2.3** Blossom-end rot (BER) caused by calcium deficiency. Photo credit: A.A. Kader, University of California.

**Plate 2.4** Blotchy ripening. Photo credit: K.A. Bergsma, University of Florida.

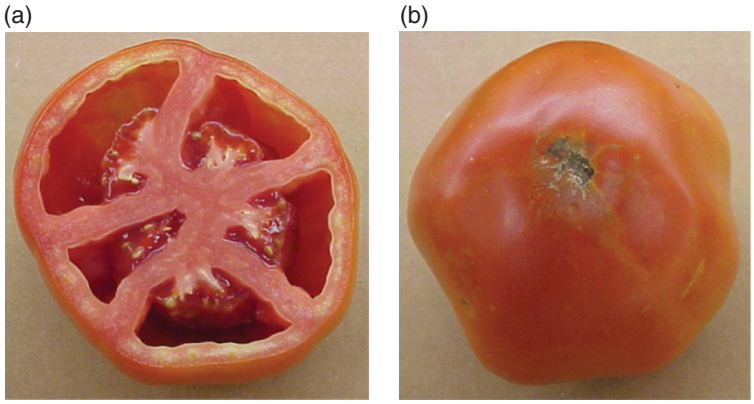


**Plate 2.5** (a) Internal view of a tomato fruit with severe puffiness due to inadequate pollination, fertilization or seed development most commonly caused by too low or high temperatures during fruit set. Photo credit: S.M. Olson, University of Florida. (b) External view of a puffy fruit – note the flat-sided shape indicating severe puffiness. Photo credit: S.M. Olson, University of Florida.

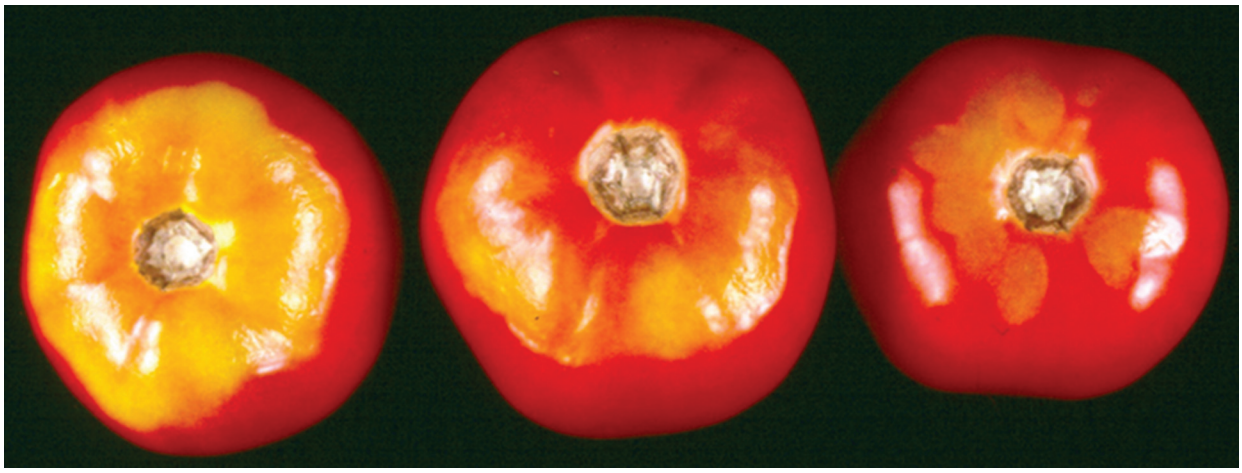

**Plate 2.6** Sunscald, sunburn or sunscorch caused by excessive temperature as a result of direct exposure to sunlight. Photo credit: J.K. Brecht, University of Florida.

**Plate 2.7** Catfacing thought to be caused by incomplete pollination leading to fruit deformity. Photo credit: S.M. Olson, University of Florida.

**Plate 2.8** Mechanical injuries inflicted on tomato fruit during harvest and handling operations. Photo credit: S.A. Sargent, University of Florida.

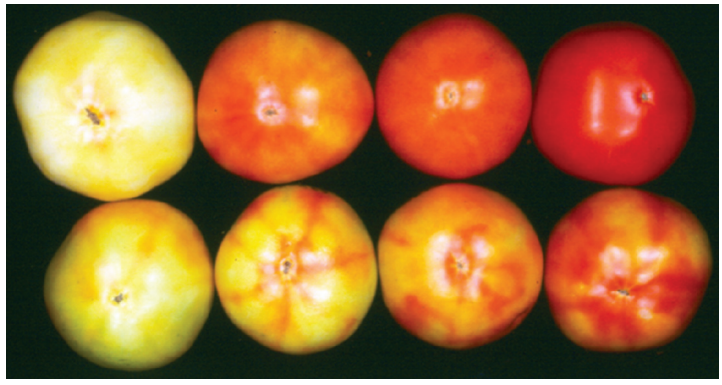

**Plate 2.9** Abnormal color development of tomato fruit following exposure to chilling temperature. Photo credit: J.K. Brecht, University of Florida.

**Plate 2.10** Alternaria rot on tomato fruit damaged by chilling injury. Photo credit: A.A. Kader, University of California.

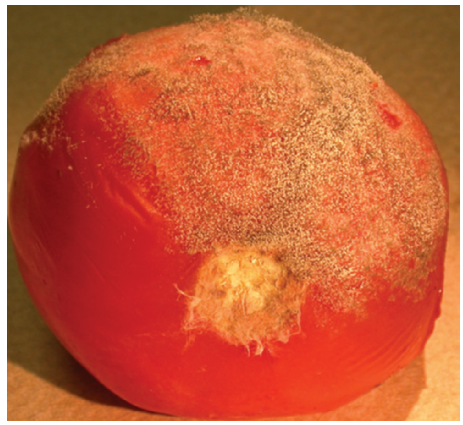

**Plate 2.11** Grey mould rot caused by *Botrytis cinerea*. Photo credit: J.A. Bartz, University of Florida.

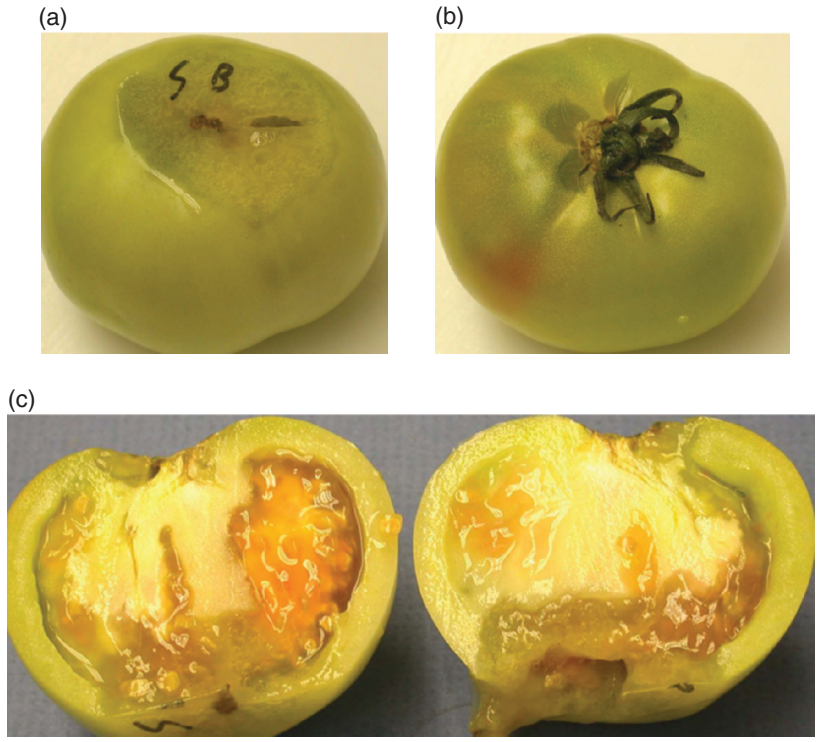


**Plate 2.12** (a) Bacterial soft rot caused by *Erwinia carotovora* at the distal or blossom end of a tomato fruit. Photo credit: J.A. Bartz, University of Florida. (b) Bacterial soft rot caused by *Erwinia carotovora* at the proximal or stem end of a tomato fruit. Photo credit: J.A. Bartz, University of Florida. (c) Bacterial soft rot caused by *Erwinia carotovora* at the stem end of a tomato fruit showing liquefaction of the affected tissue. Photo credit: J.A. Bartz, University of Florida.

**Plate 2.13** Sour rot caused by *Geotrichum candidum*. Photo credit: J.A. Bartz, University of Florida.

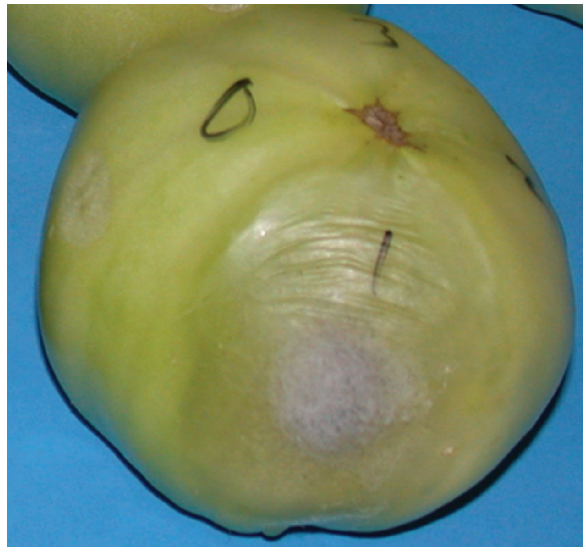

**Plate 2.14** A Rhizopus soft rot lesion that was initiated at the site of a wound on a green tomato fruit. Photo credit: M.J. Mahovic, University of Florida.

**Plate 2.15** Rhizopus soft rot on a ripe grape tomato. Photo credit: M.J. Mahovic, University of Florida.

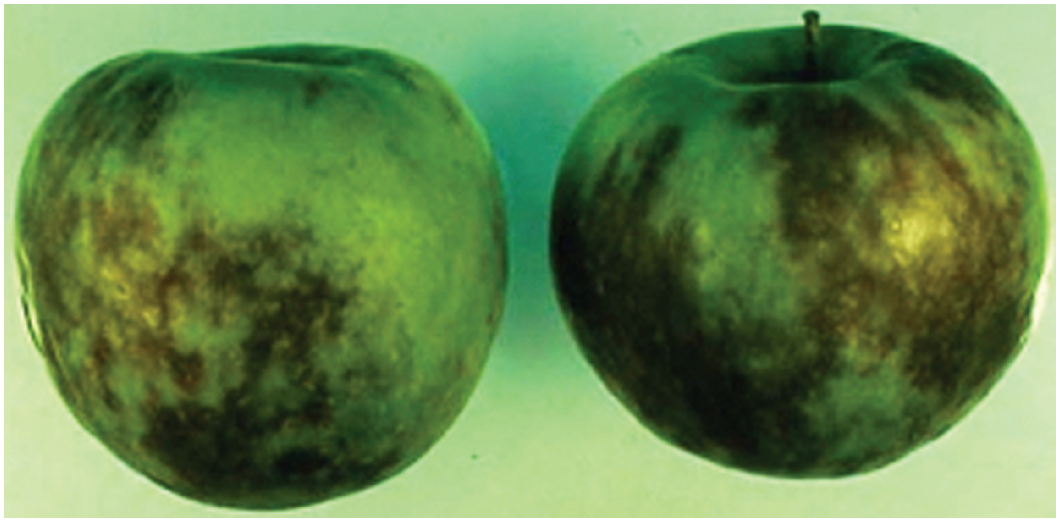

**Plate 5.1** Symptoms of superficial scald on 'Granny Smith'.

**Plate 5.2** The peel removed from a scalded and nonscalded region on 'Granny Smith', showing the superficial nature of the disorder.

**Plate 5.3** Symptoms bitter pit, a calcium-related disorder.

**Plate 5.4** Radial (left) and diffuse (right) browning symptoms in 'Pink Lady™' apples after storage.

**Plate 5.5** Blue mould infection in 'Pink Lady™' apple during storage.

**Plate 7.1** Pineapple fruit showing black rot symptoms and fungal growth on rotted tissue.
Photo credit: Minuka Weerasinghe.

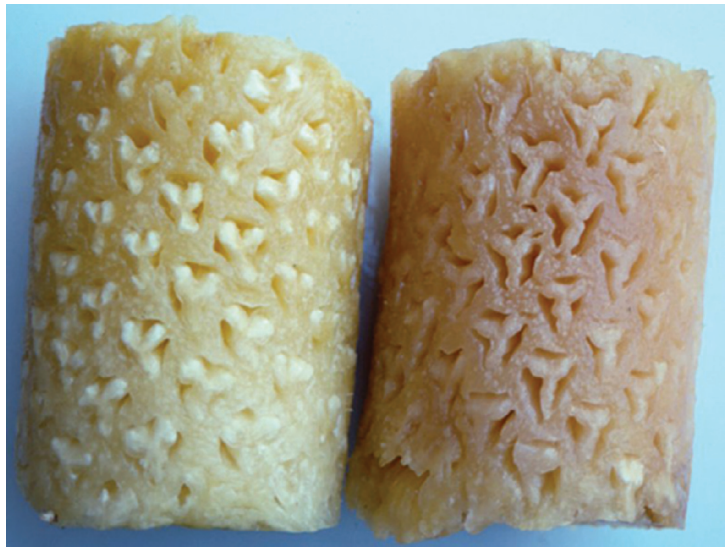

**Plate 7.2** A pineapple cylinder showing pink disease symptoms (right) and a healthy cylinder (left).
Photo credit: Queensland Department of Primary Industries and Fisheries.

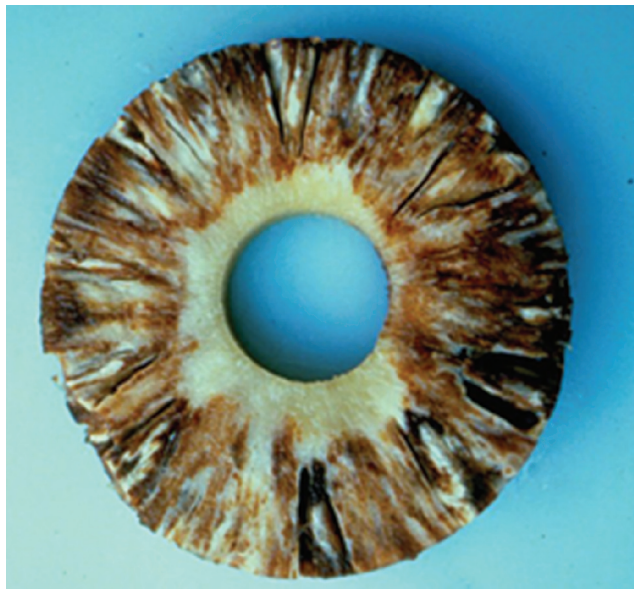

**Plate 7.3** Marbling of pineapple, a section view. Photo credit: Queensland Department of Primary Industries and Fisheries.

**Plate 7.4** Mature fruits of pineapple varieties Mauritius (left) and Kew (right).

**Plate 7.5** The development of internal browning symptoms in pineapple cv. *Mauritius* (Queen group) during cold storage. From left to right: 10, 14 and 21 days of cold storage.

**Plate 8.1** Colour change during ripening of Hass avocado.

**Plate 9.1** Botrytis rot of grapes.

**Plate 10.1** Peach chilling injury symptoms observed during cold storage: flesh mealiness and flesh browning.

**Plate 10.2** Peach gray mold (*Botrytis cinerea*).

**Plate 10.3** Peach brown rot (*Monilinia fructicola*).

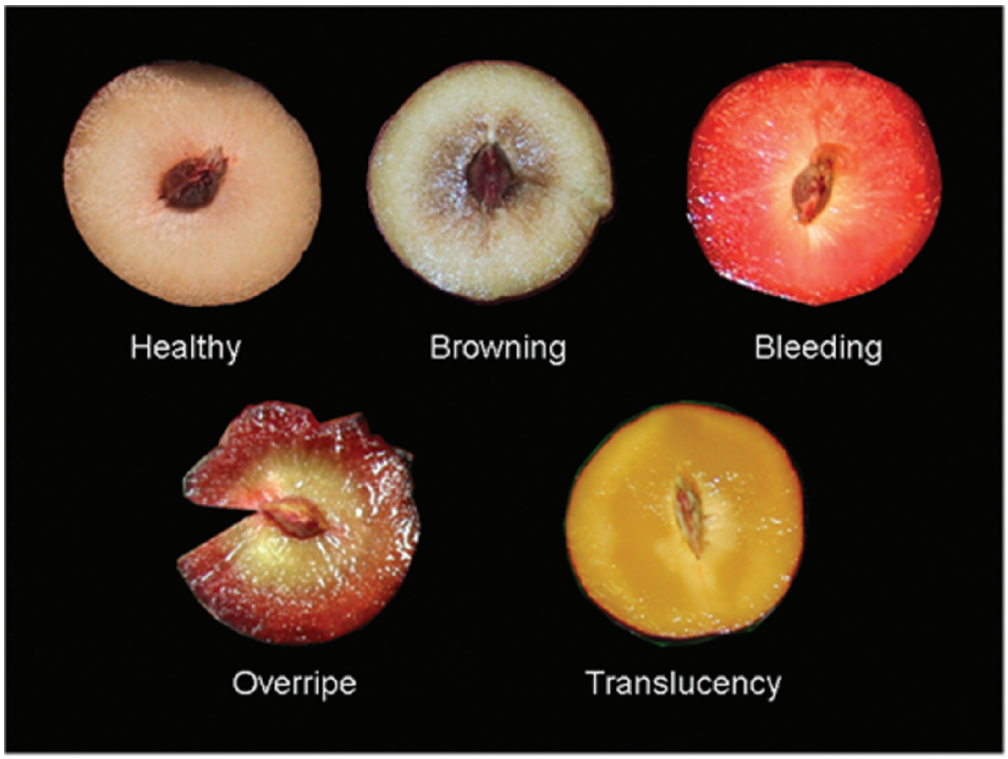


**Plate 10.4** Plum chilling injury symptoms observed during cold storage: flesh browning, flesh bleeding, gel breakdown and flesh translucency (overripe).

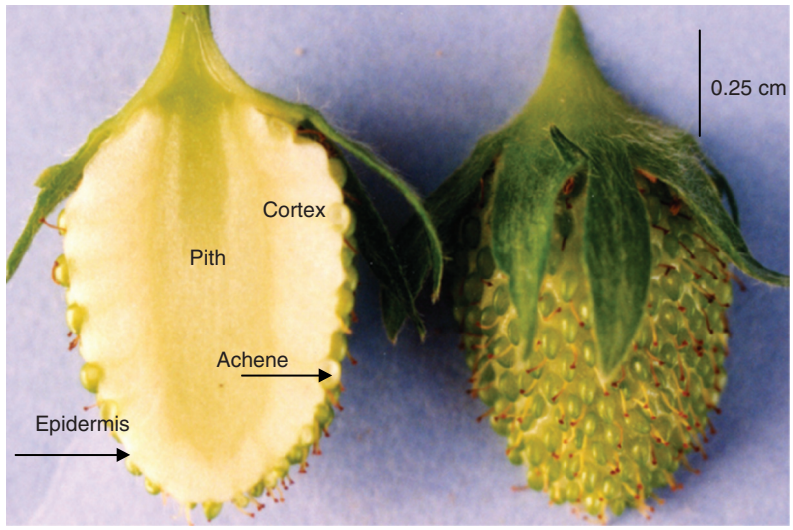


**Plate 11.1** Transverse section (LHS) through green stage I (7 days after anthesis) strawberry cv. Elsanta fruit showing pith, cortex, epidermis and achenes.

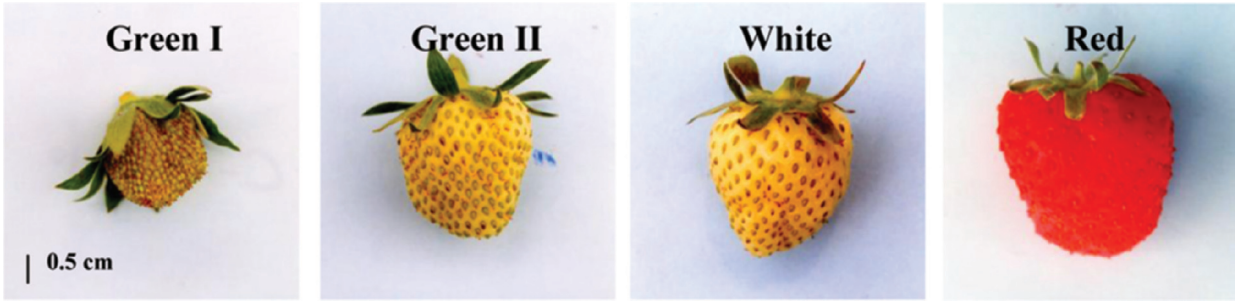


**Plate 11.2** Developmental stages of strawberry cv. Elsanta fruit.

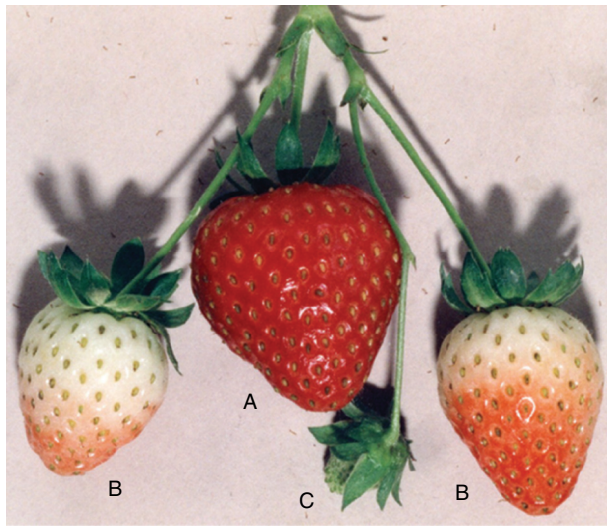


**Plate 11.3** Arrangement of strawberry cv. Andana fruit cluster (infructescence). (A) primary, (B) secondary and (C) tertiary fruit.

**Plate 11.4** Transparent storage vessel used for disease severity assessment of strawberry cv. Elsanta fruit (Terry & Joyce 2000). High RH was achieved by placing each fruit on a plastic mesh stand over distilled water (20 ml) and covering the transparent container (284 ml capacity) with perforated polypropylene film (15 μm thickness, 400 μm diameter holes, 5 holes per $cm^2$, Cryovac, UK) secured with an elastic band.

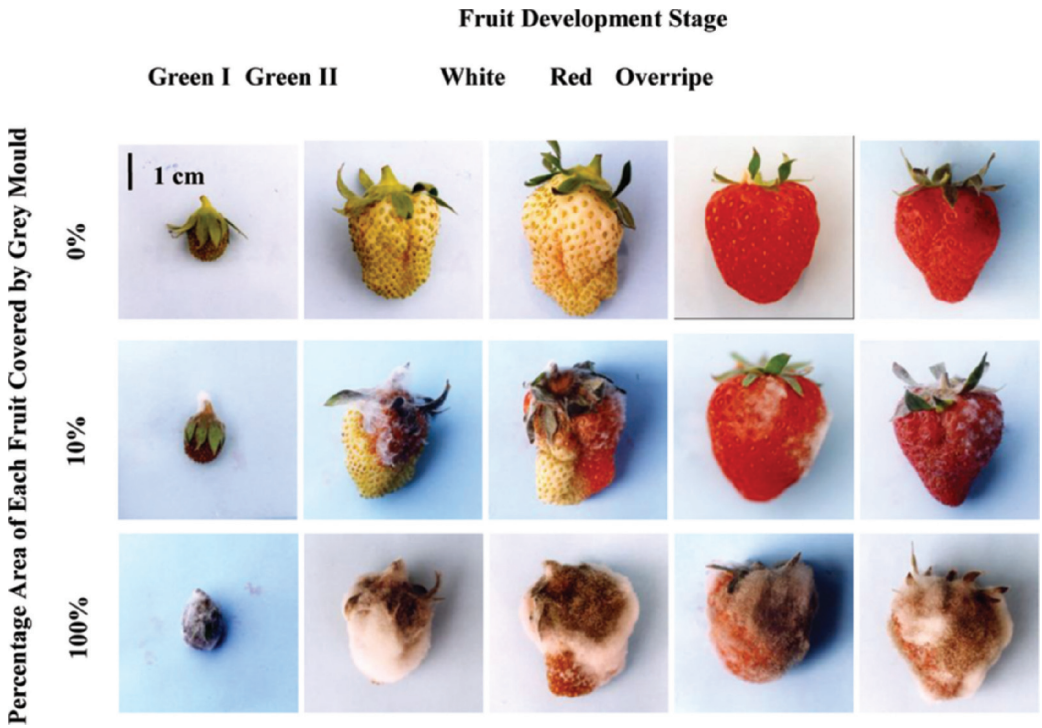


**Plate 11.5** Disease severity chart showing percentage areas of different fruit stages covered with grey mould disease.


**Plate 11.6** 1-DTLC (*C. cladosporioides*) bioassay of crude ethanol extract partitioned into an organic dichloromethane phase of green stage I (lane 1), white (lane 2) and red (lane 3) cv. Elsanta fruit (100 µl spot; 0.2 ml $g^{-1}$ FW) and run in hexane: ethyl acetate: methanol (60:40:1 v/v/v). Dotted line = origin. Dashed line = solvent front. Similar results were seen for replicate TLC plates (data not shown). (From Terry *et al*. 2004, with permission.)


**Plate 14.1** Harvest maturity for cantaloupe and Galia-type melons showing background colour.

(a)

(b)

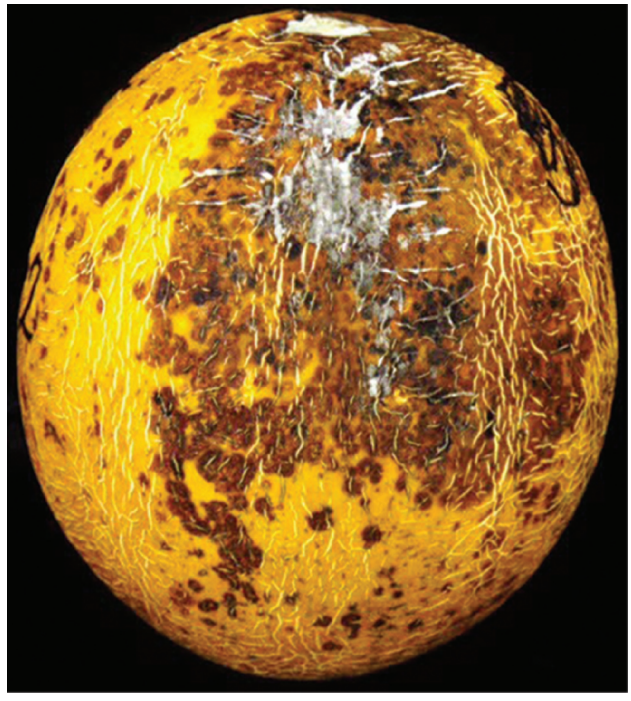

**Plate 14.2** Chilling injury symptoms include (a) pitting on watermelon, (b) bronzing on 'Galia' and (c) on honeydew, and (d) tissue collapse of Beit Alpha cucumber induced by storage at 5°C.

(c)

(d)

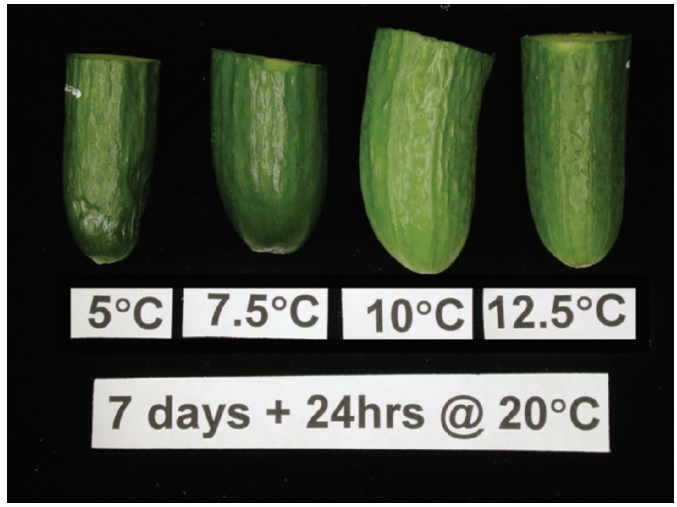


**Plate 14.2** Continued

**Plate 14.3** Senescent effects from ethylene exposure to Beit Alpha Cucumber: epidermal collapse followed by secondary infection. (Photo credit: J. Lee).

**Plate 16.1** Soft rot of potato. (Courtesy of Sutton Bridge Crop Storage Research, AHDB PCL)

**Plate 16.2** Bacterial soft rot in potato illustrating potential for disease spread. (Courtesy of Sutton Bridge Crop Storage Research, AHDB PCL)

**Plate 16.3** Dry rot of potato. (Courtesy of Sutton Bridge Crop Storage Research, AHDB PCL)

**Plate 16.4** Gangrene of potato. (Courtesy of Sutton Bridge Crop Storage Research, AHDB PCL)

**Plate 16.5** Tuber blight in potato. (Courtesy of Sutton Bridge Crop Storage Research, AHDB PCL)

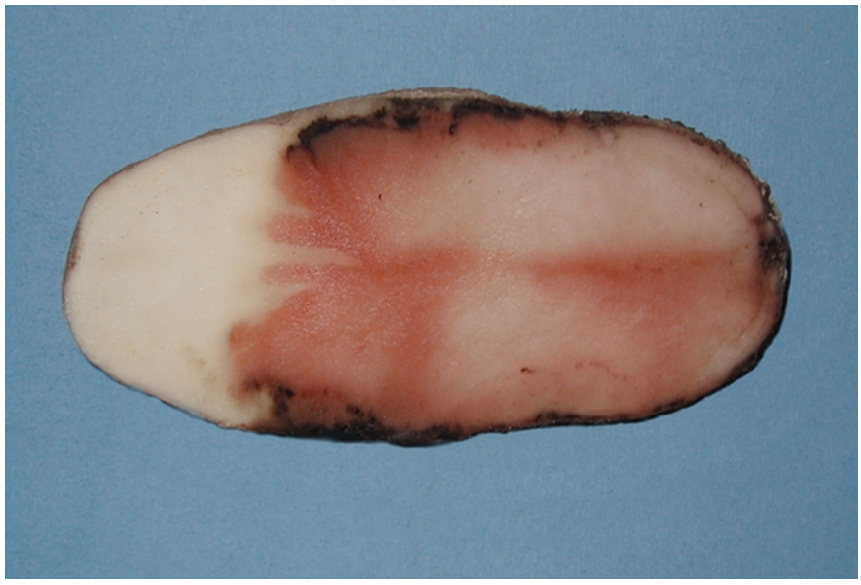

**Plate 16.6** Pink rot of potato. (Courtesy of Sutton Bridge Crop Storage Research, AHDB PCL)

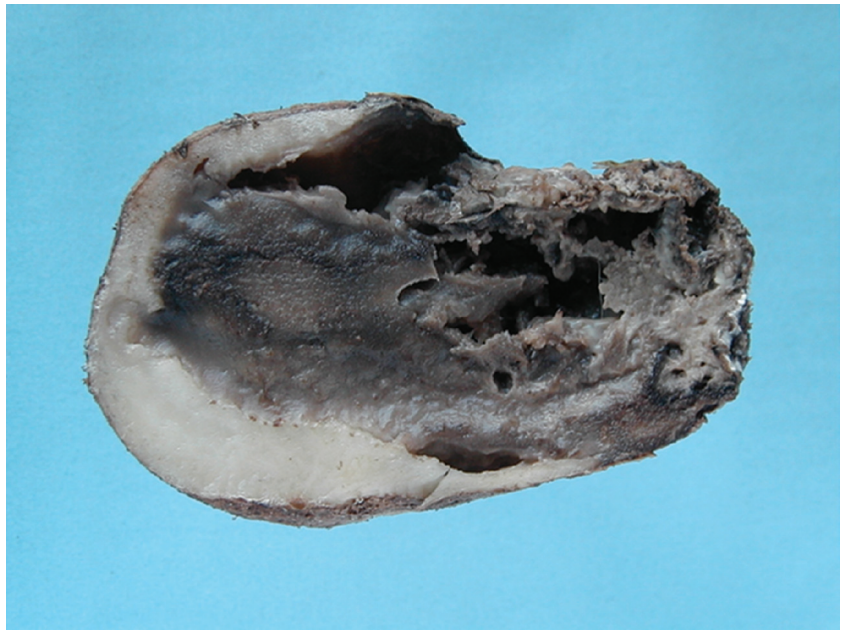

**Plate 16.7** Watery wound rot in potato. (Courtesy of Sutton Bridge Crop Storage Research, AHDB PCL)

**Plate 16.8** Rubbery rot of potato. (Courtesy of Sutton Bridge Crop Storage Research, AHDB PCL)

**Plate 16.9** Black dot in potato. (Courtesy of Sutton Bridge Crop Storage Research, AHDB PCL)

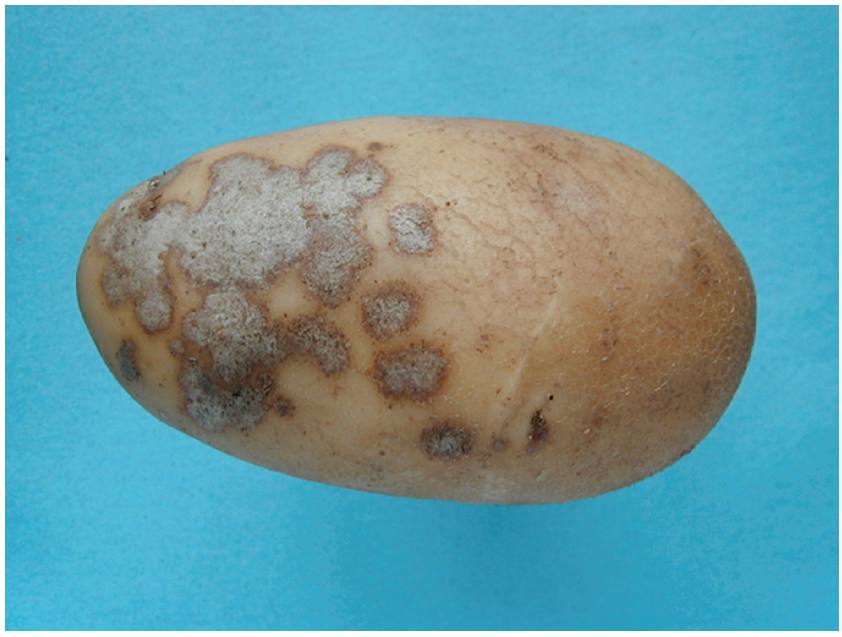

**Plate 16.10** Silver scurf in potato. (Courtesy of Sutton Bridge Crop Storage Research, AHDB PCL)

**Plate 16.11** Skin spot in potato. (Courtesy of Sutton Bridge Crop Storage Research, AHDB PCL)

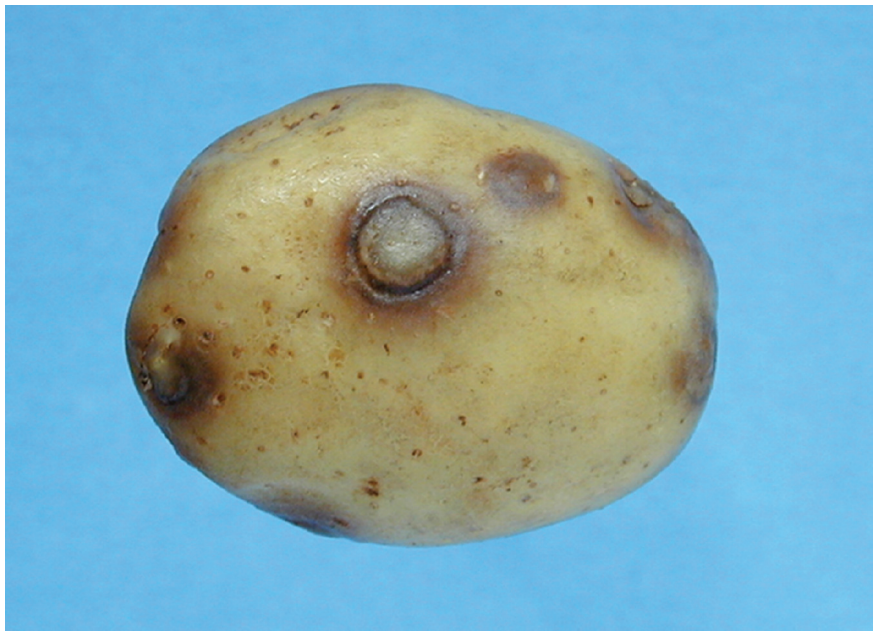

**Plate 16.12** Necrotic ring PVY NTN in potato. (Courtesy of Sutton Bridge Crop Storage Research, AHDB PCL)

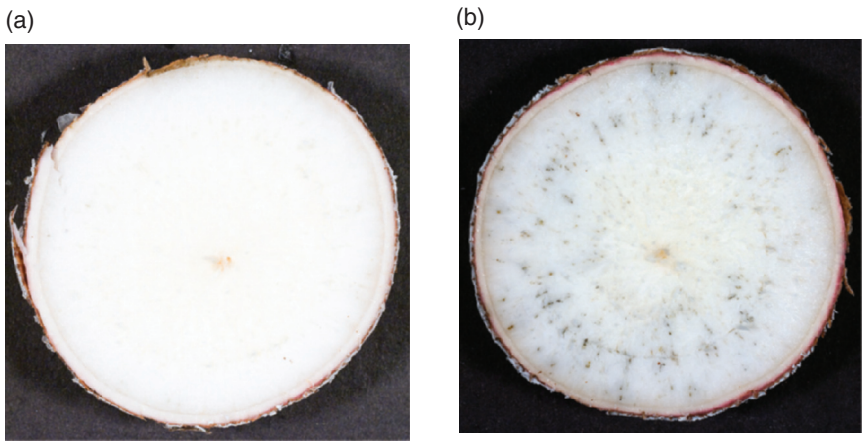


**Plate 18.1** Cross-section of (a) a fresh cassava root, and b) a root exhibiting post-harvest physiological deterioration (J. Beeching).

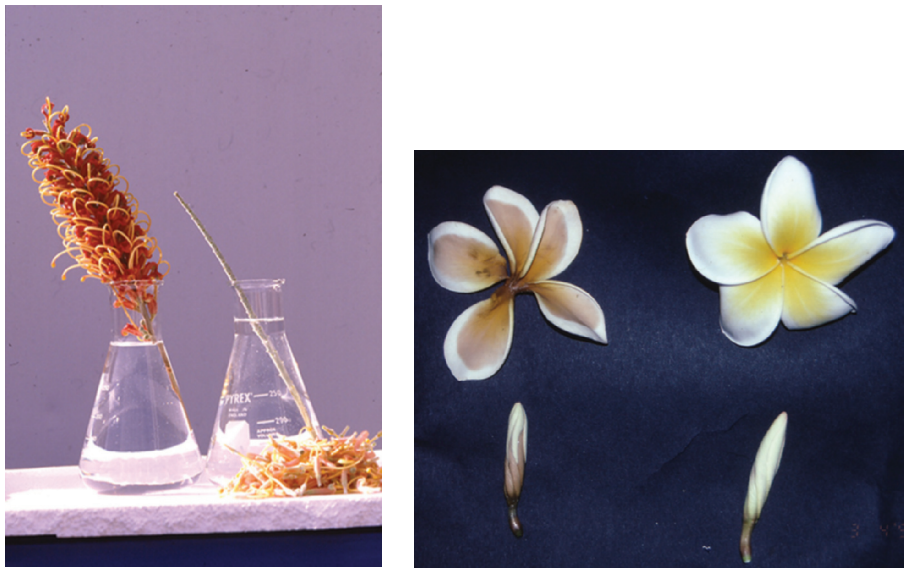


**Plate 19.1** Physiological disorders of ethylene-induced flower abscission from grevillea (LHS image; control inflorescence on left, treated inflorescence on right; Joyce and Beal 1999, courtesy of CSIRO publishing) and low temperature-induced chilling injury of frangipanni (RHS image; treated flower and bud on left, control flower and bud on right).

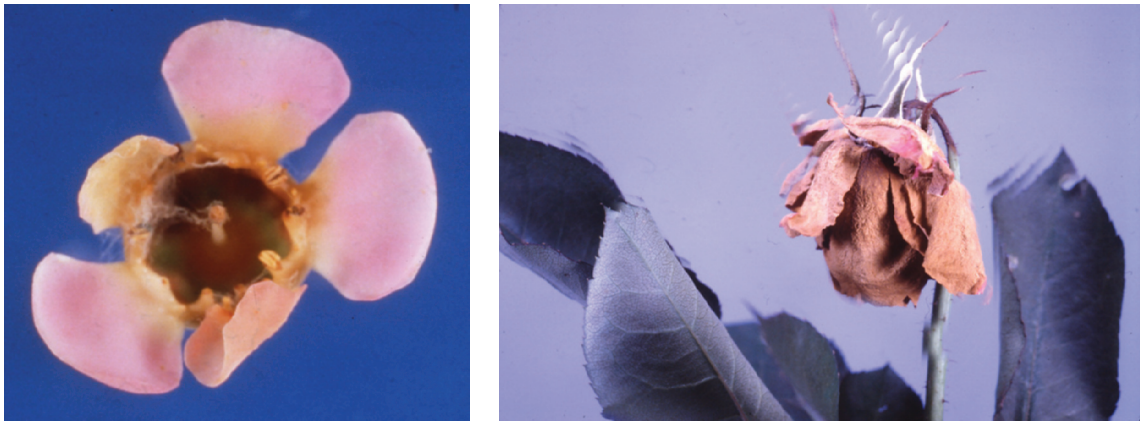

**Plate 19.2** Botrytis disease symptoms (tan lesions) on Geraldton waxflower (LHS image) and rose (RHS image) flowers.

**Plate 19.3** Fresh dyed Geraldton waxflower flowers.


**Plate 19.4** A range of primary (LHS image) and secondary (RHS image) packaging for cut flowers.

**Plate 19.5** Dutch clock auction wholesale marketing system in operation at the Aalsmeer flower market in the Netherlands.


**Plate 19.6** Basket of processed cut flowers and foliage.

**Plate 19.7** Leaf colour pattern obtained by stem-uptake bleaching (LHS image) and superficial mould growth resulting from over-glycerining (RHS image) of plant material.

whereas the tough skins of Black Corinth and Thompson Seedless usually prevent sugaring (Winkler *et al*. 1974).

Ecchymosis is when the raisins contain more than 16% water and are stored in bags or in deep bins, the lower part is pressed and the skin may be interrupted. Under these conditions the syrup migrates out of the raisin. Very soon it takes a dark colour and a lot of yeasts etc. start to ferment the molasses.

***Pests, moulds and mycotoxins***

A wide range of pests and diseases may be found on dried grape products if the product is not treated chemically with insecticidal compounds or is not protected by suitable packaging. Typical fungi include *Penicillium*, *Aspergillus*, *Cladosporium*, *Erotium and Alternaria* spp. Pests (insects and mites) may attack the grape berry before, during and after drying. Insecticide treatments before harvest may control some of these pests post-harvest (Buchanan *et al*. 1984); however, attentions should be paid to the fate of these chemical as drying can increase pesticide residue levels fourfold (Cabras *et al*. 1998). A biocontrol method with a granulosis virus has been shown to be highly effective against *Plodia* spp (Vail *et al*. 1991) and attempts have been made to combine effective packaging with parasitic wasps to control the almond moth *Cadra cautella* in commercially packaged raisins (Cline & Press 1990).

Ochratoxin A and aflatoxins may be found in dried grape products and methods for measuring concentrations of Ochratoxin A in these products and aflatoxin have been described (Bacigalupo *et al*. 1994; MacDonald *et al*. 1999).

## POST-HARVEST TECHNOLOGY FOR TABLE GRAPES

### Introduction

Table grapes are a high-value fresh-fruit commodity. Consumers will pay a premium for a quality product that has a display value as well as being a convenient and tasty fruit for consumption. 'White' (green/yellow) and red/purple/'black' cultivars are internationally popular (Figure 9.1). China grows by far the most fresh table grapes in the world. In 2006 China produced over treble the amount of table grapes (6.5 million MT) grown by the next largest producer, Turkey (USDA 2007). In both cases, the majority of this fruit is consumed internally.

World export volumes of table grapes are in the order of 2.73 million MT with the main exporter countries being, in descending order, Chile, Italy, the United States, South Africa, Mexico, the Netherlands, Greece and Turkey (FAO 2002). In many major importing markets, there is a consumer preference for seedless cultivars (Perl *et al*. 2000) and in some countries (e.g. the United Kingdom) the market for seeded table grapes has contracted substantially.


**Figure 9.1** Packaging three colours of grapes (rainbow pack) is becoming very attractive to consumers.

### Cultivars

The major cultivar of table grapes is probably Italia (Muscat) with around 700 000 tons produced per year in Italy in the early 1990s; the main table grape cultivars grown in France are Chasselas, Muscat de Hambourg and Alphonse Lavallée (Vidaud *et al*. 1993). Another important cultivar is Regina Bianca also known as Razaki in Turkey and Rosaki in Greece. In California, which produces 90% of US table grapes, the major cultivars are 'Thompson Seedless' ('Sultanina') and 'Flame Seedless', marketed mostly during the summer months. The early season market in the Coacheilla Valley is dominated by 'Perlette', 'Sugraone' ('Superior Seedless'), Midnight Beauty and Flame Seedless. 'Princess', 'Ruby Seedless', 'Crimson Seedless' and 'Autumn Royal' make up the bulk of the remaining production. There is also increasing production of the seeded 'Red Globe' cultivar which is important for export in the mid-to-late season. The Chilean and Spanish industries are being developed based on California cultivars while the South Africa grape industry has its own cultivars such as Sunred Seedless, Regal Seedless, La Rochelle, Dauphine, Bonheur and Bien Donné (ARC 2001).

### Maturity and quality indexes

The table grape is a nonclimacteric fruit with a relatively low rate of physiological activity. Optimal flavour attributes are usually obtained at commercial maturity. The main maturity index is the sugar content, determined as the %

total soluble solids (TSS), otherwise known as Soluble Solid Concentration (SSC) or °Brix. For certain specific cultivars and situations, the titratable acidity (TA) and SSC-TA ratio are used as maturity indices (Guelfat-Reich & Safran 1971; Crisosto *et al*. 1994). Cultivars other than 'white' ones also have minimum colour maturity requirements, based on the percentage of berries in the cluster that show a certain minimum colour intensity and coverage. Other quality criteria for table grapes are good appearance, free of decay, thin skin, large size, good texture and flavour. The rachis should be fresh and green (i.e. not desiccated and brown). The bloom is also an important quality factor. It is destroyed by over-handling and rubbing which causes the berries to become shiny rather than lustrous.

Minimum maturity requirements vary with cultivar, growing area and market; however, standards are gradually being harmonised within the major market places. The Economic Commission for Europe, for example, has its own standards for table grapes (UNECE 2003) but work is underway to align these standards with draft FAO/WHO Codex Standards on table grapes by the end of 2007. The EU standards define table grapes as fruits grown from cultivars of *Vitis vinifera*. L.. Minimum SSC levels are given as 12° Brix for the Alphonse Lavalleé, Cardinal and Victoria varieties, 13° Brix for all other seeded varieties, and 14° Brix for all seedless varieties. By contrast, in California, United States the minimum SSC is generally 16.5° Brix and in early production areas, an SSC/TA ratio of 20 or more is used to determine maturity for cultivars with a minimum required SSC less than 16.5° Brix.

EU standards classify cultivars into greenhouse grown varieties and field grown varieties. This latter classification is being further divided into large-berried and small-berried types. The berries of 'Extra Class' grapes must be evenly spaced along the rachis and have the bloom virtually intact. Lower classes (I-III) are determined by the bunch shape and the presence or absence of colouring defects, bruising and sun-scorch. In all classes the berries must be firm and firmly attached to the stalk. The larger the berries, the higher the class, provided other quality factors are met.

Ethnic background can influence the factors that determine consumer acceptance as shown in a study of the acceptability of 'Red Globe'. For example, TA played an important role in American and Chinese consumer acceptance (Crisosto & Crisosto 2002).

## Harvesting and packaging

Detailed information on the post-harvest handling of table grapes is well described by Nelson (1985). Traditionally most California table grapes have been packed in the field while a high proportion of grapes in South Africa and Chile were shed packed (Crisosto & Mitchell 2000). Recently, a combination of shed and field ('avenue') packing is developing in California and Chile.

Before harvesting, irrigation is usually withheld and the avenues between vines are treated to reduce dust contamination. The picker is trained to select appropriate bunches on the basis of the maturity indices described above. Grapes that fail to meet minimum standards are usually taken to local wineries or for use by other local industries such as cattle feed. Higher levels of efficiency can be obtained by training the vines at an appropriate height for convenient harvesting.

### *Field packing*

The most common field-packing system is the 'avenue pack' (Figure 9.2a). The picker usually trims the fruit to remove defective berries and obtain a better bunch shape and size. The bunches are then placed carefully into field crates ('lugs') or baskets which are made of wood or plastic. The picking lugs are then transferred a short distance to the packer, who works at a small, shaded portable stand in the avenue between vineyard blocks (Figures 9.2b). It is common for the packer and several pickers to work as a crew. Packing materials are located at the packing stand, which also shades the packer (Figure 9.2c). The bunches may be packed directly into shipping cartons which reduces damage from repeated handling. With many packing stands around the vineyard supervision to maintain quality standards is more difficult than in a packing shed.

### *Shed packing*

Shed-packed fruit is harvested by pickers and placed in field lugs. These are then moved into the shade of the vines to await transport to the shed. At the packing shed the field lugs are distributed to packers who select, trim and pack the fruit. In some operations, trimming, colour sorting, and a first quality sorting may have occurred in the field.

### *Packaging*

Whether field or shed packed, grapes are nearly always packed on a scale to facilitate packing to a precise net weight. Generally two grades are packed simultaneously by each packer. High quality bunches, often destined for export, will be individually packaged, increasingly either in 'zip and slide' polyethylene bags, or plastic 'clam shells'. Both forms of packaging provide consumer-sized units and reduce the drop of loose berries onto produce department floors.

The use of the plastic cluster bags greatly reduces fruit damage during marketing (Luvisi *et al*. 1995). Bags and

(a)

(b)

(c)

**Figure 9.2** (a) The most common field-packing system in California is the 'avenue pack'. (b) The grapes are picked and placed into shallow plastic picking lugs. The picking lug is then transferred a short distance to the packer, who works at a small, shaded portable stand in the avenue between vineyard blocks. (c) It is common for the packer and several pickers to work as a crew. Packing materials are located at the packing stand, which also shades the packer.

**Figure 9.3** Loaded pallets coming from the field often pass through a "pallet squeeze," a device that straightens and tightens the stacks of containers. These pallet loads are unitized, usually by strapping or netting.

clam shells are perforated to maintain ventilation and thus reduce microbial decay. A restricted cluster bag with 1.4% perforation (compared to about 60% perforation for standard bags) was patented in 2000. Research has shown that these bags can restrict water loss and slow shrivelling of the fruit and stem browning without affecting decay and phytotoxicity levels (Davis *et al*. 2000).

Individual bunch packs are then placed into cartons which come in a variety of forms including wooden ended technical kraft veneer (TKV) crates, returnable plastic crates ('RPCs'), corrugated cardboard 'shoe' boxes and polystyrene (Styrofoam) boxes. TKV and Styrofoam boxes are mainly used for grapes destined for longer storage periods because they maintain their structural integrity in high-humidity conditions better than corrugated boxes.

Carton dimensions will depend on the pallet size in use in particular markets (Vidaud *et al*. 1993). Detailed studies of the relationship between pack volume and packing height in the box versus grape quality have been carried out for the different box materials and sizes (Luvisi *et al*. 1995). Additional cushioning separators in cartons have been found to reduce physical damage to the grapes but the use of absorbent materials can accelerate weight loss (Mencarelli *et al*. 1994).

### *Palletisation*

After packing with grapes, cartons are palletised on disposable or re-cycled pallets. Often loaded pallets coming from the field pass through a 'pallet squeeze', a device that straightens and tightens the stacks of containers (Figure 9.3). These pallet loads are unitised, usually by strapping or netting. In shed-packing operations, some

palletising glue is used to bond the corrugated containers vertically on the pallet so that only horizontal strapping is required.

## Cooling, storage and transportation

### *Cooling and storage*

Because rachises and berries are susceptible to deterioration due to water loss (see 'Physiological disorders'), grapes are normally forced-air cooled as soon as possible after harvest. Grapes do not tolerate the wetting associated with hydro-cooling (bunches are not sufficiently robust and the presence of free water encourages grey mould and other diseases). The use of fruit coatings to control water loss in grapes has given inconclusive results and some bloom damage has been observed so it is not recommended (D. Lydakis, personal communication).

After palletisation is completed, the pallets are moved either to a fumigation chamber for immediate sulphur dioxide ($SO_2$) treatment, to a forced-air cooler and fumigation, or to a forced air cooler where fumigation is done at the end of the day's packing (Figure 9.4a). In any case, cooling must start as soon as possible and $SO_2$ applied within 6–12 hours of harvest (see *Diseases and their control*). After forced air cooling is completed, the pallets are moved to a storage room to await transport (Figure 9.4b).

Ideally the storage room operates at −1°C to 0°C (30° to 32°F) and 90 to 95 percent RH, with a moderate air flow 20–40 cubic feet per minute (CFM) per ton stored grapes. The constant low temperature, high RH and moderate air flow are important to limit the rate of water loss from fruit stems. Stores should be regularly monitored for physiological deterioration, fruit rot, $SO_2$ injury, and stem drying.

### *Transportation*

Domestic transportation is mainly by refrigerated truck (Figure 9.4c) but sometimes grapes are transported using refrigerated rail cars. Exported grapes may be transported by truck but most are transported by sea freight using cold stores or containers. When the price is justified, air freight is used. Throughout transportation, fruit pulp temperatures should be maintained at −0.5 to 0°C (31–32°F).

## Physiological Disorders

### *Stem, berry browning and water loss*

In general, cumulative water loss during post-harvest handling results in weight loss, fruit stem (rachis or peduncle and pedicels) browning, berry shatter and even shrivelling of berries.

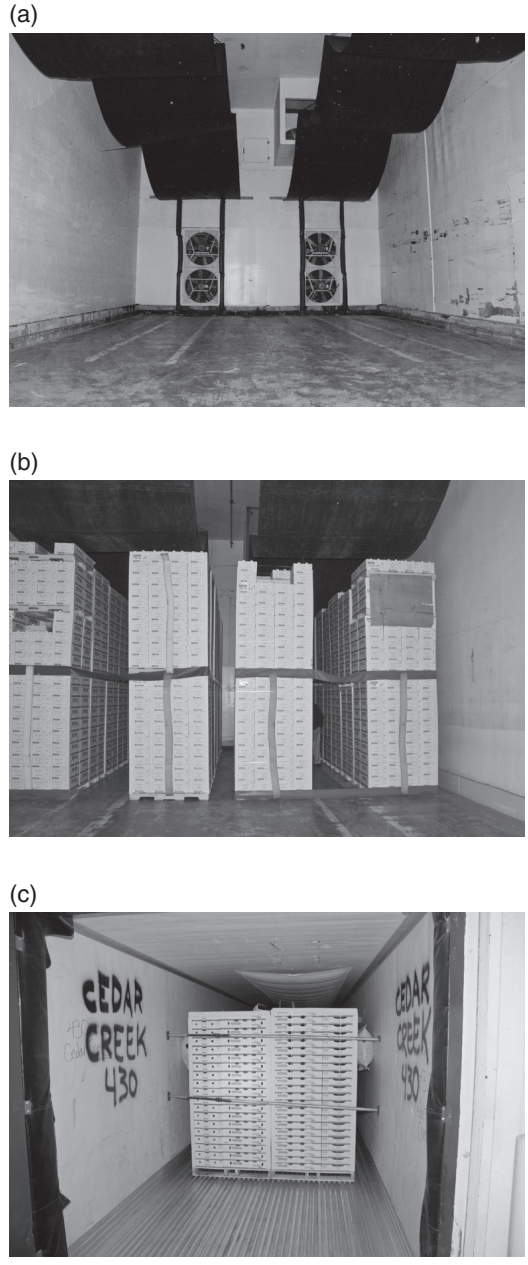


**Figure 9.4** (a) After palletisation is complete, the pallets are moved to a fumigation chamber for immediate $SO_2$ treatment, to a forced-air cooler or fumigation or to a forced-air cooler where fumigation is done at the end of the day's packing. (b) After cooling is completed, the pallets are moved to a storage room to await transport. (c) During transportation, a central loading technique is utilized to maintain cold temperature during the transportation period.

Stems are particularly susceptible to water loss due to their high surface to volume ratio. The high rate of respiration of stems may also be a contributor to stem browning, as the respiration rate of the stems may be 15 times or more that of berries. Although stem browning does not affect the eating quality of the berries, it is a serious quality defect, as it reduces the overall attractiveness of the bunch. Varieties differ greatly in the rate at which post-harvest stem browning occurs (Winkler *et al*. 1974).

There is a strong correlation between cluster water loss and stem browning. A survey indicated that water loss ranged from 0.5 to 2.1% based on the initial weight (measured at harvest) within the 8-hour period before cooling. The magnitude of the losses was directly related to the length of delay, temperature during the delay before cooling, and type of box material. Even a few hours delay at high temperatures can cause severe drying and browning of cluster stems, especially on the hottest days. When cluster water loss reaches 2.0% or more for 'Perlette', 'Superior', 'Flame Seedless', 'Thompson Seedless', 'Ruby Seedless', and 'Fantasy Seedless', stems will show symptoms of browning approximately seven days later in cold storage (Crisosto *et al*. 2001). In cultivars growing in France, water loss of as little as 3% can cause a reduction in firmness and shrivelling of berries (Chapon *et al*. 1991). In all the cases, excessive water loss leads to berry shatter. A recent study shows that chlorophyll fluorescence is well correlated to water loss at the cluster level (Wright *et al*. 2009).

Browning in both damaged and intact berries and stems is almost certainly due to oxidation of phenolics via quinones to brown pigments by the action of polyphenol oxidase (Sapis *et al*. 1983a, 1993b). The severity may be determined by the level of membrane permeability and injury of cells (Burzo *et al*. 1998). Severe desiccation causes the breakdown of cell membranes and the oxidation of phenolics in the cell sap. Berries may suffer from skin and pulp browning if they become bruised during handling. Rachis and berry browning is inhibited by $SO_2$ treatment (Morris *et al*. 1992). Berries that have not been treated with $SO_2$ are also more susceptible to gradual browning of the pulp over time (Luvisi *et al*. 1992). This may be exacerbated by the use of high levels of carbon dioxide during storage for fungicidal or quarantine purposes (Ahumada *et al*. 1996; Yahia *et al*. 1983; Crisosto *et al*. 2002c).

### *Berry Shatter*

Berry loss or shatter can be a significant problem with certain cultivars of table grapes such as Thompson Seedless (Wagener 1985; Berry & Aked 1996). The high losses of berries from Thompson Seedless have been linked to the late (post fruit-set) application of gibberellin (GA3) before harvest (Ben Tal 1990), however, GA3 treatments can have opposite effects depending on the cultivar (Jeong *et al*. 1998). There appear to be three types of berry shatter: physiological, pathological and mechanical. The first is associated with the thickening and hardening of the pedicel and production of an abscission layer (Ben Tal 1990; Nakamura & Hori 1981; Xu *et al*. 1999). The presence of fungi such as *B. cinerea*, *Rhizopus stolonifer* and *Alternaria* spp. can cause wet abscission without an abscission layer (Xu *et al*. 1999). Control of fungi with fungicides, acetic acid or $SO_2$ fumigation reduces shatter in stored table grapes (Xu *et al*. 1999; Sholberg *et al*. 1996; Morris *et al*. 1992). Some researchers reported that ethylene stimulates berry shatter (Nakamura & Hori 1981; Lydakis & Aked 2003b). Cold storage, GA, NAA or aminooxyacetic acid treatments were found to inhibit shatter (Wu *et al*. 1992). In California, berry shatter is mainly triggered by mechanical damage occurring during harvesting, packaging and transportation (Luvisi *et al*. 1995).

## Diseases and their control

### *Causal organisms*

The primary cause of post-harvest loss in table grapes is grey mould disease or Botrytis rot caused by *Botrytis cinerea* (Pearson & Goheen 1988; Snowdon 1990) (Plate 9.1). This disease occurs wherever the crop is grown. The fungus can grow at temperatures as low as −0.5°C (31°F) and so may spread from one berry to another during storage and transportation even if adequate pre-cooling is carried out and suitable temperatures are maintained. Botrytis rot can be identified by the characteristic 'slipskin' condition that develops, and later, by 'nests' of decayed berries encased in white mycelium.

Post-harvest berry infection is primarily caused by conidial infection at or after veraison (Kock & Holz 1991a) although some authors suggest it may happen at the flower stage (Nair & Allen 1993). The fungus remains quiescent in the developing fruit, with symptoms only appearing on the mature fruit. It is thought that loss of berry resistance is due to the decreasing ability of the maturing berry flesh to synthesise antimicrobial stilbenes and also due to the fall in proanthocyanidin concentration during development (Hill *et al*. 1981; Creasy & Coffee 1988). Berry cracking in certain cultivars also encourages infection.

Other less important fungal post-harvest diseases of table grapes include: Aspergillus rot (*Aspergillus niger*) which doesn't grow below 5°C, blue mould rot, (*Penicillium* spp), Rhizopus rot (*Rhizopus oryzae; R. stolonifer*),

Alternaria rot (*Alternaria alternata*), anthracnose (*Elsione ampelina*, *Glomerella cingulata*), bitter rot (*Greenaria uvicola*), black rot (*Guignardia bidwelii*), Botryodiplodia rot (*Botryodiplodia theobromae*), Cladosporium rot (*Cladosporium herbarum*), Coniella rot (*Coniella diplodiella*), Phompsis rot (*Phomopsis viticola*) and ripe rot (*Botryosphaeria ribis* and others) (Snowdon 1990).

### *General disease control*

Strict hygiene in the vineyard is necessary to minimise the amount of crop debris on which fungi can survive and form spores. Thinning of bunches helps to prevent overcrowding of berries and the resultant cracking which allows ready infection. Pre-harvest fungicide sprays can give some control of post-harvest fungal infections (Snowdon 1990). It is recommended not to harvest until at least 3 days after rain. After this period, berries infected with grey mould and other fungi should be visible and can be removed during bunch trimming. Harvesting tools should be disinfected between rows of vines to reduce the transmission of viral and bacterial diseases. After harvest it is vital to cool the grapes as rapidly as possible and to handle carefully to minimise injuries to the berries. Obviously a good control of fungus development over the growing period is critical for a good postharvest storage; however, a recent study suggested that postharvest treatments are required even with a good pre-harvest management (Smilanick *et al*. 2010).

### *Sulphur dioxide ($SO_2$) fumigation*

Table grapes are treated with $SO_2$ primarily to control grey mould which is not inhibited sufficiently by rapid cooling alone. Standard practice is to fumigate with sulphur dioxide immediately after harvesting and/or packing followed by lower dose $SO_2$ treatments weekly during storage. Usually this initial fumigation uses a high level of $SO_2$ (up to 5000 ppm) and may be carried out in specially constructed rooms. Cold storage fumigation uses lower concentration (2500 ppm or lower) and is carried out every seven to ten days. In this traditional system the excess $SO_2$ is removed from the treatment chamber by venting or scrubbing through water or sodium hydroxide aqueous solution after a treatment period of about 20 min. Formulas for calculating $SO_2$ fumigation dosages are available in the publications by Nelson (1985) and Luvisi *et al*. (1992).

Recently it has been demonstrated that the amount of $SO_2$ needed to kill *Botrytis* spores, or to inactivate exposed mycelium is dependent on both the $SO_2$ concentration and fumigation time. A cumulative concentration, calculated as the product of the concentration and contact time, called 'CT product', describes the $SO_2$ exposure needed to kill *Botrytis cinerea*. A CT of at least 100 ppm-hour is the minimum required to kill spores and mycelium of *Botrytis* at 0°C (32°F) or approximately 30 ppm-hour at 20°C (68°F). The CT-100 dose can be obtained with an average concentration of either 100 ppm for 1 hour, 200 ppm for ½ hour, 50 ppm for 2 hours or an equivalent combination of concentration and time. This finding was the basis for the development of the total utilization system.

The total utilization system differs from the traditional system in that there is no excess $SO_2$ fumigant at the end of the fumigation treatment, reducing both air pollution and sulphite residues in the fruit. It can be used with forced air cooling for initial fumigation and in cold storage for subsequent periodic treatments. Total utilization typically uses about half as much sulphur dioxide as the traditional method, and improves uniformity and effectiveness of the $SO_2$ fumigant. Details on this work are available in the Luvisi *et al*. (1992). Inexpensive $SO_2$ dosimeter tubes are available to enable fumigant penetration and distribution to be monitored in store. These dosimeters were originally designed for human safety monitoring.

When grapes are loaded for transport/shipment they may receive an additional $SO_2$ fumigation before loading to assure a longer market life because fumigation is seldom available in receiving markets. During ocean shipment period longer than 10 days or long retail handling in which $SO_2$ fumigation cannot be applied, the use of $SO_2$ generating pads in combination with a box plastic liner is advised (Crisosto *et al*. 1994). Sodium or potassium metabisulphite is incorporated into the pads, allowing the release of $SO_2$ when exposed to moisture during transit and marketing. The amount of $SO_2$ released is also affected by the temperature and the effective use of these pads depends on a good cool-chain being maintained. Dual-release pads give a rapid initial release of $SO_2$ from part of the pad while another part of the pad releases $SO_2$ slowly over a period of 8–10 weeks (Mustonen 1992). In France has been reported that $SO_2$ levels within the carton usually reach approximately 10 ppm within the first week of cold storage and then stabilise at around 2 ppm (Vidaud *et al*. 1993). A special low dosage has been developed for fumigation in trucks and overseas containers (Crisosto *et al*. 2002b). Unless $SO_2$ fumigation is available, the receiver must order grapes for immediate needs, and must complete distribution and marketing within a reasonable time after arrival.

### *Problems with sulphur dioxide treatments*

One of the problems associated with $SO_2$ fumigation of grapes is the constant potential for injury to the berries and rachis. Injured tissue first shows bleaching of colour,

followed by sunken areas where accelerated water loss has occurred. These injuries first appear on the berry where some other injury has occurred, such as a harvest wound, transit injury or breakage at the cap stem attachment. Symptoms may also be seen around the cap stem and slowly spread over the berry. Careful attention to $SO_2$ treatment procedures is necessary to minimize this damage. Additionally, treated berries sometimes develop a sulphurous taint (Austin *et al*. 1997).

Another problem with $SO_2$ fumigation of grapes is the level of sulphite residue remaining at time of final sale. Sulphur dioxide was once included on the 'generally recognized as safe' (GRAS) list of chemicals, for which no registration is required (Anon 1986). Heavy usage of sulphites in some other foods has caused a change in regulation, because some people are highly allergic to sulphites. Sulphite residues in grapes are currently limited to <10 ppm, (10 µg $SO_2$/g) and there are limits on the number of repeat $SO_2$ fumigations allowed, depending upon cultivar (Anon 1989).

### *Alternatives to the use of sulphur dioxide*

Considerable research has been conducted to find alternatives to $SO_2$ treatments for grey mould control. This is especially desirable for organic table grape growers who are prohibited from using $SO_2$ (USDA 2001). Despite many treatments showing promise in the laboratory, none is being used routinely in a commercial setting. Limitations include phytotoxicity and difficulties in getting good penetration of the treatment through the grape bunches. Methods tried include fumigation with hydrogen peroxide (Rij & Forney 1995), ozone (Sarig *et al*. 1996), chlorine (Zoffoli *et al*. 1999), chlorine dioxide (Crisosto *et al*. 1994), volatiles of natural origin such as hexenal (Archbold *et al*. 1999), acetaldehyde (Avissar & Pesis 1991), ethanol (Lichter *et al*. 2002) or acetic acid (Sholberg *et al*. 1996). Tripathi and Dubey (2004) have reviewed the potential of a large selection of natural products to control post-harvest rots.

High carbon dioxide levels have long been known to inhibit the growth of fungi. In the last few decades, controlled or modified atmospheres have been shown to have promise for the control of *Botrytis* in table grapes (Yahia *et al*. 1983, Crisosto *et al*. 1995; Retamales *et al*. 2003; Artés-Hernández *et al*. 2004). Levels of $CO_2$ at 15% or above can completely suppress the growth of *Botrytis* Levels above 10% $CO_2$ for too long a period, however, were found to generate off-flavours and accelerate stem browning. Sensitivity to $CO_2$ was, however, dependent on cultivar and maturity (Crisosto *et al*. 2002c, 2002d). In some cases the return to air atmosphere at the end of storage can be followed by strong rot development (P. Westercamp, personal communication). More work in this area is strongly recommended.

Vapour heat treatments, for example 52°C for 20 minutes have been found to be highly effective at eradicating *Botrytis* from grape berries without causing damage to the fruit (Lydakis & Aked 2003a, 2003b). Kock and Holz (1991b) found that gamma irradiation could control grey mould and Thomas *et al*. (1995) tested with some success, combinations of hot water dip and irradiation against various moulds. UV-C light has also been applied successfully to control *Botrytis* on table grapes (Nigro *et al*. 1998). A number of researchers have found a number of bacteria, yeasts and fungi to be effective as biocontrol agents against grey mould and other pathogens of table grapes (Ferreira 1990; Latorre *et al*. 1997; Lima *et al*. 1999; Zahavi *et al*. 2000). Ethanol dips showed some promise for control of *Botrytis* (Gabler *et al*. 2005), and the use of ethanol vapours (Chervin *et al*. 2005) may be developed with the pad systems that are already in use for $SO_2$ delivery. The use of pre-harvest ethanol sprays may also have positive impacts of the postharvest shelf life (Chervin *et al*. 2009).

Interesting alternatives using edible herb extracts (Gatto *et al*. 2011) or electrolyzed oxidizing water (Guentzel *et al*. 2010) have been reported recently.

### Insect quarantine treatment

Several insects that attack table grapes are of quarantine concern and they must be eradicated prior to/or during shipment to other countries. Novelties in sanitation or quarantine treatments have been noticeable over the past ten years. This has been primarily in response to the likelihood that the use of the fumigant methyl bromide, which depletes stratospheric ozone, will be phased out over the next few years.

A number of combination treatments are being developed in order to benefit from additive and synergistic effects. For example, an official approved protocol based on $CO_2$ and $SO_2$ fumigation is being used in California to export grapes to Australia, England and New Zealand. This quarantine treatment kills black widow spiders in packaged table grapes (Mitcham 2005). A potential area of development for disinfestations studies is the use of semiochemicals, chemicals that mediate interactions between organisms (Cox 2004) and that can be used to repel or attract and kill insects. Another area of development are 'systems approaches': taking into account the initial pest count in a fruit load, which can be estimated by monitoring pests in the vineyard, to adapt the post-harvest treatment (US EPA 2000).

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# 10
# Stone Fruit

*Carlos H. Crisosto and Kevin R. Day*

## INTRODUCTION

The term 'stone fruit' is used to cover fruits of the *Prunus* species, peaches, nectarines, plums, cherries and apricots. This chapter will concentrate on post-harvest issues relating to peaches, nectarines and plums. Owing to their close relationship peaches and nectarines will be considered together.

### Peaches and nectarines

Peaches and nectarines are classified from the horticultural point of view as stone fruits or drupes. They are soft fleshed with a pit, contain a high level of antioxidant but are highly perishable with a limited market life potential (Lill *et al*. 1989). The total antioxidant capacities of peaches and nectarines are about 15% and 20% of the total antioxidant capacity relative to that of 100 ml of red wine and 100 ml of green tea, respectively (USDA 2007a). Potential opportunities for export marketing, combined with the desire to store some late-season cultivars to extend the marketing season, have increased interest in understanding fruit physiology and extending postharvest life.

Peach, *Prunus persicae*, is native to China and Persia (Iran); at one time it was called 'Persian apple.' Chinese literature dates its cultivation in China to 1000 BCE. Probably carried from China to Persia, the peach quickly spread from there to Europe. In the sixteenth century, it was established in Mexico probably by the Spanish missionaries who introduced the peach to California in the eighteenth century. Nectarine (*Prunus persicae* var. nectarina) has been reported for nearly as long as peach, but its origin is unknown. Because they may have arisen from peach seeds, most peach-growing areas world-wide have also introduced nectarine cultivars.

### Plums

Plums (*Prunus salicina*) are mainly marketed for fresh consumption and not for drying. They are also used for canning, freezing and jam and jelly making. The Japanese plum is native to China, but was domesticated in Japan about 400 years ago. It was first brought to California from Japan in 1870 by John Kelsey. In 1885, Luther Burbank imported about 12 seeds from Japan, and used them to breed many cultivars. The plum industry has increased throughout California (mainly in the southern San Joaquin Valley) where most Japanese plums in the United States are grown. Prunes are cultivars of European Plum (*Prunus domestica*, L.) which can be dried whole. Like plums, prunes can be eaten fresh (if a very sweet fruit is desired); but they also have the high sugar content necessary for successful drying. The European plum, believed to have originated in the Near East, has been grown in parts of Europe for many centuries. Through its culture in France, the prune 'd'Agen' was introduced to California from France by Louis Pellier, a French horticulturist who had come to California seeking gold.

Plums (*Prunus salicina* Lindell) have the potential to contribute greatly to human nutrition because of their richness in fiber and antioxidants. These values can be found in the USDA Food Composition Database (USDA 2007b).

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## STONE FRUIT PHYSIOLOGY

Botanically, peach is a drupe. A drupe is a fleshy fruit with a thin, edible outer skin (epicarp) derived from the ovary, an edible flesh of varying thickness beneath the skin (fleshy mesocarp), and a hard, inner ovary wall that is highly lignified (endocarp) and is commonly referred to as the 'stone' or 'pit', which encloses a seed. Peaches have thin skins and soft flesh. The skin, as a protective layer, is composed of cuticle, epidermis and some hypodermal cell layers. The cuticle is a thin coating of wax and serves to reduce water loss and to protect the fruit against mechanical injury and attack by pathogens. The epidermis, consisting of heavy-walled cells, is responsible for most of the skin's mechanical strength. Surface chromosomes or hairs ('fuzz') of peach fruit are extensions of some epidermal cells. The flesh, which is the main edible portion of the fruit, consists mainly of storage parenchyma tissue composed of large, relatively thin-walled cells with high water content. On the basis of separation of stone from flesh, nectarine and peach varieties can be divided into two groups: freestone (where the stone does not adhere to the flesh) and clingstone (where the stone adheres firmly to the flesh).

Upon the completion of pollination and fertilization of the egg, the flower ovary begins to enlarge into a developing fruit. This is 'fruit set', and it marks the beginning of growth and development. Stone fruits have a double sigmoidal growth curve which includes three distinct stages of growth. Following fruit set, cell division continues for about 4 weeks, with cell enlargement beginning and proceeding rapidly (stage 1). Slow growth then occurs, during which lignification of endocarp (pit hardening) and growth of endosperm and embryo inside the seed take place (stage 2). Cell enlargement (expansion) resumes in the flesh (mesocarp) tissue. The fruit continues to increase in size until it reaches full maturity, after which growth slows markedly and finally stops (stage 3). The duration of each stage of growth depends upon variety, climactic conditions and some cultural practices (such as thinning or crop load per tree, soil moisture, girdling and nutrition). Fruit density (specific gravity) declines during Stage 1, increases during Stage 2, then declines again during Stage 3 (final fruit swell). During the pit hardening, the seed constitutes 25% of the fruit weight, and this value drops to 14% during final swell. From a postharvest standpoint, interest in Stage 3 is greatest, since maturation, ripening and senescence occur during this stage. Maturation is the time between final growth and the beginning of ripening. Maturity is the end point of maturation. An immature fruit may ripen off the tree, but it will be of poor quality. A mature fruit will attain good quality when ripened off the tree. Ripening involves changes that transform the mature fruit into one ready to eat. Changes associated with ripening include loss of green colour and development of yellow, red and other colours characteristic of a variety. As a fruit ripens, it softens, its starch is converted to sugars, its acidity declines and it produces certain volatile compounds that give it a characteristic aroma. Increased respiration and ethylene production rates are among the physiological changes associated with ripening. Once a fruit ripens, it begins senescence. Physical and chemical changes continue after 'optimum' ripeness is reached (from a flavour quality standpoint), including further softening and loss of desirable flavour. The final outcome of post-ripening changes is complete breakdown and death of the tissues.

## PEACH AND NECTARINE POST-HARVEST HANDLING SYSTEMS

### Fruit deterioration factors

#### *Water loss*

Fruit shrivelling occurs when fruit lose approximately 5–8% of the fruit's water content, based on weight at harvest. This loss is sufficient to cause visual shrivel in peaches and nectarines (Ceponis *et al*. 1987). While there is a large variability in susceptibility to water loss among cultivars, all peaches and nectarines must be protected to assure the best post-harvest life. Fruit waxes that are commonly used as carriers for post-harvest fungicides can reduce the rate of water loss when brushing has not been overdone. Mineral oil waxes can potentially control water loss better than vegetable oil and edible coatings. Because fruit shrivel results from cumulative water loss throughout handling, it is important to maintain low temperature and high relative humidity throughout harvesting, packing, storage, transport and distribution. Short cooling delays, efficient waxing with gentle brushing, fast cooling followed by storage under constant low temperature and high relative humidity are the main ways of limiting water loss.

#### *Chilling injury (CI) or internal breakdown (IB)*

The major physiological cause of deterioration for peaches and nectarines is a low-temperature or chilling injury (CI) problem generically called 'internal breakdown' (IB) (Plate 10.1) The genetic disorder can manifest itself as dry, mealy, woolly or hard-textured fruit (not juicy), flesh or pit cavity browning and flesh translucency usually radiating through flesh from the pit. In all of the cases, flavour is lost before visual symptoms are evident. However, there is large variability in CI susceptibility among peach and nectarine cultivars (Tables 10.1

**Table 10.1** Effects of Storage Temperature on Storage and Shipping Potential of peach cultivars[a].

| | | Fruit type | | | Storage and shipping potential (weeks) | |
|---|---|---|---|---|---|---|
| Cultivar | Plant breeding program | Flesh–stone adhesion | Flesh texture | Flesh color | 0°C | 5°C |
| Autumn Flame | Doyle | Freestone | Melting | Yellow | 1 | 0 |
| Autumn Lady | Merrill | Semifreestone | Melting | Yellow | 2 | 1 |
| Autumn Rose | Richards | Freestone | Melting | Yellow | 1 | 1 |
| Brittney Lane | Zaiger | Clingstone | Melting | Yellow | 5 | 5 |
| Carnival | Merrill | Freestone | Melting | Yellow | 2 | 1 |
| Country Sweet | Zaiger | Clingstone | Melting | Yellow | 5 | 5 |
| Crimson Lady | Bradford | Clingstone | Nonmelting | Yellow | 5 | 5 |
| Elegant Lady | Merrill | Freestone | Melting | Yellow | 4 | 1 |
| Fairtime | USDA | Freestone | Melting | Yellow | 3 | 1–2 |
| Fay Elberta | NA | Freestone | Melting | Yellow | 4 | 3 |
| Flavorcrest | Weinberger | Freestone | Melting | Yellow | 4 | 2 |
| Ivory Princess | Bradford | Clingstone | Melting | White | 5 | 3 |
| June Lady | Merrill | Cling | Melting | Yellow | 4 | 1 |
| Kaweah | Zaiger | Freestone | Melting | Yellow | 2 | 1 |
| Last Chance | Sprague | Freestone | Melting | Yellow | 2 | 1 |
| May Sweet | Zaiger | Clingstone | Melting | Yellow | 5 | 5 |
| O'Henry | Merrill | Freestone | Melting | Yellow | 3 | 2 |
| Parade | Merrill | Freestone | Melting | Yellow | 1 | <1 |
| Rich May | Zaiger | Clingstone | Melting | Yellow | 4 | 3 |
| Ryan Sun | Chamberlin | Freestone | Melting | Yellow | 4 | 1–2 |
| Saturn | Bailey | Freestone | Melting | White | 5 | 3 |
| September Flame | Burchell | Clingstone | Melting | Yellow | 2 | 1 |
| September Snow | Zaiger | Freestone | Melting | White | 4 | 2 |
| September Sun | Chamberlin | Freestone | Nonmelting | Yellow | 3 | 1–2 |
| Snow Fire | Zaiger | Freestone | Melting | White | 5 | 2 |
| Snow Kist | Zaiger | Clingstone | Melting | White | 5 | 2 |
| Spring Snow | Zaiger | Clingstone | Melting | White | 5 | 5 |
| Sugar Giant | Zaiger | Freestone | Melting | White | 5 | 2.5 |
| Sugar Lady | Zaiger | Freestone | Melting | White | 3 | 2 |
| Sugar Lady | Zaiger | Freestone | Melting | White | 4.5 | 3 |
| Summer Lady | NA | Freestone | Melting | Yellow | 5 | 3 |
| Summer Sweet | Zaiger | Freestone | Melting | White | 4.5 | 2 |
| Sunlit Snow | Zaiger | Clingstone | Melting | White | 5 | 5 |
| Super Rich | Zaiger | Clingstone | Melting | Yellow | 5 | 5 |
| Sweet Dream | Zaiger | Clingstone | Melting | Yellow | 1 | 0 |
| Sweet Scarlet | Zaiger | Freestone | Nonmelting | Yellow | 4 | 2 |
| White Lady | Zaiger | Freestone | Melting | White | 4 | 2 |

[a] Information was obtained from personal communications with Gary Van Sickle, Kevin Day, and David Ramming, from Brooks and Olmos (1972), Whealy and Demuth (1993), Okie (1998), nursery catalogues and US patents.

**Table 10.2** Effects of Storage Temperature on Storage and Shipping Potential of Nectarine Cultivars[a].

| Cultivar | Plant breeding program | Fruit type | | | Storage/ shipping potential (weeks) | |
|---|---|---|---|---|---|---|
| | | Flesh–stone adhesion | Flesh texture | Flesh color | 0°C | 5°C |
| Arctic Jay | Zaiger | Freestone | Melting | White | 5 | 5 |
| Arctic Snow | Zaiger | Freestone | Melting | White | 5 | 2 |
| Arctic Star | Zaiger | Clingstone | Melting | White | 5 | 5 |
| Arctic Sweet | Zaiger | Clingstone | Melting | White | 5 | 3 |
| August Glo | Zaiger | Clingstone | Melting | Yellow | 3 | 1 |
| August Red | Bradford | Clingstone | Melting | Yellow | 5 | 3 |
| Diamond Bright | Bradford | Clingstone | Melting | Yellow | 5 | 5 |
| Diamond Ray | Bradford | Clingstone | Melting | Yellow | 5 | 5 |
| Fire Pearl | Bradford | Clingstone | Melting | White | 5 | 2 |
| Grand Pearl | Bradford | Clingstone | Melting | White | 2 | 1 |
| Honey Blaze | Zaiger | Semifreestone | Melting | Yellow | 5 | 5 |
| Kay Sweet | Bradford | Clingstone | Nonmelting | Yellow | 5 | 5 |
| Ruby Diamond | Bradford | Freestone | Melting | Yellow | 5 | 3 |
| Ruby Pearl | Bradford | Clingstone | Melting | White | 5 | 5 |
| Ruby Sweet | Bradford | Clingstone | Melting | Yellow | 5 | 5 |
| September Free | USDA | Freestone | Melting | Yellow | 3 | 1 |
| September Red | Bradford | Clingstone | Melting | Yellow | 4 | 1 |
| Spring Red | Anderson | Freestone | Melting | Yellow | 5+ | 3 |
| Summer Blush | Bradford | Clingstone | Melting | Yellow | 5 | 1 |
| Summer Bright | Bradford | Clingstone | Melting | Yellow | 5 | 3 |
| Summer Fire | Bradford | Clingstone | Melting | Yellow | 5 | 3 |
| Summer Grand | Anderson | Freestone | Melting | Yellow | 5+ | 5 |
| Zee Glo | Zaiger | Clingstone | Melting | Yellow | 3 | 3 |

[a] Information was obtained from personal communications with Gary Van Sickle, Kevin Day, and David Ramming, from Brooks and Olmos (1972), Whealy and Demuth (1993), Okie (1998), nursery catalogues and US patents.

and 10.2). In general, peach cultivars are more susceptible to CI than nectarine cultivars. In susceptible cultivars, CI symptoms develop faster and more intensely when fruit are stored at temperatures between about 2°C and 7°C than when similar fruit are stored at 0°C or below, but above freezing point (Mitchell 1987; Table 10.3). At the shipping point, fruit should be cooled and held near or below 0°C if possible. During transportation if CI susceptible cultivars are exposed to approximately 5°C, it can significantly reduce their post-harvest life.

Several treatments to delay and limit development of this disorder have been tested. Among them, preconditioning treatment before storage is being used commercially in the United States, Chile and other countries. The success of the controlled-atmosphere treatment in ameliorating CI is dependent on cultivar market life potential, fruit temperature, shipping time and fruit size.

## Post-harvest treatments to reduce deterioration

### *Controlled atmosphere (CA)*

Most studies of CA storage of peaches and nectarines have found that lowering $O_2$ and raising $CO_2$ in the storage atmosphere conferred benefit on the fruit and delayed or prevented the appearance of mealiness, internal reddening and flesh browning (Zhou *et al*. 2000; Crisosto *et al*. 1995; Lurie 1992; Retamales *et al*. 1992). The $CO_2$ component appears to be critical for delaying the onset of CI (Wade 1981; Kajiura 1975; Anderson *et al*. 1969). Exposure to 10% $CO_2$ + 10% $O_2$ for 6 weeks has been reported to

**Table 10.3** Relationship between Stone Fruit Soluble Solids Content (SSC) and the Freezing Point.

| SSC | Safe Freezing Point | |
|---|---|---|
| (%) | (°F) | (°C) |
| 8.0 | 30.7 | –0.7 |
| 10.0 | 30.3 | –0.9 |
| 12.0 | 29.7 | –1.3 |
| 14.0 | 29.4 | –1.4 |
| 16.0 | 28.8 | –1.8 |
| 18.0 | 28.5 | –1.9 |

prevent CI in the nectarine cultivars 'Fantasia', 'Flavortop; and 'Flamekist' (Lurie 1992). It has been demonstrated that 'Fantasia' nectarines stored in air plus 10 to 20% $CO_2$ were juicy and had good flavour after 5 weeks at 0°C storage (Burmeister & Harmon 1998). CA conditions of 6% $O_2$ + 17% $CO_2$ have been reported to be beneficial for peaches and nectarines shipped from Chile (Retamales *et al*. 1992; Streif *et al*. 1992). In California, the major benefits of CA during storage/shipment are retention of fruit firmness and ground colour, and reduction of flesh browning development. CA conditions of 6% $O_2$ + 17% $CO_2$, the best combination, at 0°C have shown a limited benefit for reduction of mealiness during shipments for yellow flesh cultivars (Crisosto *et al*. 1999b) and white flesh cultivars (Garner *et al*. 2001). As mealiness is the main CI symptom rather than flesh browning, the use of CA technology in California cultivars has been limited. The CA efficacy is related to cultivar (Mitchell & Kader 1989), preharvest factors (Crisosto *et al*. 1997; Combrink 1996; Von Mollendorff 1987), temperature, fruit size (Crisosto *et al*. 1999a), marketing period and shipping time (Crisosto *et al*. 1999b).

The use of the modified atmosphere packaging (MAP) technique has been tested on several peach cultivars without success. Despite high $CO_2$ levels that were reached during cold storage, flesh mealiness and flesh browning development limited the potential benefits of this technology. In some commercial cases when box liners (MAP) were used, the incidence of decay increased because of lack of proper cooling and condensation during transportation.

### *Preconditioning treatment*

A commercial controlled delayed cooling or preconditioning treatment was developed to extend peach (*Prunus persica*) market life of the most popular California peach cultivars. A 48 h cooling delay at 20°C was the most effective treatment for extending market life of CI susceptible peaches without causing fruit deterioration (Crisosto *et al*. 2004a). This treatment increased minimum market life by up to 2 weeks in the cultivars tested. Weight loss and softening occurred during the controlled delayed cooling treatments, but did not reduce fruit quality. Fruit must be cooled down and fruit temperature should be maintained near 0°C during their post-harvest handling.

### Post-harvest fruit diseases

Post-harvest loss of peach and nectarine to decay-causing fungi is considered the greatest deterioration problem. Worldwide, the most important pathogen of fresh stone fruits is Botrytis rot, caused by the fungus *Botrytis cinerea* (Plate 10.2). It can be a serious problem during wet, spring weather. It can occur during storage if fruit have been contaminated through harvest and handling wounds. Avoiding mechanical injuries and good post-harvest temperature management are effective controls.

Brown rot is caused by *Monilinia fructicola* with infections beginning during flowering. It is the most important post-harvest disease of peaches in California (Plate 10.3). Rhizopus rot is caused by *Rhizopus stolonifer* and can occur in ripe or near-ripe peaches kept at 20°C to 25°C. Cooling and keeping fruit below 5°C are part of an effective control. Good orchard sanitation practices and proper fungicide applications are essential to reduce these problems. It is also common to use a post-harvest fungicidal treatment against these diseases. A Food and Drug Administration (FDA) approved fungicide(s) is often incorporated into a fruit coating or wax for uniformity of application. The regulation on the use of fruit coatings varies according to country. Careful handling to minimize fruit injury, sanitation of packinghouse equipment and rapid, thorough cooling to 0°C as soon after harvest as possible are also important for effective disease suppression.

### Physical damage

Stone fruits are susceptible to mechanical injuries including cuts, impact, compression and abrasion (vibration) bruising. Careful handling during harvesting, hauling and packing operations to minimize such injuries is important because the injuries result in reduced appearance quality, accelerated physiological activity, potentially more inoculation by fruit decay organisms and greater water loss. Incidence of impact and compression bruising has become a greater concern as a large part of the peach and nectarine industry is harvesting fruit at more advanced maturity (softer) to maximize fruit flavour quality. Several surveys carried out in south-eastern Fresno County (California,

United States) indicated that most impact bruising damage occurs during the packinghouse operation and long transportation from orchard to packinghouse. Critical impact bruising thresholds (the minimum fruit firmness measured at the weakest point to tolerate impact abuse) have been developed for many of the commercially important peach and nectarine cultivars.

Abrasion damage can occur at any time during post-harvest handling. Protection against abrasion damage involves procedures to reduce vibrations during transport and handling by immobilizing the fruit. These procedures include: installing air suspension systems on axles of field and highway trucks, using plastic film liners inside field bins, using plastic bins, installing special bin top pads before transport, avoiding abrasion on the packing line and using packing procedures that immobilize the fruit within the shipping container before they are transported to market. In situations when abrasion damage occurs during harvesting on fruit that have heavy metal contaminants, such as iron, copper and/or aluminium, on their skin, a dark discolouration (inking or peach skin discolouration) is formed on the surface of peaches and nectarines. These dark or brown spots or stripes on the fruit are a cosmetic problem and a reason for discard. Heavy metal contaminants on the surface of the fruit can occur as a consequence of foliar nutrients and/or fungicides sprayed within 15 days or 7 days before harvest, respectively. Pre-harvest intervals that have been developed for several approved fungicides in California should be followed. Light brown spots or stripes are also produced on the surface of white flesh peaches and nectarines as a consequence of abrasion occurring mainly during harvesting and hauling operations.

### Temperature management and optimum storage conditions

Optimum temperature is –1°C to 0°C. The freezing point varies, depending on SSC, from –3°C to –1.5°C (Table 10.3). Relative humidity (RH) should be 90–95% with a low air velocity during storage (Thompson *et al*. 1998). Fruit can be cooled in field bins using forced-air cooling or hydro-cooling. Hydro-cooling is normally done by a conveyor-type hydro-cooler or *in situ*. Fruit in field bins can be cooled to intermediate temperatures of 5–10°C provided packing will occur the next day or pack immediately. If packing is to be delayed beyond the next day, then fruit should be thoroughly cooled in the bins to near 0°C. In IB-susceptible cultivars, fast cooling within 8 hours and maintaining fruit temperature near 0°C are traditionally recommended.

Peaches and nectarines in packed containers should be cooled by forced-air cooling to near 0°C. Even peaches that were thoroughly cooled in the bins will warm substantially during packing and should be thoroughly re-cooled after packing. A new technique to delay IB symptoms and pre-ripen fruit has been successfully introduced to the California and Chilean industries. This technique consisted of a ≈48-hour controlled cooling delay. Forced-air cooling is normally indicated after packing.

Stone fruit storage and overseas shipments should be at or below 0°C. Maintaining these low pulp temperatures requires knowledge of the freezing point of the fruit, of the temperature fluctuations in the storage system and equipment performance. Holding stone fruits at these low temperatures minimizes both the losses associated with rotting organisms, excessive softening, water losses and the deterioration resulting from CI in susceptible cultivars.

### Horticultural maturity indices

The maturity at which stone fruits are harvested greatly influences their visual quality, ultimate flavour and market life (Crisosto 1994). Harvest maturity affects the fruit's flavour components, physiological deterioration problems, susceptibility to mechanical injuries, resistance to moisture loss, susceptibility to invasion by rot organisms, market life and ability to ripen. Peaches and nectarines that are harvested too soon (immature) may fail to ripen properly or may ripen abnormally. Immature fruit typically soften slowly and irregularly, never reaching the desired melting texture of fully matured fruit. The green ground colour of fruit picked immature may never fully disappear. Because immature fruit lack a fully developed surface cuticle, they are more susceptible to water loss than properly matured fruit. Immature and low-maturity fruit have lower soluble solids concentrations and higher acids than properly matured fruit, all of which contribute to inadequate flavour development. Low-maturity fruit are more susceptible to both abrasion and the development of flesh browning symptoms than properly matured fruit. Over mature fruit have a shortened post-harvest life, primarily because of rapid softening and they are already approaching a senescent stage at harvest and developing a mealy texture. Such fruit have partially ripened, and the resulting flesh softening renders them highly susceptible to mechanical injury and fungus invasion. By the time such fruit reach the consumer, they may have become overripe, with poor eating quality including off-flavours and mealy texture.

In several countries, harvest date is determined by skin ground colour changes from green to yellow in most cultivars. A colour chip guide is used to determine maturity of each cultivar, except for white flesh cultivars. A three-tier maturity system is used in California and a similar system

is used on other countries: (1) U.S. Mature (minimum maturity), (2) Well-Mature and (3) Tree Ripe. Measurement of fruit firmness is recommended in cultivars where skin ground colour is masked by full red colour development, especially nectarines, before maturation. In these cases, a maximum maturity index can be applied. Maximum maturity is defined as the minimum flesh firmness (measured with a penetrometre with an 8 mm tip) at which fruit can be handled without bruising damage. Bruising susceptibility varies widely among cultivars. The optimum maturity for stone fruit harvest must be defined for each cultivar. The highest maturity at which a cultivar can be successfully harvested is influenced by post-harvest handling and temperature management procedures. Maturity selection is more critical for distant markets than for local markets, but does not necessarily mean lower maturity. Because of the availability of new cultivars that adapt well to harvesting more mature (softer), the increase in popularity of high-quality, less firm fruit (more mature) and the use of more sophisticated packinghouse equipment, a large proportion of stone fruits are being picked at a more advanced maturity stage.

**Quality characteristics and criteria**

In California the minimum ripe soluble solids concentration (RSSC) needed to reach high consumer acceptance for peach and nectarine was determined by using 'in-store' consumer tests of low and high ripe titratable acidity (RTA) melting flesh cultivars as a part of our program to develop minimum quality indexes (Crisosto and Crisosto, 2005). There is high consumer acceptance of peaches with high soluble solids content (SSC). Titratable acidity (TA) and SSC:TA are currently used as an important predictor of consumer acceptance but it is accepted that volatile, flavour and texture are also important components of flavour. For these moderate/low-acid and high-acid cultivars, consumer acceptance was closely related to RSSC, but maximum consumer acceptance was attained at different RSCC levels depending on the cultivar. The fact that these cultivars reached high consumer acceptance with different RSSC levels indicates that a single generic RSSC quality index would not be reliable to assure consumer satisfaction across all cultivars. For most of the midseason peaches, a minimum of 11% SSC with a TA ≤0.7% is required to satisfy about 80% of consumers. Our 'in-store' consumer tests indicated that high consumer acceptance is attained with mid- and late-season cultivars when peaches are free of chilling injury and 'ready to eat' prior to consumption. Within these cultivars, a large population of the fruit will be highly accepted by the consumers. Traditionally, the lack of flavours has been associated with early-season fruit or mid-late CI damaged fruit. These early cultivars have low flavour quality potential and generally are consumed mature and 'not ripe'. However, lately a group of new cultivars that ripen early in our season (late April–mid-June) is becoming available. The ones that have been tested had high SSC, moderate to low acidity levels, were aromatic and had a high consumer acceptance when consumed at the 'ready to eat' stage. As production of new cultivars with diverse flesh colours, flavours, soluble solids concentrations (SSC), and titratable acidities (TA) is increasing in California and the rest of the world, we tested the concept of cultivar segregation according to the sensory perception of organoleptic characteristics. We were able to consistently segregate peach and nectarine cultivars into groups (balanced, tart, sweet, peach or nectarine aroma and/or peach or nectarine flavour) with similar sensory attributes. Based on this information, we suggest that cultivars should be clustered in organoleptic groups and development of a minimum quality index should be attempted within each organoleptic group rather than proposing a generic minimum quality index based on ripe SSC. This organoleptic cultivar classification may help to match consumer or ethnic preferences and enhance the current promotion and marketing programs.

**Harvesting and packaging handling**

Fruit are hand-picked using bags, plastic baskets or totes. Fruit are dumped in bins that are on the top of trailers between rows in the orchard. If fruit are picked into totes, the totes are usually placed directly inside the bins. Baskets are placed on racks within modified trailers. Fruit picked at advanced maturity stages and white flesh peaches or nectarines are most commonly picked and placed into baskets or totes. Fruit can be hauled for short distances by these trailers, but they are designed principally for transport within orchards. If the transport distance is longer than 5–10 km, bins are loaded on a truck or semi-truck and trailer for transportation to packinghouses. Harvest crews usually consist of 15 to 25 labourers including a foreman, who is responsible for ensuring uniformity of harvest, adherence to maturity and fruit size criteria and general supervision. Depending on the cultivar and orchard, a labourer can usually harvest 1½ to 3 bins (400–450 kg per bin) of fruit per day. Early-season cultivars are usually picked every 2–3 days, and by mid- to late season the interval can stretch to as much as 7 days between harvests. Tree heights are commonly 3.7–4.7 m, and workers require ladders to reach the uppermost fruits. Ladders are made of aluminium and are 3.7–4.0 m in length. Either four or six rows

**Table 10.4** Incidence of Bruising (Impact + Vibration) within Three Ranges of Fruit Firmness in Packages of Tray Packed Yellow Flesh Peaches, Volume-Filled White Flesh Peaches, and Volume-Filled Yellow Flesh Nectarines after a 30-Minute Vibration Treatment.

| | Percentage of bruised fruit at different levels of fruit firmness | | |
|---|---|---|---|
| Packaging scenario or bruise location | <2.3 Kg-force | 2.3–4.5 Kg-force | >4.5 Kg-force |
| Tray packed yellow flesh peach | 35.1 | 2.7 | 0.0 |
| Volume filled white flesh peach | 55.2 | 13.6 | – |
| Volume filled yellow flesh nectarine | 43.9 | 9.8 | 4.4 |

are harvested at a time with an equitable number of pickers distributed in each row as conditions warrant. Labourers pick an entire tree and leap-frog one another down the rows. The foreman is responsible for moving the pickers between rows to maintain uniformity. Picking platforms have been tried in the past, but are not an economical way of reducing reliance upon ladders due to their cost and the vast differences in tree and labourer variability. When full, the bins are taken to a centralized area and unloaded from the bin-trailers to await loading by forklift onto flatbed trailers for delivery to the packing facility. Full bins are typically covered with canvas to prevent heat damage, and loading areas are usually bordered by large shade trees that serve to help reduce fruit exposure to the sun. In instances where the orchard is close to the packing plant, the fruit can be conveyed there directly on the bin-trailers.

At the packinghouse the fruit are dumped (mostly using dry bin dumps) and cleaned. Here trash is removed and fruit may be detergent washed. Peaches are normally wet-brushed to remove the trichomes (fuzz), which are single cell extensions of epidermal cells. In the case of nectarines, the brushing operation can usually be omitted. Waxing and fungicide treatment may follow in both types of fruit. Water-emulsifiable waxes are normally used, and fungicides may be incorporated into the wax. Waxes are applied cold and no heated drying is used.

Sorting is done to eliminate fruit with visual defects and sometimes to divert fruit of high surface colour to a high-maturity pack. Attention to details of sorting line efficiency is especially important with stone fruits where a range of fruit colours, sizes and shapes can be encountered. Sizing segregates fruit by either weight or dimension. Sorting and sizing equipment must be flexible to efficiently handle large volumes of small fruit or smaller volumes of larger fruit. Most yellow-flesh peaches are packed into two-layer (tray) boxes. Small-sized, yellow-flesh peaches are generally volume-fill packed. Most white-flesh and tree-ripe peaches are packed into one-layer (tray) boxes. Limited volumes of high-maturity fruit are 'ranch packed' at the point of production. In a typical tree-ripe operation, high-maturity and/or high-quality fruit are picked into buckets or totes that are carried by trailer to the packing area. Packers work directly from buckets to select, grade, size and pack fruit into plastic trays. In these cases, the fruit are not washed, brushed, waxed or fungicide treated. In other cases, fruit are picked into buckets or totes but then dumped into a smooth-operating, low-volume packingline for washing, brushing, waxing, sorting and packaging. Because of less handling of the fruit, a higher maturity standard can be used, and growers can benefit from increased fruit size, red colour and greater yield. High-quality fruit can also be produced by managing the orchard factors properly and picking firm fruit. In this case, ripening at the retailer will be essential to assure good flavour quality for consumers.

Our transportation bruising damage work on white and yellow flesh peaches and nectarines indicated that packaging system and fruit firmness influence bruising damage occurring during transportation. In general, tray packed fruit tolerate transportation better than volume filled (Table 10.4). Fruit with firmness between 2.3 and 4.5 kilos-force on the weakest fruit position only had between 3% (white flesh) to 10% (yellow flesh) damage, respectively (Crisosto et al., 2001; Valero et al 2006).

### Handling at the receiving end

Peaches and nectarines are usually harvested when they reach a minimum or higher maturity, but are not completely ripe ('ready to eat'). Initiation of the ripening process must occur before consumption to satisfy consumers (Crisosto 1999). The ripening process can be initiated at the distribution centres (receivers) or at harvest immediately after packaging (preconditioning). In general, fruit < 27 to 36 N

(2.7 to 3.6 Kg-force) measured on the fruit cheek have high consumer acceptance and with 9 to 13.5 N (0.9 to 1.4 Kg-force) flesh firmness are considered ready to eat.

## PLUM POST-HARVEST HANDLING SYSTEMS

### Fruit deterioration factors

#### *Chilling injury (CI) or internal breakdown (IB)*

Chilling injury (CI) is a concern with most plum and fresh prune cultivars. It is expressed as flesh translucency and is associated with flesh browning (Plate 10.4). In previous publications from South Africa, flesh translucency, specifically in some plum cultivars, has been called 'gel breakdown' (Dodd 1984). In the United States, these symptoms are reported as 'internal breakdown' or CI (Crisosto *et al*. 1999b; Mitchell & Kader 1989). CI symptoms normally appear after placing fruit at ripening temperatures (20°C to 25°C) following cold storage at 2°C to 8°C. Postharvest life varies among cultivars and it is strongly affected by temperature management. Most plum and fresh prune cultivars are most susceptible to chilling injury when stored at 5°C. Market life of 'Blackamber,' 'Fortune' and 'Angeleno' plums at 0°C was > 5 weeks. 'Showtime,' 'Friar' and 'Howard Sun' plums developed chilling injury symptoms within 4 weeks, even when stored at 0°C. In all plum cultivars, a much longer market life was achieved when stored at 0°C than at 5°C (Table 10.5). However, market-life potential is affected by several other factors such as orchard conditions and maturity. For example, the role of maturity in market-life potential is well illustrated in our 'Blackamber' plum work (Table 10.6).

Pit burning symptoms are similar to internal browning but this is a heat damage problem that originates before harvest of 'Italian' and other cultivars of prunes and plum. It is associated with high temperatures during fruit maturation and can delay harvest (LaRue & Johnson 1989).

### Post-harvest treatments to reduce deterioration

#### *Controlled atmosphere (CA)*

The major benefits of CA during storage and shipment are retention of fruit firmness and delay of changes in ground colour. Decay incidence can be reduced by CA of 1 to 2% $O_2$ + 3 to 5 % $CO_2$. Currently, CA has a limited use for storage for greater than 1 month with some cultivars such as Angeleno, Casselman, Santa Rosa, Laroda and Queen Ann (Kader & Mitchell 1998; Truter *et al*. 1994; Ben & Gaweda 1992; Streif 1989; Eksteen *et al*. 1986; Mitchell *et al*. 1981; Couey 1960, 1965).

The influence of modified atmosphere packages (MAP) on quality attributes and shelf life performance of 'Friar' plums was studied on 'Friar' plum (Cantín *et al*. 2008). Flesh firmness, soluble solids concentration (SSC), titratable acidity

**Table 10.5** Effects of Storage Temperature on Market Life Potential of Plum Cultivars[a].

| | | | Storage/shipping potential (weeks) | |
|---|---|---|---|---|
| Cultivar | Plant breeding program | Fruit type | 0°C | 5°C |
| Angeleno | Garabedian | Semi-free to freestone | 5+ | 5 |
| Betty Anne | Zaiger | Clingstone | 5 | 5 |
| Blackamber | Weinberger | Freestone | | |
| Earliqueen | Zaiger | Clingstone | 3 | 2 |
| Friar | Weinberger | Freestone | 5 | 3 |
| Flavorich | Zaiger | Clingstone | 5 | 5 |
| Fortune | Weinberger | Semi-clingstone | 5+ | 3 |
| Hiromi Red | Zaiger | Clingstone | 5 | 3 |
| Howard Sun | Chamberlin | Freestone | 4 | 1 |
| Joanna Red | Zaiger | Freestone | 5 | 5 |
| October Sun | Chamberlin | Semi-clingstone | 5 | 5 |
| Purple Majesty | Bradford | Clingstone | 5 | 3 |
| Showtime | Wuhl | Freestone | 5 | 3 |

[a] Information was obtained from personal communications with Gary Van Sickle, Kevin Day, and David Ramming, from Brooks and Olmos (1972), Whealy and Demuth (1993), Okie (1998), nursery catalogues and United States Patents.

(TA), and pH were not affected by the MAP liners. Fruit skin colour changes were repressed on plums packed in box liners that modified gas levels and weight loss was reduced by the use of any of the box liners. Plums packed without box liners (bulk packed) had approximately 6% weight loss. High $CO_2$ and low $O_2$ levels were measured in boxes with MAP box liners. Percentage of healthy fruit was not affected by any of the treatments during the ripening period (shelf life) following 45 days of cold storage. After 60 days of cold storage, fruit from the MAP box liners with higher $CO_2$ and low $O_2$ levels had a higher incidence of flesh translucency, gel breakdown and 'off flavour' than fruit from the other treatments.

### Physical damage

Our previous work on impact bruising damage during harvesting and packaging (Crisosto *et al*. 2001) demonstrated that most plum cultivars with flesh firmness greater than 1.4 Kg-force tolerated very well impact forces up to 245 G (simulating impacts occurring during rough packingline operations) (Table 10.7). During transportation, our experience with plums suggested that plums will be even less susceptible to bruising damage during transportation than yellow flesh peach and nectarine. At retail, bruising potential was measured by placing an IS-100 recording accelerometer in the centre of the top layer of a two-layer tray packed box. Accelerations (G) ranging from 19.1 G to 44.9 G were measured during box handling – removal from the pallet and boxes and dropped from different heights. Thus, accelerations measured were lower than critical bruising thresholds for many plums with firmness equal to or higher than 1.4 Kg-force.

### Post-harvest fruit diseases

Brown rot is caused by *Monilinia fructicola* and is the most important post-harvest disease of plums in California. Infection begins during flowering. Fruit rot may occur before harvest, but most often is expressed during post-harvest handling (Wells *et al*. 1994). Pre-harvest fungicide application, prompt pre-cooling after harvest, and orchard sanitation to minimize infection sources are control strategies. Post-harvest fungicide treatments are used to limit decay.

Grey mould is caused by *Botrytis cinerea*. This rot can be serious during years with wet spring weather. It can occur during storage if fruit have been contaminated during harvest and if wounding has occurred. Avoiding mechanical injuries, effective temperature management and post-harvest fungicide treatments are effective control measures.

Rhizopus rot is caused by *Rhizopus stolonifer*. This rot can occur in ripe or near-ripe plums kept at 20°C to 25°C. Pre-cooling and storing fruit below 5°C is effective in controlling this fungus.

### Temperature management and optimum storage conditions

Plums and fresh prunes can be cooled in field bins using forced-air cooling, hydro-cooling, or room-cooling prior to packing. Packed plums and fresh prunes should be cooled by forced-air cooling to near 0°C. A storage temperature of –1.1°C to 0°C with 90 to 95% RH should be used. The freezing point varies from –2°C to –1°C depending on SSC. In late season plums and in fresh 'French' and 'Moyer' prunes, delays in flesh breakdown (IB) development have been attained by storing IB-susceptible cultivars at –1.1°C. However, to store plums at this low a temperature, high SSC and excellent thermostatic control are essential to avoid freeze damage.

### Horticultural maturity indices

In most of the plum cultivars grown in California, harvest date is determined by skin colour changes that are described for each cultivar. A colour chip guide is used to determine maturity for some cultivars. Firmness, measured by squeezing

**Table 10.6** Market Life of 'Blackamber' Plums Harvested on Four Different Dates, Then Stored at 0°C or 5°C.

| Harvest date | Firmness (Kg-force) | SSC | TA[a] | SSC/TA | Maximum market life[b] (weeks at 0°C) | Minimum market life (weeks at 5°C) |
|---|---|---|---|---|---|---|
| 6/20/02 | 7.0 | 10.3 | 0.78 | 13.2 | $2^{2,3}$ | $<2^{3,4}$ |
| 6/26/02 | 5.1 | 10.8 | 0.47 | 22.9 | $5^{3}$ | $2^{3,4}$ |
| 7/2/02 | 4.8 | 11.7 | 0.43 | 27.2 | $5^{3}$ | $3^{1,3,4}$ |
| 7/8/02 | 2.8 | 12.3 | 0.33 | 37.3 | $5^{3}$ | $2^{1,3,4}$ |

[a] Titratable acidity measured after ripening (0.4–0.7 Kg-force).

[b] End of market life based on chilling injury (CI) determined when ≥ 25% of the fruit became mealy[1] or leathery[2], or had flesh bleeding/browning[3] or gel breakdown/translucency[4]. Superscript indicates limiting condition.

**Table 10.7** Minimum Flesh Firmness (Measured at the Weakest Point on the Fruit) Necessary to Avoid Commercial Bruising at Three Levels of Physical Handling.

| | Drop Height[z] | | | |
|---|---|---|---|---|
| Cultivar* | (1 cm) ~66 G | (5 cm) ~185 G | (10 cm) ~246 G | Weakest position |
| **Plums** | | | | |
| Blackamber | 0 | 0 | 3[z] | Tip |
| Fortune | 0 | 0 | 0 | Shoulder |
| Royal Diamond | 0 | 0 | 0 | Shoulder |
| Angeleno | 0 | 0 | 0 | Shoulder |
| **Peaches (yellow flesh)** | | | | |
| Queencrest | 0 | 4 | 9 | Tip |
| Rich May | 0 | 0 | 9 | Tip |
| Kern Sun | 2 | 6 | 9 | Tip |
| Flavorcrest | 3 | 5 | 6–9 | Tip |
| Rich Lady | 6 | 10 | 11 | Shoulder |
| Fancy Lady | 3 | 7 | 11 | Shoulder |
| Diamond Princess | 0 | 0 | 9 | Shoulder |
| Elegant Lady | 3 | 5 | 6–9 | Shoulder |
| Summer Lady | 0 | 0 | 8 | Shoulder |
| O'Henry | 3 | 5 | 6–9 | Shoulder |
| August Sun | 3 | 4 | 9 | Shoulder |
| Ryan Sun | 0 | 0 | 10 | Shoulder |
| September Sun | 0 | 4 | 9 | Shoulder |
| **Nectarines (yellow flesh)** | | | | |
| Mayglo | 4 | 8 | 11 | Tip |
| Rose Diamond | 6 | 7 | 8 | Suture/Shoulder |
| Royal Glo | 0 | 9 | 11 | Shoulder/Tip |
| Spring Bright | 6 | 10 | 10 | Shoulder |
| Red Diamond | 6 | 7 | 11 | Shoulder |
| Ruby Diamond | 4 | 9 | 9 | Shoulder |
| Summer Grand | 2 | 5 | 6 | Shoulder |
| Flavortop | 3 | 6 | 6 | Tip |
| Summer Bright | 0 | 6 | 8 | Shoulder |
| Summer Fire | 0 | 0 | 9 | Shoulder |
| August Red | 2 | 12 | 12 | Shoulder |
| September Red | 0 | 0 | 10 | Shoulder |

Note: Fruit firmness measured with an 8 mm tip and express as Kg-force.

[a] Dropped on 1/8″ PVC belt. Damaged areas with a diameter equal to or greater than 2.5 mm were measured as bruises.

fruit in the palm of the hand ('spring'), is also a useful maturity index for a few cultivars, especially those that achieve full colour several weeks prior to harvest. A two-tier maturity system is currently used in California: U.S. Mature (minimum maturity), and California Well-Mature. Measurement of fruit firmness is recommended for plum cultivars where skin ground colour is masked by full red or dark colour development before maturation. Flesh firmness, measured using a penetrometer (8 mm tip), can be used to determine a maximum maturity index, which is the stage at which fruit can

**Table 10.8** Proposed Harvest Maturity Indexes Based on Firmness (8.0 mm Tip) and Minimum SSC for Different Plum Cultivars.

| Cultivar | Firmness (Kg-force) | Minimum SSC (%) |
|---|---|---|
| Blackamber | 3.2–4.0 | 10–12[z] |
| Fortune | 3.2–4.07–9 | 11 |
| Friar | 3.2–4.0 | 11 |
| Royal Diamond | 3.2–4.0 | 11 |
| Angeleno | 2.7–4.0 | 12 |
| Betty Anne | 3.2–4.0 | 12 |

[a] Blackamber plums with TA ≤0.60% after ripening have a high consumer acceptance. If plums have ≥ 12.0% SSC, TA does not play a role.

be harvested without suffering bruising damage during postharvest handling. Plums are less susceptible to bruising than most peach and nectarine cultivars at comparable firmness. Fresh prunes are picked on the basis of colour, at least 50% of the fruit surface is red or purple and SSC is at least 16% in 'Moyer' and 19% in 'French' prunes.

**Quality characteristics and criteria**

High consumer acceptance is attained for most fruit with high SSC. Fruit TA, SSC:TA and phenolic content (astringency) are also important factors in consumer acceptance. However, there is no established minimum quality standard based on these factors. Consumer acceptance of most traditional plums is related to SSC except for plums with high titratable acidity (TA) at consumption as in some 'Blackamber' lots (> 0.7% TA). In 'Blackamber' plums consumer acceptance and market life were highly dependent on harvest date (Crisosto *et al*. 2004b). For plums within the most common industry ripe soluble solids concentration (RSSC) range (10.0–11.9%), ripe titratable acidity (RTA) played a significant role in consumer acceptance. Plums within this RSSC range combined with low RTA (≤0.60%) were disliked by 18% of consumers, while plums with RTA ≥ 1.00% were disliked by 60% of consumers. Plums with RSSC ≥12.0% had ~75% consumer acceptance, regardless of RTA. This work also pointed out that ripening before consumption decreased TA by approximately 30–40% from the TA measured at harvest (HTA). In some cases, this decrease in TA during ripening may increase the acceptability of plums that would otherwise be unacceptable. Using 'in-store' consumer tests, we have proposed harvest maturity indexes based on firmness and minimum SSC for selected plum cultivars (Table 10.8).

**Harvesting and packaging handling**

Japanese plums and the closely related interspecific plum-type fruits including Pluots® and plumcots, are harvested entirely by hand. Maturity is determined by fruit colour, fruit pressure or a combination of both, and is cultivar dependent. Soluble solids concentration, while important from a consumer satisfaction standpoint, is not commonly used as a measurement of field or harvest maturity. As most plum cultivars are well adapted to a late-harvesting system, increase of SSC can be achieved without jeopardizing the crop (Table 10.6). We suggest the use of firmness as an indicator of how late to harvest ('Tree Ripe') without inducing bruising, thereby maximizing orchard quality. But the decision of when to harvest should also take into account other factors such as fruit drop, environmental conditions, hand labour availability, market prices, distance to market, potential transportation damage and temperature management at the receiving location.

As with other fruit trees, plum fruits ripen from top of the tree to the bottom, a consequence of light environment. Lower fruit can be delayed in maturity by as much as 10–14 days compared to well-exposed fruit at the top of the tree. Consequently, harvests are multiple – generally two to four in number – and frequently complex in logistical determination. Unlike for peaches and nectarines, the first harvest in plums is commonly the largest pick. Since many plum cultivars develop full colour up to several weeks before commercial harvest and usually soften relatively slowly, it is important to develop a method by which field labourers can easily determine fruit maturity. In such full colour cultivars this is commonly done by limiting harvest to only a portion of the tree – usually segregated by light exposure, such as the top third of the tree in the first harvest, the middle third in the second and so on – so that labourers can proceed more quickly.

The logistics of harvesting are very similar to that described for peaches and nectarines. Fruits are harvested into picking bags that can hold up to ~20 kg of fruit. The pickers dump the fruit into bulk bins that contain about 400–450 kg of fruit. The bulk bins are transported in the orchard on tractor-pulled trailers that hold four or five bins. Usually two tractors and bin-trailers are required for each harvest crew. When full, the bins are taken to a centralized area and unloaded from the bin-trailers to await loading by forklift onto flatbed trailers for delivery to the packing facility.

Sorting is done to eliminate fruit with visual defects and sometimes to divert fruit of high surface colour to a high-quality pack. Sizing segregates fruit by either weight or dimension. In general, plums and fresh prunes are packed into 12.6 kg volume-filled containers.

**Table 10.9** Ripening Rates of Plums at 10°, 20° and 25°C Measured with a UC Firmness Tester (8.0 mm Tip).

| | Rate of softening (kg per day) | | |
|---|---|---|---|
| Cultivar | 10°C | 20°C | 25°CF |
| Plums | | | |
| Black Beaut | 0.3 | 0.3 | 0.3 |
| Santa Rosa | 0.1 | 0.3 | 0.4 |
| Blackamber | <0.1 | 0.3 | 0.32 |
| Fortune | 0.18 | 0.4 | 0.6 |
| Friar | 0.14 | 0.3 | 0.6 |
| Simka | 0.36 | 0.55 | 0.77 |
| Royal Diamond | 0.14 | 0.23 | 0.5 |
| Casselman | 0.06 | 0.23 | 0.3 |
| Angeleno | 0.0.045 | 0.0.18 | 0.0.23 |
| Average | 0.18 | 0.1.54 | 0.45 |

**Table 10.10** Titratable Acidity of Plums at Harvest (Mature), and After Ripening at 20°C Until the Firmness of the Flesh Was Less Than 1.4 Kg-force (Ripe).

| | Titratable Acidity (% malic acid) | | |
|---|---|---|---|
| Cultivar | Mature | Ripe | Change (%) |
| Plums | | | |
| Black Beaut | 0.61 | 0.49 | –19.7 |
| Santa Rosa | 1.12 | 0.45 | –59.8 |
| Blackamber | 0.61 | 0.59 | –3.3 |
| Fortune | 1.11 | 0.43 | –61.3 |
| Friar | 0.98 | 0.41 | –58.2 |
| Simka | 1.31 | 0.41 | –68.7 |
| Royal Diamond | 0.54 | 0.34 | –37.0 |
| Casselman | 0.70 | 0.46 | –34.3 |
| Angeleno | 0.42 | 0.33 | –21.4 |
| Average | 0.82 | 0.43 | –40.4 |

### Retail outlet display considerations

Generally, if fruit firmness is greater than 2.3 kg-force, fruit should be displayed on a dry table. If fruit firmness is less than 2.3 kg-force, plums should be displayed on a cold table.

### Retail ripening

Ideal plum ripening conditions are different than conditions for other tree fruits. In general, plums have a significantly slower rate of flesh softening than peaches and nectarines (Table 10.9). At 10°C, plum ripening was slow enough to be considered negligible for many cultivars, and the rate of softening is still slow at 20°C for most cultivars. The best plum ripening can be accomplished when exposed to 25°C. During ripening, plum TA decreased, but the amount varied from cultivar to cultivar (Table 10.10). In general, plum TA tended to decrease approximately 40% when reaching the ripe stage (0.9–1.4 kg force).

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# 11
# Soft Fruit

*Leon A. Terry*

Soft fruit is a generic category of edible fruit that includes most berries, currants and the strawberry. Of these, the most economically important soft fruit are strawberries, raspberries and currants, respectively (Table 11.1). As their name suggests, soft fruit are characterised by their innate lack of firm texture. This attribute alone poses significant and particular difficulties for the post-harvest maintenance of quality in terms of handling, transportation, distribution and shelf life. Furthermore, soft fruit are inherently prone to post-harvest disease, primarily caused by *Botrytis cinerea* Pers. (Terry *et al*. 2004). Due to the difficulties associated with post-harvest deterioration of soft fruit quality, the majority of soft fruit production is destined for the processing market. This chapter will, however, only discuss post-harvest aspects associated with the fresh soft fruit market.

Refrigeration (<5°C) during transportation and storage is the fundamental means used to extend post-harvest life of soft fruit through retarding fruit softening, senescence and suppressing disease incidence and severity. This chapter will discuss other conventional methods of maintaining soft fruit quality, such as controlled atmosphere (CA) storage and modified atmosphere packaging (MAP), which have and are being increasingly adopted by the industry. In addition, the chapter will also focus on recent advances in extending post-harvest life through biological, chemical and physical elicitor treatments of natural disease resistance (Terry & Joyce 2004a). The effect of manipulating pre-harvest conditions on fruit quality and future developments in genetically transformed soft fruit will also be briefly reviewed. Since the overwhelming majority of post-harvest research has been conducted on strawberry, much of the information presented in this chapter refers to the post-harvest physiology, biochemistry and pathology of this important crop. Where appropriate, however, post-harvest issues for other soft fruit species are discussed.

## ORIGINS AND ECONOMIC IMPORTANCE

Soft fruit are grown in all temperate regions of the world. Their importance as a valuable horticultural commodity is evident in that over 5.5 million tonnes (MT) are produced annually (FAO 2003; Table 11.1). The commercial strawberry (*Fragaria* × *ananassa* Duch.), belongs to the Rosaceae family. It is a perennial herb with rooting runners that usually bears red-coloured berry fruit on maturity. The commercial strawberry is thought to derive from an interspecific hybrid cross between the two octaploid species, *F. chiloensis* (L.) Duch. and *F. virginiana* Duch. (Went 1957; Darrow 1966; Hancock 1999). Hundreds of strawberry cultivars have been developed (Table 11.2); the most commercially important of these is cv. Camarosa, although it is not particularly well adapted to non-Mediterranean European climates.

## GENERAL FRUIT ANATOMY

The basic morphology of soft fruit is varied. For instance, the raspberry and blackberry are classed as aggregate fruit as they consist of clusters of one-seeded drupelets. The drupelets are typically eaten as a cluster which is referred to as the berry. The strawberry is also aggregate in structure

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**Table 11.1** Examples of Economically Important Soft Fruit Types.

| Common name | Botanical name | Economic production (MT; FAO 2003) |
|---|---|---|
| Blackberry; loganberry; mulberry; myrtle berry; huckleberry, dangleberry | *Morus nigra; M. alaba; M. rubra*; *Myrtus communis*; *Gaylussacia* spp. | 563 770 |
| Blueberry | *Vaccinium myrtillus; V. corymbosum*. | 227 570 |
| Cranberry | *Vaccinium macrocarpon, V. oxycoccus* | 311 150 |
| Currants (black, red/white) | *Ribes nigrum; R. rubrum*. | 644 950 |
| Gooseberry | *Ribes grossularia* | 177 014 |
| Raspberry | *Rubus idaeus* | 415 836 |
| Strawberry | *Fragaria* spp. | 3 165 314 |

Note: Other niche berry species include: Cloudberry (*Rubus chamaemorus*), Rowanberry (*Sorbus aucuparia*), wild strawberry (*Fragaria vesca*) (*cf*. Hakkinen *et al*. 1999).

**Table 11.2** Examples of Some of the Most Popular Strawberry Cultivars for the Fresh Market.

| Cultivar | Main area of production | Fruit characteristics | Research Organization |
|---|---|---|---|
| Camarosa | World-wide | Very large, firm fruit | University of California |
| Chandler | California, all mild climates | Large, firm fruit, prone to white shoulder | University of California |
| Elsanta | Non-Mediterranean European climates | Moderate size, firm fruit, orange-red | Institute of Horticultural Research, the Netherlands |
| Earliglow | Eastern US | Moderate size, excellent flavour, relatively resistant against *Botrytis cinerea* | USDA Maryland |
| Honeoye | Mid-western and Eastern US/ UK | Large, dark coloured fruit | New York AES |
| Oso Grande | California/all mild climates | Very large, firm fruit; hollow centre | University of California |
| Selva | California/all mild climates | Large, firm fruit; somewhat hollow centre | University of California |

Source: Adapted from Hancock (1999).

(Coombe 1976), but is considered to be a false fruit (Perkins-Veazie 1995) as it does not originate from an augmentation of the ovary. Rather, the strawberry fruit develops through swelling of the parental receptacle. Esau (1977) describes the strawberry as an aggregate accessory fruit as although it is formed from an apocarpous gynoecium with each carpel retaining its identity on maturity, the strawberry contains extracarpellary tissue. The central core of the swollen strawberry receptacle is pith (Plate 11.1). This is girdled by corticular parenchyma and lightly waxed epidermis tissue. The epidermis bears a number of embedded one-seeded fruits (achenes), which are arranged in a spiral pattern (Abbott *et al*. 1970). Achenes arise from many ovaries that surround the receptacle (Darrow 1966). They are attached to the receptacle vasculature by fibrovascular connections (Lis & Antoszewski 1979). These connections are thought to be a pathway for inter-organ communication governing fruit growth and development.

## FRUIT DEVELOPMENT

During development, soft fruit typically undergo an initial growth phase followed by enlargement and then maturation. Soft fruit growth and development, including maturation and ripening, is characterised by changes in colour, texture and flavour. Four to five stages of berry growth and development have been described (Culpepper *et al*. 1935; Huber 1984; Terry *et al*. 2004). For strawberry, in accordance with the intumescence of non-ovarian receptacle tissue (cortex and pith), these descriptive stages include

**Table 11.3** Fresh Weight and Hue Angle of Strawberry cv. Elsanta Fruit at Different Developmental Stages.

| Colour stage | Fresh weight (g) | Hue Angle (H°) |
|---|---|---|
| Green I | 3.03 | 111.54 |
| White | 6.55 | 109.30 |
| Red | 16.59 | 40.30 |

Source: Terry *et al*. 2002 with permission.

**Table 11.4** Mean Number of Days after Planting (DAP) and Days after Anthesis (DAA) Until Harvest for Secondary and Primary Strawberry cv. Elsanta Fruit Grown between Winter and Early Summer (February and May) 2001 (Experiment 1) and Summer (July and July) 2001 (Experiment 2) (n = 64).

| | Experiment 1 | | Experiment 2 | |
|---|---|---|---|---|
| Fruit position | DAP | DAA | DAP | DAA |
| Primary | 94.1 | 41.5 | 40.4 | 21.3 |
| Secondary | 95.0 | 41.1 | 42.0 | 21.9 |

Source: Adapted from Terry and Joyce (2006).

green stage I, green stage II, white, and full red (Plate 11.2; Table 11.3). As fruit overripen (*ca*. 35 days after anthesis (DAA)) they become a darker red/purple. This colour change is mediated by a shift in anthocyanin glycosylation caused by cell decompartmentalisation (Manning 1993).

Depending on environmental conditions, the strawberry plant is able to bear full red fruit within approximately 24–28 days after anthesis (Terry *et al*. 2004). Variation in time to reach maturity is cultivar dependent, but is primarily governed by temperature (Perkins-Veazie & Huber 1987; Terry & Joyce 2004b) and hence enzyme mediated metabolic rate (Manning 1993). Under extreme environmental conditions, time to strawberry fruit maturity after planting and after anthesis can vary considerably (Table 11.4). Similarly, final fruit weight is dependent on rate of fruit development (Table 11.5) and preharvest irrigation (Terry *et al*. 2007b). Berry growth is usually measured by changes in fresh and/or dry weight or dimensions. Upon maturity, the full red stage and maximum weight and size of the fruit is achieved (Plate 11.2).

Soft fruit growth is often characterised by either a single sigmoidal-shaped (Woodward 1972; Stutte & Darnell 1987) or a biphasic growth curve (Thompson 1969; Coombe 1976; Miura *et al*. 1990). Large strawberry fruit size is an inherent trait, however, variations in berry size occur depending on the physiological interaction between blossom position, number of developing achenes, fruit competition, plant vigour and pre-harvest environmental conditions (Table 11.5; Janick & Eggert 1968; Terry & Joyce 2004b; Terry *et al*. 2007b). The strawberry inflorescence or infructescence possesses a terminal primary inflorescence with secondary and tertiary inflorescences attached below this primary bloom (Plate 11.3). Apical dominance within the cyme mediates interfruit competition for assimilates (Terry *et al*. 2007b). Primary fruit usually have a faster growth rate and achieve larger size on maturity (Moore *et al*. 1970; Table 11.5). This phenomenon is physiologically determined and independent of environmental conditions. Removal of the primary bloom at anthesis results in an increase in secondary fruit weight at harvest (Stutte & Darnell 1987). Final fruit size and shape are also closely correlated with the number and size of fertile achenes on a fruit (Nitsch 1950; Moore *et al*. 1970; Manning 1993). The major cause of malformed berries is inadequate pollination, whereby not all achenes are fertilised. In this respect, control of fruit growth is attributed to assimilate sink strength mediated by auxin secreted from developing achenes.

**Table 11.5** Mean Weight (g) for Secondary and Primary Strawberry cv. Elsanta Fruit Grown between Winter and Early Summer (February and May) 2001 (Experiment 1) and Summer (July and July) 2001 (Experiment 2) (n = 64).

| | Mean fruit weight | |
|---|---|---|
| Fruit position | Experiment 1 | Experiment 2 |
| Primary | 33.71 | 14.53 |
| Secondary | 26.33 | 9.62 |

Source: Adapted from Terry and Joyce (2006).

## FRUIT RIPENING

Distinct cellular and compositional changes occur during the ripening process. Auxin and its derivatives play the primary role in controlling ripening. Nitsch (1950) first demonstrated that achenes, believed to be the source of auxin, mediate the growth and therefore all ontogenetic aspects of strawberry fruit development. The removal of achenes in the early stages of growth retards the ripening process (Nitsch 1950). With the onset of ripening, changes in texture, colour,

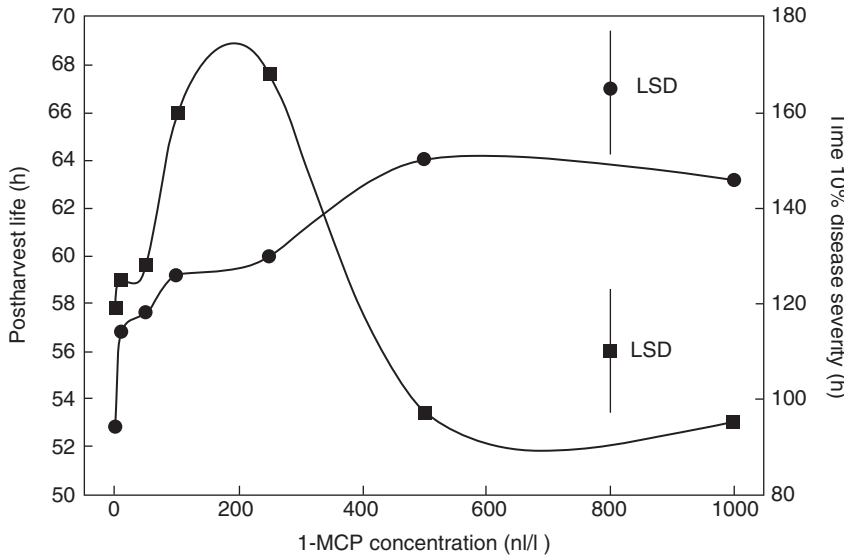


**Figure 11.1** Effects of 1-MCP treatments (0 [control], 10, 100, 250, 500 or 1000 nl $l^{-1}$) for 2 h at 20°C on strawberry fruit post-harvest life (hand firmness; •) and number of hours to 10% disease severity (■). Data are means for 15 fruit. LSDs (P = 0.05) are presented. (Jiang *et al.*, 2001, with permission.)

soluble sugar, acidity, health-related compounds (*viz*. anthocyanins and other phenylpropanoids) and aroma occur.

### Hormonal control

Ripening in most fruits is associated with either a decrease in auxin or an increase in ethylene production. However, the strawberry and other soft fruit are generally regarded as nonclimacteric in their respiratory behaviour (Lipe 1978; Given *et al*. 1988; Perkins-Veazie & Nonnecke 1992; Burdon & Sexton, 1993; Perkins-Veazie *et al*. 2000) exhibiting little respiratory increase after harvest. In general, ethylene is considered to have little or no effect on ripening of soft fruit. For instance, Siriphanich (1980) found no differences between strawberry fruit held in air or 100 µl $l^{-1}$ ethylene. On the other hand, Knee *et al*. (1977) and Abeles and Takeda (1990) highlighted the correlation between endogenous ethylene production and the ripening process. Typically, strawberry fruit are unresponsive to exogenous ethylene (Iwata *et al*. 1969; Hoad & Williams 1971). However, Perkins-Veazie and Huber (1987) demonstrated that colour development could be stimulated by using the ethylene analogue propylene (5000 µl $l^{-1}$). Application of the ACC (1-aminocyclopropane-1-carboxylic acid)-synthase inhibitor aminoethoxyvinylglycine and the ethylene binding inhibitors silver thiosulfate (STS) and norbornadiene (NBD) failed to block anthocyanin accumulation in developing strawberry fruit (Given *et al*. 1988). Tian *et al*. (1997) showed that application of the ethylene binding inhibitor diazocyclopentadiene (DACP) increased ethylene production, but not respiration, of ripe strawberry fruit. Enhanced ethylene production was explained as release from feedback inhibition on ACC synthesis. Despite this lack of evidence that soft fruit are ethylene-sensitive, exogenous ethylene can enhance the growth of *B. cinerea* on strawberry and decrease fruit firmness (El-Kazzaz *et al*. 1983). Curd (1988) showed that strawberries exposed to ethylene had more intense red colour than those stored in ethylene-free air. Moreover, exogenous ethylene induced secondary ripening processes (e.g. colour development, softening) in strawberry fruit (Tian *et al*. 2000). Wills and Kim (1995) found that use of the ethylene absorbent potassium permanganate extended the storage life of strawberries. Thus, it follows that prevention of ethylene production and/or inhibition of ethylene action could be an approach to extending the post-harvest longevity of ripe strawberry fruit. However, post-harvest treatments with 1-methylcyclopropene (1-MCP), the ethylene binding inhibitor, have been shown to have both beneficial and/or detrimental effects on strawberry fruit quality (Figure 11.1 and Table 11.6). Work

**Table 11.6** Effect of Post-harvest 1-MCP Treatment on Strawberry Fruit Quality.

| Cultivar | Concentration (nl/l) | Duration | Storage condition | Effects | Reference |
|---|---|---|---|---|---|
| — | 500 | — | 5 or 20°C | ⇑ post-harvest decay, quality | Ku *et al*. 1999 |
| Pajaro | 2000 | 18 h | 20°C | ⇓ respiration, loss in firmness, colour changes; ⇑ ethylene production, | Tian *et al*. 2000 |
| Everest | 100 and 250 | 2 h | 3d at 20°C in dark at >95RH% | ⇓ post-harvest decay (*Rhizopus stolonifer*), ethylene production, loss in firmness | Jiang *et al*. 2001 |
| | 500 and 1000 | | as above | ⇑ post-harvest decay (*R. stolonifer*), PAL activity, anthocyanins; ⇓ total phenolics | |
| NS | 10–1000 | 24 | 0 or 5°C | ⇑ post-harvest decay; ⇓ ethylene production, calyx deterioration | Bower et al. 2003 |

by Trainotti *et al*. (2005) argued that ethylene may have a role in strawberry ripening as different ethylene receptors showed increased expression during development.

Despite the wealth of evidence that supports the view that ethylene may have a role in postharvest storage of strawberry, work has shown that total removal of ethylene from a hermetically sealed environment using a newly developed and highly efficacious palladium-promoted ethylene scavenger had some benefit (Terry *et al*. 2007a). Even though ethylene was removed using the Pd-promoted material the effects on postharvest strawberry fruit quality and storage life were small. A similar conclusion was given by Bower *et al*. (2003) who concluded that despite some beneficial effects neither the removal of ethylene or treatment with 1-MCP were likely to be cost-effective methods of extending the storage life of strawberries (cv. not stated). Again, these results mirror those reported by many other authors that the effects of ethylene are not well defined for strawberry and may be affected by cultivar, maturity, disease, storage temperature and even tissue type (Jiang *et al*. 2001; Bower *et al*. 2003; Iannetta *et al*. 2006).

**Firmness**

Strawberries soften greatly during ripening, however, the biochemical basis of cell wall degradation in strawberry has not been fully established. The general consensus is that softening results from a degradation of the middle lamella between cortical parenchyma cells (Abeles & Takeda 1990). Hemicellulose and cellulose degradation may also contribute to softening (Barnes & Patchett 1976; Knee *et al*. 1977; Abeles & Takeda 1990; Rosli *et al*. 2004). However, other authors have argued that the amount of cellulose remains relatively constant during strawberry fruit ripening (Koh & Melton, 2002). Reports have implicated that strawberry fruit softening is governed, in part, by de-polymerisation of strawberry xyloglucans by *endo*-glucanase (Harpster *et al*. 1998; Trainotti *et al*. 1999; Wooley *et al*. 2001). Cleavage of xyloglucan linkages due to *endo*-glucanase may result in pectin solubilisation (Koh & Melton 2002). Similarly, progression from white stage to red stage in raspberry fruit coincides with a dramatic reduction in pectin (Stewart *et al*. 2001). Cell wall disassembly events in raspberry, blueberry and boysenberry (Vicente *et al*. 2007a, 2007b, 2007c) have been described in detail. Jiménez Bermúdez *et al*. (2002) demonstrated that strawberry fruit firmness could be maintained by engineering plants which incorporated an antisense sequence of a strawberry pectate lyase gene. Data from strawberry cultivars with differing fruit firmness suggest that strawberry fruit softening is principally related to pectin solubilisation (Woodward 1972; Knee *et al*. 1997) and also to a lesser extent de-polymerisation (Rosli *et al*. 2004) in the apparent absence of polygalacturonases (PG) (Koh & Melton, 2002). The role of PG in strawberry fruit ripening remains controversial. Despite different endo- or exo-PG activity being partially characterised (Nogata *et al*. 1993), pectin solubilisation occurs in the presence of very low PG activity. It remains unclear that all developmentally regulated PGs found in strawberry function in cell wall degradation during ripening.

### Colour and appearance

As soft fruit ripen an increase in anthocyanins is accompanied by a decrease in chlorophyll content. The predominant anthocyanins in all red strawberry cultivars and raspberry fruit is pelargonidin 3-glucoside (Pg 3-gluc) and cyanidin 3-glucoside (Cy 3-gluc), respectively (Given *et al*. 1988; João Melo *et al*. 2000). Typical concentrations of Pg 3-gluc and Cy 3-gluc found in ripe strawberry cv. Elsanta range from 110 to 150 µg $g^{-1}$ FW and from 2 to 4 µg $g^{-1}$ FW, respectively, and have been shown to be affected by preharvest water deficit irrigation (Terry *et al*. 2007b). The accumulation of anthocyanins coincides with the *de novo* induction of the activities of phenylalanine ammonia lyase (PAL) and uridine diphosphate glucose:flavonol $O^3$-D-glucotransferase (UDPGFT) (Given *et al*. 1988; Cheng & Breen 1991). Despite final ripe fruit colour being affected by environment there are distinct colour differences between genotypes (Table 11.2; Sacks & Shaw 1994). Modest changes in anthocyanin content of strawberry fruit during storage can occur according to maturity, light and storage temperature (Sacks & Shaw 1993; Saks *et al*. 1996). Fruit glossiness also diminishes post-harvest, particularly at temperatures greater than 5°C and at low humidity (Ferreira *et al*. 1994). Distinct differences in the level of anthocyanins were also found amongst blackcurrant cultivars (McDougall *et al*. 2005; Giné Bordonaba & Terry 2007). Increasingly, evidence suggests that daily consumption of soft fruit, which typically contain relatively high concentrations of anthocyanins and other phenylpropanoids (e.g. flavonoids and hydroxycinnamic acids; Aaby *et al*. 2005, 2007) with high total antioxidant capacity (e.g. ORAC or FRAP assays), may provide protection against cardiovascular diseases and cancer (*cf*. Seeram *et al*. 2006).

### Sugars

It has been reported that the total soluble solid content (TSS %) of strawberry fruit increases steadily during development, from 5% in green fruit to 7.3% in overripe (dark red) fruit (Spayd & Morris 1981). However, depending on the environment and cultivar, the TSS of fruit can vary between 4% and 12% Brix (Terry unpublished). Maroto *et al*. (1986) reported that TSS hardly changed during fruit development and ripening, with a mean value of 8%. Although the absolute and relative concentrations of fructose, glucose and sucrose vary amongst cultivars and degree of ripeness there is actually poor correlation between sugar content and TSS (Shaw 1988; Perez *et al*. 1997) and thus it is thought that organic acids and soluble amino acids may also influence TSS. Typical concentrations of fructose, glucose and sucrose found in ripe strawberry cv. Elsanta range from 22 to 36 mg $g^{-1}$ FW, from 18 to 29 mg $g^{-1}$ FW and from 23 to 28 mg $g^{-1}$ FW, respectively, and have been shown to be affected by preharvest water deficit irrigation (Terry *et al*. 2007b). Despite TSS being used ubiquitously by the strawberry industry for quality control it should be limited to comparative studies when environmental variation is low (Olías *et al*. 2001; Terry *et al*. 2005).

### Organic acids

Citric, malic, ascorbic, oxalacetic, glyceric and glycolic acids are the principle organic acids identified in strawberry fruit. Acids affect flavour directly and can regulate cellular pH, influencing fruit tissue colour. Total titratable acidity (TTA), a measure of the buffering capacity of fruit, is generally expressed as percent citric acid. Citric acid is the predominate organic acid found in strawberry (Green 1971) and decreases upon colour development on a per fruit basis. Typical concentrations of citrate, malate and ascorbate found in ripe strawberry cv. Elsanta range from 9 mg $g^{-1}$ FW, 3 mg $g^{-1}$ FW and 0.7 mg $g^{-1}$ FW, respectively (Terry *et al*. 2007b). Current standard product-orientated quality control operations do not use TTA due to the cumbersome and time-consuming nature of titrations (Terry *et al*. 2005).

### Volatile compounds

Soft fruit aroma is influenced by a complicated assortment of esters, alcohols, aldehydes, ketones, sulfur compounds and furanones. Raspberry aroma can be approximated relatively well by 4-(4-hydroxyphenyl)-butan-2-one; referred to as the 'raspberry ketone' (Larsen & Poll 1990). No single character impact compound (Baldwin 2002) is responsible for the typical aroma of fresh strawberry, however, ethyl/methyl esters and furaneol seem to be important (*cf*. Olías *et al*. 2001; Olbricht *et al*. 2008). Aroma is affected by genotype, shading, harvest maturity and post-harvest handling (Watson *et al*. 2002). Low temperature storage, although desirable for extending post-harvest life, can diminish emission of volatiles.

## POST-HARVEST HANDLING

The highest quality soft fruit, after harvest, are regularly shaped, glossy, fully coloured, firm and have achieved maximum flavour and aroma. For strawberry fruit, a healthy green calyx is also desirable. Fruit that are too large can result in lower prices. Strawberry fruit destined for export are occasionally picked at least three-quarters ripe. Fruit at this stage generally develop adequate colour

during storage (despite being classed as nonclimacteric), and are more firm than those harvested fully ripe. However, maximum flavour and aroma (volatile emission) is rarely achieved when fruit are picked before proper horticultural maturity. Overripe strawberries should not be picked for storage as both external and internal colour darkens with off-flavours being produced.

### Cooling

Once soft fruit are harvested they are more sensitive to water loss and temperature changes than when attached to the plant. Post-harvest low temperature management is the most important method for maintaining soft fruit quality. However, temperature abuse during the cold chain is common. Delays between harvest and cooling significantly hasten fruit deterioration (e.g. water loss/shrivelling, physiological deterioration, colour loss and time to disease incidence; Nunes *et al*. 1995). For every 3 h delay in cooling to 5°C, time to disease incidence has been found to double (Maxie *et al*. 1959). Thus, rapid removal of field heat immediately after harvest is paramount as strawberry respiration rate increases *ca*. fivefold from 28 to 127 ml $CO_2$ $kg^{-1}$ $h^{-1}$ between 5 and 20°C, respectively (Robinson *et al*. 1975). Soft fruit are amongst fruits with the highest respiration rates. Rapid heat removal is commonly achieved either passively by placement in a refrigerated room or using forced-air tunnel cooling (FAC) (Olías *et al*. 2001; Anderson *et al*. 2004). FAC may lead to excessive weight loss and possibly reduction in fruit aroma. Ferreira *et al*. (1996) showed that hydro-cooling of strawberry fruit by immersion in chlorinated water extended post-harvest life without significant fruit weight loss. Hydro-cooling time depends on fruit size and water flow rate, but has not been accepted commercially for soft fruit. Recent research suggests, however, that while the best temperature for long-term storage of strawberry cv. Jewel fruit is 0.5°C, nutritional quality can be improved at 10°C if only a few days storage are required (Shin *et al*. 2007).

Under ideal storage conditions strawberry quality can be maintained for 2–10 days at 0–2°C and 90–95% relative humidity (RH; Snowdon 1990; *cf*. Thompson 1996). However, strawberry fruit quality was maintained for up to 18 days when control cvs. Elsanta or Andana fruit were held in the dark at 5°C and 95–100% RH in individually closed but vented polystyrene containers (Plate 11.4; Terry & Joyce 2000). Recent results have demonstrated that strawberry cv. Elsanta can be stored at 5°C for up to 40 days without a detrimental result on appearance (Terry & Macnish unpublished, 2004).

Maintaining soft fruit at low temperature not only decreases physiological deterioration (e.g. loss in firmness, calyx discoloration, loss in glossiness) but also suppresses post-harvest disease incidence. Storage of soft fruit at <5°C generally controls leak rot caused by *Rhizopus stolonifer*, but only suppresses grey mould development (Terry & Joyce 2000) as certain *B. cinerea* isolates have a minima cardinal temperature of between –2°C to 5°C.

### Protection from mechanical damage

Soft fruit are intrinsically vulnerable to physical damage after harvest. The thin fragile epidermis of soft fruit provides little protection against injury. Compression, impact and vibrational bruising increase respiration rate and disease incidence. Strawberry fruit are especially prone to puncturing from the cut pedicel of neighbouring fruit in the punnet (or clam shell container). Susceptibility to puncture injury may be cultivar dependent. In order to reduce physical damage throughout the supply chain, soft fruit are generally only handled once (i.e. by the picker). The 'one punnet system' has been universally adopted. Bubble film (wrap) is often inserted within a punnet to give added protection. Low temperature storage increases fruit firmness and, thus, reduces incidence of mechanical damage. Other pre- and post-harvest treatments, such as foliar sprays, CA storage and hot water immersion also retard fruit softening (Table 11.7; Civello *et al*. 1997). Cheour *et al*. (1990; 1991) demonstrated that foliar applications 3–4 days before harvest of 20 kg $CaCl_2$ $ha^{-1}$ reduced fruit softening and decay during seven days storage at 5°C.

## SELECTIVE GASEOUS ATMOSPHERE STORAGE

Controlled atmosphere (CA) storage and modified atmosphere packaging (MAP) usually imply elevation of $CO_2$ and/or reduction of $O_2$ concentration. Proper low-temperature storage and management of relative humidity should always be pre-requisites to CA and/or MA of soft fruit. In contrast to CA, MAP relies on either active or passive alteration of gaseous concentrations within packaging or within shrouded pallets and, thus, is a function of fruit respiration rate versus packaging permeability. Strawberry fruit, unlike many fresh produce types, are relatively tolerant of elevated $CO_2$ concentrations. Consensus suggests that 15–20% $CO_2$ and 5–10% $O_2$ are ideal levels for successful strawberry fruit CA storage (Table 11.7). Similarly, CA and/or MAP storage significantly suppressed decay and maintained quality on other berry fruit (Agar *et al*., 1997), e.g. blueberry fruit

**Table 11.7** Examples of Effect of Post-harvest Controlled Atmosphere Storage on Strawberry Fruit Quality.

| Cultivar | $CO_2$ concentration (kPa) | $O_2$ concentration (kPa) | Storage temperature (°C) | Effects on fruit quality during storage | Reference |
|---|---|---|---|---|---|
| Chandler | $CO_2$-enriched atmosphere (ns) | > 20 | 1.7 | ⇑ post-harvest decay (*B. cinerea*) | Woodward and Topping 1972 |
| Cambridge Favourite | — | 3 | 0–20 | ⇓ respiration rate | Robinson 1975 |
| Elsanta | 20 | — | 0 | ⇓ respiration rate, post-harvest decay | Hansen 1986 |
| Elvira | 20 | — | 24 for 1 d | ⇓ post-harvest decay<br>⇔ fruit and calyx colour<br>⇑ off flavours but recovery 6h after $CO_2$ treatment | Baab 1987 |
| — | 10–30 | 0.5–2 | | ⇓ post-harvest decay, respiration rate | Hardenburg *et al.* 1990 |
| | <30 | <2 | | ⇑ off flavours, berry discolouration | |
| — | 15–20 | 5–10 | 0–5 | ⇓ respiration rate, post-harvest decay<br>⇑ firmness retention | Kader 1989 |
| | <20 | <2 | 0–5 | ⇑ off flavours, ⇑ berry discolouration | |
| — | 15–20 | 10 | 0 | | Sealand 1991 |
| Redcoat; 21[A] of 25 cvs. studied | 15 | 18.5 | 0 for 42h | ⇑ firmness, post-harvest decay<br>⇔ L*, H°, TSS or pH | Smith 1992, Smith and Skog, 1992, Smith *et al.*, 1993 |
| Chandler | 50 | 0.25 or 21 | 5 for 1–7 d | ⇑ acetylaldehyde, ethanol, ethyl acetate, ethyl butyrate concentrations and pyruvate decarboxylase, alcohol dehydrogenase activities<br>⇓ isopropyl acetate, propyl acetate, butyl acetate concentrations and alcohol acetyl transferase activity, | Ke *et al.* 1994 |
| Chandler | 20 | 10 | 4 | ⇑ pH, a*, C*, H°<br>⇓ L* | Nunes *et al.* 1995 |
| — | 20 | Air | 2 | ⇑ acetylaldehyde, ethanol and ethyl acetate | Watkins *et al.* 1999 |
| Selva | 20 | 16 | 5 | ⇑ pH, succinic acid concentration, H° | Holcroft and Kader 1999 |

(*continued*)

**Table 11.7** *Continued*.

| Cultivar | $CO_2$ concentration (kPa) | $O_2$ concentration (kPa) | Storage temperature (°C) | Effects on fruit quality during storage | Reference |
|---|---|---|---|---|---|
| | | | | ⇓ post-harvest decay (*B. cinerea*), loss in firmness, TA (citric and malic acid concentrations), anthocyanin accumulation, internal flesh L*, C*, ⇔ ascorbic acid, sucrose, fructose, glucose concentration | |
| Camarosa | — | 100 | 5 for 14 d | ⇓ post-harvest decay (*B. cinerea*), TSS. ⇔ ethylene production, firmness, TA. ⇑ acetylaldehyde, ethanol and ethyl acetate, respiration rate, H°, L* | Wszelaki and Mitcham 2000 |
| Aromas, | 20 | | | | Pelayo *et al*. 2003 |
| Diamente, | 20 | | | | |
| Selva | 20 | | | | |

Note: ⇓, decrease; ⇑, increase; ⇔, no effect; C*, chroma [ ]; HSP, H° [=arctan b*/a*], hue angle; PAL, phenylalanine ammonia lyase; TA, titratable acidity; TSS, total soluble solids; ns, not specified.

[A] = Allstar, Dana, Glooscap, Governor Simcoe, Guardian, GU62e55, Kent, Micmac, Midway, Pajaro, Raritan, Redcoat, Selva, Settler, Sparkle, Tribute, Tristar, Vesper, Vibrant, Selkirk and Scotland.

(Ceponis & Cappellini 1985; Simttle & Miller 1988; Kim *et al*. 1995), raspberry fruit (Joles *et al*. 1994; Haffner *et al*. 2002) and wild strawberry (*Fragaria vesca*) fruit (Almenar *et al*. 2005).

CA has been shown to increase storage life through decreasing respiration rate, inhibition of grey mould development and improved retention of fruit firmness (Table 11.7). Incorrect CA regimes increase production of off-flavours (e.g. ethanol, acetyladehyde and ethyl acetate) and cause berry discolouration (e.g. bleaching) and decrease TTA (Table 11.7). However, despite extensive research on elucidating optimum CA concentrations for strawberry, CA and MAP are still relatively underutilised by industry. The comparative slow uptake in CA storage regimes for soft fruit is manifest, in part, by the tendency for rapid product degradation after removal from CA conditions, as reported for other fresh produce types (Chope *et al*. 2007). In addition, the use of CA for soft fruit is only really warranted for long-distance export (e.g. from the United States to European Union) and is rarely used commercially for the home-grown soft fruit market. It follows, that further research on the use of alternative gaseous environments is required. For instance, ozone storage resulted in storage life extension for cranberry (Norton *et al*. 1965), strawberry (Perez *et al*. 1999) and blackberry (Barth *et al*. 1995). Ozone treatment can, however, lessen fruit aroma (Perez *et al*. 1999). Other gases, such as carbon monoxide have also been shown to extend post-harvest life of strawberry fruit whilst not affecting quality (El-Kazzaz *et al*. 1983). In addition, fumigation in an anaerobic nitrogen atmosphere with nitric oxide (NO; 5–10 $\mu l.l^{-1}$) for up to 2 h at 20°C doubled the post-harvest life of strawberry cv. Pajaro fruit subsequently stored at 5°C (Wills *et al*. 2000). The effects of this treatment may be transitory in a storage environment as NO is rapidly oxidized to $NO_2$ in the presence of oxygen. Although storage in superatmospheric oxygen (80–100 % $O_2$) has been shown to extend the storage life of strawberry cv. Camarosa fruit, it is doubtful that this treatment will be commercially viable in the near future as it leads to increased production of fermentation-derived metabolites that negatively affect fruit organoleptic quality (Table 11.7; Wszelaki & Mitcham 2000). Moreover, the potential dangers of using flammable gas at high concentrations are often overlooked. Incorporation of natural volatile compounds into packaging also shows promise as a method of extending storage life of soft fruit as many compounds derived from strawberry or raspberry have been found to have antifungal activity (Vaughn *et al*. 1993; Archbold *et al*. 1997; Wang, 2003).

## POST-HARVEST DISEASE

Soft fruit are inherently susceptible to post-harvest decay. Disease incidence and severity is influenced by pre- and post-harvest environmental conditions and can be suppressed using chemical, biological and abiotic treatments. Grey mould caused by *Botrytis cinerea* (Teleomorph: *Botryotinia fuckeliana*) is the most important disease affecting post-harvest soft fruit quality. Other significant diseases include leak rot, mucor rot, leather rot and anthracnose fruit rot (black spot) caused by *R. stolonifer*, *Mucor* spp, *Phytophthora cactorum* and *Colletotrichum acutatum,* respectively (Maas 1998). A comprehensive account of the major and minor post-harvest pathogens of soft fruit is given by Snowdon (1990). A detailed analysis of *Botrytis* biology and pathology is available from Elad *et al*. (2004). Strawberries are problematic with regard to the timing of prophylactic sprays because of the long development period of the cymose inflorescence and sequential production of multiple trusses. Although grey mould can be partially controlled by certain pre-harvest cultural methods (e.g. reducing inoculum load, good sanitation, protective cropping, drip irrigation) and post-harvest storage techniques, the strawberry industry is still heavily reliant on synthetic botryticides (e.g. iprodione and pyrimethanil) applied extensively during flowering and fruiting. There are, however, concerns over increasing loss of efficacy of conventional fungicides due to pathogen resistance and general unacceptability of fungicide usage in terms of public and environmental risk (Terry & Joyce 2000). These concerns have favoured the introduction of integrated pest management programmes and alternative treatments for suppressing post-harvest disease incidence and severity.

### Pre-harvest infection

Strawberry fruit vary in their inherent susceptibility to *B. cinerea* according to their physiological status and genotype (Plate 11.5 and Table 11.8). However, no strawberry cultivar is highly resistant to grey mould. *Botrytis cinerea* tends to infect inflorescences in the field, but extensive fruit decay is only usually seen following harvest after the fruit has reached and passed full harvest maturity (Powelson 1960; Bristow *et al*. 1986). Therefore, *B. cinerea* generally remains quiescent until either physiochemical defences and/or stimulation in the host fall or rise, respectively, to allow invasion to continue. The inherent natural disease resistance (NDR) of strawberry fruit declines during fruit development and senescence, including during post-harvest storage (Terry *et al*. 2004). Between flowering and

**Table 11.8** Times to 10% Grey Mould Disease Severity of Strawberry cv. Elsanta Fruit at Different Development Stages ± *B. cinerea* Inoculation Held at 5°C.

| Fruit development stage | Time to 10% disease severity (days) | |
|---|---|---|
| | + Inoculation[A] | Control[B] |
| Green stage I | 25.9 | 32.1 |
| White | 19.6 | 27.4 |
| Red | 8.7 | 19.5 |
| *Column means* | *18.3* | *26.3* |

Terry *et al*. (2004) with permission.

fruit senescence, there is evidently a period of relatively high resistance when grey mould development is rare.

**Natural disease resistance**

Authors have attributed variation in NDR in strawberry fruit to skin strength, fruit tissue firmness (Barritt 1980) and flower susceptibility (Bristow *et al*. 1986). As with many other fruit patho-systems, the lack of nutritional requirements for the pathogen, activation of fungal pathogenicity factors and the presence or decline of preformed or induced antifungal compounds during fruit development (Prusky 1996, 1998) may also influence NDR in strawberry fruit. However, relatively little work has been done to characterise and identify preformed (phytoanticipin) and/or induced (phytoalexin) compounds with activity against pathogens (Table 11.9) or pests (Luczynski *et al*. 190) of strawberry. Terry *et al*. (2004) demonstrated that antifungal activity against the pathogen, *Botrytis cinerea*, and a bioassay organism, *Cladosporium cladosporioides*, declined with advancing strawberry fruit maturity as shown by thin layer chromatography (TLC) bioassays (Plate 11.6). Preformed antifungal activity was also present in flower tissue. The fall in fruit antifungal compounds was correlated with a decline in natural disease resistance against *B. cinerea in-planta*. Crude extracts of green stage I fruit (seven days after anthesis) contained at least two preformed antifungal compounds ($R_f$ = 0.44 and 0.37) that were not present in white and red stage fruit (Table 11.10). These compounds were shown with TLC reagent sprays to be neither phenolics nor alkaloids. Positive reactions to Ehrlich's reagent suggested that $R_f$ = 0.37 was a terpene. Most antifungal activity was found in the achenes of green stage I fruit. However, antifungal activity was found in all tissue types (*viz*. pith, cortex, epidermis) of green stage I fruit. TLC bioassays revealed that all fruit stages yielded antifungal activity at the origin ($R_f$ = 0.00). The approximate area of fungal inhibition at the origin in green stage 1 fruit extracts was 1.87- fold and 1.73-fold greater than in white and red stages, respectively. TLC reagent sprays showed that the antifungal compound(s) at the origin included phenolics. This observation is consistent with previous reports that phenolic compounds in strawberry fruit are inhibitory to *B*. cinerea (Table 11.9). Such knowledge may enable strategies to enhance the levels of these compounds in strawberry through environmental manipulation, genetic transformation and/or preharvest treatment with elicitors/plant activators (Terry & Joyce 2004a). In addition, an increase in the concentration of these antifungal compounds, many of which are phenolics with reported antioxidant capacity, may lead to increased health benefits for consumers (Törrönen & Määttä 2002).

**Elicitors of induced disease resistance**

Elicitors of NDR may be biological, chemical or physical and may induce local acquired resistance (LAR), systemic acquired resistance (SAR) or induced systemic resistance (ISR). Only recently has the potential of utilising such plant responses within plant protection been widely recognised for post-harvest disease control (Terry & Joyce 2004a)

***Chemically induced resistance***

Various natural and synthetic substances activate LAR and/or SAR or ISR in horticultural produce. True chemical activators modify the plant-pathogen interaction so that it resembles an incompatible interaction with defence-related mechanisms induced prior to or after challenge. Most research on chemical activators has concentrated on pre-harvest diseases. However, chemical elicitors applied pre- and/or post-harvest have also been shown to enhance or maintain NDR in a number of harvested horticultural crops including soft fruit (Terry & Joyce 2004a). Terry and Joyce (2000) demonstrated that either multiple or a single pre-harvest application of 0.25–2.0 mg a.i.–$mL^{-1}$ acibenzolar to strawberry cvs. Andana and Elsanta plants, respectively, delayed by a factor of 1.2-fold the development of grey mould disease on harvested strawberry fruit held at 5°C. An extension in storage life was observed despite strawberry plants not receiving any botryticide treatments. Subsequent work by Terry and Joyce (2004b) showed that the efficacy of acibenzolar in suppressing post-harvest grey mould was variable and dependent on pre-harvest environmental conditions. Additional research is perhaps needed on testing efficacy of alternative plant activators to suppress post-harvest disease in soft fruit.

**Table 11.9** Preformed and Inducible Compounds Found in Strawberry Tissues That Demonstrate Antifungal Activity.

| Cultivar | Tissue | Chemical | Preformed or Inducible | Pathogen | Reference |
|---|---|---|---|---|---|
| Surecrop | Roots | N.I. | Inducible | *Phytophthora fragaria; Cladosporium cucumerinum* | Mussel and Staples 1971 |
| Howard and Surecrop type varieties (n = 18) | Roots | Quercetin | Preformed | *Phythium irregulare; Rhizoctonia solani; Alternaria alternata* | Nemec 1973, 1976 |
| Senga Sengana | Green fruit | Proanthocyanins | Preformed | *Botrytis cinerea* | Jersch *et al*. 1989 |
| Chandler | Red fruit achenes | N.I. | Preformed | *B. cinerea* | El Ghaouth *et al*. 1991 |
| Clea and Pajaro | Various developmental stages | Proanthocyanins | Preformed | *B. cinerea* | Di Venere *et al*. 1998 |
| Chandler | Leaves | Fragarin | Preformed | *Collectrichum actutatum; C. fragariae; C. gleosporioides* | Fillipone *et al*. 1999 |
| Chandler | Leaves | N.I. | Preformed and inducible | *C. fragariae* | Vincent *et al*. 1999 |
| Hokowase | Green fruit | Triterpenes | Inducible | *Colletotrichum musae* | Hirai *et al*. 2000 |
| Morioka-16 and Hokowase | Leaves | Catechin | Preformed | *Alternaria alternata* | Yamamoto *et al*. 2000 |
| Chandler and others | Various fruit[A] development stages | Proanthocyanins (catechin, epicatechin, gallate) | Preformed | *B. cinerea* | Hebert *et al*. 2001 |
| Elsanta | Green fruit | N.I | Preformed and induced | *B. cinerea; Cladosporium cladosporioides* | Adikaram *et al*. 2002 |
| Elsanta | Various fruit[AB] and flower[C] development stages | Phenolics and terpene | Preformed | *B. cinerea; C. cladosporioides* | Terry *et al*. 2004 |

N.I. = not identified; [A] = Green, white and red stages; [B] = tissue types (viz. achene, cortex, epidermis, pith); [C] = white bud; full bloom and post-anthesis.

***Physically induced resistance***

Induction of NDR in horticultural crops using physical elicitors has received increasing attention over recent years. The primary mode of action of many physical treatments is disinfection of the commodity. Thus, fungal spores and mycelial infections on and in the outer cell layers of fruit or vegetables are removed and/or destroyed. Low temperature storage, wounding, $CO_2$ treatment, heat treatment, ionising radiation and UV-C radiation can enhance NDR. Of these treatments, most research on soft

**Table 11.10** Areas ($cm^2$) of Fungal Inhibition on 1-DTLC *C. cladosporioides* Bioassay Plates for the Crude Ethanol Extract of Green Stage I, White and Red Strawberry cv. Elsanta Fruit (100 µl Spot; 0.2 ml $g^{-1}$ FW) Run in Hexane: Ethyl Acetate: Methanol (60:40:1 v/v/v).

| | Fruit development stage | | |
|---|---|---|---|
| $R_f$ value | Green stage I | White | Red |
| 0.86 | —[A] | ~1.26[B] | ~1.26 [B] |
| 0.44 | 1.96 | — | — |
| 0.37 | 3.85 | — | — |
| 0.13–0.00[C] | 13.27 | 1.26 ($R_f$ 0.00) | 3.85 ($R_f$ 0.00) |
| Total area | 19.08 | 2.52 | 5.11 |

[A] = No inhibition zone.
[B] = Weak antifungal activity.
[C] = Overlapped $R_f$.
Source: Terry *et al*. (2004) with permission.

fruit has centred on employing heat treatment or UV-C radiation (Tables 11.11 and 11.12). Non-ionising radiation has potential amongst physical methods for controlling post-harvest diseases and surface food borne bacteria. UV-C radiation at low doses (0.25–8.0 kJ $m^{-2}$) targets the DNA of micro-organisms. For this reason UV-C treatment has been used as a germicidal or mutagenic agent. In addition to this direct germicidal activity, UV-C radiation can modulate induced defence in harvested horticultural produce, including soft fruit. At appropriate wavelength and dose rates, UV-C radiation can stimulate accumulation of stress-induced phenylpropanoids. Most published research involving post-harvest UV-C treatments has used the 254 nm wavelength due to its ready availability as commercial lamps. The possibility of other wavelengths within the UV-C band (190–280 nm) enhancing NDR merits further investigation. In addition, effects of other light wavelengths (e.g. the visible region of electromagnetic spectrum) on NDR are not yet fully explored. For instance, illumination with cool white florescent light for 2 h reduced grey mould on strawberry cv. Dorit and Ofra fruit (Saks *et al*. 1996). However, pulsed (30 µs) white light from a stroboscopic xenon lamp at a frequency of 15 Hz for 40–250 s did not reduce grey mould on strawberry cv. Elsanta fruit despite 50% of the emitted light between UV-C and IR being in the UV region (200–400 nm) (Marquenie *et al*. 2003). It is, however, unlikely that UV-C treatments will be used commercially in the near future since the concept (Luckey 1980) and indeed the technology has been around for a considerable period and there has been no substantive commercial uptake to date.

***Biological control and biologically induced resistance***

The use of microbial antagonists for the control of post-harvest fruit decay has been actively pursued. In strawberry, grey mould development has been reduced using *Aureobasidium pullulans* (Bhatt & Vaughan 1962; Lima *et al*. 1997; Adikaram *et al*. 2002), *Trichoderma* isolates (Pratella & Mari 1993;Tronsmo and Dennis 1997), *Pseudomonas fluorescens*, *Bacillus pumilus* (Swaldling & Jefferies 1996), *Cryptococcus albidus* (Helbig 2002) and *Metschnikowia fructicola* (Karabulut *et al*. 2004a). Many isolates have been shown to be as effective as standard dichlorfluanid sprays (Swaldling & Jeffries 1996; Tronsmo & Dennis 1997), captan (Peng & Sutton 1991) or fenhexamid (Karabulut *et al*. 2004a) in controlling grey mould and other diseases on strawberry.

The use of avirulent or attenuated strains of either pathogenic or saprophytic micro-organisms to induce SAR has been relatively well researched (Terry & Joyce 2004a). Adikaram *et al*. (2002) demonstrated that *A. pullulans* wound-inoculated green stage cv. Elsanta fruit prevented rotting when they were subsequently inoculated with *B. cinerea*. Similar treatment of white, pink and red-ripe stage fruit with *A. pullulans* did not stop *B. cinerea* but did suppress rot expansion and reduce mycelial growth. Treatment of wound sites of green fruit with heat-killed cells of *A. pullulans* reduced *B. cinerea* infection by 60%

**Table 11.11** Effect of Post-harvest Heat Treatment on Strawberry Fruit Quality.

| Cultivar | Method | Optimum temperature (°C) | Duration (min) | Storage condition | Effects on fruit quality during storage | Reference |
|---|---|---|---|---|---|---|
| cvs. Fresno, Lassen, Shasta, Solana, Z5A | Humid air | 44 | — | | ⇓ post-harvest decay | Couey and Follstad (1966) |
| cv. Chandler | Humid air | 43 and 46 | 80 | | ⇑ severe berry damage | Yoshikawa *et al.* (1992) |
| cv. Tudla | Water immersion | 45 | 15 | | ⇓ post-harvest decay, ⇔ berry colour | Garcia *et al.* (1995; 1996) |
| cv. Selva | Air oven* | 42 and 48 | 180 | 0°C overnight followed by 3 d at 20°C | ⇓ post-harvest decay, ⇓ loss in firmness, ⇑ L*, ⇓ increase in a*/b*<br>⇓ PAL activity and anthocyanins accumulation<br>⇑ HSP (88, 76.5, 69, 19 and 17 kDa) | Civello *et al.* (1997) |
| cvs. Elsanta | Microwave (91 W) | 42 | 4 min | 12°C for 12 d | ⇓ post-harvest decay (*B. cinerea*) | Elmsallati (2000) |
| cv. Elsanta | Water immersion | 40, 43, 45 and 48 | 3, 5, 10 and 15 | 12°C for 10 d in dark | ⇔ post-harvest decay (*B. cinerea*)<br>⇓ firmness, ⇑ severe berry damage >45°C, | Marquenie *et al.* (2002) |
| cv. Selva | Air oven* | 45 | 180 | 0°C for 0, 7, 14 d followed by 2–4 d at 20°C | ⇑ H° (delay in red colour development)<br>⇓ TA, ⇓ loss in firmness, ⇔ sugars, ⇓ CFU bacterial population, ⇓ post-harvest decay | Vicente *et al.* (2002) |
| cv. Elsanta | Water immersion | 40 or 45 | 3 | 12°C for 10 d in dark | ⇓ post-harvest decay (*B. cinerea*)<br>⇑ post-harvest decay (*B. cinerea*) | Marquenie *et al.* (2003) |
| | | 40 or 45 | 15 | | ⇑ external damage and ⇓ firmness at 45°C, but not at 40°C | |
| cv. Aromas | Water immersion | 45–63 | 15 | | ⇓ post-harvest decay (*B. cinerea*)<br>⇓ berry shine, ⇑ berry shrivel | Wszelaki and Mitcham (2003) |
| cv. Selva | Air oven* | 45 | 180 | 20°C for 2 d | ⇓ loss in firmness, ⇓ hemicellulose degradation and HCl soluble pectins, ⇓ water-soluble pectins. Cell wall degradation of internal and external tissue varied. | Vicente *et al.* (2005) |

Note: ⇓, decrease; ⇑, increase; ⇔, no effect; CFU, colony forming units; HSP, heat-shock protein; H° [=arctan b*/a*], hue angle; PAL, phenylalanine ammonia lyase; TA, titratable acidity; TSS, total soluble solids; * = covered with PVC film (15 µm) to reduce water loss; initial fruit surface (10 mm) temperature of 23°C increased to 40°C during 1 h and then maintained at 42°C.

**Table 11.12** Effect of Post-harvest UV-C Treatment on Soft Fruit Quality.

| Cultivar | Optimum UV-C dose (kJ $m^{-2}$) | Targeted pathogen or surface bacteria | Reference |
|---|---|---|---|
| *Strawberry* | | | |
| cv. Pajaro | 0.5–1 | *B. cinerea* | Nigro *et al*. 1998, 2000 |
| cv. Kent | 0.25 | As above | Baka *et al*. 1999 |
| cv. Elsanta[A] | 10–15 | *Enterobacteria cloacea; Escherichia coli, Listeria monocytogenes; Salmonella typhimurium* | Terry, 2001 unpublished |
| cv. Elsanta | 0.5–15 | *B. cinerea* | Marquenie *et al*. 2002, 2003 |
| cv. Seascape | 4.6 | As above | Pan *et al*. 2003 |
| *Boysenberry* | 9.2 | As above | Vicente *et al*. 2004 |

[A] = Without calyx.

compared to controls. The partial beneficial effect of dead cells and the very different efficacy of *A. pullulans* in green versus riper fruit may suggest that complete arrest of *B. cinerea* in green fruit is not only due to antagonism or nutrient competition. *A. pullulans* treatment apparently suppressed *B. cinerea* by inducing NDR in green strawberry fruit. Thin-layer chromatography bioassays showed that *A. pullulans*-treated outer skin tissue from green fruit had greater antifungal activity against *C. cladosporioides* and *B. cinerea* than equivalent control tissue samples. Thus, induced resistance, possibly through accumulation of phytoalexins, is a probable mechanism by which *A. pullulans* may inhibit *B. cinerea* rotting of green strawberry fruit.

Although biocontrol has been shown to suppress post-harvest disease it has not generally delivered adequate or reliable control. The true test being that very few products are commercially used on a consistent successful basis. The same can be argued for plant activators.

### Nonconventional strategies to suppress post-harvest disease

The continued pressure from retailers on growers to reduce pesticide load has encouraged researchers to investigate nonconventional methods to control post-harvest disease on soft fruit. Many of these treatments can be considered to be impractical, at present, for commercial exploitation or raise additional environmental concern (e.g. irradiation), but at least they provide a basis for novel control strategies to be explored further and thus should not always be dismissed. For instance, recent work has demonstrated that post-harvest applications of acetaldehyde (Pessis & Avissar 1990), benzoic acid derivatives (Lattanzio *et al*. 1996), ethanol, sodium bicarbonate (Karabulut *et al*. 2004b), chitosan (El Ghaouth *et al*. 1992) and other coatings (Del-Valle *et al*. 2005) can extend shelf life of soft fruit. However, Terry and Macnish (unpublished, 2004) demonstrated that pre-harvest application of 50% (v/v) ethanol on strawberry cv. Elsanta plants when the majority of primary, secondary and tertiary flowers on the primary truss were at green stage 1, anthesis and white bud stages, respectively, had no effect on post-harvest disease incidence. Foliar applications of $CaCl_2$ have been reported to delay ripening and disease development in soft fruit (Chéour *et al*. 1990, 1991; Erincik *et al*. 1998). Calcium is believed to increase soft fruit firmness through maintaining cell wall integrity (Lara *et al*. 2004). Post-harvest applications of $CaCl_2$ have also been shown to maintain fruit quality and suppress disease in strawberry (García *et al*. 1996b), raspberry (Montealegra & Valdés 1993) and blueberry (Hanson *et al*. 1993).

## GENETIC TRANSFORMATION

Traditional plant breeding programmes still dominate the continued development of new commercially available soft fruit cultivars. There have been reports on the biotechnological improvement of strawberry (James *et al*. 1990; Nehra *et al*. 1990; Barcelo *et al*. 1998; Jiménez Bermúdez *et al*. 2002). Despite promising work, the commercial release of many strawberry transformants has been hindered by the steadfast objections of some consumers to the introduction of genetically modified foods. These objections are no more prevalent than in the EU.

Schestibratov and Dolgov (2005) created transgenic strawberry cv. Firework plants with enhanced resistance to *B. cinerea* via *Agrobacterium*-mediated introduction of a pathogenesis-related protein (thaumatin II; PR-5) gene. However, the possibility of resistance being conferred to strawberry fruit was not tested as disease resistance was

evaluated using leaf discs inoculated with a conidial suspension. Since the mode of *B. cinerea* infection differs between leaf and strawberry fruit, more work is required to establish whether transformants with thaumatin II expression may influence fungal quiescence during fruit development and storage.

## CONCLUSION

Soft fruit represent a heterogeneous collection of fruit species, which share common problems associated with susceptibility to post-harvest disease and physical damage throughout the supply chain. Temperature management is the fundamental process upon which all post-harvest treatments should be founded. It is unclear what future impact genetically transformed soft fruit will have on maintaining soft fruit quality after harvest. However, with consumer opposition to genetically modified foods remaining steadfast in the EU, alternative measures are actively being pursued. For instance, more research is required on the possible role that elicitors may play in boosting NDR and how the efficacies of these elicitors are modulated by environment. It is also clear that the increasing interest in minerals (e.g. folic acid) and antioxidants (which are inherently high in soft fruit), will continue and potentially lead to increased sales. Nonetheless, a dichotomy exists between the ever increasing demands from multiple retailers for better quality soft fruit versus the current trend in price deflation. It remains to be seen how further improvements in post-harvest technology for soft fruit will be paid for.

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# 12
# Kiwifruit, Guava, Passion Fruit and Lychee

*Graham Farrell*

The account presented here concentrates on recent findings and new initiatives in the post-harvest aspects of four commodities with important roles in an expanding market for exotic fruits and vegetables. General, comprehensive volumes on the post-harvest behaviour and handling of these fruits, *inter alia*, are given by Nagy and Shaw (1980), Morton (1987), Mitra (1997), Wills *et al*. (1998), Thompson (2003) and Gross *et al*. (2002). Warrington and Weston (1990) provide an in-depth study of all aspects of kiwifruit from a New Zealand perspective.

## KIWIFRUIT

The genus *Actinidia* comprises about 50 species of kiwifruit, mostly from temperate forests in south-western China. The main commercial variety is Hayward (*Actinidia deliciosa* (A. Chev.) C. F. Liang & A.R. Ferg.), preferred for its good storage characteristics over other varieties, but *A. chinensis* Planch. and the hardy kiwifruit *A. arguta* (Sieb. & Zucc.) Planch. ex Miq. are also cultivated commercially. Kiwifruit has been an economic success mainly because of its good keeping qualities over long periods at 0°C (Hewett *et al*. 1999). Mature fruits are broadly oval, green-brown in colour and densely covered with fine hairs. The pulp is bright green with a mass of small black seeds. Kiwifruit plants are vines with the fruits borne on long pedicels (Cheah & Irving 1997).

### Production

Italy is the main producer of kiwifruit, followed by New Zealand and Chile (Rushing 2002). California is the major producer in the United States, accounting for 95% of all kiwifruit produced nationally. Chinese production is forecast to increase rapidly, reaching about 0.5 million tons (MT) and accounting for half of world output by the end of 2006 (Huang *et al*. 2004). Table 12.1 shows some production figures by region.

### Harvesting

Kiwifruit are nonclimacteric and are among the few fruits that retain large amounts of starch at maturity. Hydrolysis of starch continues after harvest even at low temperatures and is complete a few weeks later, when the starch is converted to soluble sugars (mainly glucose and fructose, with some sucrose). At the limit of carbohydrate accumulation kiwifruit will have reached the best quality for consumption and so delays in harvest will not further improve the flavour (Strik 2000).

In the past, maturity was based on arbitrary harvest dates, fruit colour or firmness but these characters are not good guides to maturity. However, firmness is used in the United States, with a minimum force of 6.4 kg, using a penetrometer with an 8 mm tip, considered appropriate, together with a minimum soluble solids content (SSC) of 6.5% (Crisosto *et al*. 1999). Penetrometer readings should be taken on fruit at 37–39°C (Crisosto 1997). In New Zealand, measurement of firmness using a noncontact laser air-puff method has been described by McGlone and Jordon (2000).

Positive correlations between SSC and fruit maturity and eating quality have been established, and so refractometer

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**Table 12.1** Kiwifruit production (MT) in 2000 and 2001.

| Region | 2000 | 2001 |
|---|---|---|
| Asia | 62 775 | 62 000 |
| Central/North America | 31 074 | 20 640 |
| Europe | 512 402 | 533 700 |
| Oceania | 257 197 | 268 197 |
| South America | 115 500 | 120 000 |

Source: Fresh Produce Deskbook 2003.

measurements of SSC are the favoured method for assessing harvest maturity. In New Zealand the minimum level of SSC for export fruit is 6.2% measured in a sample of ten fruit. If two fruits from the sample have SSC less than 5.8%, then the orchard is not up to export quality standard (Rushing 2002). However, work in California suggested that some vineyards could produce kiwifruit of high taste quality (12% ripe soluble solids concentration), as measured by consumer acceptance tests, before they reach 6.5% SSC assessed when fruit are still hanging on the vines (Crisosto & Crisosto 2001).

Higher SSC levels, up to 15%, have been suggested for long-term storage (Mitchell *et al*. 1991), and in the United States a value of 14% is recommended for table ripeness (Crisosto *et al*. 2002; Rushing 2002). A rapid increase in soluble solids and softening are notable characteristics of kiwifruit maturity (Cheah & Irving 1997). Jordan *et al*. (2000) used post-harvest density as an indicator of SSC and dry matter content, whereas Osborne and Jordan (1996) and Osborne *et al*. (1999) recommended near-infrared (NIR) spectroscopy as an alternative low-cost, nondestructive method for estimating SSC and grading kiwifruit. Advances in NIR methods suggest that use of the technique at harvest could identify less mature kiwifruit leading to a reduction in post-harvest rots (Clark *et al*. 2004).

Electrical impedance spectroscopy has been used to detect ripening in nectarine, persimmon and tomato though this method revealed no impedance change as kiwifruit ripened. It was speculated that immobility of electrolytes within the cell wall of ripening kiwifruit was responsible for the effect (Bauchot *et al*. 2000).

Once maturity has been reached all kiwifruit in the vineyard can be collected at the same time since there are no visible features to enable pickers to separate mature from immature fruit (Crisosto & Kader 1999). However, larger fruit can be picked first and the smaller fruits allowed to increase in size and then picked at a later date (Mainland 1998). Picking is usually done by hand, with the fruits snapped off the pedicel at the abscission layer during dry periods to limit storage rots. Pickers should wear soft cotton gloves to prevent damage to the skin of the fruit. Fruits should be unshrivelled and free from sun scald, scars, growth cracks, insect injury, internal damage or bruising and decay (Crisosto *et al*. 2002; Rushing 2002). Avoiding mechanical damage during harvesting and transport to pack houses is important to prevent the release of ethylene that may soften adjacent fruit.

### Grading

Criteria for grading are subjective and largely rely on superficial appearance (Rushing 2002). In the United States, grades include US Fancy, US No. 1 and US No. 2 (USDA 1986). Assigning fruit according to size is difficult because of variability in length and diameter, and so size designations are based on the number of kiwifruits that can be placed in a tray. In the United States, size criteria defined by the Californian Kiwifruit Administration Committee are usually used. These vary from year to year; with recent tray equivalency size designations ranging from 21 (22 fruits in an 8 lb sample, fairly uniform size variation equals 0.5 $in^2$) to 45 (55 fruits in an 8 lb sample, fairly uniform size variation equals 0.25 $in^2$). Tolerances also apply, relating to the weight of the sample and the number of fruits that do not fall within the diameter range (KAC 2004).

### Cooling

Historically, kiwifruits were cooled to 0°C as soon as possible after harvest to prolong shelf life using forced air cooling; hydro-cooling was not advised because the hairs on the fruit surface retained moisture that hastened the development of rots. However, current advice suggests that fruits should be maintained under ambient conditions for several days since all types of cooling predispose fruits to stem-end rots, as reported by Lallu (1997) and Lallu *et al*. (1997) in New Zealand and Cheah and Irving (1997) in the United States. Furthermore, in Chile, curing for up to 72 h did not lead to softening during cold storage (Retamales *et al*. 1997). Chill sensitivity may result at temperatures near 0°C, with pitting, scalding or ring shaped, granular or water soaked lesions in the outer pericarp at the stylar end (Lallu 1997). Freezing damage may occur in the field before harvest; if late in the season the shoulders are affected when cells in that area collapse leading to a pinching of the fruit at the stem end. Freezing in store causes translucency and yellowing of the flesh after prolonged storage (Chisosto *et al*. 2002).

**Table 12.2** Rate of kiwifruit softening after ethylene exposure at 20°C.

| Temperature (°C) | Rate of softening (kg/day) |
|---|---|
| 0 | 0.5 |
| 5 | 0.6 |
| 7.5 | 0.9 |
| 20 | 1.5–1.7 |

Adapted from Crisosto 1997.

### Conditioning

Guidelines produced in California suggest that kiwifruit be marketed as ready to eat to maximise retail returns. To achieve this requires careful management of ripening, achieved through temperature (see Table 12.2) or ethylene treatments (10–100 ppm per 6 h), using firmness as a measurement. At harvest kiwifruit firmness varies from 5.5–8.2 kg. This falls during ripening to 0.9–1.4 kg, at which point the fruit is considered ripe and ready to eat. In general, fruit that has not been pre-conditioned that has been in store for less than four weeks, or has a firmness level of 3.6–4.5 kg, should receive further treatment using ethylene. Conversely, kiwifruit stored for more than four weeks, or with flesh firmness below 3.6 kg, can be ripened by temperature modification (Crisosto 1997).

Firmness of the fruit should be measured on intake at the warehouse and then the appropriate ethylene and/or temperature regime used to ensure that the required retail firmness coincides with the anticipated consumption schedule (Crisosto 1997).

### Processing

Kiwifruit are retailed as whole fruits, or as slices more usually to the catering trade. Fresh-cut fruits do not keep well, though calcium treatment and modified atmosphere storage have been reported as maintaining quality for 9–12 days (Agar *et al*. 1999). Handling at 0–2°C, 90–95% relative humidity with $O_2$ from 2–4% and $CO_2$ at 5–10% is necessary. Production of off-flavours is a consideration if kiwifruit slices are exposed to oxygen or carbon dioxide values outside these optimum ranges (Crisosto & Kader 1999).

### Storage

Good-quality kiwifruit entering the store will keep for four to six months if maintained at 0°C, >95% relative humidity and <0.01 ppm ethylene. However, using controlled atmospheres can increase the storage time to eight months, at 3–8% $CO_2$ and 1–2% $O_2$, again at 0°C. Oxygen concentrations of less than 1% may cause off-flavours, and more than 7% $CO_2$ leads to internal flesh breakdown (Crisosto *et al*. 2002; Rushing 1997). Controlled atmospheres must be established within two days of harvest for maximum benefit (Crisosto *et al*. 2002). Exclusion of ethylene is again important, such that movement of fruits around warehouses and stores should be done using electrically powered vehicles rather than ones with internal combustion engines that produce small amounts of the gas (Cheah & Irving 1997).

More recent advances in the protection of minimally processed kiwifruit involved argon and other noble gasses, and nitrous oxide, which has been allowed for food use in the EU. Argon mixtures were less effective than 90% $N_2O$, 5% $O_2$ and 5% $CO_2$ in colour retention, firmness and soluble solids of sliced kiwifruit (Rocculi *et al*. 2005).

In the United States, kiwifruits may be packed in trays, with up to three trays per wooden or cardboard carton. Alternatively, bagged fruits are placed in master cartons, perhaps twenty, 0.5 kg bags per carton. Cartons for volume filling, typically 10.4 kg, or count filling are also used. Larger, wooden bins holding 56 kg of fruits may be employed – carton size or configuration is immaterial as long as the box is labelled adequately. At retail, kiwifruit are sold individually or in bags containing 6–10 fruits per bag (Rushing 2002). Cold tables are recommended when retailing ripe fruit and warm tables for fruit that is mature but unripe (Crisosto & Kader 1999).

### Ethylene

Kiwifruit is the most ethylene-sensitive fruit, even at low temperatures, with ethylene concentrations of less than 50 ppb at 0°C enhancing softening (Crisosto *et al*. 2002; Kader 2000a). The post-harvest softening of kiwifruit occurs in two distinct stages, with an initial slow rate for about 24 h followed by a period of more rapid decline (Chen *et al*. 1999). Application of acetylsalicylic acid reduced the rate of softening, possibly by its conversion to salicylic acid that inhibits ethylene synthesis (Zhang *et al*. 2003). Similarly, 1-methylcyclopropene (1-MCP) binds to ethylene receptors and thus inhibits ethylene, and so it has also been used to modify ethylene response and production to limit post-harvest physiological changes. Thus, at 20°C 1-MCP decreased or delayed ethylene production, respiration, colour changes, glycosidase activity and softening but at 0°C ethylene production and softening were unaffected, as were soluble solids and titratable acidity. 1-MCP had no effect on superoxide dismutase and peroxidases (Colleli & Amodio 2003; Boquete *et al*. 2004; Ding *et al*. 2003; Fan & Zhang 2001; Kim *et al*. 2001; Neves *et al*. 2003).

**Post-harvest disorders**

Physiological disorders are not serious unless kiwifruit are harvested at an immature stage or are injured by post-harvest dip treatments or freezing. Under these conditions off-flavours develop and the pericarp may become granular, water soaked, rubbery or translucent. Exposure to ethylene and $CO_2$ above 8% can cause a hard-core disorder, in which the core fails to ripen whereas the flesh is soft and ripe (Crisosto *et al*. 2002). White core inclusions are also related to ethylene. These are distinct white patches of core tissue occurring within three weeks of storage at 0°C (Cristoso *et al*. 1999). Symptoms of internal breakdown begin as water soaking and discolouration at the blossom end of the fruit that spreads throughout. Eventually a 'graininess' develops below the epidermis. Granulation of the pericarp at the stylar end may also extend up the sides of the fruit. It is more severe with prolonged storage and after ripening at 20°C. Translucent patches of the pericarp have been reported in air- and controlled atmosphere-stored fruit at 0°C after 12 weeks (Crisosto *et al*. 2002).

Pre-harvest sprays with calcium chloride slowed softening and extended storage life by 10–12 weeks, but summer pruning did not affect storability (Gerasopoulos & Drogoudi 2005).

The main post-harvest problem with kiwifruits is premature ripening, to which fungal infection contributes by causing infected fruits to release ethylene (Brook 1991). Stem-end rot or grey mould infection by the major pathogen, *Botrytis cinerea* Pers., occurs peri-harvest. It gains entry through wounds, senescent flowers or direct penetration. The fungus will grow at low temperatures and appear after 5–12 weeks in store. Damage begins at the stem end, progressing down the fruit with softening and water soaking. Infection may spread to adjacent fruits in the packing tray and become apparent as 'nesting'. Control by pre-harvest fungicide, field hygiene (such as brushing the fruit to remove the remains of the flowers that contain fungal inoculum) or fungicide sprays. Several post-harvest methods have been tested, including several day's 'curing' at ambient temperature that may allow the fruit to develop defences against the fungus (Sharrock & Hallett 1991), dips in hot water at 48°C for eight minutes (Cheah *et al*. 1993b), biocontrol using yeasts or *Trichoderma* (Cheah *et al*. 1992; Cheah *et al*. 1995), fumigation with sulphur dioxide (Cheah *et al*. 1993a), fungicide dips and natural products (Ward *et al*. 1996). The use of volatile substances emitted by Isabella grapes (*Vitis labrusca* L.) to control grey mould on Hayward kiwifruit has been suggested. Kulakiotu *et al*. (2004) found that the grape volatiles limited the incidence of infection by reducing inoculum density and pathogen activity.

Other rotting fungi cause ripe rots that infest through picking wounds, leading to large, pale brown, soft lesions reminiscent of fingerprints. The genera responsible include *Botryosphaeria*, *Colletotrichum*, *Phoma*, *Phomopsis*, *Alternaria*, *Diaporthe* and *Fusarium* (Snowdon 1990; Cheah & Irving 1997). Control is by pre-harvest fungicide sprays and good field hygiene. A blue mould caused by *Penicillium* sp is also found (Snowdon 1990). Infection by *Phialophora* sp may cause pitting which does not become apparent until several months of storage have elapsed (Testoni *et al*. 1997).

Pests cause little post-harvest damage in themselves but are important commercially because of their quarantine implications and associated fumigation costs. Pests of concern are the two-spotted spider mite (*Tetranychus urticae* Koch), armoured scale insects (*Hemiberlesia* spp, *Aspidiotus nerii* Bouché and *Quadraspidiotus perniciosus* (Comstock)), Fuller's rose weevil (*Asynonychus cervinus* (Boheman)) and several leafroller caterpillars, the most important of which is the brown-headed leaf roller *Ctenopseutis obliquana* (Walker).

**Future needs**

New cultivars are needed, with hairless fruit being more attractive to consumers; currently there is heavy reliance on cv. Hayward. Premature softening remains a problem but the mechanisms underlying this phenomenon are not well understood. Effective pest and disease control without pesticides is required because of pest resistance and general consumer concern with residues. IPM has not been fully achieved in kiwifruit (Cheah & Irving 1997).

Ethylene causes very large losses when fruit soften in storage. The effectiveness of ethylene removal methods using catalytic converters, potassium permanganate filters, ozone generators or ventilation systems require careful evaluation (Rushing 2002).

**GUAVA**

The common guava (*Psidium guajava* L.) is the most important cultivated type of the 100 species of the myrtle family (Mabberley 1997). It is indigenous to tropical America but has spread and become a commercial crop in Brazil, Colombia, India, Egypt, South Africa and the West Indies (Wilson 1980).

Guavas are evergreen trees or shrubs that grow to about 10 m in height. The fruits have a rough yellow or green skin and are round or pear shaped. Fruits vary from 8 to 13 cm in diameter and weigh up to 700 g. They contain

few or many small seeds in the centre, and sclereid stone cells that may give the flesh a gritty texture. Flesh colour varies from white to salmon pink, with a sweet musky scent. Common guava fruits are eaten fresh or processed into jellies, cheese, ketchup, purée and juice. The cattleya or strawberry guava (*P. cattleianum* Sabine) is smaller than the common variety and less valuable for commercial purposes, though it may be preferred for its sweet, strawberry flavour by cooks (Wilson 1980). Guava can be consumed at the mature green stage, with a sweet apple taste and white flesh, or fully ripe when the flesh is white to bright red and the skin is yellow (Paull & Chen 2002a).

End use of the fruits affects the choice of cultivar. Thus, cultivars for fresh consumption produce slightly acid, sweet and less gritty fruits, whereas those for processing give fruits of high acidity with deep pink or salmon red flesh (Ali & Lazan 1997). Guavas are usually consumed whole, but slices of mature green fruits are eaten in southeast Asia. Ripe fruit is also sliced, with seeds and skin removed. Both types are sold from trays with an over-wrap (Paull & Chen 2002a).

### Harvesting

Firm, mature and undamaged fruits are harvested by hand two or three times a week and collected in baskets. Skin colour is usually used to assess maturity, depending on whether firm or fully ripe flesh is required (Paull & Chen 2002a). The harvest period is eight to ten weeks. The recommended optimum time for harvesting is two to three weeks before the fruits are fully mature, because of deleterious physiological changes associated with ripening, such as yellowing and decrease in flesh firmness (Ali & Lazan 1997). Soluble solids content at maturity varies from 3% in green fruit to >10% in fully ripe fruit. Titratable acidity ranges from 0.2% to 1.5%, depending on the cultivar. Seasonal variation in acidity occurs in some cultivars (Paull & Chen 2002a).

Mature guavas decline rapidly in quality and so they are usually processed without delay. Carriage is in wooden crates that protect the delicate fruit from mechanical damage, with the fruits preferably upright (Siddiqui *et al*. 1991) and wrapped individually in newspaper or similar impregnated with 0.5 g per pack biphenyl and/or 3 g $l^{-1}$ potassium permanganate (to absorb ethylene). Refrigeration during transport is advisable; at 5°C to 10°C and 85% to 90% relative humidity, storage life is up to three (Snowdon 1990) or five weeks (Wilson 1980). In the United States, guavas are pre-cooled immediately after harvest (Campbell 1994) but care must be taken to avoid chilling injury to which they are susceptible. Responses to chilling and shelf lives vary with the type of cultivar. Thus, cv. Beaumont takes about five days to ripen and has a shelf life of 1–2 weeks, whereas cv. Kampuchea ripens after 24 days and has a shelf life of 3–4 weeks (Lazan & Ali 1997). Guavas are sensitive to sunlight and so transport is best done at night (Wilson 1980). In the United States, guavas are usually shipped in 4.5 kg boxes in single layers, with foam wrapping to limit damage (Paull & Chen 2002a).

### Cooling

After harvest guavas should be cooled to about 10°C, using room-, forced air- or hydro-cooling. Fruit maturity influences keeping qualities. Thus mature green guavas can be kept at 8–10°C for two to three weeks, whereas ripe fruit keeps for up to one week at 5–8°C. Both types should be maintained at 90–95% relative humidity (Snowdon 1990; Kader 1999). Shelf life at 20°C is also about a week (Paull & Chen 2002a).

### In-store treatments

Given that guava has a short shelf life of 2–3 days at room temperature (Carvalho 1994), efforts to prolong keeping times using various sprays have been tested, but different cultivars respond differently. Spraying with 1% calcium nitrate, alone or together with 0.2% zinc chloride reduced respiration and weight loss, maintained firmness and extended shelf life (Ali & Lazan 1997). Coatings of 5% carnauba- or cellulose-based (2–4% hydroxypropyl cellulose) emulsions delayed colour changes and limited increases in total soluble solids and softening, but led to skin blackening in some cultivars (McGuire & Hallman 1995). Sprays of 1-MCP at 300 nl $l^{-1}$ for 6 h, or 900 nl $l^{-1}$ for 3 h, delayed ripening for up to nine days (Bassetto *et al*. 2005).

### Modified and controlled atmosphere storage

Guavas are climacteric fruit and respond well to modified atmosphere storage. Storage in low-density polyethylene films retards ripening by slowing down the processes of softening and increasing soluble solids, acidity and ascorbic acid (Lazan & Ali 1997). Treatment with 10% $O_2$ and 5% $CO_2$ for 24 h, prior to storage in air for two weeks at 4°C, delayed colour development and reduced damage from chilling (Bautista & Silver 1997). Controlled atmosphere storage with elevated carbon dioxide also delays ripening but may damage the fruit at levels of 10% $CO_2$. For fruit at room temperature, continuous flushing with saturated air extends shelf life, as does removal of ethylene. Vacuum infiltration with 10% $CaCl_2$ at ambient temperature has been shown to delay softening and suppress rises in pectin and titratable acidity, but with no effect on the incidence of disease (Lazan & Ali 1997).

**Quality issues**

Physiological disorders resulting from chilling or the use of modified atmospheres are among the most common post-harvest quality problems. Chilled fruits may show abnormal ripening, skin browning or other discolouration, and prompt decay when the fruits return to ambient temperatures. Also important are desiccation and mechanical damage (Paull & Chen 2002a). Modified atmospheres may cause skin blackening and off-flavours (Ali & Lazan 1997). Pre-harvest use of herbicides or pesticides may lead to phytotoxic effects, with red or brown blotches on the skin. Sun scorch leads to premature ripening and infection which can be combated by wrapping fruits in brown paper bags.

Post-harvest diseases mainly arise from pre-harvest infection, and so treatment and care in the field can markedly reduce the incidence of post-harvest problems. Anthracnose is the most important disease of guava, caused by *Glomerella cingulata* (Stonem.) Spauld. & v. Schrenk (Snowdon 1990). Symptoms include brown or black spots, leading to sunken patches becoming more apparent as the fruit matures. Other important pathogens are *Botryodiplodia theobromae* Pat. that causes a soft, watery rot and *Pestalotiopsis psidii* (Pat.) Mordue, the cause of canker or stylar end spot. Species of *Mucor, Aspergillus, Rhizopus* and *Phomopsis* may occur, particularly on injured fruits (Paull & Chen 2002a). Post-harvest control is by fungicide dipping, refrigeration or irradiation at 0.15 to 0.45 kGy. The use of antagonistic fungi and bacteria has also been suggested (Pandey *et al*. 1993).

Post-harvest pests also usually arise from pre-harvest infestations, with eggs laid on mature fruit that hatch during storage. Fruit flies are the major concern here, from the genera *Dacus*, *Anastrepha* and *Bactrocera*, particularly for concerns related to quarantine. As well as feeding damage by larvae, puncture wounds allow entry of pathogenic fungi and bacteria. Control is by bagging fruits, spraying, pheromone or bait trapping or deployment of parasitoids and other bio-agents. Mealy bugs can also be a problem, leading to misshapen fruits and secondary infections. Promising post-harvest control of pests has been achieved by coatings and modified atmospheres. Use of hot-water dips is generally considered not applicable because the thin skin of guavas provides little protection from heat damage (Yusof & Hashim 1992) but hot water has been used as a quarantine treatment against fruit flies (Gould & Sharp 1992).

## PASSION FRUIT

*Passiflora* is a perennial woody vine native to the Americas. About 50 or 60 of the 450 species bear edible fruits (Mabberley 1997). The main commercial species are the purple passion fruit or purple grenadilla, *P. edulis* Sims forma *edulis*, and the yellow passion fruit, *P. edulis* Sims forma *flavicarpa* Deg (Chan 1980). The purple form is grown extensively in Brazil, East Africa, Sri Lanka, Australia and India, whereas the yellow type is mainly exploited in the Caribbean, Hawaii and the South Pacific.

Mature purple passion fruits are round or egg-shaped, 4–9 cm long and 3.5 to 7 cm in diameter, and they weigh 25–50 g. The skin is moderately thick and hard, containing a yellow to orange pulp. Yellow types have slightly larger fruits, are 50–150 g and have a hard skin, again with yellow to orange flesh but more aromatic and juicy (Chan 1980; Paull & Chen 2002b).

Passion fruit may be consumed fresh but most are processed into juice or purée in jams, jellies and marmalade (Morton 1987).

**Harvesting**

Passion fruit takes about 72 days to mature after flowering. The fruits should be completely mature at harvest with fully developed skin colour. Fruits with a green rind exhibit off-flavours despite being internally mature (Bora & Narain 1997). Size, shape, acidity, skin colour and soluble solids are the main criteria used to evaluate quality. In yellow passion fruit the SSC ranges from 10 to 18%, with a range of 10–20% in purple types. Yellow passion fruit have higher acidity (Paull & Chen 2002b).

Fruit is harvested when more than 75% of the skin has turned yellow or purple (Chan 1980). Purple fruit should be 5 to 8 cm in diameter, yellow should be 6 to 8 cm, with a fully developed skin colour (Paull & Chen 2002b). Mature fruits for processing are usually collected, allowed to abscise and picked up from the ground every two to seven days. Fruits for sale as fresh product are picked directly from the vines to preserve good appearance and keeping quality (Bora & Narain 1997).

Passion fruit are transported in boxes and placed in room or forced-air cold storage if they are to be immediately processed. Recommended storage conditions for yellow passion fruit are 7–10°C at 90–95% relative humidity, which gives a storage period of two weeks (Arjona *et al*. 1992). Storage below 6.5°C causes chill injury, with discolouration, off-flavours, pitting, water-soaking and ripening uneven or absent (Bora & Narain 1997; Paull & Chen 2002b). Purple fruit is chill tolerant and can be stored at 3–5°C for three to five weeks (Paull & Chen 2002b). Loss of water is the main storage problem, leading to weight loss, shrivelling and wilting, though pulp quality is not significantly affected (Paull & Chen 2002b). Thus ripe fruits kept at ambient temperature and humidity (27 + 2°C

and 76–77% RH) stored up to seven days before decay and wilting became apparent. In the United States, passion fruit is packed in 4.5 and 6 kg cartons, in one- or two-layer trays (Paull & Chen 2002b).

In Queensland, Australia, interstate certification assurance describes the principles of operation and standards, and the responsibilities and practices of personnel handling and grading fruit. The procedure for purple passion fruit (ICA-15) defines mature green fruit as having skin free from wrinkling and unbroken skin (i.e. with 'no pre-harvest crack, puncture, pulled stem or other break that penetrates through to the flesh and has not healed with callus tissue'). Other aspects covered by the procedure include accreditation, audit, sorting, packing, sampling (selection, examination, identification and action on nonconformance), dispatch and record keeping (ICA 2002).

### Processing

Processing for juice and pulp production is mechanised. In Hawaii, fruits from the field are dumped into a wash tank with agitation. Conveyors lift the fruits past wash sprays whence they are sorted by hand to remove damaged or otherwise unfit fruit. Skins are cut with rotating knives spaced 1.6 cm apart and the sliced pieces fed into a continuous basket centrifuge. Juice, pulp and seeds pass through the centrifuge screen while rinds pass to waste. Screened pulpers and finishers separate the seeds and fibres from the juice and pulp. In Australia, the juice may be extracted using rollers; in New Zealand pulp and seeds are removed from halved fruits using suction (Chan 1980). Extraction yields have been increased by 35% by using pectinolytic enzymes (Lipitoa & Robertson 1977). Once processed, the juice is preserved by heating or freezing.

### Atmosphere modification

Various coatings and wrappings, such as sucrose (Bepete *et al*. 1994) or plastic films (Mohammed 1993), have been used to extend storage life. Wrapping fruits in VF-60 plastic film prevented water loss and maintained the external fruit appearance (Arjona *et al*. 1994). The main beneficial influence of wraps and coatings is probably due to reduction in water loss rather than any modified atmosphere effect.

Passion fruits are climacteric and produce large amounts of ethylene during ripening; peak climacteric rates are 160–400 l $kg^{-1}$ $h^{-1}$ at 20°C (Shiomi *et al*. 1996).

### Post-harvest pathology and entomology

Relatively few pathogens or pests attack passion fruit to any major degree. The main disease agents are the fungi *Alternaria alternata* (Fr.) Keissler, causing brown spot in the Pacific Islands and *A. passiflorae* Simmonds in East Africa, Australia and Hawaii. The disease is characterised by circular, sunken light brown spots with a green border. It is most severe after periods of warm wet weather (Paull & Chen 2002b). Attack by *Septoria passiflorae* Louw. leads to uneven ripening and fruits that are fit only for processing. Other fungi found on rotting passion fruits include species of *Aspergillus*, *Cladosprium*, *Colletotrichum*, *Botryodiplodia*, *Penicillium*, *Phytopthora*, *Rhizopus*, *Fusarium*, *Phomopsis* and *Pestalotiopsis* (Snowdon 1990; Bora & Narain 1997). A *Phytophthora* fruit rot (caused by *P. nicotiana* var. *parasitica*) leads to water-soaked, dark green lesions that dry on the skin (Kader 2002). Management of fungal diseases before harvest is achieved through sanitation in the orchard, pruning to reduce relative humidity and fungicides (Paull & Chen 2002b). Post-harvest control relies on good temperature and relative humidity control in storage (Kader 2002).

Bacterial spotting is caused by *Pseudomonas syringae* pv. *passiflorae* (Reid) Young, Dye & Wilkie and *Xanthomonas campestris* pv. *passiflorae* (Pereira) Dye (Snowdon 1990).

Insect pests include the fruit flies *Anastrepha*, *Dacus* and *Ceratitis*. Infestation occurs pre-harvest with damage becoming apparent as the fruits mature. Control using irradiation has been successful (Paull & Chen 2002b).

## LYCHEE

*Litchi chinensis* Sonn., in the Sapindaceae or soapberry family, is a dense evergreen tree that reaches 30 m in height (Mitra 2002). The species is native to the low elevations of southern China where it is eaten fresh or dried as brown 'litchi nuts'. Production in China dates back at least 4000 years (Ochse *et al*. 1961; Menzel 2002). However, lychee has only spread relatively recently through Southeast Asia and the Pacific, reaching Florida in 1883 and Hawaii in 1973 (Anon. 1996). It is now grown commercially in most Asian countries, and in Australia, Central America and South Africa, as well as the United States.

The literature on lychee post-harvest is relatively recent, with much attention focused on new areas of production in Asia and Australia. Thus the following account draws heavily on FAO publications by Menzel (2002), and Papademetriou and Dent (2002) in southern Asia, and Australian government reports described by Olesen *et al*. (2003).

### International trade

At 2 000 000 metric tonnes, or 95%, Asia accounts for the bulk of world supply of lychee (Table 12.3) (Menzel 2002).

**Table 12.3** Lychee production.

| Country | Year | Area (ha) | Tonnage (MT) | Reference |
|---|---|---|---|---|
| Australia | 1999 | 1 500 | 5 000 | Menzel 2002 |
| Bangladesh | 1999 | 4 750 | 13 000 | Menzel 2002 |
| China | 1999 | 580 000 | 1 260 000 | Menzel 2002 |
| India | 1998 | 56 000 | 429 000 | Ghosh 2001 |
| Madagascar | 1994 | | 8 000 | Fintrac 1994 |
| Nepal | 1999 | 3 000 | 14 000 | Menzel 2002 |
| Taiwan | 1999 | 12 000 | 110 000 | Menzel 2002 |
| Thailand | 2000 | 23 000 | 80 000 | Menzel 2002, Mitra 2002 |
| USA | 1998 | | 1 045 | Mossler & Nesheim 2002 |
| Viet Nam | 1999 | 30 000 | 50 000 | Menzel 2002 |

Hong Kong and Singapore are major international markets and receive about 12 000 to 15 000 MT of lychee from China and Taiwan during June–July. Taiwan exported about 5900 MT in 1999; the main destinations were Philippines (1735 MT), United States (1191 MT), Japan (933 MT), Canada (930 MT), Thailand (489 MT) and Singapore (408 MT) (Mitra 2002). The total world trade in lychee is about 100 000 MT (Menzel 2002). European markets take about 20 000 MT of fresh lychee of which nearly 50% was imported by France alone and the rest mainly by Germany and the UK, an increasing market (McNeil 1997). The market is especially buoyant between Christmas and New Year with Madagascar (80%) and South Africa (12.6%) as the main suppliers (Mitra 2002).

In the Asian region, Australia exports about 25–30% of its total production. Other lychee growing countries in this region export much smaller amounts, typically 0.2–5.5%. The main reason is that all these countries have good domestic markets and lack proper cool-chain and other exporting facilities. Nonetheless, small quantities are frozen and canned (about 2500 MT in China and 500 MT in Taiwan) and exported to Japan, United States, Canada, Malaysia, the Republic of Korea and Australia. About one third of the total production of China (300 000 MT) was dried in 1999 as lychee nut, for domestic and local export (Mitra 2002).

**Fruit development**

For best flowering lychee needs seasonal temperature fluctuations, with winter chilling (100–200 hours at 0°C to 10°C) to initiate flower bud development and warm humid summers for flower and fruit formation (Anon. 1996). After insect pollination, trees produce clusters of small round fruit with 5–80 fruit per inflorescence (Mitra 2002). These are covered with tubercles as part of a leathery rind or pericarp that is pink or bright red in colour. The fruits are oval, heart shaped or round and 2.5 to 4 cm long, weighing about 20 g (Cavaletto 1980). They mature about 100–110 days after pollination. The edible portion is the aril which is translucent, white, firm and juicy, and sweet flavoured. The seed inside the aril varies considerably in size; the most desirable varieties having atrophied seeds described as 'chicken tongue', caused by faulty pollination (Morton 1987). A distinction is also made between desirable fruit that remains 'dry and clean' when the skin is broken, as against those types that leak juice when the skin is breached (Anon. 1996).

**Fruit maturity**

During maturation, fruits undergo colour changes from green to yellow green to dark red to bright red 7–10 days later. Bright red fruits are overripe. In China, the recommendation is to harvest when the pericarp is about 80% red (Huang 2002).

Maturing lychee have increasing concentrations of sugars such as sucrose, glucose and fructose and decreasing concentrations of organic acids, mainly malic acid. The aril should be sweet and translucent with a Brix level about 17° (Fintrac 1992). During ripening the acid content decreases, from 5.5% to 0.5%, and sugars increase from 10% to 17%. Acid contents need to be within a fairly narrow range for good palatability. Thus, acid contents of 0.9% give a sour taste to the fruit but lychee with acid levels below 0.4% are bland because of the imbalance between sugar and acid (Fintrac 1992).

Titratable acidity (TA) is the best guide to maturity; alternatively, the ratio of total soluble solids (TSS,

degree Brix) to titratable acidity can be used (Batten 1989). Although recommendations vary, a TSS:TA value of 30 (Kader 2000b), 35 (Menzel & McConchie 1998) or 40 (Menzel 2002) or higher is suggested for commercial fruit. Maturity standards based on the TSS:TA value, fruit weight and size and peel colour have been established for most of the commercial cultivars of Australia, China, India, Taiwan and Thailand (Mitra 2002).

Fruit quality declines after harvest, with concentrations of ascorbic acid, phenols, sugars and organic acids decreasing. However, dipping fruit in the ethylene precursor, ethephon, can significantly achieve ripening. Thus, Sadhu and Chattopadhyay (1989) reported that a five-minute dip in a 2.5 g $l^{-1}$ ethephon solution gave rise to a 50% increase in total sugars, a 20% increase in ascorbic acid and an increase in the TSS:TA from 20 to 30–40 over three days. Nonetheless, ethephon has not been commercialized and so the focus of current research and development activities in southern Asia is to maintain rather than improve the quality of harvested lychee (Menzel 2002).

Once lychee are harvested they begin to dry out and turn from red to brown. This is the first sign of fruit decline. The mechanisms of pericarp browning, colour retention and pulp quality maintenance have been the main focus of post-harvest research (Mitra 2002). After harvest no further ripening occurs (Joubert 1986) and the respiration rate declines during storage (Akamine & Goo 1973).

The colour of mature lychee results from anthocyanins in the mid- to upper mesocarp (Underhill & Critchley 1993). These are stable below pH 3 but are converted to colourless chromenols as the pH rises, when polyphenol oxidases become active at pH values between 4.1 and 4.6. This colour change may be reversed depending on pericarp pH, anthocyanin and brown pigment contents. Thus the bright red colour could be maintained if the pericarp pH was kept at 4. If the pericarp pH was above 4, reversing the colour change depended on the storage time (Chu *et al*. 2004). However, Olesen *et al*. (2003) reported that although treatment of lychee with acid alone changed the fruit colour it then took on a patchy appearance. The acid effect could be made more uniform if the fruit was pre-treated with hot water. Unfortunately, acid and heat led to artificially brightly coloured fruit that was softer and more prone to rots, nor was the colour fixed and so browning reappeared. It was of concern that treatment of lychee in this way disconnected the appearance of the fruit from its eating quality. The treatment was therefore not recommended because it could easily lead to attractive fruit that would not taste as it should. However, workers in Israel have suggested a hot-water brush/acid/prochloraz treatment (Lichter *et al*. 2000).

**Pre-harvest influences on fruit quality**

Menzel (2002) noted that fruit quality at harvest determines its later shelf life and market price. Damage present at the time of harvest is worsened as the fruit moves through the supply chain. A good supply of nutrients and water to the trees will produce sound fruit. Thus uneven watering during fruit development may cause fruit splitting (Kumcha 1998), as do low concentrations of pericarp calcium (Huang *et al*. 2002; Li *et al*. 2001).

Damage by insects also needs to be minimised. The use of pesticides or bags in the field limits harm and increases the proportion of sound, marketable fruit (Menzel 2002). It was suggested by Tyas *et al*. (1998) that bagging of the fruit bunches may enhance fruit colour.

The risk of rots during storage can be reduced by good hygiene in the orchard. Judicious pruning keeps canopies open, skirting lowers the risk of infection from the soil level and collecting dead wood removes pathogenic propagules (Menzel 2002).

**Harvesting methods**

Lychee are delicate fruit and so handling should be kept to a minimum. Given that they have a short shelf life resulting from their perishability, a rapid turn-around is needed to provide the best quality fruit for consumers. Menzel (2002) suggested that fruit should ideally be shipped on the day of harvest.

After harvest lychee keep their colour and quality for only three to five days, though this period can be extended by treatment with 0.5% copper sulphate and packing in perforated polythene bags. Other post-harvest treatments vary with the country of production. Thus, in the United States fruits are destemmed during grading and packed in shallow, ventilated cartoons cushioned with shredded paper. In South Africa, lychee may be placed on trays and dusted with sulphur, and then left in ventilated sheds overnight. They are then allowed to wilt in lugs for one or two days – this allows damaged fruit to become conspicuous so that they can be removed before grading and packing (Morton 1987).

Fruits for local consumption and markets are harvested fully coloured whereas those for export destinations are picked when the pericarp colour has not fully developed. During the later stages of maturation swelling of the skin reduces the density of the skin tubercules and causes them to flatten out. Experienced pickers can detect these changes and thus recognise the stage of full maturity (Morton 1987), rather than relying on measurements of TSS:TA. Mechanized methods for harvesting lychee are not

available, beyond the use of cherry pickers and other elevated platforms (Menzel 2002).

Fruits are left on the cluster during harvesting because removing single fruits causes damage to the stem end. To preserve freshness the clusters are cut leaving a portion of the stem with a few leaves attached. Individual fruits are later removed with a piece of stem attached but removal of the stalks is necessary when the fruits are packed individually. Mechanical destalking using stiff bristle brushes is sometimes done in Australia but these methods often cause damage, particularly when fruit are wet. Lychee is frequently sold on the panicle in Asia, but loose fruit are more common in Australia, Europe and North America. Over-ripe fruit are sweet, but bland (Menzel 2002). Fully turgid fruit can be mechanically damaged quite easily and should not be dropped more than 30 cm on to a hard surface or 60 cm on to other fruit (Bryant *et al*. 2001).

Harvesting takes place every three to four days over a period of three to four weeks, always during dry periods since wetting of the fruits at harvest leads to quick decay. Experienced pickers can collect about 25 kg per hour (Morton 1987). Average yields range from 1 to 15 T $ha^{-1}$; in Taiwan yield is about 9.4 T $ha^{-1}$ (Anon. 2000) compared with 7.63 in India, 3.83 in Thailand, 2 in Viet Nam (Ha Min Trung 2000), 1.8 in China and 1.66 in Australia (Mitra 2002).

**Sorting and grading**

These operations should be done in a cool, shady area, either indoors in a packhouse or shed as in Australia and the United States or outdoors as is common in Asia. Since pathogens can accumulate in debris on surfaces and in waste fruit, good hygiene is needed such that crates and shelving should be washed with chlorinated water on a daily basis and damaged fruit removed. Inferior fruit must be removed during sorting to maintain overall quality. In Asia sorting may be done on tables or as fruits move along a series of rollers, as in Australia. Because even small areas of damage can lead to rapid decay, the whole surface of every lychee must be examined. This requires good lighting and close attention to detail. Immature fruit and mature fruit with mechanical damage from pulled stems, splits, cracks and insects must be rejected (Menzel 2002).

In Australia, piercing moths such as *Othreis fullonia* (Clerk) and *Eudocima salaminia* (Cramer) may attack fruit the night before harvest (Menzel & McConchie 1998). Little damage will be apparent initially but signs of weeping and tissue darkening are revealed within 24 h. Therefore, fruit may be kept overnight in high humidity cool-rooms. This ensures that the stung fruit are detected. Conversely, if cool-rooms are unavailable or a quick turn-around is necessary, freshly stung fruit can often be identified by leakage of juice when they are gently squeezed. Some buyers will not accept cosmetic defects and so fruit of this type are usually downgraded and not sent to the central markets, but can be processed or sold at roadside stalls (Menzal 2002).

Most buyers have at least two grades of fruit but ultimately grading systems depend on market requirements. There are no international standards (Paull *et al*. 2002). Grades are normally based on the colour and size of the fruit size and the size of any blemish (Paull *et al*. 2002). There are three grades in Australia; extra, first and second. Fruit diameter should be larger than 20–25 mm for standard or second class, and larger than 33 mm for extra class fruit. Extra class lychees should be defect-free; first class can have some defects but skin marks must not exceed 60 $mm^2$ in total on any one fruit (Menzel & McConchie 1998). All fruit should weigh within 20% of the mean fruit weight in the container (Fintrac 1994). Soluble solids content should be greater than 18%, and sulphur residue in the flesh should not exceed 10 mg/kg (Menzel 2002). As with other perishable produce, fruit for export has higher standards than that for domestic markets (Menzel 2002). FAO CODEX export standards for fresh lychee stipulate a predominantly red skin, with only a small area of green allowed.

**Disinfestation for quarantine purposes**

Sale of lychee from Australia to Japan and the United States is limited because of plant health concerns about fruit flies. Holcroft and Mitcham (1996) reported several methods of killing the insects. However, the fruit may be damaged in the process and there are residue and consumer concerns regarding, for example, fumigation with ethylene dibromide or irradiation with gamma rays (Menzel 2002), though in the United States, irradiation at 0.25–0.3 kGy has been used without causing damage to the fruit (Follett *et al*. 1998; Kader 2000b). Hot air has also been tested as a quarantine disinfectant but is not recommended for lychee because of the damage the fruit sustains at temperatures needed to disinfest them of quarantine pests (Sharp 1994; Kerbel *et al*. 1987).

Lychee for export from Israel to the United States may be disinfested at low temperature for different periods depending on the temperature e.g. 10 days at 0°C, 11 days at 0.55°C, 12 days at 1.11°C, 14 days at 1.65°C or 16 days at 2.22°C (Fintrac 1992).

**Transport to markets**

Square or round and padded bamboo baskets are used for carriage to markets in much of Asia. Rapid water loss

from fruits on the outside layers can be minimised if the baskets are lined or covered by a tarpaulin. Larger commercial operations may carry their fruit in cardboard boxes or plastic trays that reduce water loss. Dipping fruit in cold water or covering in ice is also done (Huang 2002) but this may leave the fruit open to chilling damage, and free water on the fruit encourages the growth of pathogens (Menzel 2002).

In Asia, rough roads, lack of refrigeration and poor truck maintenance damage all fresh produce. Harm from these sources can be alleviated to some extent if baskets are not overfilled and are packed firmly so that movement during the journey is restricted. Exposure to warm air can dry out the fruit very quickly, so transport during the warmer part of the day is best avoided, to avoid exposure to warm dry air. A covering will go some way to addressing this problem (Menzel 2002).

Lychee shipped by air from Madagascar to France may be packed in 6 kg loads, cushioned with leaves from the traveller's palm (*Ravenala madagascariensis* Sonn.). Sea freighted fruits are hydrocooled at 0–5°C, packed in sealed polyethylene bags, carried to the port at −20 to −25°C and containerised at 0–2°C (Morton 1987).

In Australia, lychee is shipped in crispywrap bags in 9 l cartons that contain 5 kg of fruit, packed in two, 2.5 kg polybags. Conversely, fruit may be shipped in 250 g punnets under cling wrap (Menzel & McConchie 1998). In the United States fibreboard boxes with polyethylene liners, holding 2.25 or 4.5 kg of fruits, are used. Lychee is also packed into 0.12 l styrene containers (Paull *et al*. 2002).

Containerised lychee have a post-harvest life of 21–35 days when kept at 1.7–10°C, with 15 cfm fresh air exchange. Acceptable receiving temperature is 1.1 to 10°C (APL undated).

### Water losses

Lychee has a very short shelf life as quality is lost within a couple of days of picking. Skin browning and subsequent rotting result from loss of membrane integrity. It has been suggested that structural calcium plays a role in senescence of lychee through its role in cell wall integrity. However, pre-harvest spraying of calcium chloride at 40 mmol $l^{-1}$ did not increase amounts of structural calcium within the pericarp, nor was senescence delayed (Huang *et al*. 2005).

In Australia, lychee should be harvested prior to the extremes of temperature that occur around late morning and early afternoon. Using fruit water potential, Olesen *et al*. (2003) showed that turgor was rapidly lost at about 8 am, with a recovery at about 4 pm, and that the loss of turgor could be equivalent to 3–5% of fruit weight. Thus harvesting at an inappropriate time could produce a substantial loss in the fresh weight of fruit. By the time 10% of the harvested fresh weight has been lost through desiccation, browning of the pericarp takes place, and the period before browning will be reduced if lychee is harvested at less than optimal times. However, Olesen *et al*. (2003) showed that there was potential to rehydrate fruit after harvest. Nonetheless, given that the capacity to rehydrate fruit reduced during the first hour following harvest, they were uncertain whether rehydration could be used commercially as the time from harvest to delivery at the packhouse may be greater than one hour. Olesen *et al*. (2003) were also concerned that the risk of contamination should be addressed since the rehydration mechanism was not clear.

### Controlled atmospheres

Use of controlled atmospheres such as 3–5% $CO_2$ and 3–5% $O_2$ (at 5–7°C) reduces water loss, skin browning, polyphenol oxidase activity, ascorbic acid loss, acidity and soluble solids. However, exposure to $O_2$ at less than 1%, or $CO_2$ above 15% may give rise to off flavours and a dull grey appearance (Kader 2000b). Browning and decay in cv. Mauritius were slowed in an atmosphere of 4% $O_2$, 5–7.5% $CO_2$, balance nitrogen, at 90% relative humidity and 5°C (Pornchaloempeng *et al*. 1998). Jiang and Fu (1999) reported a 75% reduction in water loss in lychee stored under 3–5% $CO_2$ and 3–5% $O_2$ for 30 days at 1°C. However, the mechanism of the response was not clear and it has been suggested that this type of gassing may affect the metabolism of the fruit as well as the pathogens (Menzel 2002). Modified atmosphere packaging has been tried in sealed polythene bags, with and without $SO_2$ but is not widely used (Kader 2000b). Deterioration during MAP storage can be enhanced if lychee is kept for extended periods on the trees during the harvest period, when fermentation that begins on the tree continues during MAP storage (Pesis *et al*. 2002).

### Temperature

Menzel (2002) suggested that the optimum storage temperature for lychee seemed to depend on the method of assessment, ranging from 5°C (Huang & Wang 1990) to 10°C (Olesen & Wiltshire 2000). Kader (2000b) suggested 5°C as optimum, with a range from 1.5 to 10°C, depending on the cultivar and length of storage period. The higher temperature presents less of a risk of condensation in the pack. Lychee should store successfully at 2–5°C and 90–95% relative humidity for three to five weeks (Paull & Chen 1987), or at 5–10°C and 95% relative humidity for

four to six weeks (Snowdon 1990). Storage at 20°C and 60% relative humidity reduces shelf life to 3–5 days.

Work in Australia by Olesen *et al*. (2003) showed that cvs. Kwai May Pink and Wai Chee were affected by the storage temperature and the method of cooling (air- or water-cooling). Chilling injury was apparent at 2°C and the fruit had poorer colour characteristics with lower L and chroma, and higher hue angle. Water loss was also greater than in fruit kept at 5°C. Although lychee at 5°C retained colour, had lower water loss and less rot development than fruit held at 10°C or 15°C, these temperatures were adequate for about two weeks of storage. Water-cooled fruit had more rot and worse colour retention than air-cooled but water loss was less.

Olesen *et al*. (2003) also investigated the effects of storing fruit at combinations 5°C, 10°C and 15°C during three consecutive 80 h periods. They found that lychee at 5°C during the third 80 h period had the least rot, irrespective of whether the fruit had been held at 5°C, 10°C or 15°C during the first period. The authors described cool chain handling of lychee in Australia as 'perverse', since most effort went into cooling the fruit immediately after harvest when it was most resistant to variations in temperature, but its retailing at room temperature just when refrigeration was most needed. Lychee should be displayed and retailed from refrigerated cabinets, preferably in polystyrene containers or plastic bags. It is important that the fruits are not exposed to ambient air since this causes rapid skin browning (Paull *et al*. 2002).

The temperature of lychee on arrival in Sydney ranged from 0°C to 20°C, often in mixed loads with no option to impose refrigeration temperatures. Although the temperature during the early post-harvest period was less critical than later on, condensation during temperature changes may enhance the development of moulds. Therefore the use of packaging that maintains high humidities while minimising the occurrence of free water should be considered. Minimising temperature fluctuations by ensuring fruit are pre-cooled to 5°C prior to packing, followed by wrapping pallets with temperature regulating blankets during transport has been suggested by Olesen *et al*. (2003).

### Ethylene

Lychee is nonclimacteric, and produces less than 0.51 $kg^{-1}$ $h^{-1}$ ethylene at 20°C. Excess ethylene may accelerate aril breakdown and decay (Kader 2000b).

### Pests and diseases

Given its high perishability, sulphur dioxide fumigation, modified atmosphere packaging, fungicide and hot-water dips, and cool storage are used to reduce disease losses (Johnson *et al*. 2002). Sulphur dioxide fumigation has been the main post-harvest handling technology to prevent browning and maintain fruit quality. Fruit exposed to sulphur may appear slightly bleached (Menzel 2002). Fumigation with $SO_2$ has been widely used in South Africa and Israel, and experimentally in China and Thailand. However, its continued use may be limited because of concerns about residues, taint and bleaching of the pericarp, though the colour gradually returned after removal of the pads (Mitra 2002).

Hot thiabendazole at 50–52°C was found to be an effective replacement of hot benomyl, at the same temperature, as a dip in controlling *Alternaria alternata*, *Phomopsis* sp and other fungi on cv Bengal during storage at 5°C for up to 30 days. However, dipping cv. Kwai Mai Pink was less effective because pericarp heat damage interacted with disease expression. Tainting was a drawback in the use of prochloraz (Johnson *et al*. 2002).

In Australia, under-mature lychee developed fewer rots than mature or over mature fruits with no significant differences in the deterioration of mature and over mature types. There was a 20% increase in harvested weight between each of the maturity stages and so there was a risk of a possibly large yield loss due to harvesting under-mature fruit (Olesen *et al*. 2003).

Fruits inadequately fumigated were prone to infection by *Penicillium* spp. On cv. Bengal, storage at 5°C delayed disease expression for up to 16 days. The main post-harvest pathogens were *A. alternata, Colletotrichum gloeosporioides* (Penz.) Sacc., *C. acutatum* Simmonds ex Simmonds and *Pestalotiopsis* sp. (Johnson *et al*. 2002) with *Cladosporium* and *Penicillium* also contributing to post-harvest decay; these fungi mainly infect the fruit in the field and then remain dormant until after harvest (Menzel 2002). A review of Australian post-harvest diseases of lychee is given by Coates *et al*. (1994).

Olesen *et al*. (2004) showed that several products and biological agents already registered for use on other crops or products in Australia reduced levels of rot when applied post-harvest; these included acetic and lactic acid, potassium silicate, and biocontrol with *Trichoderma* sp. Although field application of these agents modified the microflora on the surface of the fruit, no post-harvest benefit was observed, probably because spraying stopped two weeks before harvest. This may be unnecessary since these products are registered in other crops as post-harvest dips and food additives.

Olesen *et al*. (2003) also assessed post-harvest rot development on a commercial packing line, collecting

fruits from different stages along the line. Lowest amounts of rot were found in fruit sampled immediately prior to the packing line and highest amounts at the end of the line, after the lychee had been destalked by hand, sorted and hydro-cooled. The authors suggested further work to determine if handling practices could be improved to reduce accumulation of rots during commercial processing.

An alternative to fungicides is a hot-water spray and dip, for example at 45°C for 30 minutes in Florida (Kader 2000b) or 49°C for 20 minutes in Hawaii (Follett *et al*. 1998). Using cv. Kwai May Pink, Olesen *et al*. (2001) found that control fruit reached 50% rot coverage 15% more quickly than the best 52°C dipped fruit. This is approximately half the effect of a 52°C benomyl dip on rot development on the same cultivar, a useful effect given that benomyl is no longer registered.

A patented heat treatment method has been used in Israel, involving five weeks of refrigeration followed by three days at 28°C.

### Physiological disorders

Browning is the main physiological disorder in lychee (Underhill *et al*. 1997). Browning of the pericarp from water loss is manifest by the appearance of brown spots against the normal bright red background colour. In severe cases the spots may coalesce and cover the whole surface of the fruit. Arils within may not be affected but the fruit will be downgraded because of the external colour change. Water loss may also lead to percarp splitting or cracking. Breakdown of the arils results from prolonged storage and/or over maturity – the effects are seen as softening, loss of turgor and translucency and loss of flavour. Damage commences at the blossom end of the fruit and spreads towards the stem end. Chill injury symptoms such as pericarp browning and increased decay susceptibility resulted from 12 day's storage at 1°C followed by one day at 20°C (Kader 2000b).

### Future needs

Olesen *et al*. (2004) pointed out that methods of improving lychee shelf lives in commercial outlets have not been investigated. In retail outlets fruits may be exposed on shelving and lose their attractive appearance in less than a day. Promising developments include coatings to reduce water loss. Thus Zhang and Quantick (1997) used a solution of chitosan and L-glutamic acid to reduce water loss at 4°C by 20% and significantly slow browning. Packaging that maintains high humidity but minimises the appearance of free water on fruit surfaces is another promising area. The use of hot-water sprays does not bring problems of packing fruit wet because the water evaporates quickly from the treated fruit. However, there are concerns about packing fruit when it is warm (Menzel 2002). These technologies should be integrated to provide a range of strategies to improve lychee post-harvest handling.

Other suggestions in Australia highlighted the need for a checklist of best practice for post-harvest handling along the supply chain and case studies to identify the components of successful systems, guidelines for fruit sampling and systems' monitoring, market access protocols and consumer research to identify key attitudes to lychees so that research and development would better match consumer expectations (Chay-Prove 2003).

Use of modified atmospheres containing oxygen and carbon dioxide have been assessed but the use of other gases such as nitrous oxide (Qadir & Hashinaga 2001) and low oxygen (Techavuthiporn *et al*. 2003a, 2003b) deserves examination.

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# 13
# Prickly Pear Fruit and Cladodes

*Elhadi M. Yahia*

## INTRODUCTION

The prickly pear cactus plant belongs to the family Cactaceae, subfamily Opuntioideae, and is a xetrophyte producing about 200–300 species, mainly growing in arid (less than 250 mm annual precipitation) and semi-arid (250–450 mm annual precipitation) zones. The crop is produced and consumed in several countries. It is native to North America, and densely produced in the desert zones of the southern United States, north-central Mexico and Peru. From there it has been taken to several other parts of the world including Africa and Europe. The plants thrive well in subtropical, semi-arid climates. It is adapted to grow and produce under low water regimes and poor soils (Nobel 1994). As a CAM (crassulacean acid metabolism) plant, *Opuntia* spp. is characterized by high water use efficiency of 4–10 mmol $CO_2$ per mol $H_2O$ compared to $C_3$– and $C_4$– plants, with efficiencies of 1.0–1.5 mmol and 2–3 mmol $CO_2$ per mol $H_2O$, respectively. It exhibits the highest production rate in terms of above-ground biomass of all known crop plants, and the biomass production was found to increase upon the increase in atmospheric $CO_2$ concentrations (thus counter-acting the greenhouse effect) (Nobel 1991; Nobel & Israel 1994; Goldstein *et al*. 1991). Because of its high adaptability and multiple uses, it has been dispersed from its native habitats in North America to other regions in the world (Barbera 1995). Cactus fruit and cladodes (Figures 13.1 and 13.2) can be readily and abundantly produced under high temperature and little water, conditions unfavourable for the production of many other crops. Cactus plants serve numerous purposes; such as sources for fruit and vegetables, for medicinal and cosmetic purposes, as forage, for building materials, as source for natural colours. However, many of these uses are still very restricted to a very few countries, and in light of global desertification and declining water sources, *Opuntia* spp. is gaining importance as an effective source of food including as vegetable (Flores 1995). Internationally, about 100 000 ha are devoted to *Opuntia* fruit and cladode commercial production; however, more than 3 million hectares of *Opuntias* are grown in native habitats (Barbera 1995). In Mexico over 50 000 ha of prickly pear cactus are cultivated commercially, of which over 10 000 ha are devoted to the production of cladodes, with an annual production of about 600 000 metric tons per annum. Mexico is the only country planting cladodes for commercial use as a vegetable. *Opuntia ficus-indica* is cultivated in more than 20 countries (Nobel 1988). *Nopalea cochenillifera* is primarily cultivated in southern California and Texas, and the cladodes of this species are softer, devoid of spines, contain less mucilage, and are greener than those of *Opuntia* spp. (Mizrahi *et al*. 1997). The *Opuntia ficus-indica* (L.) Mill. species has gradually attained economic importance in Sicilian agriculture (Galati *et al*. 2002). Similarly its importance has grown in northern Mexico (Borrego-Escalante *et al*. 1990), the Mediterranean basin (Le Houérou 1996a), the arid highlands of western Asia (Le Houérou 1996b) and the south-western United States (Parish & Felker, 1997). Cold hardiness of *Opuntia spp*. clones used for fruit, forage or vegetable production have been reported by Le Houérou (1971), Russell and Felker (1987), Guevara *et al*. (1999, 2000), Gregory *et al*. (1993)

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**Figure 13.1** (A) Prickly pear plantation in Mexico, (B) different stages of prickly pear fruit, (C) elimination of spines in Chile and (D) coloured prickly pear fruit. Courtesy of Dr. Carmen Saenz.

and Parish and Felker (1997). In many countries prickly pear cactus is considered an important re-vegetation crop to control wind and water erosion in disturbed areas (Guevara & Yahia, 2005). In North Africa, the cultivation of *Opuntia ficus-indica* cactus is also used to protect against soil erosion in arid areas, and as a forage substitute during drought. Throughout the history of Mexico, the indigenous iconography recognizes the significance acquired by some of the cactaceous plants among pre-Hispanic tribes. Cactaceous plants had great importance in Mexico for the production of foodstuff as well as for medicinal properties.

## HARVESTABLE PLANT PARTS

### *Opuntia* fruit

*Opuntia* fruit (Figure 13.1), also known as prickly pear fruit, cactus pear, tuna (in Mexico) or higo (in Colombia), is harvested from various species of the prickly pear


**Figure 13.2** (A) Intensive plantation of nopalitos in Mexico, (B) nopalitos in supermarket in Mexico and (C) different products and supplements from nopalitos. Courtesy of Dr. Carmen Saenz.

cactus, genus *Opuntia* of the cactus family (Cactaceae) (Guevara & Yahia 2005). The fruit is a berry and is botanically considered as an accessory fruit formed from an inferior ovary adhering to the receptacle (Laksminarayana 1980). The edible portion of the fruit is made up of a number of funicles intermixed with juicy papillary hairs. The funicles are produced as outgrowths from the internal fruit wall and involve many black, soft seeds. The fruit contains abundant seeds and fleshy pulp of sweet flavour and is consumed as fresh fruit, juice or sweet. Fruit juice and fruit juice concentrate are considered as functional ingredients for the soft drink market, as well as a betalainic colouring foodstuff (Castellar *et al*. 2003; Stintzing *et al*. 2001, 2003). The fruit typically weighs 100 to 200 g, and consists of a thick fleshy skin or rind surrounding a juicy pulp that contains many hard-coated seeds. Fruit vary considerably in colour, size and flavour. In Mexico, the sour fruit produced by some species of prickly pear are called 'xoconoxtle', whereas the sweet fruit produced by other species are called 'tuna'. There are several species of *Opuntia* that yield edible fruit, but the most important are *O. ficus-indica*, *O. robusta*, *O. streptocantha*, *O. amyclaea*, *O. megacantha* and *O. hiptiacantha*. The fruit is perishable, but can be kept for 2 to 5 weeks at 5°C to 8°C with 90% to 95% RH. Several factors can limit storage life such as decay, dehydration and chilling injury (CI). In addition to its

consumption as a fresh fruit, tuna is used in Mexico in the preparation of cheese, honey of tuna, crystallized fruit, raisin-like dried fruit, etc.

### Cladodes

Cladodes, cactus stems, cactus pads, cactus vegetables or phylloclades, also called 'nopal' or 'nopalito' in Mexico (the name is used in Mexico for all Cactaceous plants from the Genus *Piatyopuntia* and *Nopalea*), are the rapidly growing succulent stems of the prickly pear cactus (*Opuntia* spp) (Figure 13.2). These are flat, oval or round, and the surface exhibits groups of thorns. The vestigial true leaves, often subtended by spines (glochids), are present in the early stages of growth, but usually begin to abscise by the time the cladodes reach commercial size. Although the young stems of many *Opuntia* species can be eaten, most commercial plantings of cladodes are from *O. ficus-indica* and *O. inermis*. Cladodes are mostly water (92%) and carbohydrates, including fibre (4–6%) and a little protein (1–2%). They also contain some minerals, principally calcium (1%), and moderate amounts of vitamin C and vitamin A (Table 13.1).

Cladodes are marketed either whole or in slices. Spines are commonly removed just after harvest or just before marketing. They are commonly ingested broiled, blended or as a juice (Guevara & Yahia, 2005). Different products from cladodes also exist in the local Mexican markets, especially in combination with other products, including bread, jelly, jam, candies, wine, vinegar, juice, flavourings and cheese. Pharmaceutical products include cream, gel, shampoo, tablets and syrups (Sáenz-Hernández 1995). In the southern United States, prickly pear cactus stems are pre-treated by scalding in saline solutions (for texture and colour stability) and vacuum-packed, yielding a product with relatively stable colour and texture characteristics and a shelf-life of 3 months at 4°C. In Chile, prickly pear cactus flour from *O. ficus-indica* is integrated into different baking processes. Many of these products are intended for the market of high dietetic fibre content products. Companies processing cladodes into various foods are found almost exclusively in Mexico and the greatest variety of products is found in Mexico and the United States (Guevara & Yahia 2005).

### Composition and uses of cladodes

The characterization of mucilage of prickly pear cactus stem (Yahia *et al*. in press; Trachtenburg & Mayer 1982) has been performed with the purpose of using it as a nourishing additive, either as a viscosity-increasing agent or together with other gums hoping to obtain a synergistic effect with such polymers (Medina-Torres *et al*. 2000; 2003). An important application of prickly pear cactus stem mucilage is in formulations of water-proof materials and paint. The mucilage is neutral with mainly D-galactose and L-arabinose residues (Harlay, 1902). The mucilage of *O. ficus-indica* Mill. is neutral and contains arabinose, galactose, rhamnose and xylose residues (Amin *et al*. 1970). Others suggest that the mucilage is acidic and contains L-arabinose, D-galactose, L-rhamnose and D-galacturonic acid (Anderson *et al*. 1925; Sands & Klaas 1929). Parikh and Jones (1965, 1966a, 1966b) reported that the mucilage of *Opuntia fulgida* consists of a backbone of β(1, 3)-linked galactose units with branches on carbon C-6 containing D-galacturonic acid, D-galactose, D-xylose, L-rhamnose and L-arabinose units. However, the mucilage of *Opuntia ficus-indica* cv 'Burbank's spineless' contains both neutral and acidic fractions (Paulsen & Lund, 1979). Trachtenberg and Mayer (1987) isolated carbohydrate polymers from *O. ficus-indica* and found galacturonic and rhamnose residues.

Another application of prickly pear cactus stems is in cosmetics: cleansing creams, moisturizing creams, shampoos and gels. These have been developed by using the excess fluid (which contains the mucilage), derived from the process of prickly pear cactus cooking. Other products include masks and soaps. Production of the red dye acetocarmine may also be possible through extraction of the parasitic insect cochineal *(Dactylopius coccus*), which relies on prickly pear cactus as the host plant (Flores-Flores & Tekelenburg, 1995). Cladodes are also used as cattle food and because of its strength it is used as field fences.

### Composition of *Opuntia* fruit

The isolation and characterization of storage proteins from the seeds of prickly pear showed that such proteins (molar masses of ~6500 g $mol^{-1}$) have an amino acid composition similar to the 2S albumin storage protein family (Ochoa *et al*. 1998). *O. ficus-indica* growing in desert and subdesert areas is a potential source of pectins (Majdoub *et al*. 2001; Sawaya *et al*. 1983). The polysaccharide component of prickly pear peel is characterized by very high neutral sugar content, mainly consisting of rhamnose and galactose and enough galacturonic acid content to be useful as a thickening additive (Forni *et al*. 1994).

### Nutritional composition and health benefits

Information on the composition of *Opuntia* Spp. is incomplete. However, cactus fruit and cladodes are valued because of their high nutrient content, vitamins and other health components (Hegwood 1990). Chemical

**Table 13.1** Average Chemical and Nutritional Contents of Prickly Pear Fruit and Cladodes.

| Content | Fruit | Cladode |
|---|---|---|
| Moisture (%) | 84.7–87.0 | 88–95 |
| Edible portion (%) | 55 | |
| Total soluble solids (°Brix) | 14.8–15.5 | |
| Titratable acidity (%) | 0.03–0.04 | |
| pH | 6.2–6.6 | |
| Total chlorophyll (mg/100 g) | | 12.5 |
| Chlorophyll a (mg/100 g) | | 9.5 |
| Chlorophyll b (mg/100 g) | | 3.0 |
| Fibre (%) | 1.8 | 4–6 |
| Vitamin C (mg/100 g) | 22–32 | 7–22 |
| Vitamin A (IU) | 50 | |
| β-carotenes (μg/100 g) | | 11–53 |
| Pectin (% dry wt basis) | 1.8–2.0 | 0.5–1.0 |
| Sugars (%) | 12–16 | |
| Glucose (%) | 6.0–8.2 | |
| Fructose (%) | 5.7–7.6 | |
| Sucrose (%) | 0.1–1.1 | |
| Lipids (%) | 0.1 | 0.2 |
| Proteins (%) | 0.3–0.5 | 0.5–2.0 |
| Energy (kcal) | 38 | |
| Thiamine (mg/100 g) | 0.01 | 0.14 |
| Riboflavin (mg/100 g) | 0.02 | 0.60 |
| Niacin (mg/100 g) | 0.3 | 0.46 |
| Minerals (g/100 g) | | 1–2 |
| Potassium (mg/100 g) | | 166 |
| Calcium (mg/100 g) | 60 | 90 |
| Phosphorous (mg %) | 34 | |
| Sodium (mg/100 g) | | 2.0 |
| Iron (mg %) | 0.8 | 1.6 |
| Arginine (mg/100 g, fresh weight) | | 2.4 |
| Asparagine (mg/100 g, fresh weight) | | 1.5 |
| Glutamic acid (mg/100 g, fresh weight) | | 2.6 |
| Glutamine (mg/100 g, fresh weight) | | 17.3 |
| Histidine (mg/100 g, fresh weight) | | 2.0 |
| Lycine (mg/100 g, fresh weight) | | 2.5 |
| Methionine (mg/100 g, fresh weight) | | 1.4 |
| Phenylalanine (mg/100 g, fresh weight) | | 1.7 |
| Serine (mg/100 g, fresh weight) | | 3.2 |
| Tryptophan (mg/100 g, fresh weight) | | 0.5 |
| Valine (mg/100 g, fresh weight) | | 3.7 |

Sources: Batista *et al*. (2003), Guevara *et al*. (2001), Hernandez *et al*. (1974), Laksminarayana (1980), Mizrahi *et al*. (1997), Retamal *et al*. (1987), Rodriguez and Cantwell (1988), Teles *et al*. (1994), Forni *et al*. (1992; 1994) and Fuentes-Rodriguez (1997).

**Table 13.2** Organic Acid Composition (mg/100 g Fresh Weight) of *Opuntia* spp. Cladodes in the Morning and Evening.

| Organic acid[a] | 6 A.M. | 6 P.M. |
|---|---|---|
| Oxalic acid | 35 | 35 |
| Malic acid | 985 | 95 |
| Citric acid | 178 | 31 |
| Malonic acid | 36 | Trace |
| Succinic acid | Trace | Trace |
| Tartaric acid | Trace | Trace |

[a]Total oxalic acid including soluble and insoluble, dry weight basis

Source: McConn and Nakata (2004), and Teles *et al*. (1994).

composition of fruit and cladodes vary depending on species, cultural practices and weather conditions, age of the plant and stage of development at harvest.

The composition of cladodes including the effect of time of day are shown in Tables 13.1 and 13.2. Generally, they are low in calories, high in fibre and contain proteins (Retamal *et al*. 1987), some minerals, vitamin C, and β-carotenes, sugars (Muñoz de Chavez *et al*. 1995), organic acids such as citric, malonic, and traces of tartaric and succinic (Teles *et al*. 1984; 1994) and piscidic and phorbic acids (Teles 1984, 1994). Younger cladodes commonly have higher carbohydrates, protein and water content. Amino acid profile of *Opuntia ficus-indica* cladodes showed the presence of 18 compounds (Stintzing & Carle 2005). Proteins and fibres usually decrease by age of the plant (Stintzing & Carle 2005). Carotenoid profiles showed the presence of β–carotene, α-cryptoxanthin, and lutein (Jaramillo-Flores *et al*. 2003), and total phenolic content was about 8–9 mg/100g (Jaramillo-Flores *et al*. 2003). Fertilization low in nitrogen usually leads to an increase in crude protein content, and phosphorous supplementation with 112 kg/ha improved the low phosphate content of the cladodes (Pimienta-Barrios 1990). Potassium is the main mineral, followed by calcium, sodium, and iron (Muñoz de Chavez *et al*. 1995). Based on their composition pattern, cladodes are judged more nutritive than lettuce, but less than spinach (Retamal *et al*. 1987). Lysine, methionine and tryptophane contents in cladodes were reported to be higher than in most cereals (Muñoz de Chavez *et al*. 1995).

The weight of a typical commercial cactus fruit of *O. ficus-indica* ranges from 120 to 200 g, with 45–60% of the fruit being edible, yielding juice of 12° to 15° Brix. The fruit is characterized by a high sugar content (12–17%) and low acidity (0.03–0.12%), with a small amount of vitamin C, thiamine, riboflavin and niacin, lysine, tryptophan and methionine, and fairly rich in calcium and phosphorous (Table 13.1). Titratable acid content is higher in the peel than in the pulp, and the pulp contains very low acid content at all stages of development (Guevara & Yahia 2005). Total pectin content in "white" prickly pear fruit is commonly very low in the pulp and does not change very much. Fruit colour varies from lime green, yellow, orange and red to purple (Inglese *et al*. 1995; Felker & Inglese 2003). Cactus fruit are rich sources of yellow-orange betaxanthins and red-violet betacyanins (Stinzing *et al*. 2003, 2005; Castellar *et al*. 2003; Odoux & Dominguez-Lopez 1996). Stinzing *et al*. (2005) have identified five different betaxanthins and six betacyanins structures in different *Opuntia* coloured fruits. The ratio and concentration of betalains were responsible for the yellow, orange, red and purple colours in coloured clones of *O. ficus-indica* and *O. robusta* (Stinzing *et al*. 2005). The main yellow betalain of all clones was praline-betaxanthin, which is considered as the typical compound of cactus pear (Stinzing *et al*. 2001, 2002). Cactus pear fruit have been suggested as a promising source of red and yellow food colorants for use at neutral pH (Stinzing *et al*. 2001, 2003).

Cladodes are used in various pharmaceutical applications for their therapeutic, dermatological and medical properties. Experimental evidence showed that prickly pear cactus cladodes could decrease blood glucose levels (Frati 1992). The intake of broiled *Opuntia* stems for 10 days improved glucose control in a small group of adults with non-insulin-dependent diabetes mellitus (NIDDM) (Frati *et al*. 1990a). The increase of serum glucose levels which follow the intake of a sugar load (oral glucose tolerance test) was lower with previous ingestion of *Opuntia* stems compared to if the sugar is ingested alone (Frati *et al*. 1990b). In patients with NIDDM, the ingestion of some species of cladodes (*Opuntia streptacantha*, *O.ficusindica*) in fasting condition is generally followed by a decrease of serum glucose and serum insulin levels (Frati 1992). Experimental evidence demonstrated that the ingestion of some species of cladodes (*Opuntia streptacantha*, *O. ficus-indica*) could decrease both blood glucose and blood lipid levels in patients with NIDDM (Frati *et al*. 1983). *Opuntia* stems administered to diabetic, obese and healthy volunteers, caused a decrease of serum levels of triglycerides, total cholesterol and LDL-cholesterol, and body weight also decreased in obese subjects, while HDL-cholesterol did not change and the 'atherogenic index' improved (Frati *et al*. 1983; Fernandez

*et al*. 1994). These positive health effects of *Opuntia* stems might be associated to dietary fibres, since similar results can be achieved by *Plantago psyllium* or other sources of dietary fibres (Frati 1992). Ethanol extract of *Opuntia ficus-indica* shows potential analgesic and anti-inflammatory effects (Park *et al*. 1998). Ingestion of raw and cooked *Opuntia ficus-indica* extracts presents beneficial effects on growth and total cholesterol, without any secondary effect on glucose and lipoproteins amounts in blood (Medellin *et al*. 1998).

The consumption of prickly pear fruits is recommended for their beneficial and therapeutic properties (Barbera & Inglese 1993). Recently there has been a surge in interest in *Opuntia* because of nutritional and health benefits, including among others, improving platelet function (Wolfram *et al*. 2003); reducing blood lipid and total cholesterol, low-density lipids and triglycerides (Wolfram *et al*. 2003; Wolfram *et al*. 2002; Palumbo *et al*. 2003); lowering isoprostane concentrations in blood indicating lower oxidative injury (Budinsky *et al*. 2001); antiulcerogenic activity (Galati *et al*. 2003a, 2003b) and as a source of antioxidants (Butera *et al*. 2002). Aqueous extracts of cactus pear (*O. ficus-indica* L. Mill) possess a high total antioxidant capacity, expressed as trolox equivalents, and exhibit a marked antioxidant capacity in several *in vitro* assays, including the oxidation of red blood cell membrane lipids and the oxidation of human LDLs induced by copper and 2,2′-azobis(2-amidinopropane-hydrochloride) (Butera *et al*. 2002). Antioxidant components reported by these authors included vitamin C, negligible amounts of carotenoids and vitamin E and no polyphenols. The fruit of some types of prickly pear contain 2 betalain pigments, the purple-red betanin and the yellow indicaxanthin, both with radical scavenging and reducing properties (Forni *et al*. 1992; Fernandez-Lopez & Almela 2001; Stintzing *et al*. 2002). Daily supplementation with 500 g cactus fruit (*O. ficus-indica*) pulp for 2 weeks greatly improved the oxidation stress status of healthy humans (Tesoriere *et al*. 2004). The effects included remarkable reduction in plasma markers of oxidative damage to lipids, such as isoprostanes and malondialdehyde (MDA), an improvement in the oxidative status of LDL, considerably higher concentrations of major plasma antioxidants, and improvement in the redox status of erythrocytes. The nutritional and health benefits of cactus fruit are believed to stem from their alleged antioxidant properties related to ascorbic acid, phenolics including flavonoids, and a mixture of yellow betaxanthin and red betacyanin pigments (Galati *et al*. 2003b; Gurrieri *et al*. 2000; Tesorieri *et al*. 2003). Total antioxidant activity of differently coloured cactus fruit (nine *Opuntia ficus-indica* clones and one *O. robusta* clone) (measured by Trolox-equivalent antioxidant capacity TEAC, and oxygen radical absorbance capacity, ORAC, assays) were very highly correlated among each other and also with total phenolic contents, betalains contents and ascorbic acid concentrations (Stintzing *et al*. 2005). Total phenolic content had the greatest contribution to ORAC and TEAC values. Total antioxidant activity measured by six assays highly correlated with the content of vitamin C (Corral-Aguayo *et al*. 2008). However, these correlations would depend on many factors such as the different type of cactus, growing region, harvesting time and so on. Generally, nutritional and health benefits of the different cactus fruit can be contributed by diverse components such as pigments (Butera *et al*. 2002; Tesoriere *et al*. 2003), colourless phenolic compounds (Galati *et al*. 2003b; Kuti, 2004; Pellegrini *et al*. 2003), mucilages, fibres and other constituents (Stintzing *et al*. 2001, 2005; Gurrieri *et al*. 2000).

Reports indicate that other parts of this plant are also used in folk medicine as emollient, moisturizing, cicatrizant, hypocholesterolemic, hypoglycemic agent and in gastric mucosa diseases (Cruse 1973; Meyer & McLaughlin 1981; Harvala *et al*. 1982; Camacho-Ibanez *et al*. 1983; Brutsch 1990; Frati *et al*. 1990a; Hegwood 1990; Pimienta 1990; Fernandez *et al*. 1992, 1994; Rosado & Diaz 1995). In Sicilian folk medicine, a flower infusion has an effect generally defined as depurative, and in particular it is used because of its diuretic and relaxant action on the renal excretory tract (Arcoleo *et al*. 1961, 1966; Sisini 1969). Therefore, it is stipulated that a flower infusion may help the expulsion of renal calculus. The fruit also enhances renal function (Cacioppo 1991). Galati *et al*. (2002) reported that flower infusion shows a modest increase in diuresis and natriuresis. Treatment with cladode infusions increases diuresis but does not significantly influence the uric acid pattern. The fruit infusion instead had diuretic and antiuric activity. The diuretic action observed may depend on stimulation of the urinary tract and is linked to the activation of neurohumoral mechanism, mediators of stimuli acting on glomerules, tone acid on the pyelo-uretral peristaltis. These effects might be due to the influence that the electrolytes, present in considerable quantities on the plant, exert on renal epithelium. In particular, O. *ficus-indica* is rich in $K^+$ ions, which are present in concentration of 548 mg $kg^{-1}$ in the cladodes, 21.7 mg $kg^{-1}$ in the flowers and 18 mg $kg^{-1}$ in the fruit (d'Aquino 1998). Galati *et al.* (2001) reported preventive and curative effects of *O. ficus-indica* Mill. cladodes preparations on rats affected by ethanol-induced ulcers. The cactus consumption gives rise to cytoprotection phenomena by breaking up the epithelial cells and stimulating an increase in mucus production.

When *O. ficus-indica* cladodes are administered as a preventive therapy, they keep the gastric mucosa under normal condition by preventing mucus dissolution caused by ethanol and favouring mucus production. An increase of mucus production is also observed during the course of the curative treatment. The treatment with *O. ficus-indica* cladodes provokes an increase in the number of secretory cells. Probably, the gastric fibroblasts are involved in the antiulcer activity.

## POST-HARVEST PHYSIOLOGY

The prickly pear is a CAM plant (Pimienta-Barrios *et al*. 2000), and therefore opens its stomata during the night to fix $CO_2$ as malic acid, which is then converted into sugar during the day. Therefore, the acid content and the flavour of the cladodes may fluctuate greatly during the day. The acid content of cladodes can also be affected by post-harvest storage temperature. For example, the acidity of young (10 cm) and commercial size (20 cm) cladodes which have been harvested in the morning was maintained or increased during storage at 5°C, and decreased at 20°C. At the time of fruit set sugar content was very low in the fruit peel (0.1%) and fruit pulp (0.16), whereas total soluble solids were relatively high (4.5° to 5.5° Brix) (Lakshminarayana *et al*. 1979; Alvarado 1978). From the eleventh week onwards, sugars increased 100-fold both in the peel and in the juice, but the major accumulation occurred in the final 6 weeks of fruit development. Glucose is generally the highest sugar, followed by fructose and sucrose.

*Opuntia* fruit are nonclimacteric. Respiration rate declines during fruit development and is not different for fruit harvested at different stages of ripeness (Lakshminarayana *et al*. 1978, 1979; Moreno-Rivera *et al*. 1979). Respiration rates of fruit are temperature dependent, but low during storage (Table 13.3). The fruit also produce very low amounts of ethylene (about 0.2 µL $kg^{-1}$ $h^{-1}$ at 20°C), and are not sensitive to ethylene exposure, but exposure at warm temperatures will enhance yellowing (Schirra *et al*. 1997).

**Table 13.3** Respiration Rates of Prickly Pear Fruit at Different Temperatures.

| Temperature | mg $CO_2$ $kg^{-1}$ $h^{-1}$ |
|---|---|
| 5°C | 16 to 19 |
| 10°C | 38 to 42 |
| 15°C | 52 to 59 |
| 20°C | 68 to 79 |

## PHYSIOLOGICAL DISORDERS

Cactus pear fruit and cladodes are chilling sensitive when stored at lower than 5°C, but chilling injury (CI) may occur in some varieties even at less than 10°C. CI symptoms in fruit include pitting, surface bronzing and dark spots on the peel, and increased susceptibility to decay. CI occurred in a red-fruit variety after only 2 weeks at 6°C, but fruit from other varieties were held for few weeks without signs of chilling, and summer-harvested fruit were reported to be more chilling sensitive than autumn-harvested fruit (Schirra *et al*. 1999). Applications of calcium chloride, conditioning, and intermittent warming of fruit have been reported to have variable success in reducing CI. Cladodes are chilling sensitive when stored below 10°C, and symptoms may appear after 3 weeks at 5°C or sooner. CI damage in cladodes may be manifested as a superficial bronzing or unattractive surface discolouration and increased susceptibility to decay especially at the cut stem end. Fluid (mucilage) loss and brown discoloration from the cut stem end is commonly a potential quality problem.

## DISEASES AND ROTS

Cladodes can be infected by various fungi, namely *Colletotrichum gloeosporoides*, which produces round black necrosis under high humidity (Fucikovski 1992). *Phythophthora cactorum* and P. *omnivora* can cause wilting and possible rot of cladodes (Cacioppo 1991), and *Phillosticta opuntia* can cause a certain type of scab. Other moulds such as *Phyllostitica concave*, *Fusarium solani* and *F. oxysporum* produce black rot and soft rot, respectively (Granados and Castañeda 1996). Bacteria of the coliform group, with isolates similar to *Erwinia chryanthemi* and *E. carotovora* subspp. *caro tovora* and *atrosepica* were identified as agents of soft rots in cladodes by Fucikovski and Jaimes (1981), and Vavaro and Gargata (1990). *E. carnegieana* infect the plant through natural holes, injuries, probably by direct contact or from root to root, causes wilt and can destroy the cladode. Bacteria of the genus *Leuconostoc, Bacillus*, *Pseudomonas*, *Micrococcus* and *Ruminicoccus* were identified in the microflora of *O. ficus-indica* cactus stems in modified atmosphere packages (Guevara *et al*. 2003). The moulds isolated were of the genus *Absidia*, *Cladosporium*, *Penicillium* in addition to the yeast *Pichia*, but no pathogenic microorganisms were identified. Modified atmosphere packaging (up to 8.6% $O_2$ and up to 6.9% $CO_2$) at 5°C decreased the growth of mould and yeast and mesophilic aerobic microorganisms in cladodes. Decay at the cut stem end may be a problem if cladodes are stored

for up to 2 weeks. Decay can be avoided by ensuring that cladodes are not damaged when cut from the plant. Fungicide dips reduce post-harvest decay of cladodes, but are not used commercially.

In the case of the fruit, harvest damage to the peel and stem end of cactus fruit will lead to attack by numerous pathogens and result in fruit decay. Common post-harvest pathogens on cactus fruit are mostly fungi and include *Fusarium* spp., *Alternaria* spp. and *Penicillium* spp., but yeasts and bacteria also cause decay. Hot water dips at 53°C to 55°C for 5 minutes and fungicide-containing waxes may reduce surface decay, but are not effective when there is damage to the stem ends. Pre-harvest calcium sprays result in less post-harvest decay (Schirra *et al*. 1999).

## INSECT PESTS

Among the natural enemies of prickly pear cladodes are *Cactoblastis coctorum* and *Dactilopius opuntia*, and both are used in Australia and South Africa to control the expansion of the plant. *Cactophagus spinolae Gyll*, *Chelinidea tabulata Burm*, *Hesperolabops gelastops Kyrkaley*, *Olyacella nephelepsa Dyar*, *Lanífera cyclades Druce*, *Dactylopies indicus Green*, *Seriocatrips opuntia Hood* and *Moneilema variolaris* feed on cladodes internal tissue, decrease the production and in some cases cause the death of the plant. *Diabrotica sp*. and *Phyllophaga spp*. attack the roots of cactus and generate severe injuries (Granados & Castañeda 1996).

## PHYSICAL DAMAGE

Physical damage is an important problem that limits the post-harvest life of prickly pear fruit. Fruit can be bruised easily during harvest, but damage to the stem end is by far the most serious because it leads to attack by pathogens and fruit decay. Damage at the stem end of the fruit can be eliminated by careful harvesting, twisting fruit from the stem or cutting fruit with a small piece of stem attached. Fruit harvested with a small piece of the stem attached may be packed that way or cured at moderate temperatures of 15°C to 20°C with airflow so the stem dries and falls off before fruit are packed. However, in some *Opuntia* species large subtending spines makes this technique difficult. High-gloss fruit waxes are often used to improve visual appearance and reduce dehydration, especially when fruit are dry-brushed to remove small tufts of spines or glochids.

## QUALITY CHARACTERISTICS AND CRITERIA

Prickly pear fruit consist of a thick fleshy skin surrounding a juicy pulp, of different colours and flavours depending on species. High-quality fruit are characterized by a high percentage of pulp, low seed content of seeds, a peel that is easy to remove, high sugar content (12–17%), low acidity (0.03–0.12%) and freedom from defects.

Good-quality cladodes (nopalitos) are thin, fresh-looking and turgid and have a brilliant green colour. In the early stages of growth, vestigial true leaves, usually subtended by spines, are present on the stems, but the leaves often abscise by the time cladodes reach commercial size. However, an indication of freshness is when true leaves remain on the stem and are green. The popularity of *O. atropes* has increased recently in Mexico because of its texture and pleasant smell (Vigueras & Portillo, 2001). *O. leucotricha* (duraznillo) and *O. robusta* yield high-quality cladodes because the pericarp can easily removed, do not fall apart during boiling and do not release mucilage.

### Maturity and harvesting indices

Stage of maturity or ripeness at harvest is very important for fruit quality. As discussed above, being a CAM plant the acid content of cladodes may fluctuate greatly during the day and affect their flavour (Rodríguez-Felix & Cantwell 1988). Therefore, because of diurnal acidity changes it is recommended that stems be harvested 2 to 3 h after sunrise to be best used as a vegetable (Mizrahi *et al*. 1997). Small cladodes, however, are not CAM-active. Cladodes are harvested based on size and can be small (< 10 cm long) or medium (< 20 cm long). In Mexico, cladodes are harvested when they are 15 to 20 cm long (weight 90–100 g), by cutting at the articulation with the 'mother cladode'. Over-mature cladodes are thick with spongy white tissue, are acidic in flavour, and are not commonly consumed. Cladodes should be harvested when young and tender and not early in the morning to avoid a high acid content (Table 13.2). Acid content will not only depend on time of harvest, but also on the species and post-harvest conditions. Low temperature storage at 5°C maintains acid levels, while warmer storage conditions of 15°C to 20°C result in decreased acid content (Cantwell *et al*. 1992). Cladodes harvested before reaching a length of 10 cm are usually CAM inactive and virtually lack spines.

Prickly pear fruit takes about 4 months from fruit set to reach harvest maturity (Alvarado 1978). Fruit maturity indices include fruit size and fullness, changes in peel colour, abscission of the small spines or glochids, fruit firmness and flattening of the floral cavity or receptacle. Peel colour is the single most important index for commercial harvest. Soluble solids content have been reported to correlate well with colour for some types of prickly pear fruit, but not by others (Lakshminarayana *et al*. 1979). Different "white" prickly pear fruit maturity can be described as

follows: (1) Mature-green fruit are well developed with a light green peel; (2) ripening fruit, where harvesting is commonly done, begin to show colour change on the peel, from about 25% to 75% yellow, and the glochids begin to fall off; (3) ripe fruit commonly have 95% to 100% pale yellow peel colour and are usually soft and can be damaged easily during and after harvest; and (4) overripe fruit may show an increasing intensity of the yellow peel colour with the development of some small rusty-brown discoloured areas. The fruit has a number of prickles all over, and they fall off easily on rubbing. There are no special harvesting techniques; however, it is important that harvesters use thick rubber or canvas-type gloves to avoid injury from prickles. Generally, fruit are harvested by twisting the short peduncle. The fruit is then spread on grassy ground, after which they are rubbed with gloved hands or with other means to loosen the prickles. Some harvesting aids have been tried (Lara-Lopez & Martinez-Yepez 1985).

## PACKAGING

In Mexico, cladodes are collected in baskets or stacked in cylindrical packs about 1 metre tall for transport to market, where they are commonly cleaned by eliminating spines and vestigial leaves and trimming the sides prior to sale within 2–3 days. Cladodes produced in the United States or exported from Mexico are commonly packed in 10 kg wooden or fibre boxes.

Fruit are commonly packed according to colour, size, and condition (Piga *et al*. 1996) in ventilated wooden or plastic crates, 4.5 kg cartons, or in single or double layer tray cartons. They are also loose packed in 4.5 to 9.0 kg cartons or boxes. Large fruit may be wrapped in tissue paper to reduce scuffing and other physical injury. Fruit may also be packaged in cartons with perforated plastic liners to reduce water loss under dry storage conditions.

### Cooling and storage

Cladodes are cooled to about 5°C to reduce loss of visual appearance (shiny surface) due to water loss, and to reduce respiratory weight (and hence weight loss as well as senescence). They are usually room-cooled, but can also be forced-air cooled. Hydro-cooling should be avoided as it favours discolouration in damaged areas, especially where spines have penetrated the surface, and decay. Major factors limiting the storage life of cladodes are decay and dehydration. Cladodes stored under ambient conditions rapidly lose their brilliant shiny appearance, become dull-green and may begin to yellow and shrivel due to water loss. Storage life can reach up to 3 weeks at 5°C and 2 weeks at 10°C when polypropylene foil is used (Rodriguez-Felix *et al*. 1997). *Nopalea cochenillifera* cladodes lost only 7% water after 12 days storage at 20°C, and high relative humidity (85–89%) proved to be disadvantageous for this species (Nerd *et al*. 1997). Some discolouration due to CI can occur if cladodes are stored longer than 2 weeks at 5°C (Cantwell *et al*. 1992). Ascorbic acid content decreased 20–40% after 7 days storage at 20°C (Rodriguez-Felix *et al*. 1997).

Fruit should be cooled to 5°C to reduce loss of visual appearance (shiny surface) due to water loss. They are commonly room-cooled, but may also be forced-air cooled. Cooling may be delayed if fruit undergo a curing treatment. Fruit can be maintained for 2 to 5 weeks at 5°C to 8°C and 90% to 95% RH, depending on variety, ripeness stage and harvest season. Factors that limit fruit storage life include decay, water loss and CI. Attempts to prolong storage life using aqueous wax emulsion coatings did not result in significant benefits (Estrella-Bolio 1977).

Post-harvest treatments of cactus pears (*Opuntia ficus-indica* Miller (L.) cv. Gialla) with 1000 mg/L thiabendazole (TBZ) at room temperature did not affect the expression of slight-to-moderate CI, but reduced severe CI by approximately 50% and decay development by 63.4% (Schirra *et al*. 2002). The effectiveness of TBZ was much higher with the treatment at 150 mg/L TBZ at 52°C, providing 91% control of severe CI and approximately 89% suppression of decay; with no treatment damage occurred during storage and simulated marketing period. External appearance was better in fruit treated with 150 mg/L TBZ at 52°C. Respiration rate, titratable acidity, soluble solids contents and acetaldehyde in the flesh were not significantly influenced by treatments, but ethylene production rate and ethanol levels in the flesh were significantly higher in the TBZ-treated fruit as opposed to those in the untreated control fruit.

## MODIFIED (MA) AND CONTROLLED ATMOSPHERE (CA)

Very little work has been done on MA and CA of prickly pear fruit and cladodes, but holding at 5°C in 2% $O_2$ + 2 to 5% $CO_2$ can delay ripening and senescence and extend storage life of fruit and cladodes. Packaging cladodes in Cryovac PD960 films created a MA as a result of the high respiration rate of the cactus stems, where oxygen decreased to about 8.6% and $CO_2$ increased to about 6.9% after 30 days in storage (Guevara *et al*. 2001; 2003). Cladodes packaged in MA had very low weight loss (Figure 13.3).

The texture and crude fibre contents of cladodes that were maintained in MA packages (MAP) decreased only

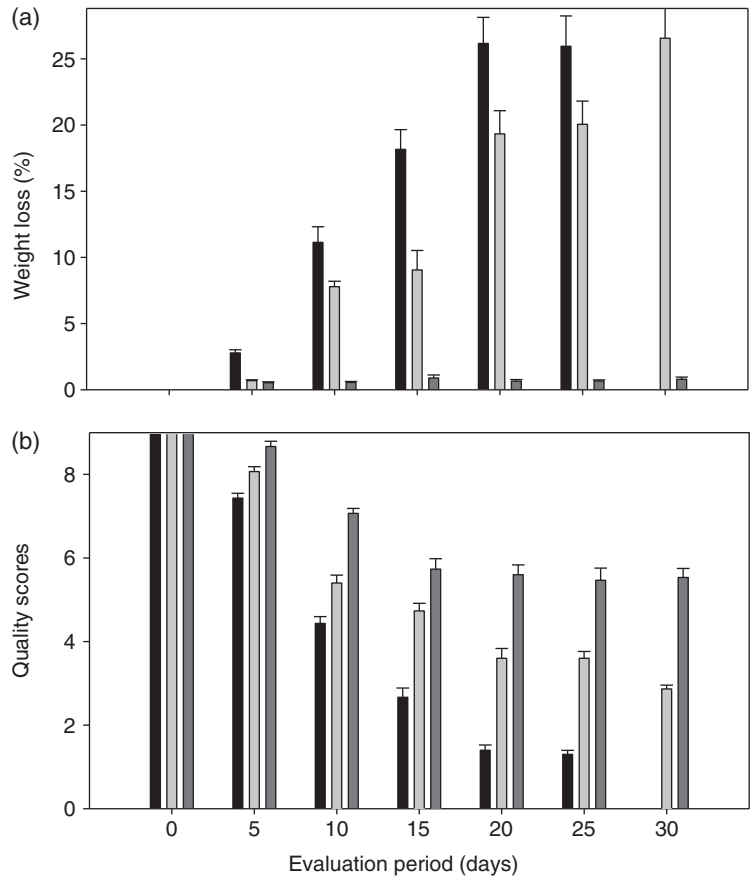


**Figure 13.3** Weight loss (%) and overall quality scores in prickly pear cactus stems (cladodes) held for up to 30 days at 5°C with and without packaging in modified atmosphere. Without packaging (black: ): packaging in polyethylene bags with holes (high relative humidity), MAP (light grey: ) and packaging in modified atmospheres (dark grey: ). Vertical bars indicate standard error of the mean (Guevara *et al.* 2001, with permission).

very slightly during all of the storage period, and there was a close relation between them, indicating that the retention in texture might be due to the positive effects of MA on preventing crude fibre losses (Figure 13.4, Guevara *et al.* 2003). It is possible that the decrease in crude fibre content was due to the decrease in the activities of enzymes such as cellulases, hemicellulases and pectinases.

The decrease in chlorophyll (total, a and b) was the least in cladodes that were maintained in MAP, and chlorophyllase activity was very low in cladodes held in MAP (Figure 13.5, Guevara *et al.* 2001). Therefore, the slow decrease in chlorophyll in cladodes held in MAP is apparently due to the decrease in the chlorophyllase activity. The lower chlorophyllase activity in cladodes maintained in MAP is probably due to the lower ethylene accumulation or the reduced ethylene action.

MAP reduced microbial activities in cladodes stored at 5°C for up to 30 days (Figure 13.6; Guevara *et al.* 2001). Therefore, packaging of prickly pear cactus cladodes in MA (up to 8.6% $O_2$ and up to 6.9% $CO_2$) and holding at 5°C for up to 30 days prolonged their storage life and maintained their quality (Guevara *et al.* 2001; 2003). MAP decreased the loss in water, texture, crude fibre content, chlorophyll content and colour, and decreased the activity of chlorophyllase, mould, yeast and mesophilic aerobic microorganisms.

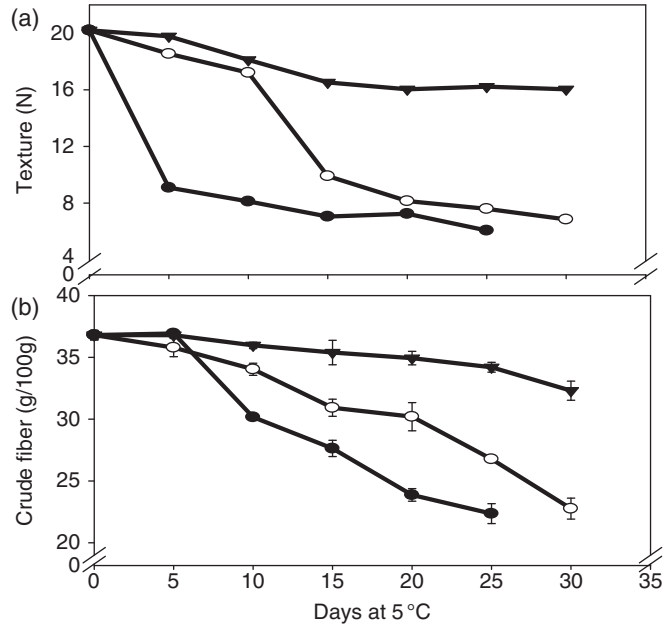


**Figure 13.4** Changes in texture (N) and crude fibre content (g/100 g) in prickly pear cactus stems (cladodes) held for up to 30 d at 5°C. (●): without packaging, (❍): packaging in polyethylene bags with holes (high relative humidity) and MAP (▼): packaging in modified atmospheres. Vertical bars indicate standard error of the mean (Guevara *et al*. 2001, with permission).

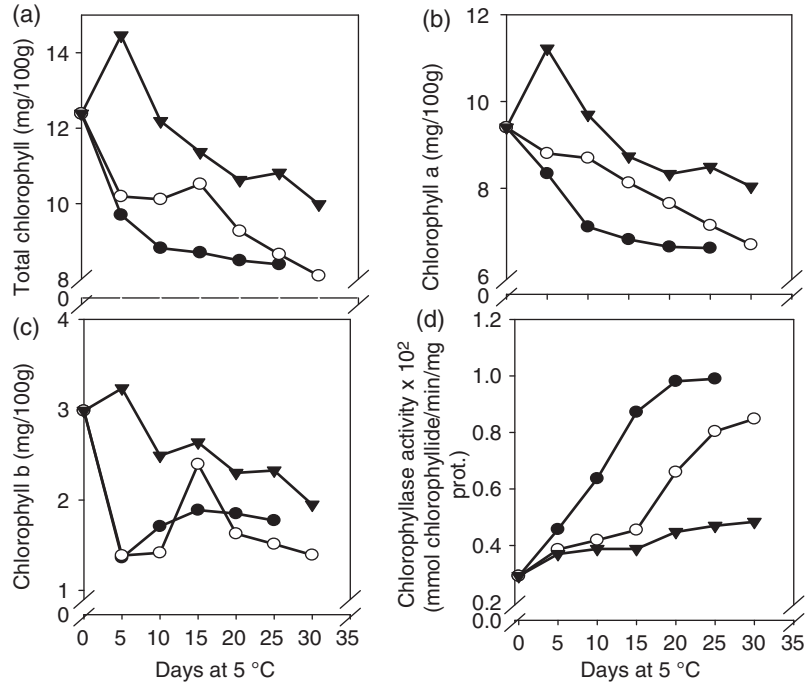


**Figure 13.5** Changes in chlorophyll content (a, total; b, chlorophyll *a*; c, chlorophyll *b*; and d, chlorophyllase activity) in prickly pear cactus stems (cladodes) hold for up to 30 d at 5°C. (●): without packaging, (❍): packaging in polyethylene bags with holes (high relative humidity) and MAP (▼): packaging in modified atmospheres. Vertical bars indicate standard error of the mean (from Guevara *et al*. 2001, with permission).

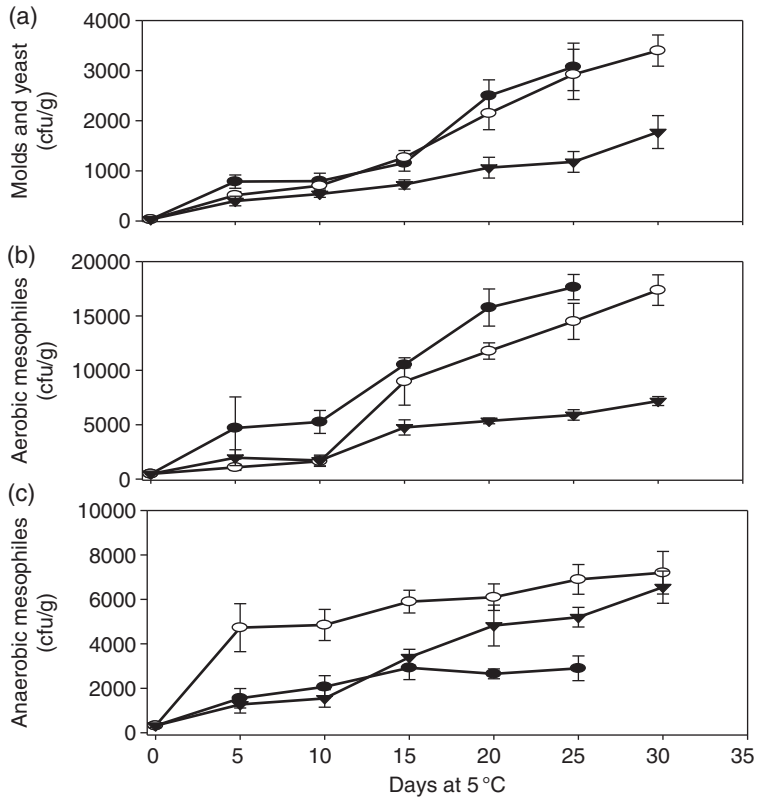


**Figure 13.6** Changes in total microbial counts (yeast and moulds, mesophilic aerobic micro-organisms, mesophilic anaerobic micro-organisms) in *Opuntia* cactus stems (cladodes) held for up to 30 d at 5°C. (●): without packaging, (❍): packaging in polyethylene bags with holes (high relative humidity), MAP (▼): packaging in modified atmospheres. Vertical bars indicate standard error of the mean (From Guevara *et al.* 2001 with permission).

The application of passive or semi-active MA ($CO_2$ ≤ 20%) to cladodes using RS425 Cryovac films increased the shelf life even further to up to 35 days (Guevara *et al.* 2003). The oxygen concentration in passive MA packaging decreased and reached about 8% after 35 days in storage, while the $CO_2$ concentration increased to about 7.5% in the same period of time.

In the semi-active MA, where 20% $CO_2$ is added to the package, the oxygen level decreased to about 13%, and the $CO_2$ level decreased to about 13.5% after 35 days in storage. On the other hand, the $CO_2$ level in semi-active MAP with an initial $CO_2$ level of 40% and 80%, decreased to about 15 and 25%, respectively, and the oxygen level slightly increased to about 15%, at the end of the storage period (Guevara *et al.* 2003). The $CO_2$ levels created in the semi-active MAP with initial of 40% and 80% were higher than the minimum tolerated levels for many fresh horticultural crops (Yahia 1998) and yet did not appear to have a significant deleterious effect on *Opuntia*.

Firmness decreased in all cladodes, but the decrease was faster in those that were kept in semi-active MAP with initial concentrations of 40% and 80% $CO_2$, and cladodes that were maintained without packaging, and the least firmness loss was observed in the passive MAP and in semi-active MAP with an initial 20% $CO_2$ (Figure 13.7, Guevara *et al.* 2003). The trends in changes in fibre content were similar to those for firmness. The highest loss in fibre was observed in cladodes maintained in semi-active MAP with initial concentrations of 40% and 80% $CO_2$, and in cladodes that were maintained without packaging, and the lowest loss was observed in the cladodes maintained in passive MAP and in semi-active MAP with an initial concentration of 20% $CO_2$ (Figure 13.7). It is possible that the loss in

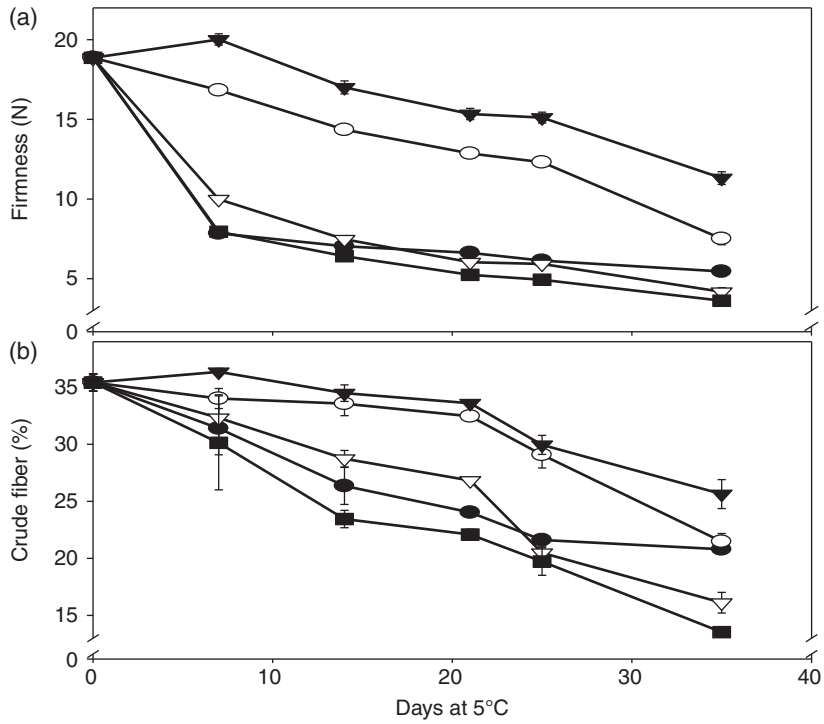


**Figure 13.7** Changes in firmness (N) and crude fibre (%) in passive and semi-active MA-packaged prickly pear cactus stems stored at 5°C for up to 35 days. Nonpackaged (●), passive MAP (○), 20% $CO_2$ (▼), 40% $CO_2$ (∇) and 80% $CO_2$ (■). Vertical bars represent standard error of the mean (Guevara *et al*. 2003, with permission).

firmness is caused by losses in fibre resulting in the softening of the cladodes.

The retention in firmness of cladodes maintained in passive MAP or in semi-active MAP with an initial concentration of 20% $CO_2$ might be due to the positive effects of MA with intermediate $CO_2$ concentrations.

Weight loss was least in cladodes that were packaged in passive MAP and in semi-active MAP with an initial concentration of 20% $CO_2$, and the rest of the conditions showed a high weight loss of more than 25% (Figure 13.8). There was a close relation between weight loss and the overall quality (Figure 13.8). Overall quality of the cladodes as judged subjectively was highest in cladodes that were package in semi-active MAP with an initial 20% $CO_2$, followed by those packaged in passive MAP. Levels < 20% $CO_2$ can decrease the rates of respiration and transpiration, resulting in low weight loss. On the other hand, high $CO_2$ concentrations (over 20%) result in changes in cell permeability and increased metabolic processes. Elevated $CO_2$ concentrations inactivate glycolytic and tricarboxylic enzymes (malate dehydrogenase, succinic dehydrogenase and cytochrome oxidase), generate an accumulation of succinic acid, malate, acetaldehyde and ethanol, and reduce cytochrome activity.

The decrease in chlorophyll content (total, a and b) (Figure 13.9) during most of the storage period was the least in cladodes that were maintained in passive MAP and in semi-active MAP with an initial of 20% $CO_2$, followed by those packaged in semi-active MAP with initial concentrations of 40% and 80% $CO_2$, and in those kept without packaging (Guevara *et al*. 2003). Total chlorophyll and chlorophyll a of cladodes kept in passive MAP and in semi-active MAP with 20% $CO_2$ decreased about 23 and 35%, respectively, while elevated $CO_2$ concentrations (40% and 80%) caused a decrease of about 53% and 63%, respectively. Chlorophyll b content decreased about 57%, 58%, 37%, 80% and 99% in cladodes that were not packaged, packaged in passive MAP, or packaged in semi-active MAP with initial 20%, 40% or 80% $CO_2$, respectively, after 35 days in storage.

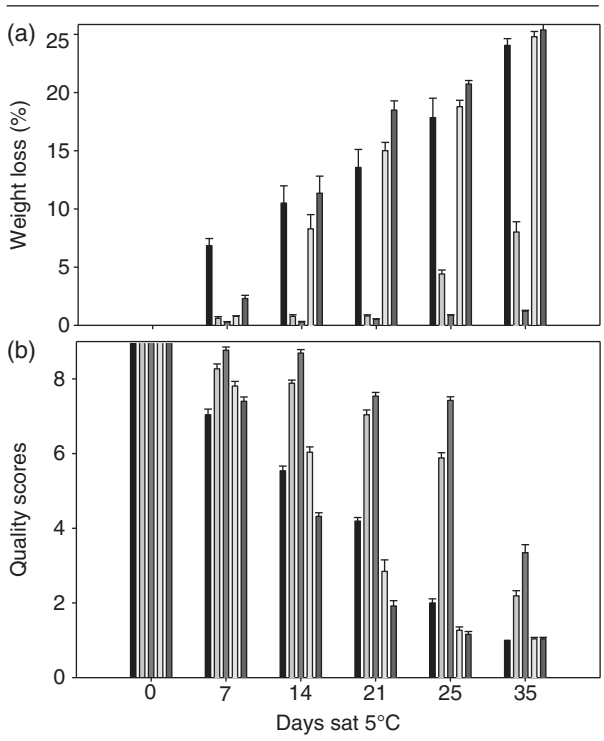


**Figure 13.8** Changes in weight loss (%) and overall quality scores in passive and semi-active MA-packaged prickly pear cactus stems stored at 5°C for up to 35 days. Nonpackaged (■), passive MAP (▒), 20% $CO_2$ (▓), 40% $CO_2$ (□) and 80% $CO_2$ (▓). Vertical bars represent standard error of the mean (Guevara *et al.* 2003, with permission).

Chlorophyllase activity was lowest in cladodes maintained in MAP (Figure 13.9d; Guevara *et al*. 2003). The lowest activity was in cladodes packaged in passive MAP and in semi-active MAP with 20% $CO_2$, and the highest activity was found in cladodes packaged in semi-active MAP with an initial concentration of 40% and 80% $CO_2$, and in cladodes kept without packaging. The highest chlorophyllase activity present in treatments with elevated $CO_2$ concentrations (semi-active MAP with initial 40% and 80%) is probably due to the stress caused by $CO_2$ injury. There was a clear relation between chlorophyll degradation and chlorophyllase activity. Conditions that show the highest chlorophyll degradation also had the highest chlorophyllase activity. This is in disagreement with Baardseth and Von Elbe (1989) who concluded that gradual chlorophyll disappearance in spinach did not coincide with the activation of chlorophyllase. The chlorophyllase activity was found to either increase (Rodriguez *et al*. 1987) or decrease (Majumdar *et al*. 1991) during the senescence of leaves and ripening of fruit. This suggests that chlorophyllase may or may not be responsible for chlorophyll degradation. However, it seems likely that chlorophyllase is important for chlorophyll degradation in prickly pear cactus stems.

Microbial population started to increase after 15–20 days of storage (Figure 13.10, Guevara *et al*. 2003). The least increase in total aerobic mesophiles (AeM) population was in cladodes that were kept in semi-active MAP with an initial of 20% $CO_2$, followed by those maintained in semi-active MAP with an initial concentration of 40% $CO_2$, and the highest increase was in cladodes maintained in semi-active MAP with an initial of 80% $CO_2$, and in cladodes that were maintained without packaging. AeM population reached up to $1.9 \times 10^5$ CFU $g^{-1}$ after 35 days in storage. Total anaerobic mesophiles (AnM) were highest in cladodes that were held in semi-active MAP with an initial of 80% $CO_2$ and least in those held without packaging and in those held in semi-active MAP with an initial of 20% $CO_2$. The highest AnM count was $2.0 \times 10^5$ CFU $g^{-1}$. The highest increase in mould and yeast (MY) was found in cladodes that were held in semi-active MAP with an initial of 40% $CO_2$, followed by those maintained without packaging, while the least MY population was in cladodes maintained in semi-active MAP with initial concentrations of 20% and 80% $CO_2$.

The highest MY population reached up to $5 \times 10^4$ CFU $g^{-1}$. Isolation of single colonies was performed by randomly selecting the square root of the total number of colonies counted on each plate. On the basis of the macro- and microscopic characteristics of AeM bacteria isolated and the biochemical test done, identified bacteria were from the genus *Leuconostoc*, *Pseudomonas*, *Micrococcus* and *Bacillus*. The AnM were identified in the same way as the AeM, and the bacteria found were of the *Ruminicoccus* genus. In the case of MY the fungi identified were *Absidia*, *Cladosporium* and *Penicillium* and the yeast *Pichia*, which produces necrosis of tissue.

**Summary of findings on MA packaging**

It is possible to extend the shelf life of prickly pear cactus stems by MA by generating an atmosphere with $O_2$ levels of up to 8% and $CO_2$ levels of up to 7% in passive MAP, or up to 20% in semi-active MAP. $CO_2$ concentrations between 7% and 20% decreased the loss in colour, firmness and fibre content, and reduced chlorophyllase activity, and microbial flora load on the stems. These benefits are due to atmospheric modification and not to increased

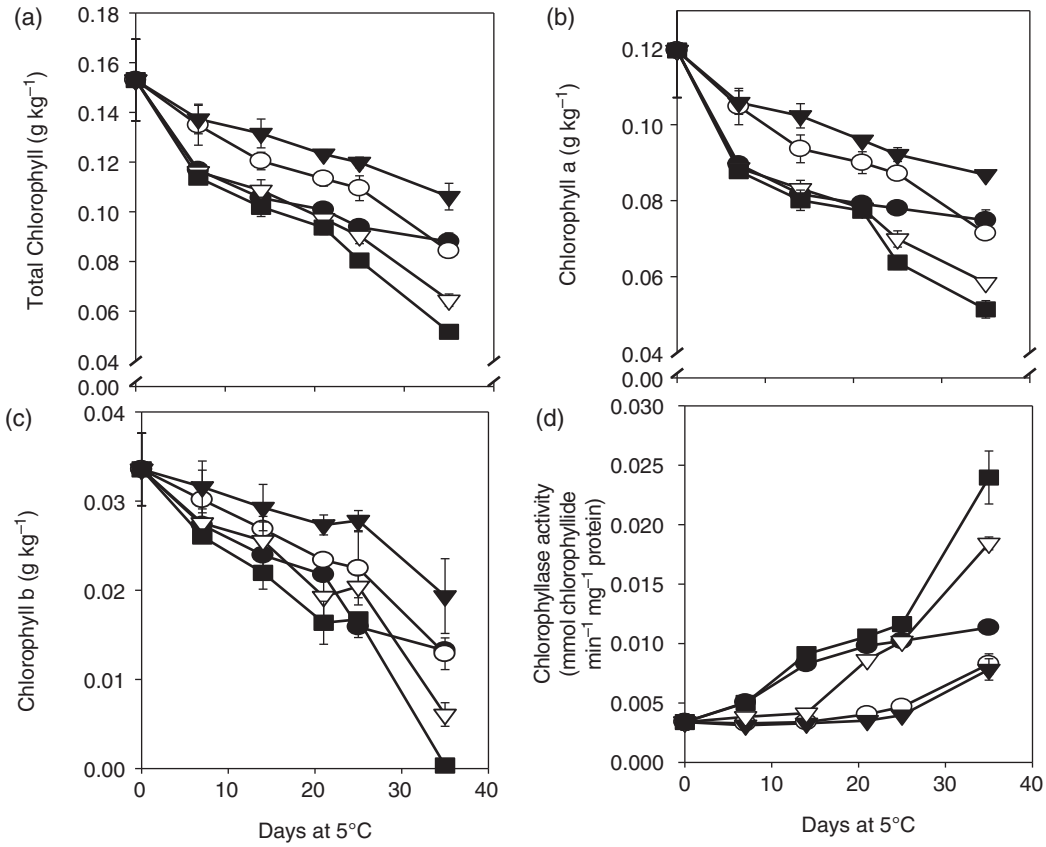


**Figure 13.9** Changes in chlorophyll content (total, a and b) and chlorophyllase activity in passive and semi-active MA-packaged prickly pear cactus stems stored at 5°C for up to 35 days. Non packaged (●), passive MAP (❍), 20% $CO_2$ (▼), 40% $CO_2$ (▽) and 80% $CO_2$ (■). Vertical bars represent standard error of the mean (Guevara *et al.* 2003, with permission).

humidity in the atmosphere (Guevara *et al*. 2001; Yahia *et al*. 2005). On the other hand, elevated $CO_2$ levels (≥40%) caused injury in cladodes in comparison with nonpackaged cactus stems. There were no big differences in the quality of prickly pear cactus stems packaged in passive MAP or in semi-active MAP with an initial $CO_2$ concentration of 20%. The relative limit of tolerance of prickly pear cactus stems to $CO_2$ is 20%. The storage life of the cactus stems can be up to 32 days in passive MAP or in semi-active MAP with an initial $CO_2$ concentration of 20%.

Several models have been used to describe the modified atmosphere in packages of horticultural products; nevertheless, none of them integrate the effects of temperature and the relative humidity as system variables. A model has been generated and applied to describe the gas profile of prickly pear cactus stems in passive and semi-active MAP (Yahia *et al*. 2005; Guevara *et al*. 2006a, 2006b). The model describes the gas exchange in nonsteady state, taking in consideration the effect of temperature at 5°C, 14°C, 20°C and 25°C and the relative humidity from 65–90% RH (at intervals of 5 %) on film permeability characteristics, respiration rate and tissue permeance of prickly pear cactus stems. The model suitably describes the changes in $CO_2$ concentration and overestimates the $O_2$ concentration in passive (no addition of gases) MAP of prickly pear cactus stems. However, when a concentration of >20% $CO_2$ is added to the packages, the model adequately describes the changes in $O_2$ but sub-estimates the changes in $CO_2$. This might be due to high $CO_2$ concentration alterations in tissue metabolism. The temperature and RH integration and the small number of the measurable parameters in the proposed model may help the model to be easily used for a

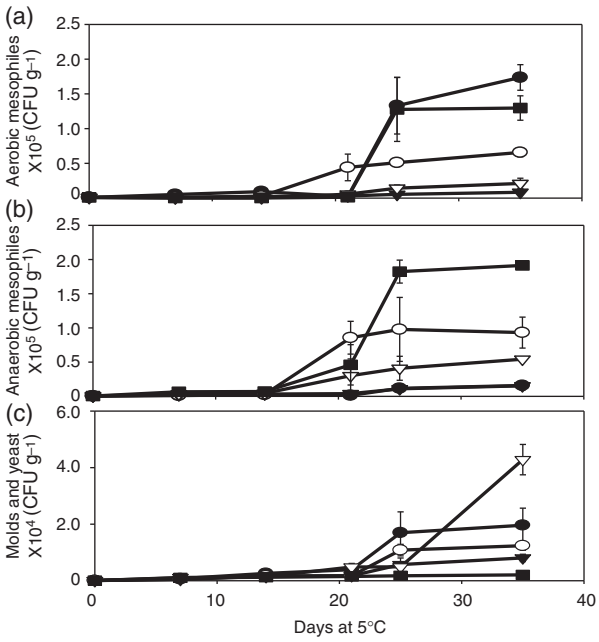


**Figure 13.10** Changes in total microbial count (AeM, AnM, molds and yeast) in passive and semi-active MA-packaged prickly pear cactus stems stored at 5°C for up to 35 days. Non packaged (●), passive MAP (○), 20% $CO_2$ (▼), 40% $CO_2$ (▽) and 80% $CO_2$ (■). Vertical bars represent standard error of the mean (Guevara *et al*. 2003, with permission).

great variety of situations involving different commodities. This approach should facilitate package designing for fresh produce, and therefore maximizing the benefits of MAP for horticultural products. Another major conclusion of this study, however, is that the relative humidity around the packages (e.g. in the display cabinet of retail stores) can have a major impact on the respiration and gas exchange of MAP packed products. This could well be the missing link in understanding the sometimes erroneous and incomprehensible results obtained with MAP packages in practice.

## FRESH-CUT

In Mexico cladodes are commonly processed and packed as fresh-cut, however, reducing brown discolouration at cut surfaces and preventing fluid (mucilage) loss are the main problems in handling diced cactus stems. Cut cladodes cannot be washed before marketing, because it will cause mucilage to exude and enhance discoloration of cut surfaces. Shelf-life of diced cladodes was 1 day at 20°C and 6 days at 5°C (Rodríguez-Felix & Soto-Valdez 1992). Moderate $CO_2$ (5% to 10%) may be useful to reduce discoloration and other visual defects of cut cladodes.

An extension of shelf life and maintenance of chemical and sensory attributes of prickly pear fruit (*Opuntia ficus-indica* cv. Gialla) for 8 days was achieved by placing in polystyrene trays sealed with polyolefinic films and stored at 4°C (Piga *et al*. 2000, 2003). Fruit texture was also reported to be maintained in ethylene-vinyl acetate (EVA) for 7 days at 5°C (Saenz *et al*. 2001). MAP at 4–8°C for up to 7 days was reported to reduce microbial spoilage by mesophilic bacteria (staphylococcus spp., Enterobacter spp., Leuconostoc mesenteroides), as well as yeasts (Corbo *et al*. 2004).

## SUMMARY

Prickly pear fruit are produced and consumed in several countries, and cladodes are traditionally consumed in Mexico and some parts of the United States as vegetable, and also exported to few other countries. Both have been suggested to have several health benefits. They can be readily and abundantly produced under high temperature and little water, conditions unfavourable for the production of many other crops, and therefore interests in their production and consumption is increasing. Cactus plants serve numerous purposes; such as sources for fruit and vegetables, for medicinal and cosmetic purposes, as forage, for building materials and as a source for natural colours. However, many of these uses are still very restricted to a very few countries, and in light of global desertification and declining water sources, *Opuntia* spp. is gaining importance as an effective source of food including as a vegetable. The fruit is relatively perishable an can be kept for 2 to 5 weeks at 5°C to 8°C with 90–95% RH, and several factors can limit storage life such as decay, dehydration and CI. Cladodes are more perishable than fruit and can be maintained for only a few days at 5°C with 95–99% RH, and major factors limit their storage life including CI, decay and dehydration. Modified and controlled atmospheres can delay ripening and senescence and extend storage life of both fruit and cladodes.

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# 14
# Cucurbits

*Steven A. Sargent and Donald N. Maynard*

## INTRODUCTION TO THE CULTIVATED CUCURBITS

The cultivated species of the Cucurbitaceae or gourd family are collectively called cucurbits. The horticultural types are mostly monoecious, frost-intolerant herbaceous annuals. All are tendril bearing vines with alternate, mostly dissected, palmate leaves. The flowers are mostly yellow, sometimes white and often quite showy. Staminate flowers have five petals and three stamens. Pistillate flowers have an inferior ovary with three carpels (Figure 14.1). Flowers are open for only one day and pollen transfer is effected by insects, mostly bees. The fruit is a single to multi-seeded, fleshy berry called pepo. Fruit size varies from 100 g in some miniature gourds to the Guinness Book of Records 118 kg watermelon and 513 kg pumpkin making cucurbits the largest known fruits. The cultivated cucurbits are native to the subtropical and tropical Americas, Africa, and Asia.

### Melon (*Cucumis melo*)

The principal melons of commerce are grouped in *C. melo* Cantalupensis Group having such local names as cantaloupe, muskmelon, rock melon, and sweet melon and *C. melo* Inodorus Group that includes honeydew, crenshaw casaba and juan canary types.

Melon is thought to have originated in southern Africa where landraces abound. Diverse local populations are found in India and the Middle East suggesting that these areas may be centres of origin as well. Melon was first noted in Europe in the fifteenth century following widespread dispersal throughout Asia, Africa and the Middle East. At the end of the century, Columbus brought melon to the Americas.

Cantaloupe is andromonoecious. Fruit are round or oval, tan or straw-coloured, and usually weigh 1 to 3 kg (Figure 14.2). They are netted to some degree and are smooth or have apparent vein tracts. Fruit separate from the peduncle (slip) at maturity.

Inodorus melons also are andromonoecious. Fruit are round to oval, white to yellow at maturity, smooth or wrinkled and not netted. Fruit usually weigh 2 to 4 kg and do not slip at maturity (Maynard & Maynard 2000; Robinson & Decker-Walters 1997).

### Cucumber (*Cucumis sativus*)

There are three horticultural types of cucumbers: slicing, pickling and greenhouse (Figure 14.3). The former two are grown outdoors, and the latter in some protected structure. Fruit morphology serves to distinguish among these types.

Slicing cucumber fruit are white spined, smooth and cylindrical with tapered ends and have a length:diameter ratio of about 4:0. Pickling cucumbers may have black or white spines, have a somewhat warty appearance, and have a length:diameter ratio of about 3:0. There are two distinctive cucumbers for greenhouse culture: Beit Alpha and English or Dutch type. Both types are parthenocarpic and gynoecious. The English types are very smooth, cylindrical, 30 to 35 cm long, and are typically constricted at the stem end. Beit Alpha types are cylindrical, tapering at both ends, with inconspicuous longitudinal striations, and are 15 to 20 cm long.

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**Figure 14.1** Pistillate and staminate watermelon, squash and cantaloupe flowers (l–r).

**Figure 14.2** Cantaloupe fruit.

**Figure 14.3** An array of cucumber fruit. (Source: National Garden Bureau, Downers Grove, IL.)

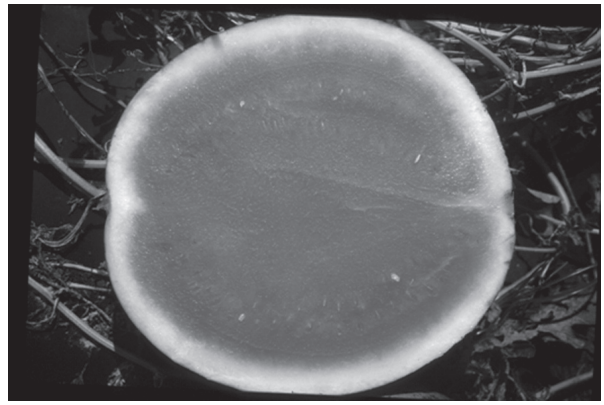


**Figure 14.4** A triploid (seedless) watermelon fruit section.

Cucumber originated in India where wild types can still be found and it is cultivated in many diverse forms. Secondary centres of diversity for cucumber are in China and the Near East. Cucumber was probably domesticated in Asia, and then introduced into Europe, where the first horticultural types were selected in the 1700's. Cucumbers were brought to the Americas by Christopher Columbus, and Native Americans were growing cucumbers from Florida to Canada by the early sixteenth century (Maynard & Maynard 2000; Robinson & Decker-Walters 1997; Whitaker & Davis 1962).

**Watermelon (*Citrullus lanatus*)**

Watermelon plants are monoecious annuals with long trailing thin and angular vines which bear branched tendrils and lobed leaves. Watermelon flowers, which are smaller and less showy than those of many other cucurbits are borne solitary in leaf axils and remain open for only one day. Staminate flowers appear first and outnumber pistillate flowers by about 7:1. Pollination is effected mostly by honeybees. Fruit vary in weight from 1 to over 100 kg, but market types are usually between 4 and 14 kg. The most popular size is 8 to 10 kg in the United States. Fruit shape is round to elongated and rind colour is light to dark green, often with a typical striping pattern that identifies the cultivar or type. Consumers desire watermelons with dark pink to deep-red flesh. There is a niche market for yellow and orange-flesh watermelons.

Watermelon is native to southern Africa, perhaps where Botswana is currently located. Wild types, often with bitter flesh can still be found in that area. Watermelon fruit frequently served as 'living canteens' in times of prolonged drought in this area.

**Table 14.1** Names, Origin and Use of Some Cultivated Cucurbits.

| Species | Common names | Origin | Use |
|---|---|---|---|
| *Cucurbita argyrosperma* C. Huber | Pumpkin, squash | Mexico | Food, animal feed |
| *Cucurbita ficifolia* Bouche | Fig-leaf gourd, Malabar gourd | South America | Food, animal feed |
| *Cucurbita maxima* Duchesne | Squash, pumpkin | Northern Argentina | Food |
| *Cucurbita moschata* Duchesne | Squash, pumpkin | Northern South America | Food, medicinal |
| *Cucurbita pepo* L. gourd | Squash, pumpkin, | Mexico vegetable oil | Food, ornamental |
| *Legenaria siceraria* (Molina) Standl. | Bottle gourd food | Africa | Utilitarian, ornamental, |
| *Tricosanthes cucumerina* L. | Snake gourd | India | Food, medicinal |

**Table 14.2** Some Defining Characteristics of the Economically Important *Cucurbita* Species.

| Species | Seed | Leaf | Stem | Peduncle | Fruit flesh |
|---|---|---|---|---|---|
| *C. maxima* | White to brown, oblique seed scar | Almost round, unlobed, prickly | Soft, round flared at fruit | Round, corky, not deep orange attachment | Fine, not fibrous |
| *C. moschata* | White to brown, rough margin, oblique seed scar | Shallow lobes, almost round, soft pubescence | Hard, ridged at fruit attachment | Hard, angled, flared | Fine, not fibrous, deep orange |
| *C. pepo* | Light tan, prominent smooth margin, rounded seed scar | Deeply lobed, very prickly | Hard, ridged | Hard, angled, ridged | Coarse, orange |

So-called seedless watermelons (Figure 14.4) have become very popular in recent years, and by some estimates now represent more than 90% of the US market. The first step in construction of a seedless hybrid is to double the chromosome number of an appropriate female parent, usually with a pale-green rind, by treatment with a chemical agent. The resulting 4N (tetraploid) parent is crossed with a 2N striped parent to produce 3N (triploid) seeds which when planted produce sterile fruit that are mostly seedless. (Maynard 2001; Maynard & Maynard 2000). Mini, seedless watermelons (< 3 kg) have also grown in popularity in recent years.

**Squash, pumpkin and gourd (*Cucurbita* spp.)**

The common names in the three genera and seven species of this general group of cucurbits overlap considerably (Table 14.1). *Cucurbita maxima*, *C. moschata* and *C. pepo* are the economically important species in this group and are the focus of this section. The other species are included in Table 14.1 to assist in sorting out the confusing common names. Products commonly called squash, pumpkin or gourd are found in four of the seven species. The gourds are the source of least confusion since they are more or less readily identified by appearance, regardless of species. Squash and pumpkin are used interchangeably depending on local custom. As a general rule, pumpkins are round or nearly so whereas squash are irregularly shaped. The decorative or Halloween pumpkin (*Cucurbita pepo*) is always referred to by that name.

Defining characteristics of the economically important *Cucurbita spp*. are in Table 14.2. Within squash it is useful to differentiate between summer and winter types. The summer types (yellow, zucchini or scallop) are fast maturing, have soft rinds, are consumed when the fruit is immature and are quite perishable. Harvest of very immature fruits (e.g. baby squash) and the edible blooms are in high demand by up-scale restaurants and command high prices (see Figure 14.1). On the other hand, winter squash take longer to mature, have a long storage life, several months versus two weeks, are consumed when the fruits and seeds are fully mature and have durable rinds. Any confusion that may exist

**Table 14.3** Horticultural Types in Economically Important Cucurbita spp.

| Species | Type | Description | Typical cultivars |
|---|---|---|---|
| *C. moschata* | Tropical pumpkin | Round, oblate, or irregular shape. Green buff, yellow, or piebald hard rind. | La Primera, Seminole, Solar, El Dorado, La Estrella |
| | Cheese pumpkin | Variable shape, smooth, hard, buff-coloured hard rind. | Dickinson, Kentucky Field |
| | Neck squash rind fruit, usually buff. | Long curved or straight neck. Smooth hard | Golden Crookneck, Winter Crookneck, Waltham Butternut, Zenith, Ultra |
| *C. maxima* | Banana squash | Elongated fruit pointed at the ends. Orange or pink moderately hard rind. | Banana, Pink Banana |
| | Delicious squash | Top shaped. Orange or green hard rind. | Delicious, Golden Delicious |
| | Hubbard squash | Round in the middle tapering at each end. Blue, orange, or green hard warty rind. | Hubbard, Blue Hubbard, Golden Hubbard |
| | Marrow squash | Lemon-shaped with orange hard rind. | Boston Marrow |
| | Show pumpkin | Very large globular, sutured, light orange fruit. Moderately hard rind. | Atlantic Giant, Big Max |
| | Turban squash | Turban shaped with a large button. Hard rind. | Turks Turban, Warren, Turks Cap |
| *C. pepo* | Acorn squash | Acorn-shaped, grooved fruit. Dark green, orange, or white hard rind. | Table Ace, Tay Belle, Heart of Gold, Table Gold |
| | Cocozelle squash | Long, cylindrical, bulbous blossom end. Striped or variegated green soft rind. | Cocozelle, Long Cocozelle |
| | Crookneck squash | Elongated with narrow curved neck. Yellow soft rind. | Dixie, Yellow Summer Crookneck, Supersett |
| | Ornamental gourd | Variously shaped and coloured. Smooth or warty hard rind. | Egg, Striped, Pear, Bicolour, Spoon, Orange Ball, Crown of Thorns, Warted |
| | Pumpkin | Large, round, oval oblate shape. Mostly orange, sometimes white relatively soft rind. | Connecticut Field, Small Sugar, Howden, Jack-Be-Little |
| | Scallop squash | Flattened with scalloped margins. White, yellow, green, or bicoloured soft rind. | White Bush Scallop, Peter Pan, Sunburst |
| | Straightneck squash | Long, cylindrical, yellow soft rind. | Enterprise, Goldbar, Early Prolific Straightneck, Multipik |
| | Vegetable Marrow | Short, tapered, cylindrical. Light green to gray soft rind. | Clarita, Goya, Zahra, Caserta |
| | Zucchini squash | Uniformly cylindrical. Green or yellow soft rind. | Dividend, Revenue, Spineless Beauty, Gold Rush |

**Figure 14.5** An array of summer squash fruit.

is the making of academics who quibble over nomenclature. Retailers, consumers and cooks generally differentiate among squash, pumpkin and gourd.

The *Cucurbita spp*. are native to the subtropical and tropical Americas, whereas the bottle gourds are native to Africa and the snake gourds are of Indian origin. Note, however, that they all have similar uses and quickly became established throughout the world.

The principal *Cucurbita spp*. may be further grouped according to horticultural traits (Table 14.3). Fruit shape and colour and rind durability are the main discriminating characteristics. Some of the types are arbitrary and of historical interest only. For example, cushaw squash, winter crookneck squash and marrow squash are not commonly grown, but they may be regionally important. The gourds and pumpkins of *C. pepo* are mostly grown for ornamental rather than culinary purposes and are increasing in economic importance in the United States. Show pumpkins are grown exclusively for competition in the heaviest-fruit contests held in various parts of the United States. Note that the word 'pumpkin' or 'squash' has been attached to each type. Some may disagree with these designations. The hard-rind types are generally called winter squash, whereas the soft-rind types (Figure 14.5) (cocozelle, crookneck, scallop, straightneck, vegetable marrow and zucchini) are generally referred to as summer squash. Winter squash are mostly indeterminate or vining in growth habit, and summer squash are mostly determinate or have a bush growth habit. Harvest, post-harvest handling and storage of these diverse horticultural types of *Cucurbita spp*. will vary greatly as detailed later.

**Figure 14.6** Butternut squash fruit.

With good growing conditions, summer squash should be ready for harvest in about 40 days from establishment. Fruit should be harvested about six to eight days after pollination, when they are small and the rind has a distinctive sheen. The rind becomes dull in over-maturity with a concomitant loss of quality. Summer squash should be consumed soon after harvest for best quality but may be kept in good storage conditions for a few days. Summer squash fruits should be harvested every day or two in warm weather.

Winter or hard-shelled squash like butternut (Figure 14.6), are named as such because they are grown to maturity, requiring much longer to produce a marketable product, 80 to 110 days depending on weather and cultivar. Fruits should be harvested when fully mature (when seeds are fully developed) but before they are injured by frost. Winter squash, unlike summer squash, have a long post-harvest life. For instance, the tropical pumpkin (*C. moschata*) fruits have remained in good condition for two to three months in uncontrolled conditions in my garage in Florida (Decker-Walters & Walters 2000; Robinson & Decker-Walters 1997; Whitaker & Davis 1962; Wien 1997).

**Bitter melon (*Momordica charantia*)**

Also known as bitter gourd, bitter cucumber, or balsam pear, bitter melon is native to the tropics of Southeast Asia and India. It was probably introduced to the New World with the African population in the seventeenth or eighteenth century.

Bitter melon plants are perennials that are usually cultured as annuals. Because of their very long vines they are trained on an inverted U-shaped trellis that is high enough so that workers can harvest fruit within the trellis. Bitter melon fruit are harvested when immature

**Figure 14.7** Bitter melon fruit.

**Figure 14.8** Smooth luffa fruit.

(Figure 14.7). They exhibit various shades of green, have a warty, shiny surface and measure about 15 cm in length.

The tender shoots and leaves of bitter melons can be prepared as cooked greens. The fruit may be boiled, curried, fried or pickled. It is often soaked in salt water to reduce bitterness before cooking. Bitter melon is very popular in many Asian countries and with Asian people living elsewhere (Nayer & More 1998; Robinson & Decker-Walters 1997).

### Smooth luffa (*Luffa aegyptiaca*) and angled luffa (*Luffa acutangula*)

Smooth luffa or loofah (Figure 14.8) is also known as sponge gourd, vegetable sponge, dishcloth gourd or rag gourd; angled luffa (Figure 14.9) may be referred to as

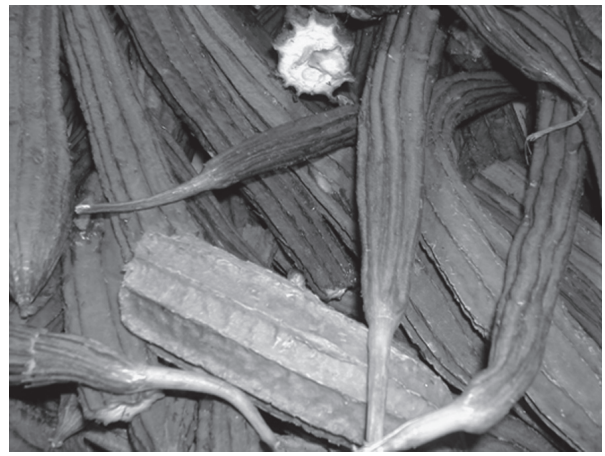


**Figure 14.9** Angled luffa fruit.

ridged gourd, angled gourd or ridged luffa. Both species probably originated in India. They are grown throughout tropical Asia, South America and the Caribbean with the smooth type being the most common.

Luffa vines are very large, lending themselves to training on a stout vertical trellis that encourages the development of straight fruit. The principal food use is immature fruit prepared like summer squash. Young shoots and leaves may be used as greens. When grown to maturity, fruit of smooth luffa produce phytosponges. After harvest, they are soaked in water to encourage decay of the outer fruit wall and inner pulp, then washed thoroughly to remove extraneous matter. The remaining fibre is dried in the sun and bleached white. Luffa is widely grown in Asia, especially China, and in the New World, especially Guatemala and Colombia (Nayer & More 1998; Robinson & Decker-Walters 1997).

### Chayote (*Sechium edule*)

Mirliton and vegetable pear are other common names for chayote (Figure 14.10). Its centre of origin is in Guatemala and Mexico. Today, large scale production occurs in Costa Rica, Guatemala and Brazil, as well as in other tropical areas.

Chayote is the only cultivated vegetable in the subtribe Sicyinae, tribe Sicyeae. Plants are perennial in frost-free areas. Because they are short-day plants in respect to flowering, their production is restricted to subtropical and tropical areas of the world. Commercial fruit are generally pear shaped, white to dark green coloured and about 10 cm long. They bear a single seed that may sprout within the fruit (vivipary). Propagation is by planting the entire fruit or the excised seed.

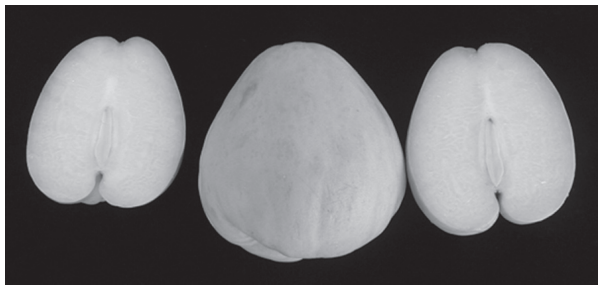


**Figure 14.10** Chayote fruit and longitudinal section.

**Figure 14.11** Wax gourd fruit.

The very long vines are supported on an overhead trellis so workers can walk beneath the crop and easily identify and harvest fruit ready for market. Fruit are transported, sometimes via a miniature train system, to a packing house for sorting and placement in shipping containers. They are often wrapped in tissue paper to prevent bruising of the tender skin.

The fruit is used as vegetable and is similar to scallop summer squash in texture and flavour. Young shoots and leaves as well as portions of the tubers also are used as food. It is also used in the food industry as an ingredient in sauces and fillings (Robinson & Decker-Walters 1997).

### Wax gourd (*Benincasa hispida*)

Also known as Chinese winter melon, ash gourd, Chinese preserving melon and other local names, the wax gourd (Figure 14.11) is named for the white waxy bloom that covers the fruit surface. Japan and Indonesia are thought to be the centres of origin with India and Indochina being the present day areas of greatest diversity. Wax gourd thrives in areas with a long, warm growing season and will withstand rain during production. China and India are the greatest producers by far. However, wax gourds can be found throughout Asia as well as in locations wherever there are people of Asian descent.

Wax gourd is the only cultivated cucurbit within the genus *Benincasa* and together with watermelon, bottle gourd, luffa and lesser cucurbits is found in the Tribe Benincasea. Wax gourd shares many characteristics with *Cucurbita*, the squashes, but differs in certain critical flower characteristics, centres of origin and chromosome number.

The mostly round, but often irregularly shaped fruit are produced at intervals along the trailing vines. The fruit may be harvested when the waxy bloom is fully developed and fruit have reached the desired weight, or they may be left in the field until needed or until market conditions favour harvest. The designation winter melon indicates successful storage over an extended period.

As the plants grow, their young shoots and leaves may be used as greens. The immature fruit may be used in ways similar to summer squash. The mature fruit flesh can be eaten as a vegetable or its seed cavity can be hollowed out for use as a container for soup made with other vegetables, fish, or meat. Because of its mild flavour, wax gourd is complimented by many foods. The wax gourd often serves as the centrepiece for festive occasions (Nayer & More 1998; Robinson & Decker-Walters 1997).

### World production

Melon and pumpkin, squash, gourd are each grown on slightly over one million hectares worldwide producing over 19 million tons and 15 million tons, respectively from yields of about 17 000 kg/ha$^{-1}$ and 13 000 kg/ha$^{-1}$, respectively (Table 14.4). Watermelon is grown on almost 3 million hectares with annual production exceeding 63 million tons. Average yields exceed 21 000 kg/ha$^{-1}$. Cucumber production is intermediate between watermelon and that of melon and pumpkin, squash and gourd (FAO, 2002).

Asia, by every measure, is the largest cucurbit producer (Table 14.5). China is the leading country in production of all cucurbits for which data are available. India is a major pumpkin, squash, gourd producer and Japan is an important producer of cucumber. Cucurbits are important in the Middle East as well, with Turkey and Iran being centres of cucumber, melon, and watermelon production. In Europe, Spain is an important melon producer and Ukraine is a major squash and pumpkin producer. The United States and Mexico are the principal cucurbit producers in North America, and Egypt holds that distinction in Africa (FAO 2002).

Certainly, cucurbits are important locally elsewhere in the world. Historically, winter squash has been an important

**Table 14.4** World Cucurbit Production, 2001.

| Cucurbit | Area harvested (1000 ha) | Yield (kg.ha$^{-1}$) | Production (1000 t) |
|---|---|---|---|
| Cucumber, gherkin | 1 796 | 17 352 | 31 158 |
| Melon | 1 142 | 17 222 | 19 665 |
| Pumpkin, squash, gourd | 1 244 | 12 526 | 15 581 |
| Watermelon | 2 929 | 21 729 | 63 637 |

Source: FAO (2002).

**Table 14.5** Principal Cucurbit Producing Countries, 2001.

| | Rank | | | | |
|---|---|---|---|---|---|
| Cucurbit | 1 | 2 | 3 | 4 | 5 |
| Cucumber, gherkin | China | Turkey | Iran | United States | Japan |
| Melon | China | Turkey | United States | Spain | Iran |
| Pumpkin, squash, gourd | China | India | Ukraine | Egypt | Mexico |
| Watermelon | China | Turkey | Iran | United States | Egypt |

vegetable in New England in the United States as it provided nutrition and variety to the diet during the long winter when fresh vegetables were scarce. In Sri Lanka and the Ukraine, production of gherkins or small pickling cucumbers for export to Europe provides needed foreign exchange in these developing countries where labour for harvest is readily available. Even though cucurbits are less important economically than tomato or potato, for example, they may make vast contributions to the local economy and to the well-being of the population in terms of monetary returns or nutrition.

**Nutritional composition**

A casual examination of the cucurbit compositional data in Table 14.6 shows that water is the principal fruit constituent, with dried seeds being the only exception. Otherwise, fruit water content varies from 86% to 96%. The fruits are also low in energy, protein, fat and carbohydrates making them an excellent choice for weight-conscious individuals. Orange-fleshed winter squashes provide an excellent source of vitamin A. Melons and some squashes provide useful sources of vitamin C. Two compact tropical pumpkin hybrids (*Cucurbita moschata*) were recently released and reported to contain 49 and 57 mg/kg fresh mass (FM) total carotenoids in the pulp, higher than that reported for butternut squash (45 mg/kg FM) (Maynard *et al*. 2002).

Red-fleshed watermelon fruit contained 6300 to 6800 µg/100 g lycopene whereas orange-fleshed and yellow-fleshed fruit contained 370 to 420 µg/100 g and 10 to 80 µg/100 g fresh weight, respectively (Perkins-Veazie *et al*. 2002a). Within the red-fleshed types, fruit of diploid hybrids (seeded) cultivars generally had higher lycopene concentrations than fruit of diploid open-pollinated (seeded) cultivars. One exception was 'Dixielee' that was developed specifically for intense red flesh. Triploid (seedless) cultivar fruit had lycopene concentrations equal to or higher than those in fruit of diploid hybrid (seeded) cultivars. Fruit at peak ripeness had higher lycopene concentrations that unripe (–7 days) or overripe (+7 days) fruit. Minimally processed watermelon fruit lost about 10% of its lycopene after 7 or 10 days at 2°C (Perkins-Veazie *et al*. 2002b).

Lycopene makes an enormous contribution to human health. Until recently, it was thought to be important only as it contributed to flesh colour. Watermelon flesh has an average of 4100 µg/100 g (range 2300–7200) lycopene compared to 3100 µg/100 g (range 879–4900) in raw tomato, 3362 µg/100 g in pink grapefruit, and 5400 µg/100 g (range 5340–5500) in raw guava. Processed tomato products have two or three times greater lycopene concentrations than raw tomatoes because of water depletion in those products. Lycopene is one of the major carotenoids in Western diets and accounts for about 50% of the carotenoids in human serum. Among the common dietary carotenoids, lycopene

**Table 14.6** Nutritional Composition of Cucurbits (Amounts per 100 g Fresh Product).

| Cucurbit | Water (%) | Energy (kcal) | Protein (g) | Fat (g) | Carbohydrate (g) | Fiber (g) | Ca (mg) | P (mg) | Fe (mg) | Na (mg) | K (mg) | Vitamin A (IU) | Thiamin (mg) | Riboflavin (mg) | Niacin (mg) | Ascorbic Acid (mg) | Vitamin $B_6$ (mg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bitter melon | 94 | 17 | 1.0 | 0.2 | 3.7 | 1.4 | 19 | 31 | 0.4 | 5 | 296 | 380 | 0.04 | 0.04 | 0.40 | 84.0 | — |
| Chayote | 93 | 24 | 0.9 | 0.3 | 5.4 | 0.7 | 19 | 26 | 0.4 | 4 | 150 | 56 | 0.03 | 0.04 | 0.50 | 11.0 | — |
| Cucumber | 96 | 13 | 0.5 | 0.1 | 2.9 | 0.6 | 14 | 17 | 0.3 | 2 | 149 | 45 | 0.03 | 0.02 | 0.30 | 4.7 | 0.05 |
| Melon, casaba | 92 | 26 | 0.9 | 0.1 | 6.2 | 0.5 | 5 | 7 | 0.4 | 12 | 210 | 30 | 0.06 | 0.02 | 0.40 | 16.0 | — |
| Melon, honeydew | 90 | 35 | 0.5 | 0.1 | 9.2 | 0.6 | 6 | 10 | 0.1 | 10 | 271 | 40 | 0.08 | 0.02 | 0.60 | 24.8 | 0.06 |
| Melon, netted | 90 | 35 | 0.9 | 0.3 | 8.4 | 0.4 | 11 | 17 | 0.2 | 9 | 309 | 3224 | 0.04 | 0.02 | 0.57 | 42.2 | 0.12 |
| Pumpkin | 92 | 26 | 1.0 | 0.1 | 6.5 | 1.1 | 21 | 44 | 0.8 | 1 | 340 | 1600 | 0.05 | 0.11 | 0.60 | 9.0 | — |
| Pumpkin flowers | 95 | 15 | 1.0 | 0.1 | 3.3 | — | 39 | 49 | 0.7 | 5 | 173 | 1947 | 0.04 | 0.08 | 0.69 | — | — |
| Pumpkin leaves | 93 | 19 | 3.2 | 0.4 | 2.3 | — | 39 | 104 | 2.2 | 11 | 436 | 1942 | 0.09 | 0.13 | 0.92 | 11.0 | 0.21 |
| Pumpkin seeds[1] | 7 | 541 | 24.5 | 45.9 | 17.8 | 3.9 | 43 | 807 | 15.0 | 18 | 535 | 380 | 0.21 | 0.32 | 1.75 | — | 0.22 |
| Squash, acorn | 88 | 40 | 0.8 | 0.1 | 10.4 | 1.5 | 33 | 36 | 0.7 | 3 | 347 | 340 | 0.14 | 0.01 | 0.70 | — | 0.15 |
| Squash, butternut | 86 | 45 | 1.0 | 0.1 | 11.7 | 1.4 | 48 | 33 | 0.7 | 4 | 352 | 7800 | 0.10 | 0.02 | 1.20 | 21.0 | 0.15 |
| Squash, hubbard | 88 | 40 | 2.0 | 0.5 | 8.7 | 1.4 | 14 | 21 | 0.4 | 7 | 320 | 5400 | 0.07 | 0.04 | 0.50 | 11.0 | 0.15 |
| Squash, scallop | 94 | 18 | 1.2 | 0.2 | 3.8 | 0.6 | 19 | 36 | 0.4 | 1 | 182 | 110 | 0.07 | 0.03 | 0.60 | 18.0 | 0.11 |
| Squash, summer | 94 | 20 | 1.2 | 0.2 | 4.4 | 0.6 | 20 | 35 | 0.5 | 2 | 195 | 196 | 0.06 | 0.04 | 0.55 | 14.8 | 0.11 |
| Squash, winter | 89 | 37 | 1.5 | 0.2 | 8.8 | 1.4 | 31 | 32 | 0.6 | 4 | 350 | 4060 | 0.10 | 0.03 | 0.80 | 12.3 | 0.08 |
| Squash, zucchini | 96 | 14 | 1.2 | 0.1 | 2.9 | 0.5 | 15 | 32 | 0.4 | 3 | 248 | 340 | 0.07 | 0.03 | 0.40 | 9.0 | 0.09 |
| Watermelon | 93 | 26 | 05 | 0.2 | 6.4 | — | 7 | 10 | 0.5 | 1 | 100 | 590 | 0.03 | 0.03 | 0.20 | 7 | — |
| Watermelon seeds[1] | 5 | 557 | 28.3 | 47.4 | 15.3 | — | 54 | 755 | 7.3 | 99 | 648 | 0 | 0.19 | 0.15 | 3.6 | — | 0.09 |
| Wax gourd | 96 | 13 | 0.4 | 0.2 | 3.0 | 0.5 | 19 | 19 | 0.4 | 111 | 6 | 0 | 0.04 | 0.11 | 0.40 | 13.0 | — |

[1]Dried.

Source: US Department of Agriculture (2002), http://www.ars.usda.gov/main/site_main.htm?modecode=12354500.

**Table 14.7** Commercial Harvest Indices to Maximize Post-harvest Quality for Selected Melons.

| Melon type | Fruit shape | Stem abscission zone | Epidermis | Typical soluble solids content (°brix) | Total titratable acidity (% major acid) |
|---|---|---|---|---|---|
| Cantaloupe | Round | Fully formed | Green | 12–17 | — |
| Honeydew | Round | None | White | 9–12 | — |
| Galia[x] | Round | Fully formed | Light yellow, some green | 10.8 | 0.054 |
| Charantais | Round | Fully formed | Smooth sutures | | |
| Watermelon | Oblong; round | None | According to type; yellow groundspot | 9.8 (cv. Millionaire) | 0.3 (cv. Millionaire) |

Source: Artes *et al*. (1993), Bower *et al*. (2002), Cartaxo (1998), Evensen (1983), Fallik *et al*. (2001) and Lester and Shellie (1992).

has the highest singlet oxygen quenching capacity in vitro. Other outstanding features are its high concentrations in testes, adrenal gland and prostate. In contrast to other carotenoids, its serum values are not regularly reduced by smoking or alcohol consumption, but with increasing age. Remarkable inverse relationships between lycopene intake or serum values have been observed in particular for cancers of the prostate, pancreas, and to a certain extent of the stomach. In some studies, lycopene was the only carotenoid associated with risk reduction. Accordingly, although watermelon consumption may help reduce risk of certain cancers, tomato has a larger role in risk reduction because of greater per capita consumption, 165 lb, compared to 17 lb for watermelons (Clinton & Giovannucci 1998; Maynard 2001). The Food and Agriculture Organization of the United Nations has compiled a thorough list of the regional data centres that report nutritional composition of foods (FAO 2002).

## POST-HARVEST PHYSIOLOGY OF CUCURBITS

Quality maintenance from harvest through handling and shipping is crop dependent. In the case of cucurbits, post-harvest physiology varies widely due to the great number of phenotypes that are commercially grown around the world. In this section we will briefly discuss the underlying physiological factors that affect post-harvest quality. Two comprehensive reviews have been written regarding post-harvest physiology of melons (Pratt 1971; Seymour & McGlasson, 1993); another excellent resource is Rubatzky and Yamaguchi (1997).

### Maturity and ripening, and harvest indices

As fruits, cucurbits are harvested at several maturities (or stages of maturation), depending on the crop and on the intended market. Those consumed as vegetables are harvested either immature or mature, while those consumed as dessert fruits are always harvested mature during ripening. Immature-harvested types (e.g., summer squash and cucumber) are selected for tenderness and characteristic epidermal and stem colour, and are normally graded dimensionally according to applicable grade standards. Chayote should be harvested immature firm, with tender, smooth skin (absence of spines) with natural gloss (Aung *et al*. 1996). Bitter melon is harvested immature, until seed hardening, and should have uniform green colour and freedom from splitting (sign of over-maturity) (Zong *et al*. 1995).

On the other hand, winter squashes must be harvested upon reaching physiological maturity or during ripening when the fruit has reached a minimal level of acceptable quality. For example, immature-harvested spaghetti squash (<6 weeks after anthesis), have poor quality when cooked (Edelstein *et al*. 1989).

Melons and watermelon consumed as dessert fruits have special harvest considerations (Table 14.7). Netted melons have climacteric respiratory and ethylene patterns and, hence, must be harvested after physiological maturity is reached for proper post-harvest ripening (Larrigaudiere *et al*. 1995). Evensen (1983) found that cantaloupe had best post-harvest quality and storage life when harvested with green epidermis and at full-slip (complete formation of the stem scar); those harvested at half-slip stage had poorer flavour following storage and ripening. Best post-harvest quality for honeydew melons was obtained by sampling for the following parameters at harvest: white epidermal colour, soluble solids above minimally required value and typical fruit shape, as determined by length-to-diameter ratio (Lester & Shellie 1992). Galia-type melons harvested when background colour became light yellow (Plate 14.1) had higher soluble solids content and higher

**Table 14.8** Respiration Rates and Ethylene Production for Selected Cucurbits.

| | Reported Storage Temperature (°C) | Respiration Rate | Ethylene Production |
|---|---|---|---|
| *Cucumis melo* (melon) | | | |
| Cantaloupe | 5 | 9 to 10 mg /kg-hr | 10 to 100 µL kg-hr |
| Honeydew | 5 | 8 mg /kg-hr | Very low |
| Galia | | | |
| Charantais | 20 | 2.2 mmol/kg-hr | 27 µL/kg-hr |
| *Cucumis sativis* (cucumber) | | | |
| Slicing | 10 | 23 to 29 mg/kg-hr | 0.6 µL/kg-hr (@ 20C) |
| Beit alpha | 10 | 4 to 9 mL/kg-hr | Very low |
| *Citrullus lanatus* (watermelon) | 10 | 6 to 9 mg/kg-hr | < 1.0 µL/kg-hr (@20C) |
| *Cucurbita pepo* (summer squash) | 10 | 65 to 68 mg/kg-hr | < 1.0 µL/kg-hr (@ 20°C[r]) |
| *Cucurbita pepo* (zucchini squash) | 5 | 35 ml/kg-hr | 0.5 µL/kg-hr |
| *Cucurbita maxima* (pumpkin) | 12 | 2 micromol/g-hr | – |
| *Cucurbita moschata* (buttercup squash) | 12 | 88 to 110 mg/ kg-hr | – |
| *Momordica charantia* (bitter melon) | 10 | 15 microL/g-hr | 0.1–0.3 nL/g-hr |
| *Sechium edule* (chayote) | 5 | 4 mg/kg/hr | – |

Source: Aung *et al*. (1996), Bower *et al*. (2002), Elkashif *et al*. (1989), Gross *et al*. (2002), Irving *et al*. (1999), McCollum (1989), Mencarelli *et al*. (1983), Villalta (n.d.) and Zong *et al*. (1995).

aroma volatile concentrations (Fallik *et al*. 2001). 'Haon' and 'Polidor' melons grown in greenhouse conditions had higher soluble solids when the plants had higher leaf area and when growth rate was slowed due to cooler night temperatures (12°C to 15°C) (Welles & Buitelaar 1988). Charantais melons are considered mature when the suture becomes smooth and the fruit cheeks are filled (Bower *et al*. 2002). These authors also reported that melons ripened on the vine had lower respiration and ethylene production rates than those harvested preclimacteric.

Watermelon is a nonclimacteric fruit (Elkashif *et al*. 1989) and, as such, cannot be harvested prior to attaining minimal fruit quality. An indicator of ripeness is when the ground-spot becomes light yellow (Pratt 1971). Respiration and ethylene production rates for cucurbits are compiled (Table 14.8).

## Quality parameters

### *Visual and other nondestructive quality parameters*

First impressions have a great influence on consumer purchases of fresh produce, affecting commercial markets from wholesale through retail levels. Appearance was ranked second in importance (behind flavour) by consumers in a recent study (The Packer 2001). Consumers associate a number of quality factors with specific commodities, notably shape, colour, surface texture and sheen; other sensory factors such as aroma and firmness also are important at purchase. Visual quality also means freedom from defects caused by mechanical injuries (cuts, abrasions, bruises), insect feeding, shrivel and decay.

Grade standards promote uniform marketing and packers must adhere to the standards in order to sell the commodity by a specific grade. The standards are requested by commodity groups and, once approved by governing agencies, delineate quality norms including grade definitions, tolerances, packing definitions and defects. The defect standards are higher at shipping point than at receiving to account for senescence and minimal losses during to handling. When a dispute arises between buyer and seller the crop in question is graded according to the appropriate standard by a certified inspector.

Grade standards for fresh produce vary from country to country. For example, in Canada greenhouse-grown, European seedless cucumbers (also known as English or Dutch cucumbers) must be at least 280 mm in length and not vary by more than 13 mm in diameter nor by 63 mm in length to be classified as No. 1 grade small (Canadian Dept. of Justice, 2001). Beit Alpha-type seedless cucumbers must exceed 152 mm in length and not vary by more than 13 mm in diameter or by 38 mm in length. In contrast,

US grade standards for greenhouse cucumbers are less stringent than Canadian standards and are written specifically for European seedless types, specifying only a minimum length (279 mm) (USDA 1985).

The Codex Alimentarius Commission (CAC) was established in 1963 by FAO and WHO of the United Nations, with the goals to protect consumer health, ensure fair trade practices and assist in coordination of food standards by individual governments and nongovernmental organizations (CAC 2002). The Commission publishes reports, hosts meetings and maintains standards relevant to foods and drugs. Other grade standards are available online, including Australia and New Zealand (http://www.foodstandards.gov.au) and Japan (http://www.maff.go.jp/eindex.html).

### *Flavour and Aroma*

Flavours and aromas associated with cucurbit types are composed of complex interactions between sugars, acids and aroma volatiles, which in turn are impacted by preharvest conditions, fruit maturity and storage environment. For example, starches degraded and sucrose accumulated prior to harvest of buttercup squash (Irving *et al*. 1997) and during ripening of 'Galia' melon (McCollum *et al*. 1988). The sweeter flavour attributed to 'Galia' melon may be due to the lower acidity than other specialty melons. Artes *et al*. (1993) reported 'Galia' to have a soluble solids content of 10.8 °Brix, similar to that for three other melon types ('Piel de Sapo', 'Amarillo' and 'Tendral'), but 'Galia' had a total titratable acidity of 0.054 (% citric acid), 50% to 75% lower than the other cultivars (see Table 14.7). Sugar concentrations in placental tissue decreased during storage of 'Charleston Gray' watermelon as a function of increased storage temperature (Chisholm and Picha 1986).

No starch reserves are present in cantaloupe that can be converted to sugars (Bianco & Pratt, 1977). However, significant variability in flavour has been reported due to cultivar. Some cantaloupe cultivars lost sugars during storage, while others maintained them (Cohen & Hicks, 1986). Highest aroma volatile concentrations were found in 'Galia' melons harvested with yellow background colour and slight green areas, a ripeness stage that permits transport to distant markets while maintaining high quality (Fallik *et al*. 2001).

### Senescent processes and environmental factors

Senescent processes occur during storage and handling of cucurbits and are characterized by softening, loss of cellular integrity, breakdown of chlorophyll, breakdown of epicuticular waxes, conversion of sugars to starches, loss of acids, decreased production of aroma volatiles and eventual development of off-flavours and aromas due to fermentation processes.

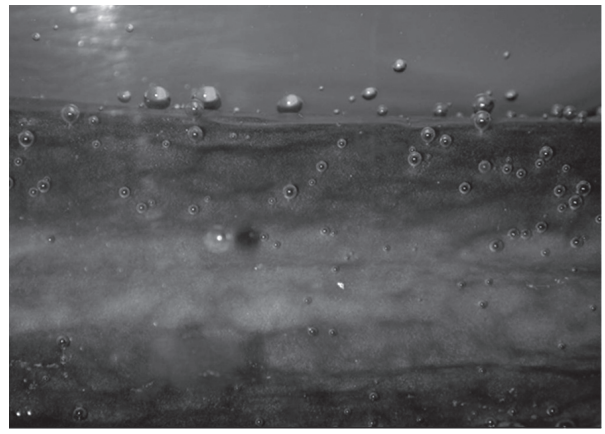


**Figure 14.12** Submerging a Beit Alpha cucumber and pulling a slight vacuum draws air from intercellular spaces, revealing open lenticels in the epidermal tissue.

### Moisture loss

Immature-harvested fruits, such as yellow summer squash, are much more perishable during post-harvest handling than those harvested mature for several reasons. Immature fruits generally have a thin epidermis and partially formed epicuticular wax, making them more susceptible to moisture loss and decays. These also have higher moisture contents in the edible portion than mature fruits (see Table 14.6). Open lenticels, stem-end and blossom-end scars are the primary points of gas exchange, and shrivel symptoms generally first appear at the stem end which has the highest gas exchange rate (Figure 14.12). For this reason protective coatings are often applied to immature cucurbits prior to marketing.

The correlation between weight loss and appearance varies widely between cucurbits. For instance, weight loss of 7% during storage was judged as the limit of marketability for cucumber appearance (Kang *et al*. 2002), whereas shrivel symptoms became apparent on unwaxed, yellow-crookneck summer squash following 18% weight loss and were moderate by 24% weight loss (Hrushka 1977). Summer squash types (vegetable marrow, zucchini and scallop) became unacceptable from 6 to 20 days storage at 5°C and 85% relative humidity, with those having the Gene B (yellow epidermal pigmentation) being most

susceptible to chilling injury and shrivel (Sherman *et al*. 1987). Unwrapped cantaloupes were considered unmarketable with 6% weight loss (Lester & Bruton 1986). One consequence of weight loss is not readily apparent. Hollowneck is a storage disorder in butternut squash characterized by the gradual development of internal open areas in the neck; it is not visible externally until it becomes severe. Hollowneck symptoms become visible when weight loss exceeds 10% (Francis & Thomson 1964). Curing (drying) winter squashes at ambient or elevated temperatures prior to storage did not extend post-harvest life nor reduce decay, but rather promoted weight loss (Schales & Isenberg 1963).

During storage at three temperatures, chayote lost the following fresh weights per day: 25°C: 1.3%, 15°C: 0.5%/day and 10°C: 0.02% (Aung *et al*. 1996). Wrapping with polyvinyl chloride (PVC) film reduced weight loss by 80% to 90% at these same temperatures.

Excessive weight loss during post-harvest handling leads to fruit softening and greater susceptibility to mechanical injuries, which in turn facilitates growth of pathogenic microorganisms in the weakened tissue. Unwrapped cantaloupe lost 6% fresh weight (40% softening) during storage, while fruit covered with shrink-wrapped plastic lost only 0.3% fresh weight and were considered acceptably firm (Lester & Bruton 1986). In another study, although shrink-wrapped cantaloupe had excellent appearance following 21 days storage at 4°C, trained taste panellists rated flavour and aroma inferior to that of unwrapped fruit (Collins *et al*. 1990).

**Table 14.9** Relative Epidermal and Pulp Firmness (Bioyield Point) for Selected Cucurbit Fruits.

| Fruit type | Skin firmness (N)[z] | Pulp firmness (N) |
|---|---|---|
| Kabocha squash | 60.8 | 18.6 |
| Pumpkin | 51.0 | 18.1 |
| Chayote | 22.1 | 14.3 |
| Cucumber | 20.6 | 3.7 |
| Zucchini | 19.6 | 5.9 |

[z]Probe: flat-end plunger, 3.2 mm diameter. Crosshead speed: 25 mm/min.

Source: Aung *et al*. (1996). Reproduced from the *Journal of Horticultural Science*.

### Firmness

As apparent from the previous section, fruit firmness is one of the key factors for marketing fresh produce (Table 14.9). It is also a reason for harvesting as early as possible without negatively affecting edible quality so as to extend post-harvest life to reach more distant markets. Firmness decreases during handling and storage due to excessive number and/or intensity of drops, weight loss and metabolic activity.

### Plant nutrition and fruit quality

Abiotic disorders can be induced in cucurbit fruits due to a number of environmental stresses. Nutritional deficiencies during growth and development can lead to many disorders. Nitrogen deficiency in the plant causes poor chlorophyll synthesis in fruits that are prized for intense green epidermis such as cucumber and zucchini. Nitrogen deficiency decreases fruit size (yield), but it increases dry matter content, causing the fruit to have a coarse or tough texture (Locascio *et al*. 1984). In this same review the authors also stated that nitrogen deficiency stunts plant and leaf growth leading to smaller and fewer fruits and more potential for sunburn in watermelon, and to poor net formation and a higher percentage of cull fruit in cantaloupe.

Calcium concentration in cucurbits can be a serious limiting factor to post-harvest quality. It plays a key role in maintaining plasma membrane integrity via the cytoplasm, thus slowing disruption of cellular functions (Lester *et al*. 1998; Lester & Grusak 2001). Cucumbers are not as susceptible to calcium deficiency as other fruits since the fruit is the primary sink on the plant (Ho & Adams 1994). However, under severe conditions, calcium deficiency appears as water-soaked lesions in the blossom end of the fruit that later became necrotic (blossom-end rot); carpel separation from mesocarp tissue that formed air cavities at the stem end was also observed (Frost & Kretchman 1989). Fresh pickling cucumbers can develop pillowy fruit disorder, characterized by white, porous areas in mesocarp tissue; following fresh-pack pickling process, these areas appear as water-soaked regions (Thomas & Staub 1992). This is another calcium-related deficiency induced by water stress conditions.

Pacheco (1996) reported higher total soluble solids content and better appearance in 'Galia' fruit with increased potassium application (applied pre-plant), where 140 kg/ha was determined as the optimal rate for marketable yield and fruit size.

Boron deficiency symptoms in Beit Alpha-type cucumber cause small fruits to abort, while on older fruits symptoms include stunted and curved growth and 'mottled yellow longitudinal streaks which develop into corky markings (scurfing) along the skin' these symptoms are most severe at the blossom end (Cresswell & James, 1998).

Phosphorus deficiency in European seedless cucumbers caused cell membranes to become more permeable, increasing electrolyte leakage and inducing a stress-related burst in respiration, reducing post-harvest life (Knowles *et al*. 2001).

The shift from water-intensive furrow irrigation to nutrient solution applied via drip irrigation had no negative effects on cantaloupe yield or quality in California (Hartz 1997). 'Galia'-type melons were successfully grown using saline irrigation water, with no significant effects in fruit quality and yield (Mendlinger & Pasternak 1992). Pre-harvest application of AVG (aminoethoxyvinylglycine, an ethylene synthesis inhibitor) on cantaloupe slightly delayed initial development of the abscission zone and caused leaf chlorosis, but did not affect fruit quality at harvest or following storage. During storage AVG-treated fruits had decreased ethylene production up to 30% over control fruit without an effect on quality (Shellie 1999).

Feeding of the silverleaf whitefly (*Bemisia argentifolii*) on squash leaves induces leaf silvering and fruit colour blanching, significantly reducing marketability (Maynard & Cantliffe 1989). Instead of typical medium to dark green colouration, zucchini fruit appear light green, whereas acorn squash are mottled green and/or yellow; golden acorn squash are white. Although all squash types are susceptible to whitefly feeding, symptoms have not been observed on cucumber, watermelon or cantaloupe fruits.

**Temperature stress**

Excessive field exposure to sunlight due to poor foliage coverage can lead to development of heat injury symptoms. Prolonged high temperatures in the exposed tissues disrupt normal ripening, resulting in off-colours and off-flavour/aroma in epidermal and mesocarp tissues. Sub-epidermal pulp temperatures of honeydew melons exposed to direct sunlight reached as high as 48°C in tests in California, leading to solar yellowing ('sunburn') (Lipton *et al*. 1987). Protective coatings of clay-based materials assist in circumventing this problem (Figure 14.13). Yellow pigment synthesis was reported for honeydew melons exposed to high amounts of solar radiation (Forney 1990).

Hot, dry weather discourages foraging by pollinating insects and desiccates flowers, reducing pollination in field-grown squash and cucumbers resulting in misshapen fruits (Wehner 1996) (Figure 14.14a). These conditions can also cause the development of internal void spaces during the fruit growth phase, eventually appearing as soft, sunken areas under the epidermis that can be easily mistaken for bruising. However, upon slicing, the underlying voids may be several millimetres in diameter and

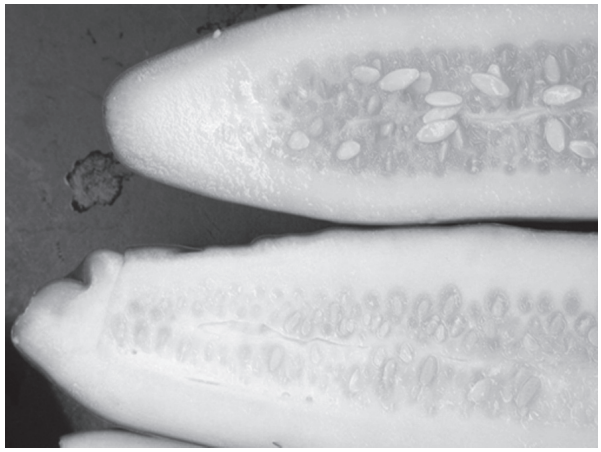
**Figure 14.13** Clay applied to developing fruits can reduce solar injury.

20 to30 centimetres in length (Figure 14.14b). Wehner (1996) also reported that cucurbits can develop bitter flavour when drought stressed during fruit development, a consequence of high cucurbitacin content. Breeding programs have developed cultivars with low cucurbitacin content; however, cross-pollination of these cultivars with high cucubitacin types can induce bitterness.

Light intensity and spectral quality have been correlated to fruit quality of European seedless cucumbers grown in greenhouses, particularly as encountered in northern climates during winter months. Poor light quality significantly reduces post-harvest quality by limiting chlorophyll synthesis, thereby hastening the onset of yellowing and reducing post-harvest life (Lin & Jolliffe 1996).

Cucurbits are susceptible to chilling injury, a physiological disorder that occurs when the crop is exposed to temperatures below the safe storage temperature and above freezing. It can occur in the field, but most commonly occurs during handling and shipping. Chilling injury is time and temperature related and is caused by a disruption in normal functions in cell membranes leading to localized necrosis. Once the integrity of the tissue is compromised, infection readily takes place by saprophytic microorganisms. External symptoms of chilling injury in cucurbits include the appearance of water-soaked or sunken areas on cucumber and cantaloupe, pitting on watermelon (Plate 14.2a), (Snowden 1992), and bronzing of the epidermis of 'Galia'-type melons (Plate 14.2b) (Pacheco 1996) and honeydew (Plate 14.2c). Chilling injury occurred in cucumber after 7 days storage at 4°C (Hariyadi & Parkin, 1991), and after 7 days storage at 7.5°C in Beit Alpha cucumbers (Stapleton *et al*. 2002) (Plate 14.2d). 'Dixie' yellow crookneck summer squash

(a)



(b)

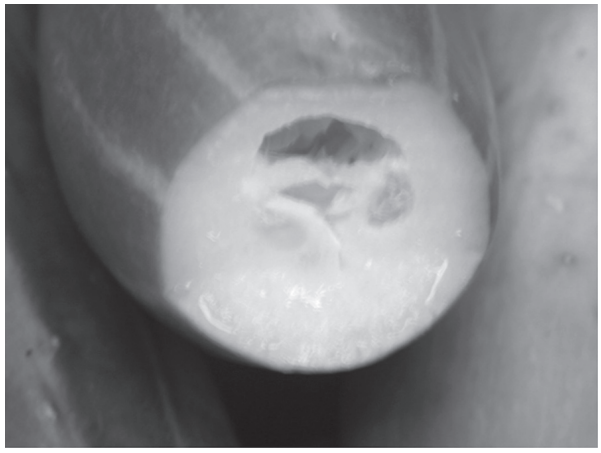


**Figure 14.14** Poor pollination can lead to misshapen fruit (a) and, in severe cases, the formation of internal cavities (b).

developed surface pitting and had increased water loss during storage at 2°C; after 3 days storage this stress stimulated ethylene evolution (from virtually undetectable to 1.5 nl/g-hr), and after 6 days respiration also increased (McCollum 1989). Internal tissues can also be affected by chilling injury, such as necrotic tissue below the epidermis of yellow summer squash and discolouration of mesocarp tissue in cantaloupe.

Seedless watermelon fruit were susceptible to chilling injury during storage at 1°C (Risse & Maynard 1990). Warm temperatures can impart some resistance to chilling injury. Kang *et al*. (2002) reported that greenhouse-grown cucumbers at average daytime temperatures of 32°C were more resistant to chilling injury and remained firmer

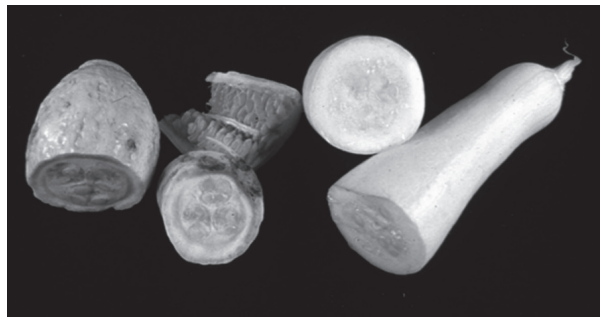


**Figure 14.15** Freezing injury in epidermal tissue in summer squash (center fruit).

during subsequent storage at 10°C over cucumbers grown at 27°C. Small, round watermelons that received a preconditioning treatment (3 days at 26°C) prior to storage at 1°C had fewer chilling injury symptoms than those not receiving the pre-treatment (Risse *et al*. 1990). Honeydew melons exposed to high solar radiation accumulated more unsaturated lipid fatty acids in epidermal tissue (Forney 1990) and lower amounts of ACC (1-aminocyclopropane-1-carboxylic acid, a precursor of ethylene) (Lipton *et al*. 1987), possible reasons for induced tolerance to otherwise chilling temperatures.

Transgenic Charentais melon fruit were developed which produced almost no ethylene. Ethylene was implicated as contributing to chilling injury; these melons developed no chilling injury during 3 weeks storage 2°C, whereas wild-type fruit developed chilling injury (Ben-Amore *et al*. 1999). When treated with ethylene at ambient temperatures, the transgenic fruit later developed chilling injury symptoms during storage.

Zucchini squash exhibited less visible chilling injury symptoms when stored at 2.5°C and in low oxygen (4%), however after transfer to air at 10°C for 2 days, chilling injury symptoms developed. Severe off-flavours developed after storage at 2.5°C or 10°C; some were even more apparent after cooking (Mencarelli *et al*. 1983).

Freezing injury can occur in the field or during shipping and handling. It is distinguished from chilling injury in that frozen tissues appear necrotic, water soaked and flaccid, generally covering larger areas of the fruit surface and extending into the flesh, depending upon severity (Figure 14.15). Formation of intercellular ice is the main cause (Kays, 1991). Freezing injury can occur during shipping in refrigerated trailers that have top air delivery. In these systems, refrigerated air is blown to the rear of the trailer via a ceiling duct (or, 'air chute'). Often the outlet

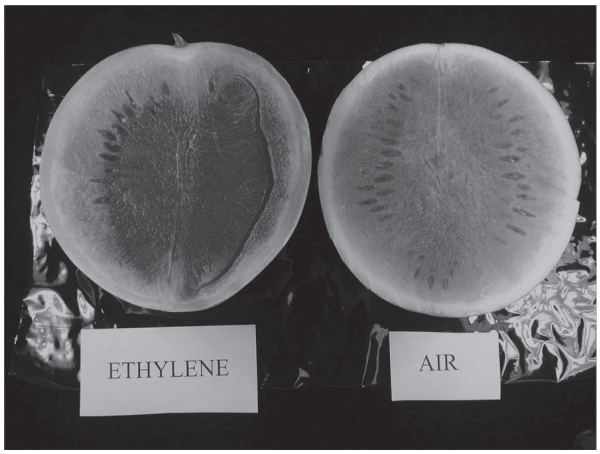



**Figure 14.16** Senescent effects from ethylene exposure to watermelon: tissue disintegration. (Photo credit: D.J. Huber.)

air temperature is below freezing, causing fruit loaded directly under the air outlet to freeze or suffer chilling injury during transit.

**Exposure to various atmospheres**

Exposure to ethylene gas during storage or transport can accelerate senescent processes in nonclimacteric cucurbits. Premature chlorophyll degradation is induced in cucumber and zucchini. A 12 hr exposure to 25 ppm ethylene caused necrotic lesions and decay in Beit Alpha-type cucumbers within 72 hr at 12°C (Sargent *et al*. 2002) (Plate 14.3). Ripe watermelon had breakdown of placental tissue when exposed to extremely low concentrations of ethylene (1 ppm) (Risse & Hatton 1982). Elkashif and Huber (1988) reported two- to threefold increases in watermelon electrolyte leakage rates and greater breakdown in cell wall ultrastructure after six days exposure to 50 ppm ethylene at 18°C. They later noted that this same ethylene exposure accelerated placental senescence in both immature and mature watermelon (Elkashif *et al*. 1989) (Figure 14.16). Mature cantaloupe can be treated with exogenous ethylene (50 to 100 ppm, 24 to 72 hr) after harvest to stimulate uniform initiation of ripening (Reid 2002), as is also commercially done for banana, honeydew, mango and tomato.

Exposure to abnormal atmospheres can likewise stress fruits. Whole and fresh-cut (minimally processed) cucurbits are increasingly stored in film-wrapped packaging systems. If the oxygen transmission rate of the film is too restricted, respiratory activity can produce anoxic conditions, leading to accumulation of fermentation by-products in the tissues.

(a)

(b)

**Figure 14.17** (a) Internal bruising in 'Galia' melon due to impact bruising during harvest; (b) ompression bruise on Beit Alpha cucumber from protruding surface in carton bottom.

These by-products initially cause off-flavours and off-aromas; eventually discolouration and necrosis appear. With only 24 hours of exposure to elevated (60%) $CO_2$ levels at 25°C, cucumber respiration and ethylene production spiked (Mathooko *et al*. 1995), an indication of tissue stress.

**Mechanical stresses**

Careless handling significantly reduces post-harvest life. Impact bruises from careless handling stimulate respiration and ethylene production, hastening senescent processes such as tissue ripening, softening (Figure 14.17a) and breakdown of chlorophyll leading to yellowing in

**Table 14.10** Principal Post-harvest Diseases of Cucurbits.

| Common name | Organism | Commonly affected crops |
|---|---|---|
| Alternaria rot | *Alternaria alternata* | Cucurbits |
| Anthracrose | *Colletorichum orbiculare* | Cucurbits |
| Bacterial soft rot | *Erwinia caratorona* | Cucurbits |
| Belly rot | *Rhizoctonia solani* | Cucumber |
| Black rot | *Didymella bryoniae* | Winter squash |
| Blue mold | *Penicillium spp*. | Cucumber, melon |
| Choanephora rot | *Choanephora cucurbitarum* | Summer squash |
| Cottony leak | *Pythium spp*. | Cucurbits |
| Fusarium rot | *Fusarium spp*. | Cucurbits |
| Phytophthora rot | *Phytophthora capsici* | Cucurbits |
| Rhizopus rot | *Rhizopus stolonifer* | Cucurbits |
| Scab | *Cladosporim cucumerinum* | Cucurbits |
| Sclerotinia rot | *Sclerotinia sclerotiorum* | Cucurbits |
| Southern blight | *Sclerotinia rolfsii* | Cucurbits |

Source: Snowdon (1992) and Zitter *et al*. (1996).

cucumber. This has been attributed to stimulation of peroxidase activity. Miller and Kelly (1989) reported a positive correlation between peroxidase activity and bruise severity in pickling cucumbers; mesocarp and carpel tissues also became water-soaked. Transmission electron microscopy revealed cellular disorganization in bruised cucumbers after 48 hours of storage at 23°C (Abbott *et al*. 1991). The authors noted the disappearance of starch granules and appearance of dense inclusions in chloroplasts from bruised fruits.

Compression bruising of packed fruits is a common problem during handling and shipping. It is caused by constant force exerted on the fruit due to excessive weight in the package or pressure from the lid from overfilling of the package, protrusions on inner package surfaces (Figure 14.17b), and variable firmness of individual fruits in which case firmer fruits gradually deform softer fruits over time.

Harvest maturity affects resistance to physical impacts and compression in cantaloupe. Muskmelon harvested at full-slip withstood up to 120 cm drop onto a conveyor belt, while half-slip harvested fruit were less resilient and bruised or cracked when dropped 90 cm (Foster *et al*. 1979).

Abrasion and cuts promote moisture loss by removing epicuticular wax and by creating ports of entry for decay organisms. Puchalski and Brusewitz (1996) developed a procedure for quantifying the pulling force necessary to abrade the surface of a watermelon and determined that epicuticular wax was removed at approximately 12 N, and upper layers of the pericarp were removed at about 13 N.

### Plant Diseases

Plants must be maintained healthy and adequate disease control strategies must be followed to minimize fruit diseases in the field and the development of latent infections during handling and shipping. Major and minor diseases (Table 14.10) are thoroughly described in Zitter *et al*. (1996) and Snowden (1992).

Post-harvest decay control is limited because few fungicides are registered. Currently, only thiabendazole (TBZ) is approved for post-harvest application to cantaloupe (Adaskaveg *et al*. 2002). Sanitation is one of the primary means for minimizing pathogen build-up during harvest and handling operations and will be discussed in greater detail in the following section. Other treatments have been successful in reducing disease. Addition of silicon to nutrient solution in greenhouse-grown cucumbers in British Columbia was found to increase the plants' resistance to powdery mildew (Samuels *et al*. 1993). However, excess silica that accumulated in trichomes and epicuticular wax resulted in a noticeably rougher epidermis and duller appearance. Despite these slightly negative effects this practice has been widely adopted in that industry.

Bower *et al*. (2002) reported lower incidences of powdery mildew in Charantais melons with anti-sense gene for ACC oxidase (non-ethylene producing) as compared to wild type Charantais melons. Since plant tissues generally produce ethylene as a defence response to infection, the reason for lower incidence of disease in the anti-sense melons is unclear.

Post-harvest heat treatment shows promise for decay control in cantaloupe. Full-slip fruits heat-treated for 3 minutes at 57°C by immersion and shrink-wrapped maintained good quality and low surface decay rates up to 20 days at 4°C (Lester 1989). However, irradiation treatment (2 kiloGrays) was ineffective in controlling decay and accelerated fruit softening, weight loss and electrolyte leakage.

In a later study, Mayberry and Hartz (1992) applied heat treatment to cantaloupes for 3 minutes with 60°C water prior to storage at 3°C. Fruits had excellent appearance and firmness and showed no stem-end decay up to 28 days of storage; untreated control fruits, however, were unmarketable. 'Galia' melons were free from decay up to 8 days at 20°C following immersion in 52°C water for 2 minutes; however, off-flavours were noted (Teitel *et al*. 1989). Dry heating the surface of the melons to 52°C did not reduce decay. Teitel *et al*. (1991) found that 'Galia' melons could be dipped for 1 to 2 minutes in 55°C water and immediately wrapped with PVC plastic film; acceptable quality was maintained for up to 9 days at 18°C storage. Heat injury symptoms ranged from small pits to general browning up to 50% of the fruit surface.

Hot-water treatments did not reduce decay or extend post-harvest life of winter squash. 'Delica' was immersed for up to 12 minutes at 50°C; after 12 weeks of storage there was no difference from untreated fruit (Arvayo-Ortiz *et al*. 1994).

**Food safety**

Sales of fresh fruits and vegetables continue to increase due to greater consumer awareness of health benefits. However, precautions must be taken to minimize cross-contamination of fresh produce with human pathogens during production and post-production practices. Sales of a few crops have been severely curtailed following outbreaks of illness attributed to contaminated produce. Fortunately, consistent application of sanitation procedures minimizes the risk.

A number of outbreaks of gastroenteritis have been traced to the presence of human pathogens on fresh produce, mainly vegetables (Mead *et al*. 2002). Pathogenic listeria and salmonella species have been isolated from samples of raw cucumber and melons, and several outbreaks have been traced to contaminated cantaloupe (Beuchat 1995). Pathogens have also been isolated from vegetable salad samples of commercial establishments (Lin *et al*. 1996) Salmonella can survive in tissues infected with bacterial soft rot and on the surfaces of fresh-cut produce, highlighting the necessity for maintaining sanitary conditions during harvest, handling and distribution (Wells & Butterfield 1997).

As a result, guidelines were published by the US Department of Agriculture and the US Food and Drug Administration to assist growers and handlers in maintaining safe produce (USDA 1998). This guide outlines practical steps to avoid cross-contamination of fresh produce with human pathogens, beginning with production of transplants and seeds, and continuing through production practices related to soil and water quality, run-off situations, and harvest, packing, storage and shipping operations. Worker hygiene is also a critical component at each of these steps.

There is a significant amount of research being conducted to determine efficacy of post-harvest sanitizers in reducing fruit surfaces contaminated with human pathogens. *Escherichia coli* O157:H7 multiplied on cantaloupe cut surfaces and rinds at 25°C up to 3 weeks (Del Rosario & Beuchat 1995). *Campylobacter jejuni* survived at least 6 hours on the surfaces of cut watermelon at room temperature (Castillo & Escartin 1994). Immersion in chlorine (1000 ppm) solution was more effective than hydrogen peroxide in reducing populations of *E. coli* spp. inoculated on whole cantaloupes, although efficacy decreased with increased delay after inoculation (Ukuku *et al*. 2001). Neither of these treatments completely sanitized contaminated surfaces.

As mentioned above, anoxic conditions can develop in poorly designed film packages. As the oxygen level falls below 2% in an enclosed package of low-acid produce (such as squash and cucumber), if *Clostridium botulinum* is present, it can grow and produce a deadly neurotoxin (Centres for Disease Control 2002). Proper temperature management is critical in minimizing the potential for pathogen growth. Cantaloupe and honeydew melon cubes were inoculated with *C. botulinum*; after 9 days at15°C toxin was detected, whereas inoculated cubes stored at 7°C had no toxin present (Larson & Johnson 1999). Presence of toxin was also associated with severe fruit decay, although the presence of background flora appeared to limit growth of *C. botulinum*.

There are numerous resources available regarding food safety:

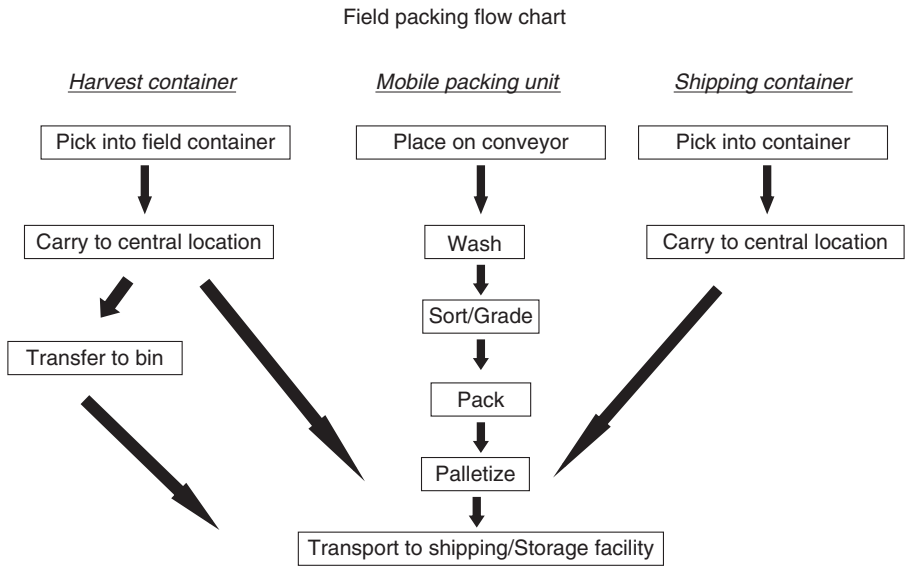



**Figure 14.18** Typical handling steps for three field-packing options for cucurbits.

Codex Alimentarius Commission, 1999. European Community: http://www.codexalimentarius.net

US Centres for Disease Control. Food Safety Office: http://www.cdc.gov/foodsafety/default.htm

USDA Food Safety Information Office: http://riley.nal.usda: http://fsrio.nal.usda.gov

US FDA Centre for Food Safety and Applied Nutrition: http://www.fda.gov/Food/Foodsafety

## POST-HARVEST HANDLING

### Harvest operations

Multiple harvests are employed for many cucurbits. The crop can be packed directly into the shipping container in the field, or transported to a packing facility for washing, grading, packing and storage (Figure 14.18). Field packing involves harvest and packing of the unwashed crop into the shipping container (plastic lugs or returnable plastic containers, corrugated cartons, wooden wire-bound crates). Squashes may be packed on mobile field units ('mule trains') that consist of a mini-packing line for washing, waxing and sizing (Figure 14.19). Watermelon and cantaloupe are often loaded into field bins (plastic, corrugated or wood) (Figure 14.20a) and shipped directly to the buyer and onto the supermarket floor. Larger melons and squashes may also be harvested into trailers or gondolas for transport to a central packing facility (Figure 14.20b).

**Figure 14.19** Field packing of summer squash using a mobile packing unit.

### Packinghouse operations

Packinghouse design is a critical factor that must facilitate and integrate all crop handling operations. Product flow should be smooth from each operation, beginning with temporary storage of the product arriving from the field to shipping operations (Sargent, 2001; Figure 14.21). Upon arrival at the packing facility, field-packed crops are placed directly into cold storage for cooling prior to shipping. Crops transported in bulk containers must be carefully transferred to the packing line. For cantaloupe, field bins, trailers and gondolas are tipped, allowing the melons to roll onto conveyors (Figure 14.22a), whereas watermelons are generally unloaded manually (Figure 14.22b). Delicate crops such as summer squashes and cucumbers are often dumped into water to minimize transfer impacts and abrasions (Figure 14.23 a, b).


**Figure 14.20** Harvest into (a) field bins or (b) wagons for transport to packing facilities.

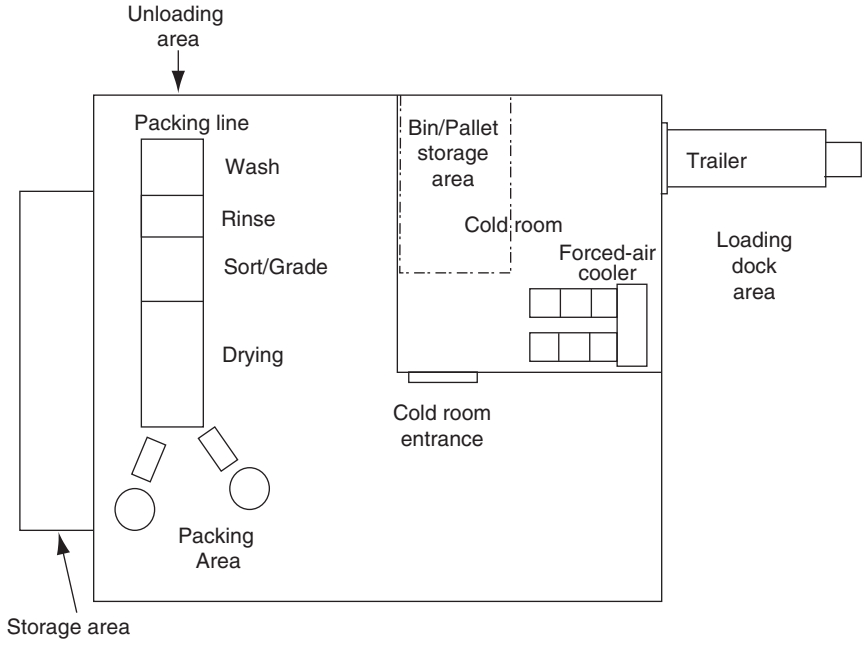



**Figure 14.21** Generalized schematic of a packing facility (top view). (From Sargent 2001.)

Sorting and grading operations for fresh produce are very labour intensive and, therefore a major expense for packers and shippers (Figure 14.24). Packing line equipment must be properly designed and maintained to minimize mechanical injury. Adequate illumination is critical to ensure consistent grading and reduce worker fatigue. Marshall and Brown (1991) noted that high contrast is the main factor that can be manipulated in the grading area, since the product has inherent colour and reflective properties that cannot be changed. Best grading discrimination, therefore, is achieved with light intensity of at least 1800 lux and use of a dark or black background to minimize reflection and glare.

Automation of packing line operations is becoming more prevalent, increasing efficiency for many commodities and showing potential for cucurbit operations. For example, electronic, in-line equipment is commonly employed in citrus,

(a) (b)

**Figure 14.22** (a) Unloading of field wagon at the packinghouse, and (b) manual unloading of seedless watermelons for packing into bulk bins.

(a) (b)

**Figure 14.23** (a) Submerged bin unloading system for (b) floating summer squash onto the packing line.

pome fruit and tomato repacking for defect/colour sorting and sizing. The resultant labour savings can reduce payback of the initial investment for citrus packers to five years or less (Miller & Drouillard 1999). Other nondestructive techniques have also been tested to quantify fruit quality such as soluble solids content and to detect internal defects due to mechanical injuries. One method, delayed light emission, quantifies low-intensity light emissions from chlorophyll in the epidermis to estimate harvest maturity. Forbus *et al*. (1992) compared the spectral data from immature- and mature-harvested juan canary melons with destructively measured quality parameters (chlorophyll, yellow pigments, soluble solids content and firmness). This technique shows promise to predict soluble solids content.

In many cases internal mechanical injuries are not readily apparent during sorting and grading operations. Methods to detect these defects have also been studied. Cucumbers subjected to an impact were measured with refreshed delayed light emission, and differences in pericarp chloroplasts could be detected as soon as one hour after impact (Abbott *et al*. 1991). In a later study, Miller *et al*. (1995) successfully sorted fresh, whole cucumbers with damaged carpels from sound fruits using visible-infrared light transmission. Volatiles (ethanol, acetaldehyde) from low oxygen stress have been reported for cucumber (Kanellis *et al*. 1988); volatiles may serve as indicators of fruit quality or disease (Forney & Jordan 1998).

**Figure 14.24** Primary sorting and grading of cantaloupe.

Immature fruits, such as cucumber and summer squash, have underdeveloped cuticles and consequently readily lose moisture during handling. In the United States, slicing cucumbers are typically coated with edible wax, while European greenhouse types are placed in shrink-wrap plastic film to control moisture loss. Smaller, Beit Alpha-type greenhouse cucumbers have less weight loss than the European types (Lamb *et al*. 2001); Stapleton *et al*. (2002) reported good quality up to 14 days at 10°C without waxing or overwrapping, although use of both methods further reduced moisture loss. Permeability of wax and edible coatings to water, oxygen and carbon dioxide varies and must be matched with the respective fruit (Hagenmaier & Shaw 1992; Baldwin *et al*. 1999).

### Packaging

Packages must be selected for strength, cooling method, end market and cost (Sargent *et al*. 2003). Rigid packages such as cartons, returnable plastic containers and clamshell containers provide better protection from mechanical injury than plastic sleeves and plastic, overwrapped trays. Inserts and padding materials also provide added protection (Figure 14.25a and 14.25b). Corrugated cartons are often coated with paraffin wax in North America to protect against moisture absorption and collapse during hydro-cooling or shipping, while providing extra stacking strength. Wooden wire-bound crates have intermediate stacking strength if cross-stacked, since the end panels provide the stacking strength. In the case of bulk shipping in field bins or trailers, care must be taken to avoid crushing fruit at the bottom of the load from stacking the product too high. The package footprint (base dimensions) should be designed to completely cover a standard shipping pallet (40 × 48 inches; 100 cm × 120 cm). This will maximize use of shipping space while facilitating palletisation (Sargent *et al*. 2003).

(a)


(b)


**Figure 14.25** (a) Vertical dividers bear the weight of stacked cartons, while (b) padding materials from paper and pulp provide protection against abrasion during handling.

Ventilation is important for cooling efficiency. For example, cantaloupe can be forced-air cooled or hydro-cooled. Vent openings in side walls of the container must be of ample size and proper alignment to adequately remove field heat during forced-air cooling and the heat of respiration during subsequent handling and storage (Talbot *et al*. 1992). For hydro-cooling or package icing, the container must be water-resistant and permit drainage. Openings must be of sufficient size without compromising the structural integrity of the container. Several of these design features have been incorporated into returnable plastic containers (RPCs), contributing to increased adoption worldwide. RPCs offer convenience in that they

**Table 14.11** Recommended Cooling Methods for Selected Cucurbits.

| Commodity | Cooling methods[z] |
|---|---|
| Chayote | ROOM |
| Cucumber | HY |
| Cantaloupe (3/4-slip) | FA, HY |
| Cantaloupe (full-slip) | FA, HY, ICE |
| Casaba, Crenshaw, Honeydew, Persian melons | ROOM |
| Summer squash | FA, HY |
| Pumpkin, Watermelon, Winter squash | ROOM |

[z] ROOM: room cooling; HY: hydro-cooling; FA: forced-air cooling.

Source: From Sargent *et al*. (2003).

are delivered to the packer and retrieved from the destination, are cleaned and sanitized between uses, and maximize shipping space if they are collapsible.

Consumer packs have increased in popularity for smaller fruits like summer squash. These traditionally consisted of trays from pulp or expanded polystyrene with over-wrapped plastic film. The introduction of rigid, plastic hinged containers (clamshells) has become very popular in that this container protects the product while modulating internal relative humidity with vent openings.

**Cooling, storage and shipping operations**

Refrigerated storage is the most effective means for extending post-harvest quality of fresh produce (Thompson *et al*. 1998). Rapid cooling (precooling) within a few hours of harvest is necessary for highly perishable immature fruits (e.g. summer squash, cucumber and netted melon types); mature fruits are less perishable and can be room cooled to storage temperature (e.g. watermelon, smooth-skinned melon, chayote and luffa) (Table 14.11). Netted melons must be cooled rapidly, either by continuous hydro-cooling of individual fruits (Figure 14.26a) or by hydro-cooling or forced-air cooling of fruits packed in field bins or in shipping containers. Summer squash and cucumber are either individually hydro-cooled in flumes (Figure 14.26b) or in shipping containers by hydro-cooling or forced-air cooling. Package icing ('slush icing') may also be used for cantaloupe (Figure 14.26c).

For sales to distant markets air or marine shipment may be required or preferred, imposing other requirements on the product. Air shipment is fairly rapid, however temperature control is lost for 24 hours or more and

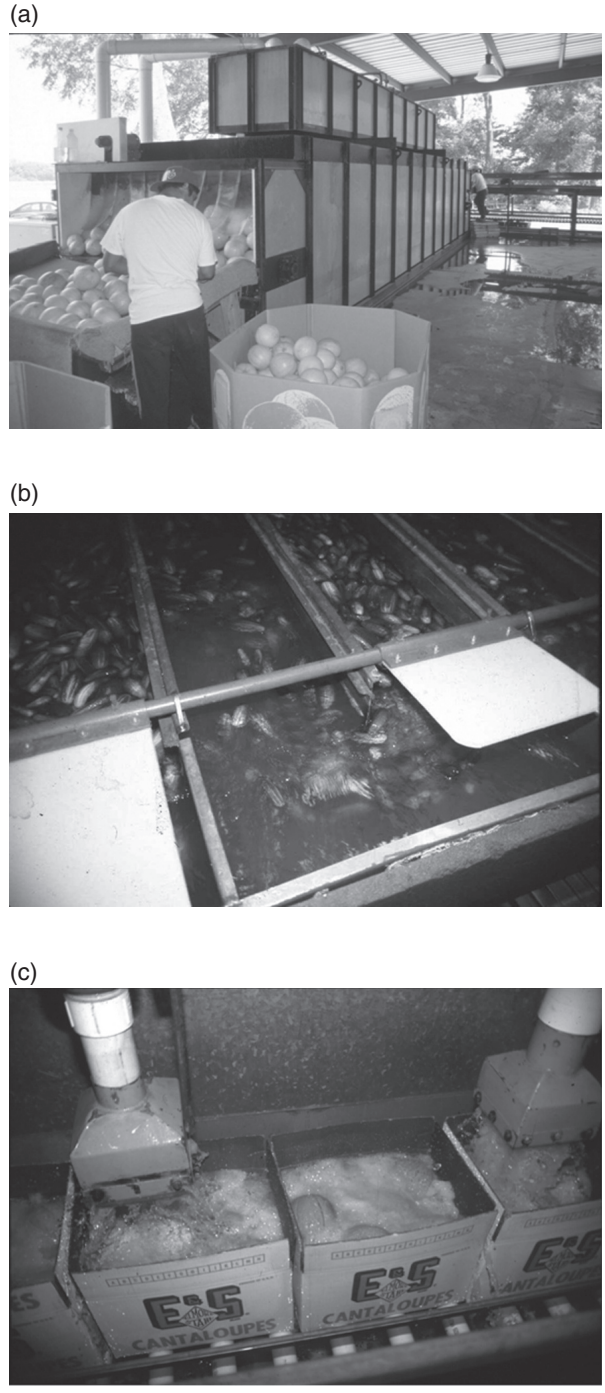



**Figure 14.26** Continuous hydro-cooling of individual fruits is very efficient as shown for (a) cantaloupe and (b) pickling cucumber. (c) Package icing is effective for cold-tolerant crops such as cantaloupe.

**Table 14.12** Recommended Storage Conditions for Cucurbits.

| | Storage Temperature (°C) | Relative Humidity (%) | Expected Storage Life | Controlled Atmosphere (%) | |
|---|---|---|---|---|---|
| | | | | Oxygen | Carbon Dioxide |
| *Cucumis melo* | | | | | |
| L. Cantaloupe, Galia | Whole: 2–7 | 95 | 10–14 d | 3–6 | 6–15 |
| Charantais | Fresh-cut: 0 | | 3–5 d | 10–20 | — |
| Honey Dew | Whole: 10 | 95 | 21 d | Not Rec. | Not Rec. |
| | Fresh-cut: 5 | | 6–10 d | 5% | 5% |
| Casaba, Crenshaw, Canary | 10 | 90–95 | 21 d | Not Rec. | |
| *Cucumis sativis* | | | | | |
| Slicing cucumber | 10–12 | 95 | 14 d | 1–4 | 0 |
| Dutch (English) | 10–13 | 95+ (wrapped) | 14 d | NA | NA |
| Beit alpha (mini) | 10 | 95 | 14 d | NA | NA |
| Pickling | 3–5 | 95 | 7 d. | 3 | 5 |
| *Citrullus lanatus* (watermelon) | Whole: 10–15 | 90 | 14–21 d | Not rec. | |
| | Fresh-cut: 3 | | 15 | 5 | 10 |
| *Cucurbita pepo* (summer squashes) | Whole: 5–10 | 95 | 14 d | Not rec. | |
| | zucchini Fresh-cut: 5 | 100 | | 0.25–1.0 | 0 |
| *Cucurbita maxima* (winter squash) | Whole: 10–13 | 50–70 | 1–3 mo. | Buttercup only: 7 | 15 |
| *Cucurbita moschata* (pumpkin; calabasa) | Whole: 10 | 50–70 | 2–3 mo | NA | |
| | Fresh-cut: 0 | | | 2 | 15 |
| *Momordica charantia* (bitter melon) | 10–12 | 85–90 | 2–3 wk | NA | |
| *Trichosanthes anguina* L. (snake gourd) | 15–18 | 90–95 | 2–3 wk | NA | |
| *Luffa acutangula* (angled luffa) | 10–12 | 90–95 | 14 d | NA | NA |
| *Sechium edule* (chayote) | 7–10 | 85–95 | 4–6 wk | NA | |

Source: Cartaxo (1998), Gorny (2001), Lim (1998), Saltveit (2001), Post-harvest Technology Research & Information Center (2003), Villalta *et al*. (2003) and Zong *et al*. (1995). Selected authors from Gross *et al*. (2002): J.K. Brecht (Pumpkin and Winter Squash), T.G. McCollum (Summer Squash), S. Morris and J. Jobling (Luffa), J.W. Rushing (Watermelon), K.C. Saltviet (Cucumber) and Shellie and G. Lester (Netted Melons).

significant quality losses can occur due to fluctuating temperatures (Nunes *et al*. 2003). Marine shipment is slower but temperature control is excellent and other treatments are possible including relative humidity control and use of controlled atmospheres. A thorough review of shipment via marine container is found in Thompson *et al*. (2000).

**Post-harvest treatments**

Modification of the storage atmosphere can significantly extend post-harvest quality. This ranges from maintaining high relative humidity within a package or pallet via plastic films to changing the composition of the atmosphere surrounding the product. Maintaining high relative humidity (90–95%) is accomplished with use of films or packing in vented clamshell containers. Care must be taken to avoid condensation on the product to minimize growth of decay organisms during handling and storage. For this reason, winter squashes are stored at lower relative humidity (50–70%).

Modification of the atmosphere with low oxygen and/or elevated carbon dioxide atmospheres benefits netted melons and immature fruit types by slowing ripening and senescence and by retarding the growth of spoilage organisms (Table 14.12). Controlled atmosphere shipping involves active monitoring and control of the storage atmosphere to fairly exact concentrations and is used

**Figure 14.27** Properly selected films can be used to induce a modified atmosphere in the shipping container.

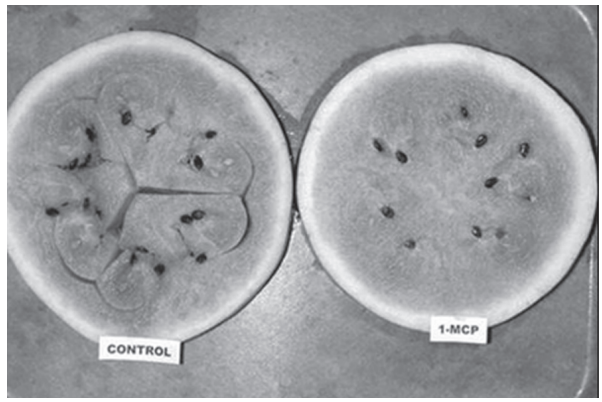



**Figure 14.28** Watermelon pretreated with 1-MCP maintained texture during after 24 days of storage at 13°C, whereas untreated fruit was unmarketable. (Photo credit: D.J. Huber.)

mainly for container loads. 'Galia' melons had less decay and better appearance after 16 days storage in 10% oxygen/10% carbon dioxide at 6°C; use of an ethylene absorbent further reduced decay (Aharoni *et al*. 1993). Cartaxo (1998) reported that chunks of 'Millionaire' seedless watermelon stored at 3°C and 5% oxygen/10% carbon dioxide maintained low microbial counts up to 15 days, five times longer than for chunks stored in air.

Determination of optimal controlled atmosphere requirements for the various melons led to the development of modified atmosphere packaging. Modified atmosphere packaging (MAP) employs selectively permeable films to passively establish and maintain a desired range of low oxygen or high carbon dioxide within an enclosed consumer package, shipping container (Figure 14.27) or pallet (Lange 2000). It has revolutionized the produce industry by extending the storage life of fresh-cut vegetables, and more recently fruit that have extremely short post-harvest life due to high sugar content. MAP requires constant temperature since the desired atmosphere is a factor of product respiration and transmissivity of the film to oxygen and carbon dioxide (Garrett 1998).

A new gaseous compound, 1-methylcyclopropene (1-MCP), is quickly becoming commercialized for treating certain fruits and vegetables to retard ripening and senescence. It is active in extremely low concentrations, <1 ppm, and functions by inhibiting ethylene action in plant tissues (Blankenship & Dole 2003; Huber 2008). 1-MCP slows ripening in netted melon and protects ethylene-sensitive crops during storage. Senescence of watermelon and cucumber was significantly delayed during constant exposure to 40 ppb ethylene when pretreated with 1-MCP (Mao *et al*. 2004; Lima *et al*. 2005; Figure 14.28).

**Value-added fresh produce**

Increasing consumer demand for convenient and nutritious foods since the late 1980s has driven a rapid rise in the amount of fresh produce that is sold as fresh-cut products. Also known as minimally processed, this fresh produce is prepared in ready-to-eat portions. In the United States, more than 10% of all fresh produce is currently processed into some form of fresh-cut product, amounting to sales of $10 to 12 billion (US dollars) (IFPA 2003). It was also reported that 75% of respondents to a consumer survey considered themselves regular purchasers of fresh-cut produce, buying an item at least once per month.

Fresh-cut processing involves peeling and slicing the fruit or vegetable into the final form. This process makes the product extremely perishable because peeling removes the natural barriers (waxy, epidermal tissues) to disease micro-organisms and slicing, shredding, etc., induce wound stress and accelerate senescent processes (Saltveit 2003). Post-harvest life of fresh-cut products is reduced to 3 days (watermelon cubes) and to 15 days (cantaloupe cubes). For these reasons, fresh-cut produce must be of high initial quality (e.g., commercial fresh-cut processors must not use cull products as raw material), it must remain cool throughout processing and sanitizing, and it must be packed in properly designed packaging.

Edible portion varies with melon type. Ates *et al*. (1993) reported edible portions (% of whole fruit), 62% for Piel de Sapo 63% for Amarillo, 58% for Galia and 53% for Tendral.

(a)

(b)

**Figure 14.29** Fresh-cut products are more commonly displayed in (a) refrigerated displays than (b) crushed ice displays due to better temperature management and longer post-harvest life.

Edible portion for 'Millionaire' seedless watermelon was significantly lower at 43.9%, where 33.1% was considered suitable for fresh-cut chunks (30–50 g each) and 10.8% consisted of unusable pieces that could be converted into juice or another product (Durigan *et al*. 1996).

Storage at 4°C maintained acceptable quality in fresh-cut cantaloupe for 4 days and honeydew melon for 14 days, based on ratings of trained sensory panellists and microbial counts (O'Connor-Shaw *et al*. 1994). At the retail level, studies by Durigan *et al*. (1996) determined that refrigerated display cases maintained critical temperatures better than display in crushed ice cases (Figure 14.29a, 14.20b). Successful efforts to extend post-harvest life of fresh-cut cantaloupe involved combinations of treatments, including more effective sanitizing, use of calcium solutions and modified-atmosphere packaging.

Cantaloupe cubes stored in modified-atmosphere package (5% $O_2$, 10% $CO_2$) suppressed microbial growth more than those held in normal air at 5°C (Bai *et al*. 2001). Packages flushed with the gas mixture had higher visual quality than those in which the product modified the internal atmosphere.

Surface sanitation of whole fruits is critical to reduce contamination of the pulp during cutting operations. In a study by Ayhan and Chism (1998), whole fruit surfaces were sanitized by scrubbing with 200 ppm active chlorine at pH 6.0, sliced into cubes and dipped in 50 ppm chlorine prior to packaging in 5% oxygen atmosphere. Acceptable quality was maintained for 15 days at 2.2°C; 2000 ppm chlorine was not more effective than 200 ppm, and no off-odours or flavours were noted by taste panellists. Sapers *et al*. (2001) found that washing whole cantaloupe with 5% hydrogen peroxide was more effective in sanitizing the rind than 1000 ppm chlorine or other commonly used sanitizing treatments. In another study, cut cantaloupe cylinders had a potential post-harvest life of 15 days at 5°C, following a 1-minute dip in 2.5% calcium chloride at 60°C (Luna-Guzman *et al*. 1999). This treatment significantly retarded softening. Fresh-cut watermelon has a porous texture, making it difficult to rinse after processing; therefore, whole fruit sanitation and cooling to 5 °C prior to and during processing were critical to significantly reduce microbial growth, extending post-harvest life to 8 days during subsequent storage at 3°C (Durigan *et al*. 1996).

The enormous variety found in cucurbits presents challenges in maintaining post-harvest quality during commercial harvest and handling operations. By applying the principles and techniques presented in this chapter, growers and shippers should be able to provide consistently high-quality produce to their clients.

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# 15
# Herbs, Spices and Flavourings

*Graham Farrell*

Herbs and spices are used in small quantities to supplement the flavour and aroma of staple foods. The International Standards Organisation defines spices as 'Vegetable products or mixtures thereof, free from extraneous matter, used for flavouring, seasoning and imparting aroma to foods'. Peter (2001) distinguished herbs from spices by describing the former as the dried leaves of aromatic plants used to impart flavour, odour or colour to foods, usually traded separately from stems and leaf stalks. Examples include mint, basil and rosemary. Many herbs, of course are sold in fresh form. Flavourings, in this account, refer to compounds in which the aromatic essence is derived from a post-harvest treatment of the raw ingredient, such as soy sauce made from fermented soya beans.

Herbs and spices have always been important constituents of the human diet, providing variation and adding interest to the bland taste of many staples. Historically, some have also been valuable in food preservation and disguising off-flavours, particularly when transportation times were long and preservation techniques were limited to salting or drying (Cantwell & Reid 1993). Today the main commercial form of herbs and spices is the dried product. Most spices and many herbs are grown in tropical and semi-tropical countries and so there is little seasonality in harvesting and they are available fresh all year round (FAO 2002). However, their use is world-wide, and so the dried forms are cheaper and easier to transport, and have much longer shelf lives than fresh produce. At one time, fresh herbs were grown in kitchen gardens and available only in local markets, despite having a better flavour than the dried product. It is only recently that improvements in harvesting, processing and packaging techniques have made it economical for supermarkets and convenience stores to stock fresh herbs (Cantwell & Reid 1993). This has coincided with increasing demand for some herbs as a result (in developed countries) of their being featured on popular television cookery programmes and an increase in foreign tourism that exposes tourists to spicy, indigenous cuisines in the tropics. Basil and rocket are good examples of this in the United Kingdom.

Herbs and spices are complex structurally and physiologically. They may consist of leaves, stems, roots, flower parts, flower buds, seeds or seed structures, which may be mature or immature. Most herbs are harvested soft or semi-woody and those that are harvested whole may contain leaves at different physiological states. Although this diversity suggests that post-harvest treatments should be tailored to suit the individual characteristics of each plant, most herbs are handled in a similar fashion to other leafy vegetables (Cantwell & Reid 1993) with little or no differentiation between handling methods.

Although supply of fresh herbs has increased through the major food distribution channels, marketing has not always been successful. Given their soft, leafy habit many herbs are perishable. Despite their high value the comparatively small quantities sold means that even a small stock takes time to turn over. In addition, marketing has relied on similar strategies for all herbs. In Australia, for example, it was apparent that the industry was unaware

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of the specific post-harvest handling needs of different species, and all were treated the same after harvest (Lopresti & Tomkins 1997). Most herbs are sold alone but some are packaged with other herbs or leafy vegetables, particularly *Cruciferae*. However, since herbs are botanically diverse in origin and physiological status, post-harvest treatments or conditions that suit one may not suit another (Cantwell & Reid 1993). With herbs sold as mixtures this can lead to difficulties with shelf lives in that the different components decay at different rates. Thus the shelf life of the whole pack is limited to the shelf life of the most vulnerable component. Chervil, for example, is quickly perishable but rosemary, sage and thyme are not, and so shelf life considerations will influence the choice of components for mixed packs.

The literature on post-harvest systems for herbs and spices is relatively scanty, largely resulting from the limited economic value of these commodities compared to staple foodstuffs. However, recent increases in demand, and improvements in processing techniques using modified atmospheres and microprocessor control of temperature and humidity, has drawn attention to a high value and potentially profitable industry.

There is a wide range in the number of herbs, spices and flavourings used around the world. Table 15.1 shows the common leafy herbs, with their areas of origin and how they are manipulated after harvest. Most are used fresh. Spices, on the other hand tend to be used in the dried form. Table 15.2 lists spices of major, world-wide economic importance. Some spices are restricted to a limited range of cuisines or are seldom found outside their country of origin, and these are shown in Table 15.3.

## CONSUMPTION AND MARKETING TRENDS

Approximately 85% of spices are traded internationally in whole form. The final product has traditionally been processed and packed by importing countries. More recently the trade in value-added spices has increased as exporters develop their processing technologies and quality systems (Peter 2001). The annual global trade in spices was about 600 000 to 700 000 t at the end of the 1990s with a value of US$3–3.5 billion (Peter 2001), though this has declined to approximately 520 000 t in 2002–2003, worth about US$1.5 billion (SBI 2003). The main component of the international spice trade is pepper, and so the value of the trade as a whole fluctuates as the price of pepper rises and falls (Peter 2001).

Spices can be important components of national economic activity. For example, exports from India registered substantial growth during the last decade of the twentieth century, from 110 000 t, valued at US$135 million, in 1990–1991 to 235 000 t, worth US$472 million, in 1999–2000. During 2002–2003 the quantity of spices exported from India reached an all-time high of 251 000 t, although this has since dropped to US$370 million. The decline was due to a low volume of pepper exports coupled with a decline in unit price. Nonetheless, India commands a formidable position in the world trade in spices, with about 48% share in volume and 24% in value in 2003 (SBI 2003).

Fresh herbs are seldom differentiated in production and marketing statistics, usually being lumped together as ‘miscellaneous herbs’. Thus, in the United States, domestic shipments increased from 2800 t in 1989 to 3700 t in 1990, an increase of 34%. Over the same period imports increased by 280%, from 900 t to 3400 t. These trends continued into 1991, with 99% increases in domestic shipments, imports and exports (USDA 1991).

The United States imports the largest amount of spices, followed by Germany and Japan. The EU as a whole imports more than the United States in terms of value at US$2.2 billion (by 2001; see Peter 2001). Demand for spices in the United States, particularly the ‘hot’ types, has risen markedly since the beginning of the 1980s. Since 1990 over 360 000 t have been consumed every year; 40% of these are ‘hot’ types such as black and chilli pepper, mustard and ginger. Many herbs, particularly those associated with pizza and spaghetti sauce, have also increased in popularity and thus annual imports of basil went from 1200 t in 1983 to 2400 t by 1993. Oregano use nearly doubled from 3600 t to 6800 t in the same period; use of sage also increased, though less impressively from 1500 to 1800 t (Wolf 1995). In the United Kingdom, spice imports expanded by 27% in the five years leading to the millennium, mainly through increases in cinnamon, cloves, garlic and seed spices (Peter 2001).

## POST-HARVEST ISSUES IN HERBS AND SPICES

### Quality, authenticity and standards

The disparity between the terms ‘authenticity’ and ‘quality’ in assessing herbs and spices has been highlighted by Muggeridge and Clay (2001). Authenticity may be defined as freedom from adulteration (i.e. the absence of foreign bodies or extraneous material), but it also suggests that the product comprises a single species. In practice, the use of the term ‘authenticity’ may be misleading because some common herbs and spices are traded as blends but are not described as such on the label. For example, a packet labelled as dried sage leaves may contain the ‘classic’ sage

**Table 15.1** Herbs Usually Marketed as Leafy Fresh Produce.

| Herb | Main production areas | Post-harvest treatments |
|---|---|---|
| Basil (*Ocimum basilicum, O. americanum, O. gratissimum, O. kilimandscharicum, O. sanctum*; Labiatae) | Mediterranean | Fresh, whole, preserved in olive oil or vinegar, dried and powdered, puréed, freezes well |
| Chervil (*Anthriscus cereifolium*; Umbelliferae) | Eurasia | Fresh |
| Chives (*Allium schoenoprasum*; Liliaceae) | Temperate worldwide | Fresh, puréed, dried and chopped or powdered |
| Coriander (*Coriandrum sativum*; Umbelliferae) | Middle East, North Africa, India, South America, Russia, Hungary, The Netherlands | Fresh, puréed, dried and chopped or powdered |
| Dill (*Anethum graveolens*; Umbelliferae) | United States, Scandinavia, Russia, Balkans, southern Europe | Fresh, dried, powdered, oil extract |
| Epazote (*Chenopodium ambrosioides*; Chenopodiaceae) | Tropical America | Fresh |
| Mache or lamb's-lettuce (*Valerianella locusta*: Valerianaceae) | Mediterranean North America | Fresh |
| Mint (*Mentha spicata*; Labiatae) | Mediterranean North America, Middle East, United Kingdom | Fresh, dried and chopped, freezes well |
| Mitsuba (*Cryptotaenia canadensis*; Umbelliferae) | North America, East Asia, Australia | Fresh |
| Parsley (*Petroselinum crispum*; Umbelliferae) | Mediterranean, North America, Europe | Fresh, puréed, dried and chopped |
| Purslane (*Portulaca oleracea* subsp. *sativa*; Portulacaceae) | Tropics | Fresh |
| Rocket, arugala (*Eruca vesicaria* subsp. *sativa*; Cruciferae) | Mediterranean | Fresh |
| Rosemary (*Rosmarinus officinalis*; Labiatae) | Mediterranean | Fresh, dried and chopped |
| Sage (*Salvia officinalis*; Labiatae) | Mediterranean, Spain | Fresh, dried and chopped |
| Savory (*Satureja montana*, *S. hortensis*: Labiatae) | Europe, North America | Fresh, dried |
| Shiso (*Perilla frutescens*: Labiatae) | Japan, South-east Asia, South Europe | Fresh |
| Tarragon (*Artemisia dracunculus*; Compositae) | | |
| Thyme (*Thymus vulgaris*; Labiatae) | Mediterranean | Fresh, dried, powdered |

Source: From Cantwell and Reid (1993), Mulherin (1994) and Mabberley (1997).

species *Salvia officinalis* mixed with *S. trilobula* and *S. tomatosa*. Packs of thyme may be *Thymus vulgaris* with quantities of *T. capitatus* and *T. serpyllum*. Among spices, powdered turmeric, although defined botanically as *Curcuma longa*, may be mixtures of subspecies such as Alleppy and Cuddaph. Thus it has been suggested that the term quality is preferable to authenticity, quality being defined as 'fit (and customary) for the purpose intended' (Muggeridge & Clay 2001).

Although flavour is a critical factor for spices, reflected for example in the eight grades of paprika quality (Berke & Shieh 2001), cleanliness and freedom from microbial contamination

**Table 15.2** Culinary Spices and Flavourings of Major Economic Significance.

| Item | Main production areas | Plant part used | Post-harvest treatments | Maximum shelf life* |
|---|---|---|---|---|
| Allspice (*Pimenta dioica*; Myrtaceae) | Caribbean, Central and South America | Berry | Sun dried, available whole or powdered | 2–3 years |
| Aniseed (*Pimpinella anisum*; Umbelliferae) | Warm temperate and Mediterranean countries | Seed | Whole or powdered | 2–3 years |
| Anise pepper (*Zanthoxylum piperitum, X*. spp; Rutaceae) | United States, temperate Asia, China, Japan | Berry, leaves | Dried, available whole, powdered or pickled (leaves only) | 2–3 years |
| Asafoetida (*Ferula assa-foetida*; Umbelliferae) | Western Asia, Iran, Afghanistan, Mediterranean | Hardened sap from roots or stems | Available in blocks or powder | 18 months |
| Bay (*Laurus nobilis*: Lauraceae) | Asia Minor, Mediterranean | Leaves | Fresh or dried, whole or ground | 2–3 years |
| Caper (*Capparis spinosa* 'inermis'; Capparidaceae) | Mediterranean, California | Unopened flower bud | Pickled in wine vinegar or dry salted | 3–4 years |
| Caraway (*Carum carvi*; Umbelliferae) | Europe, Russia, India, North Africa, United States, Canada | Seed | Dried, usually whole | 2–3 years |
| Cardamom (*Elettaria cardamomum*; Zingiberaceae) | India, Sri Lanka, Tanzania, Thailand, Central America | Seed pods and seeds | Washed in water and 2% soda to remove adhering soil, retain green colour and limit mould growth. Dried by sun (5–6 days), over fire, convection drying, electrical dryer (10–12 h) or flue pipe curing (18–22 h), may be bleached with $SO_2$, peroxide or metabisulphite. Stored in tea chests (Madhusoodanan & Rao 2001; Korikanthimath 2001). Whole dried pods, loose or ground seeds. | 2–3 years |
| Cassia (*Cinnamomum cassia*; Lauraceae) | Burma, China, east Indies, Caribbean, Central America | Whole bark | Chips, pieces or powdered | 12 months |
| Cayenne (*Capsicum frutescens*; Solanaceae) | Africa, Mexico, United States, India | Fruits | Dried and powdered | 2–3 years |
| Celery (*Apium graveolens* 'dulce'; Umbelliferae) | Europe, United States, Near East | Seed | Whole dried or powdered and mixed with salt (celery salt) or other herbs (celery seasoning) | 2–3 years |

| | | | | |
|---|---|---|---|---|
| Chilli pepper (*Capsicum frutescens*; Solanaceae) | Central and South America | Fruits | Fresh, dried, canned, flaked, powdered puréed or in sauces | 2–3 years |
| Chocolate and cocoa (*Theobroma cacao*; Sterculiaceae) | Tropical America, West Africa, Brazil, Mexico | Seeds or beans | Dried, fermented and ground into liquid mass containing about 50% cocoa butter; mass may be combined with sugar, cocoa solids, powdered or condensed milk or vanilla. | 12 months (plain chocolate), 6 months (milk chocolate) |
| Cinnamon (*Cinnamomum verum* syn. *C. zeylandicum*) | Sri Lanka, India, Brazil, Caribbean | Inner bark | Rolled into sticks or powdered (Thomas & Duethi 2001) | 2–3 years |
| Clove (*Eugenia caryophyllus*; Myrtaceae) | Indonesia, Zanzibar, Madagascar, Caribbean, Brazil, India, Sri Lanka | Unopened flower buds | Artificial or sun dried and stored in gunny bags. Whole or ground (Nurdjannah & Bermawie 2001) | 2–3 years |
| Cumin (*Cuminum cyminum*; Umbelliferae) | Mediterranean, North Africa, Middle East, India, Americas | Seed | Sun dried, packed in cotton bags (Amin 2001), whole or powdered | 2–3 years |
| Curry leaf (*Murraya koenigii*; Rutaceae) | India, Sri Lanka, Malaysia | Leaves | Oven dry at 50°C (Salikutty & Peter 2001), fresh or dried (vacuum packed) | 2–3 years |
| Fennel (*Foeniculum vulgare*; Umbelliferae) | Mediterranean, India, Far East | Seeds, stalks and leaves | Seeds dried, used whole or crushed; stalks dried | Seeds: 2–3 years; fresh: 2 weeks under MAP |
| Fenugreek (*Trigonella foenum-graecum*; Leguminosae) | India, Morocco, Egypt | Seed | Dried, powdered or sprouted | 2–3 years |
| Garlic (*Allium sativum*; Liliaceae) | Asia, worldwide | Bulb (cloves) | Cloves whole, fresh, dried, powdered, granulated, puréed; combined with salt (garlic salt) (Pandey 2001) | 2–3 years |
| Ginger (*Zingiber officinale*; Zingiberaceae) | Southeast Asia, worldwide in tropics | Rhizome | Fresh, dried, parboiled, skinned, bleached, limed, ground, puréed, crystallised or candied; also in syrup as stem ginger or preserved in sherry or vodka (Vasala 2001) | Fresh: 6 weeks if refrigerated, 2 years if puréed, 2–3 years if powdered |
| Horseradish (*Armoracia rusticana*; Cruciferae) | Eastern Europe, United Kingdom, United States | Root | Fresh whole or grated, dried, flaked or powdered | 2–3 years |

**Table 15.2** *Continued*

| Item | Main production areas | Plant part used | Post-harvest treatments | Maximum shelf life* |
|---|---|---|---|---|
| Juniper (*Juniperus communis*; Cupressaceae) | Northern hemisphere, Hungary, Italy | Berry | Whole dried | 2–3 years |
| Lemon grass (*Cymbopogone citratus*; Gramineae) | Southeast Asia, Central and South America. Central Africa, Caribbean, Australia, United States | Stems and leaves | Fresh, dried, powdered, puréed | 2–3 years |
| Liquorice (*Glycyrrhiza glabra*; Leguminosae) | Southeast Europe, Middle East, Russia, Spain, Italy, Turkey | Root | Dried or powdered root, boiled (to make liquorice sticks) | 2–3 years |
| Mace (*Myristica fragrans*; Myristicaceae) | Molucca, New Guinea, Caribbean, Sri Lanka, Indonesia | Aril enclosing nutmeg seed | Removed from nutmeg by hand, washed, flattened, sun or oven dried and broken into 'blades', powdered (Krishnamoorthy & Rema 2001) | 2–3 years |
| Marjoram (*Oregano majorana. O. onites*; Labatiae) | Mediterranean, United Kingdom, North America | Leaves and upper stems | Fresh or dried, broken into small pieces. Sun, solar or freeze dried, may be blanched by microwave radiation (Potty & Kumar 2001) | 2–3 years |
| Mustard (*Brassica alba, B. juncea, B. nigra*; Cruciferae) | Mediterranean, Canada, Europe (*B. alba*); Italy, Ethiopia (*B. nigra*); China, India, Poland (*B. juncea*) | Seed | Dried, dehusked, powdered; may be mixed with vinegar, sugar, wine, salt, other spices | 2–3 years |
| Nigella (*Nigella sativa*; Ranunculaceae) | Southern Europe, west Asia, India, Middle East, Egypt | Seed | Dried whole | 2–3 years |
| Nutmeg (*Myristica fragrans*; Myristicaceae) | Molucca, New Guinea, Caribbean, Sri Lanka, Indonesia | Seed | Unshelled nuts sun dried for a week, seed coat removed mechanically. Used whole, powdered, limed (Krishnamoorthy & Rema 2001) | 2–3 years |
| Oregano (*Origanum vulgare*; Labiatae) | Mediterranean, United Kingdom, North America | Leaves and upper stems | Fresh or dried, broken into small pieces | 2–3 years |
| Paprika (*Capsicum annum*; Solanaceae) | South America, Spain, Hungary, Turkey, United States | Fruit | Dried, powdered or broken into small pieces | 2–3 years |

| | | | | |
|---|---|---|---|---|
| Pepper (*Piper nigrum*; Piperaceae) | India, Cambodia, Brazil, Caribbean, Southeast Asia | Ripe (skin removed – white) or unripe (black or green) fruit | Harvested spikes kept in bags overnight for brief fermentation to ease despiking. Spikes threshed by hand or trampled underfoot, peppercorns then sun dried 7–10 days (black), powdered or soaked to remove skin and dried (white) before further industrial processing (Ravindran & Kallupurackal 2001); fresh peppercorns preserved in brine or vinegar, mashed into paste, freeze dried, powdered (green) | 2–3 years |
| Pepper or Brazilian peppertree (*Schinus terebinthifolius*; Anacardiaceae) | South America | Near-ripe fruit (pink) | Pickled or dried | 4 years |
| Poppy (*Papaver somniferum*; Papaveraceae) | Middle East, China, India, Southeast Asia, Germany | Seed | Dried, whole | 2–3 years |
| Saffron (*Crocus sativus*; Iridaceae) | Mediterranean, Spain, India, Turkey, Iran, China | Stigma | Dried in sun (Iran), over charcoal embers (Spain) or fan oven at 30°C for 34 h (New Zealand), powdered (Velasco-Negueruela 2001) | 3 years |
| Sesame (*Sesamum indicum*; Pedaliaceae) | India, China, Middle East, Far East, Africa, United States, Mexico | Seed | Dried, whole or powdered and made into paste (tahine) | 2–3 years |
| Soy (*Glycine max*; Leguminosae) | China, Japan, Korea, India, Africa, United States | Seed | Fermented, mashed and combined with other flavourings – made into sauce, paste, tofu, bean curd, miso; canned or sprouted (mung bean) | 2 years for soy sauce |
| Star anise (*Illicium verum*; Illiciaceae) | China, Southeast Asia | Fruit | Sun dried, whole or ground | 18 months |
| Sumac (*Rhus coriaria*; Anacardiaceae) | Mediterranean, Italy, Sicily, Iran, Turkey, Middle East | Seed | Dried, whole or powder | 2–3 years |
| Tamarind (*Tamarindus indica*; Leguuminosae) | India, south-central Asia, Africa, Caribbean | Pods | Pulp separated from seeds and fibres and sun dried, compressed into blocks, syrup, paste (Rao & Mathew 2001) | Indefinitely |
| Turmeric (*Curcuma domestica, C. longa*; Zingiberaceae) | Southeast Asia, India, Sri Lanka, Java, China, Peru, Caribbean, Africa, Australia | Rhizome | Boiled in mild alkali for 40–60 min, sun dried for 10–15 days, polished, peeled and ground. Cured product may be stored for up to one year in pits in India (Sasikumar 2001) | 2–3 years |
| Vanilla (*Vanilla planifolia, V. fragrans*; Orchidaceae) | Mexico, Central America Seychelles | Pod or bean | Dried, alcohol extract (vanilla essence) | 2 years (pods) |

* Indicated as 'best before end' date.

Source: From Mulherin (1994), Peter (2001) and market surveys.

**Table 15.3** Herbs, Spices and Flavourings of Lesser Economic Importance.

| Item | Where grown and used | Plant part used | End use | Post-harvest treatments |
|---|---|---|---|---|
| Ajowan (*Carum ajowan*; Umbelliferae) | Middle East, India | Seed | Food flavouring, medicine (indigestion, diarrhoea, asthma) | Dried or water extract |
| Amchoor (*Mangifera indica*; Anacardiaceae) | India | Unripe slices of flesh | Food flavouring | Dried |
| Annatto (*Bixa orellana*; Bixaceae) | Caribbean, tropical America | Seed | Food colouring, flavouring | Dried |
| Bengal cardamom (*Amomum aromaticum*; Zingiberaceae) | Asia, Australasia | Fruit, seed | Fresh or dried | — |
| Black caraway (*Bunium persicum*; Umbelliferae) | Europe, North Africa | Seed, tuber | Fresh or dried | — |
| Calamus (*Acorus calamus*; Acoraceae) | India, northern temperate | Rhizome | Tincture, fresh | — |
| Carob (*Ceratonia siliqua*; Leguminosae) | Mediterranean, Middle East, India | Seed | Food flavouring | Dried and powdered |
| Chinese pepper (*Zanthoxylum bungei, Z. acanthopodium*; Rutaceae) | Asia, Africa, Americas | Fruit | Food flavouring | Fresh or dried |
| Cubeb (*Piper cubeba*; Piperaceae) | Java, Indonesia | Unripe berry | Food flavouring | Dried |
| Galangal (*Alpinia galanga, A. officinarum*; Zingiberaceae) | Indonesia, Malaysia | Root | Food flavouring | Fresh or dried and powdered |
| Garcinia (*Garcinia cambogia, G. indica*; Guttifeae) | Asia, South Africa | Pericarp of fruit | Food flavouring | Sun or smoke dried (Raju & Reni 2001) |
| Grains of paradise (*Aframomum melegueta*; Zingiberaceae ) | Coast and islands of West Africa | Seed | Food flavouring | Dried and powdered |
| Guinea pepper (*Xylopia aethiopica*; Annonaceae) | Africa | Fruit | Food flavouring | Fresh or dried |
| Lemon balm (*Melissa officinalis*; Labiatae) | Europe, Central Asia, Iran | Leaves, terminal shoot | Food flavouring | Fresh or dried |
| Lovage (*Levisticum officinale*; Umbelliferae) | Mediterranean | Fruit, leaves, roots | Food flavouring | Fresh or dried |
| Mastic (*Pistacia lentiscus*; Anacardiaceae) | Middle East, Turkey, Cyprus | Hard resin | Food flavouring | Pulverised |
| Mexican oregano (*Lippia graveolens*; Verbenaceae) | Africa, Americas | Leaves, terminal shoot | Infusion | Fresh |

**Table 15.3** *Continued*

| Item | Where grown and used | Plant part used | End use | Post-harvest treatments |
|---|---|---|---|---|
| Nasturtium (*Tropaeolum majus*; Tropaeolaceae) | Europe, North America | Buds, flowers, seed | Food flavouring | Fresh or pickled in vinegar, dried seeds powdered |
| Papaya (*Carica papaya*; Caricaceae) | Tropics | Seed | Food flavouring | Fresh |
| Pomegranate (*Punica granatum*; Punicaceae) | Mediterranean, Middle East, India | Seed | Food flavouring | Fresh, dried, syrup or paste |
| Sandalwood (*Santalum album*; Santalaceae) | India | Bark chips | Food flavouring, perfume | Fresh |
| Screwpine (*Pandanus odoratissimus, P. odorus*; Pandanaceae) | India, south-east Asia | Leaves | Food flavouring | Fresh or water extract |
| White mustard (*Sinapis alba*; Crucuferae) | Mediterranean, Europe | Seed | Food flavouring | Fresh, dried, powdered |

Source: From Mulherin (1994), Mabberley (1997), Peter (2001) and market surveys.

are also important. Extraneous matter such as insect or plant parts, stones or microbes may contaminate spices when they arrive from suppliers, and processors have a duty to treat these problems before the products can be sold into the market (Wolf 1995). In the United States, specifications for foreign material (defects) in spices have been developed by the Federal Drug Administration (FDA) and the American Spice Trades Association (ASTA). Spice processors may use air, gravity or centrifugal separators for cleaning the product and metal detection and magnets are used to remove metal contaminants (Muggeridge & Clay 2001). Irradiation, methyl bromide fumigation and cold chill have been used for quarantine disinfestation (McGuire 2000). However, since 2005 use of methyl bromide has been completely phased out, except for allowable exemptions such as critical use exemptions agreed to by the Montreal Protocol Parties.

Because spices continue to be mainly traded in the dried form, the major quality criteria are based on this form. These include ash level and acid insoluble ash (both measures of impurities), volatile oil (to test for adulteration), moisture content (usually 12% maximum, assessed using the Dean and Stark method by refluxing a known weight of product in petroleum spirit and measuring the volume of water that condenses out), water availability (usually below 0.6 $a_w$), microbial contamination, pesticide levels, mycotoxin levels (see Table 15.4a), bulk density and mesh or particle size (e.g. 95% pass through a sieve of specified size) (Muggeridge & Clay 2001). Pesticides are not seen as a major problem because of the low consumption rates of herbs and spices; Codex limits of the nearest equivalent commodity provide a guide (Muggeridge & Clay 2001).

Thus, the International Standards Organisation lists spices and condiment standards for post-harvest detection of extraneous matter content (ISO 927:1982), determination of total ash (ISO 928:1997), determination of acid soluble ash (ISO 930:1997), determination of moisture content (ISO 939:1980), sampling (ISO 948:1980), specification of ginger (whole, in pieces or ground) (ISO 1003:1980) and determination of filth (ISO 1208:1982). Individual herbs and spices may also have their own specific quality criteria, for example paprika, garlic and cardamom (Peter 2001).

For fresh herbs, quality criteria are largely visual. Prized visual characteristics are freshness, colour, uniformity of size and lack of defects such as browning, discolouration or decay. Leaves should be uniform in size (Wright 2002a). There are no specific standards for flavour or aroma, but appearance can be considered as a proxy measure since the fresher the herb the more likely it is to have an appreciable flavour.

In the United States, there are no market grades or sizes for fresh culinary herbs (Wright 2002a, b). However, the ASTA and the European Spice Association (ESA) publish

**Table 15.4a** Specifications of the European Spice Association.

| Item | Specification |
|---|---|
| Extraneous matter | Herbs 2%, spices 1% |
| Sampling | Routine sampling: square root of units/lots to a maximum of 10 samples Arbitration sampling: square root of all containers. |
| Foreign matter | 2% maximum |
| Ash, acid soluble ash, moisture content, volatile oil | See Table 15.4b. |
| Heavy metals | To comply with national/EU legislation. |
| Pesticides | Used in accordance with manufacturers' recommendations and good agricultural practice and comply with national/EU legislation. |
| Treatments | Use of EU approved fumigants in accordance with manufacturers' recommendations. Irradiation only if agreed between buyer and seller. |
| Microbiology | Salmonella absent in at least 25 g; yeasts and moulds $10^5$ target, $10^6$ maximum; *Escherichia coli* $10^2$ target, $10^3$ maximum. |
| Off odours | Free from off odour or taste. |
| Infestation | Free in practical terms from live and/or dead insects, insect fragments and rodent contamination visible to the naked eye. |
| Mycotoxins | Should be grown and processed as to prevent the occurrence of ochratoxin A and aflatoxins or minimise the risk of occurrence. Aflatoxin total maximum 10 ppb, $B_1$ 5 ppb. |
| Adulteration | Shall be free from. |
| Bulk density, water activity, species, packaging | To be agreed between buyer and seller. |
| Documents | Should provide details of treatments, name of product, weight, country of origin, lot and year of harvest. |

Source: From European Spice Association as quoted by Muggeridge and Clay (2001).

cleanliness criteria, quality minima and quality standards; some examples are shown in Tables 15.4a, 15.4b and 15.4c. In addition, the ASTA and the Spices Board India have recently produced HACCP protocols for spices in their respective countries (ASTA 2003; SBI 2003).

The ESA draws on national (e.g. from BSI in the United Kingdom and AFNOR in France) and international standards from the International Standards Organisation. Muggeridge and Clay (2001) point out that the ESA criteria are more relaxed in their quantitative aspects than the American ones since they refer to minimum standards, and do not prevent buyers and sellers setting additional standards if they wish. The onus would then be on the seller entering into a commercial contract to satisfy the buyer that the contractual conditions have been met.

Organic standards for spices are developed and established in much the same way as for other plant products, namely by private organisations, companies, certifying agencies or states. To be effective and trustworthy, organic production and processing should be certified by an independent body. Currently there are over one hundred organic standards for spices world-wide (George 2001).

As with other perishable produce, there are several major considerations when dealing with fresh herbs. Improvements in post-harvest handling measures developed for other fresh produce have also been made use of in this sector. In Australia, wastage of fresh herbs in domestic markets has been high, so that supermarkets have had to renew stock every 24 to 48 hours to ensure quality (Lopresti & Tomkins 1997).

### Temperature

Temperature has a major influence on the keeping quality and storage life of fresh herbs. Most herbs store best at 0°C and 95–98% relative humidity, as shown in Table 15.5. Chives and mints can be stored for two to three weeks at 0°C

**Table 15.4b** US Specifications for Some Herbs and Spices.[1]

| Name of spice, seed or herb | Whole insects (maximum) | Mammalian excreta (mg/lb) | Other excreta (mg/lb) | Mould (% by weight) | Insect defiled (% by weight) | Extraneous matter (% by weight) |
|---|---|---|---|---|---|---|
| Basil | 2 | 1 | 2 | 1 | 1 | 0.5 |
| Cardamom | 4 | 3 | 1 | 1 | 1 | 0.5 |
| Cinnamon | 2 | 1 | 2 | 1 | 1 | 0.5 |
| Dill seed | 4 | 3 | 2 | 1 | 1 | 0.5 |
| Ginger | 4 | 3 | 3 | 3 | 3 | 1 |
| Marjoram | 3 | 1 | 10 | 1 | 1 | 1 |
| Pepper (black) | 2 | 1 | 5 | 6 | 6 | 1 |
| Rosemary | 2 | 1 | 4 | 1 | 1 | 0.5 |
| Tarragon | 2 | 1 | 1 | 1 | 1 | 0.5 |

[1]This list is not exhaustive.

Source: From American Spice Trade Association as quoted by Muggeridge and Clay (2001).

**Table 15.4c** EU Specifications for Some Herbs and Spices.[1]

| Product (whole form) | Ash (% w/w maximum) | Acid insoluble ash (% w/w maximum) | Moisture content (% w/w maximum) | Volatile oils (% w/w minimum) |
|---|---|---|---|---|
| Basil (BSI) | 16 | 3.5 | 12 | 0.5 (ESA) |
| Cardamom (ESA) | 9 | 2.5 | 12 | 4 |
| Cinnamon (ESA) | 7 | 2 | 14 | 0.4 |
| Dill seed (ESA) | 10 | 2.5 | 12 | 1 |
| Ginger | 8 (ISO) | 2 (ESA) | 12 (ISO) | 1.5 (ISO) |
| Marjoram (ISO) | 10 | 2 | 12 | 1 |
| Pepper (black) | 7 (ISO) | 1.5 (ESA) | 12 (ESA) | 2 (ISO) |
| Rosemary | 8 (ESA) | 1 (ESA) | 10 (ISO) | 1 (ISO) |
| Tarragon (ESA) | 12 | 1.5 | 8 | 0.5 |

[1]This list is not exhaustive. BSI: British Standards Institute; ISO: International Standards Organisation; ESA: European Spice Association.

Source: From European Spice Association as quoted by Muggeridge and Clay (2001).

and 95–100% relative humidity. Marjoram, oregano and tarragon will keep fresh for one to two weeks at the same temperature but slightly lower relative humidity of 90–95%, and rosemary, sage and thyme for two to three weeks under similar conditions (Cantwell 1997; Hruschka & Wang 1979).

Many herbs maintain acceptable quality if held at 10°C during a 10-day notional marketing period, but decline markedly if kept at 20°C. In contrast, basil and shiso suffer from chilling injury when stored at 0°C, which can give rise to cause for concern since basil is often a component of mixed herb packets. Thus packs containing basil may be held at intermediate temperatures between 5°C and 10°C. Notwithstanding, these temperatures can still cause chilling injury to the basil while allowing deterioration of the other herbs in the bag. Basil will keep its quality for 2 weeks if stored at 12°C and 95% relative humidity (Lange & Cameron 1994).

Management of temperature during harvest and packing is important in maintaining herb freshness, but given the low volumes grown temperature controlled facilities may be basic or absent. The objective is to keep the herbs cool, and so many growers will harvest early in the morning to reduce the need for artificial cooling later in the day. In the United States, growers may send their

**Table 15.5** Effect of Temperature and Ethylene on the Equality of Herbs after 10 Days.

| | Visual quality score[1] | | |
|---|---|---|---|
| Herb | 0°C | 10°C | 20°C |
| Basil | 2 | 8 | 7 |
| Chervil | 8 | 6* | 1 |
| Chive | 9 | 6 | 3 |
| Dill | 9 | 6* | 2 |
| Epazote | 9 | 7* | 5 |
| Mache | 8 | 5 | 2 |
| Marjoram | 9 | 8* | 1 |
| Mint | 9 | 6* | 2 |
| Mitsuba | 9 | 7* | 4 |
| Rosemary | 9 | 9 | 7 |
| Sage | 9 | 8 | - |
| Shiso | 6 | 8* | 3 |
| Tarragon | 8 | 6 | - |
| Thyme | 9 | 8 | 7 |

* Indicates reduced quality after exposure to ethylene at 5–10 ppm.

[1] 9: excellent; 7: good, minor defects; 5: fair, moderate defects, limit of saleability; 3: poor, major defects; 1: unusable.

Source: Modified from Cantwell and Reid (1993).

produce to distributors who handle the main leafy vegetables and who have facilities for cooling. Alternatively, the more robust fresh herbs have been stored on ice, or forced-air or room cooling used for the more tender types. Vacuum cooling has also been employed (Aharoni *et al*. 1989; Cantwell & Reid 1993). Refrigerated road and rail transport of fresh herbs may be done in mixed loads with other leafy greens. However, given their light weight, high perishability and low volume, fresh herbs are more usually transported by air to reduce the time in transit. Gel-ice packs are sometimes used to limit the build-up of heat during the journey (Cantwell & Reid 1993). Producers in Australia faced similar problems in that temperature and humidity control during handling, distribution and marketing were identified as key issues in limiting expansion of the industry (Lopresti & Tomkins 1997).

### Shelf life

The shelf life of a commodity depends on the conditions under which it was packed and stored, and the form in which the product is maintained. In stores and supermarkets shelf lives are usually indicated as 'best before end' or 'sell by' dates. The shelf lives of dried spices or herbs in sealed containers (glass, plastic or sealed bags) are usually 2–3 years. Shelf lives are typically 4–5 days for most fresh herbs, though chervil will last for 1 week (Gorini 1988), coriander and dill for 2 weeks and savory up to 3 weeks (Wright 2002a).

### Traceability

Increasing consumer interest in food safety and convenience, allied to improvements in packaging, has increased the amount of pre-packed produce to over 90% in the United Kingdom. Traceability is also an issue, and the rise of the web and bar coding techniques has allowed much more information to be made available to consumers. For example, in the United Kingdom all fresh produce must have a unique code and web address on it, so that consumers can search for the origin of the product (growers' name and address), when it was harvested, packed and shipped and which route it took to the retail outlet from where it was purchased (Anon. 2003).

### Cultivation, harvesting and handling

Herbs are grown in the field or under glass, in cloches or greenhouses, and production is usually small scale. Harvesting, grading and packing are often done manually or with small mowers and so labour costs are high. In the United States, fresh plants are cut with scissors and bunched in the field or taken to packing houses for trimming and packaging in bulk or bunches, or packed into plastic bags or rigid plastic boxes designed as point-of-sale containers (Cantwell & Reid 1993).

Most herbs for fresh culinary use are best harvested before flowering, except for marjoram and oregano (occasionally sold with flower buds) and chive blossoms. Basil also keeps its quality with some flowers still attached (Wright 2002a).

Methods of drying depend on the crop and locality. Thus in tropical countries much use is made of sun drying in the field for three to four days, by hanging the stalks on racks or laying them out on screens in the sun. Alternatively, plants may be spread on wire trays in ventilated drying sheds for a week or so. Once dried, leaves are separated from stems by rubbing on hand sieves (Potty & Kumar 2001). Delicate species should not be hung in bunches since the soft foliage will dry too slowly and may spoil. Oven drying is not dependable since leaves are liable to scorch, but forced air dryers are effective (Simon 1984).

### Controlled and modified atmospheres

The keeping quality of fresh herbs is improved under conditions of reduced $O_2$ and elevated levels of $CO_2$, and so fresh and pureéd herbs may be sealed under modified atmospheres (MA) during packing, although the technique is not widely used for fresh herbs because of their relatively short post-harvest life (Aharoni *et al*. 1993; Saltveit 1997). The value of modified atmospheres is somewhat degraded if packs are sold in illuminated display cabinets, since these increase photosynthesis and may reduce $CO_2$, making it difficult to sustain the modified atmosphere within the pack and so reducing the quality of the contents. Modified atmosphere packaging will lengthen the shelf life of coriander (Loaiza & Cantwell 1997), chervil (Aharoni *et al*. 1993) fennel (Artés *et al*. 2000) and basil (Lange & Cameron 1998), and $CO_2$ and gibberellic acid combinations have been assessed on parsley (Lers *et al*. 1998).

### Ethylene

Ethylene production is low in fresh herbs but sensitivity to the gas can be high (Wright 2002b). As shown in Table 15.5, ethylene will affect some herbs causing leaf yellowing, leaf drop and epinasty. Many herbs exhibit epinasty but only the most sensitive species succumb to yellowing and abscission. These effects can be minimised by careful control of storage temperatures, preferably maintained at 0°C (Cantwell 1997; Cantwell & Reid 1993), except for basil. MA packaging would also reduce the effect of ethylene.

An alternative approach involves the inhibition of ethylene action using 1-methylcyclopropene (1-MCP). Regulation of senescence in coriander leaves using 1-MCP has been reported by Jiang *et al*. (2002).

### Handling and packing

The leaves of fresh herbs can be easily bruised by rough handling, particularly mint, basil and coriander, because they are of relatively low mechanical strength. Sites of the damage may provide entry for pathogens, thus speeding up decay, but will in any case lead to discolouration, yellowing and browning. Careful handling and rigid packaging will limit this type of damage. Thus bags of fresh herbs may be further protected by being packed in waxed cartons of corrugated card or plastic boxes. Much work has been done recently on modified atmosphere packaging; increased use of and improvements in intelligent packaging solutions such as ethylene and moisture absorbers have increased the shelf life of fresh produce by 50% in the United Kingdom over the last decade (Anon. 2003).

Fresh herbs may be bought pure or in mixed packs, in cellophane bags or trays, and sold on refrigerated display cabinets. They are marketed as *bouquet garni* and as components of bags of mixed *Cruciferae* (e.g. rocket, lollo verde, lollo rossi and cos lettuce or rocket, coriander, chive, spinach and baby leaf). Pack weights of mixed herbs range from 90 to 120 g. Fresh herbs may also be sold as separate leaves or bunches in MA bags or trays (e.g. coriander, parsley, sage, rosemary, mint and basil) in which case weights are smaller at 12–15 g per pack. They may also be marketed as small, rooted plants in pots (such as chives, thyme, parsley and coriander) at room temperature.

Dried herbs and spices are usually sold pre-packed in small quantities (1–12 g) in supermarkets or convenience stores, or loose by weight in traditional markets.

Puréed formulations are a relatively recent introduction to the marketplace. Herb concentrations in these formulations range from 40% to 60% with syrups, emulsifiers, stabilizers and flavourings comprising the balance. In the puréed form the product is packed in plastic squeezable tubes in modified atmospheres with a pack weight of 110–120 g. If kept refrigerated a shelf life of three to four months is possible, with an extra six months if the tubes are frozen.

### Insects

Insect contamination in spices is not usually of concern, though some products are subject to post-harvest insect attack. For example, the drugstore beetle (*Stegobium paniceum* (L.)) and the cigarette beetle (*Lasioderma serricorne* (Fab.)) can cause problems on dried herbs and chillies (Berke & Shieh 2001). Also on chillies, the mite *Curimosphena villosa* (Haag-Rutenberg) has been reported from Ethiopia and *Cryptolestes* spp. beetles from Thailand (Haynes 1991).

*Lasioderma serricorne* and *Caulophilus oryzae* (Gyllenhal) have been found on ginger from the West Indies and *Gnatocerus cornutus* (F.) on ginger in Africa. The nitidulid beetle *Lasiodactylus tibialis* Boheman were reported on cloves from Madagascar and *Caryedon serratus* (Olivier) and *Sitophilus linearis* (Herbst) on tamarind pods. In Sri Lanka *Cryptolestes klapperichi* Lefkovich and beetles of the family Scolytidae have been found on nutmeg. In addition, the moths *Ephestia cautella* (Walker) and *Corcyra cephalonica* (Stainton), and the beetles *S. linearis*, *Tribolium castaneum* (Herbst), *Oryzaephilus surinamensis* (L.), *Henoticus californius* (Mannerheim), *Araecerus fasciculatus* (Degeer) and *Necrobia rufipes* (Degeer) have all been found on spices but are not considered as major pests (Haines 1991). These insects can be controlled by fumigation.

### Moisture

Fresh herbs loose water rapidly once they are cut, which results in early wilting. Keeping herbs at low temperatures limits the rate of water loss. Other techniques involve placing the cut stems in water, but rapid growth of micro-organisms is a problem and the method is not suitable during transport and storage. Delicate herbs such as basil can be packed in boxes lined with wet newspaper. Alternatively, and more commonly, fresh herbs are packed into plastic bags though the packed bags must be kept at constant temperatures to reduce condensation inside the bag that encourages growth of microbes. Bags may be perforated to improve ventilation or made from semi-permeable membranes that allow water vapour egress. In all cases the relative humidity of packing areas, cold rooms and vehicles should be kept above 95%.

One method of getting around the water loss problem is to market herbs as rooted plants in pots so that they continue to grow when purchased and can be 'harvested' by the customer over a period of time, with no loss of freshness in the interim.

Although herbs and spices are usually dried to about 12% moisture content for safe storage and transport, individual products may have different requirements. For example, the maximum moisture content for onion powder is 6% under the ISO standard. Requirements for garlic powder (7%), parsley (7.5%) and bay, celery seed, chives, dill tops and tarragon (all at 8%) are also low. Cinnamon and cassia have the highest allowable moisture content at 14%, under ESA criteria (Muggeridge & Clay 2001).

### Mycotoxins

In common with other foods, mycotoxins have been of concern in recent years within the spice industry (Muggeridge & Clay 2001). Legislation has resulted such that the total aflatoxin maximum in the EU was set in 2001 at 10 ppb and 5 ppb for aflatoxin $B_1$, for capsicum, piper, nutmeg, ginger and turmeric. In the United States, the total aflatoxin maximum is 20 ppb. Documented evidence of mycotoxins in herbs and spices is scarce, although in 24 samples from markets in Egypt aflatoxin was detected at 8–35 ppb, sterigmatocystin at 10–23 ppb, but neither ochratoxin or zearalenone were found (El-Kady *et al*. 1995).

### Fungal and bacterial pathogens

In fresh herbs, attack by pathogens can be reduced by careful handling to prevent injury and correct temperature control, and appropriate choice of packing material to limit condensation. Using chlorinated water for washing as part of a hygiene regime is beneficial. In the absence of such measures attack by ubiquitous bacterial soft rotting organisms or fungi such as grey mould or pin mould are likely.

Spices are also subject to microbiological spoilage, though once dried growth of microbes is largely prevented. However, allspice, black and chilli peppers, caraway, celery seed, cumin, paprika and turmeric may carry a heavy microbial load. Other spices and herbs produce antimicrobial compounds and are less likely to be heavily contaminated, for example cinnamon, cloves, fennel, garlic powder, mint, mustard and nutmeg. Several fungi are of concern in spices, as are the bacteria *Clostridium perfringens*, *Bacillus cereus* and *Salmonella* spp. (Wolf 1995).

Various methods have been used to disinfect herbs and spices, though all have some drawbacks in terms of effectiveness or consumer concern. Microbial counts in spices can be reduced by 90% by treatment with ethylene oxide, though its use is being phased out because of residue and health risks. Propylene oxide has also been used but this gas is less effective. Methyl bromide fumigation of fresh herbs appears to damage the leaves by reducing their green hue (McGuire 2000), though the gas has been used successfully on spices (Yokohama 1994). Another disinfection method is sterilisation by heat though this method seriously degrades flavours. In addition, wet heat would exacerbate decay in fresh herbs and dry heat may be prohibitively expensive (McGuire 2000). In spices, microwave radiation is not effective in reducing microbial levels, and ultraviolet radiation does not have the necessary penetrative power. One of the most effective disinfestation methods for spices is perhaps least likely to find favour with consumers at present, namely, the use of ionising radiation. The FDA permits low levels of radiation for this purpose (Table 15.6) but such products must then have 'treated with radiation' on the label, and the industry is very wary of public reaction to this, although foodstuffs containing irradiated ingredients do not need an irradiation label (Wolf 1995). Few if any spices in retail stores in the United States are known to be irradiated and less than 1% of spices used in processed foods are treated in this way. Notwithstanding, with the banning of many chemical treatments irradiation use has increased such that about 25 000 t are now treated this way world-wide (Peter 2001). Newer preservation technologies to extend shelf lives and limit contamination include osmotic drying and storage in high-fructose corn syrup (Peter 2001).

Fresh herbs may be washed and chlorine dipped to reduce microbial loads. Andress *et al*. (2002) found that microbial counts from a range of herbs and spices

**Table 15.6** Radiation doses for safe microbe levels in some herbs and spices.

| Herb or spice | Dose (kGy) |
|---|---|
| Anise | 5 |
| Basil | 4–10 |
| Capsicum | 5–8 |
| Caraway | 4 |
| Cardamom | 5–8 |
| Cinnamon | 5–10 |
| Coriander | 5 |
| Cumin | 5–6 |
| Fennel | 8 |
| Fenugreek | 5–10 |
| Garlic powder | 5–7 |
| Ginger | 5–10 |
| Mace | 5 |
| Mustard seed | 4–10 |
| Nutmeg | 5 |
| Onion powder | 5–10 |
| Organo | 4–10 |
| Paprika | 4–8 |
| Pepper, black | 4–6 |
| Pepper, white | 5–10 |
| Sage | 4 |
| Thyme | 5–7 |
| Turmeric | 5–7 |

From Kiss & Farkas 1988; Sjöberg *et al*. 1991.

depended on the source. Aerobic mesophile counts varied from $2.9\times10^2$ to $3.2\times10^7$ cfu/g, coliform counts were $7.9\times10^2$ to $1.9\times10^7$ cfu/g and salmonella levels were $7.9\times10^2$ to $2.7\times10^5$ cfu/g. Fungal, *B. cereus* and *C. perfringens* counts ranged from undetectable to $1.7\times10^7$, $1.4\times10^6$ and $8.0\times10^3$ cfu/g, respectively. Washing reduced the aerobic mesophile counts by 0.25–1.0 $\log_{10}$; and dipping in chlorine at 25 ppm reduced levels by an additional 0.2–$\log_{10}$. The efficacy of washing and dipping depended on the initial microbial load.

### Respiration

Given the relatively short shelf lives of fresh herbs increasing life by an extra day or two could extend display times by a large percentage. Maximising shelf life is thus valuable in fresh herbs, and information on their post-harvest behaviour is very important. One of the most notable inherent aspects is respiration rate, which is often a fairly good indicator of the rate of quality loss post-harvest. As well as $CO_2$ and $H_2O$, respiration produces vital heat that presents a heat load to cooling systems. Knowledge of respiration behaviour is therefore important in prediction of shelf lives and demands for storage cooling (Peiris *et al*. 1997). Some respiration rates at different temperatures are shown in Table 15.7.

**Table 15.7** Respiration rates of some fresh herbs.

| | Respiration rate (mg $CO_2$ $kg^{-1}$ $h^{-1}$) | | | | |
|---|---|---|---|---|---|
| Herb | 0°C | 5°C | 7.5°C | 10°C | 20°C |
| Basil | 36 | — | — | 71 | 176 |
| Chervil | 12 | — | — | 80 | 170 |
| Chive | 22 | — | — | 110 | 540 |
| Chinese chive | 54 | — | — | 99 | 432 |
| Coriander | 22 | 30 | 46 | — | — |
| Dill | 22 | — | — | 103 | 324 |
| Marjoram | 28 | — | — | 68 | — |
| Mint | 20 | — | — | 76 | 252 |
| Oregano | 22 | — | — | 101 | 176 |
| Sage | 36 | — | — | 103 | 157 |
| Tarragon | 40 | — | — | 99 | 234 |
| Thyme | 38 | — | — | 82 | 203 |
| Turmeric (rhizome) | 5 | 9 | — | 17 | 28 |

From Cantwell & Reid 1993; Peiris *et al*. 1997; Loaiza & Cantwell 1997.

## POST-HARVEST LOSSES

Over the years a great deal of attention has been given to the magnitude of post-harvest losses in general perishable commodities, although there is little reliable information (Coursey & Proctor 1975). Conservative data in the literature, and anecdotal evidence, suggest losses in the order of 25% in the developed world. Losses in tropical countries are certainly worse but even less hard information is available (FAO 2002). Nor have losses in fresh herbs and spices been quantified but they are likely to be in the same range.

Given the difficulty in assessing losses in perishables, and the huge range of losses (anywhere between 0% and 100%) depending on the commodity, it has generally been accepted that the magnitude of loss is impossible to quantify without reference to the specific crop and post-harvest regime. Rather the value of loss figures lies in indicating the size and extent of the problem and highlighting the need for remedial action (FAO 2002).

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# 16
# Potatoes

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## INTRODUCTION

Potato (*Solanum tuberosum*), sometimes referred to as "white" or "irish" potato, originated in the highlands of South America. Today, potato is the fourth most important food crop in the world after wheat, rice and maize. The world annual production is approximately 300 million metric tons. More than one-third of the global potato output now comes from developing countries and world production is growing by approximately 4% per anum. (CIP 2009). The world distribution of potato production is summarised in Table 16.1.

Primarily, potatoes are grown to be eaten. There is some production for potato starch but overall this is a small proportion. Potatoes may be boiled, baked roasted or fried. Slices fried and eaten hot are known as chips or French fries, while wafer-thin slices fried and packaged for eating cold are called crisps, or sometimes chips. The worldwide market demand for crisps and chips contributes to the potato's commercial importance. There is a wide range of varieties grown, and these tend to be devoted to specific purposes so that commercial processing potato varieties are not the same as those produced for fresh home consumption.

## POST-HARVEST PHYSIOLOGY

The potato plant is a dicotyledon and the tubers develop from underground shoots or stolons. The structure of the tuber is illustrated in Figure 16.1 (derived from Diop & Calverley 1998). The skin, or periderm, can vary in thickness between varieties and growing conditions, but generally consists of six to ten suberized cell layers. It is usually thicker at the stem than at the bud end. Pores, called lenticels, are visible to the naked eye, and are necessary for gas exchange as the periderm is almost impermeable to oxygen and carbon dioxide. Visible potato eyes are the sites where sprouting occurs. Generally between five and 20 eyes are arranged spirally in each tuber, either evenly along the length of the tuber, or concentrated at the apical end (Burton 1989). The main part of the tuber is made up of starch storing paremchyma cells in the cortex and perimedullary zone, which are separated by a ring of vascular tissue. When a tuber is cut longitudinally, the medullar rays and medulla which make up the pith can be observed (Fig. 16.1).

A wide range of characteristics can be observed among potato varieties, in terms of skin texture and colour, and flesh colour. (Burton 1989); thus skin may be smooth, rough, partially netted, totally netted, heavily netted. Skin colour may be uniform white-cream, yellow, orange, brownish, pink, red, purplish red, purple, dark purple-black, or multicoloured and a mixture of two or more of these. Likewise flesh colour, may be uniform or with secondary colour- white, cream, yellow, red, violet or purple.

Tubers may be harvested when the above ground parts of the plant (the haulm) are still green, in which case they have thin delicate skin and are referred to as "new potatoes". Most crops are not harvested until the haulm has died down either naturally or has been deliberately killed off using chemicals. In this case the tuber is mature and has developed a thicker periderm (Snowden 1991).

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**Table 16.1** Summary of World Potato Supply Statistics (1993–1997).

| Continent | Planting (000 ha) | Yield (t/ha) | Production (000 t) |
|---|---|---|---|
| Africa | 737.6 | 11.5 | 8457 |
| Asia | 7476.1 | 14.1 | 105 532 |
| Eastern Europe | 6716.1 | 13.0 | 87 301 |
| Latin America and Caribbean | 1051.8 | 13.3 | 13 967 |
| North America | 691.0 | 35.6 | 24 593 |
| Oceania | 50.3 | 29.6 | 1489 |
| Western Europe | 1538.7 | 32.1 | 49 408 |
| World | 18262 | 15.9 | 290 746 |

Source: FAO (1999).

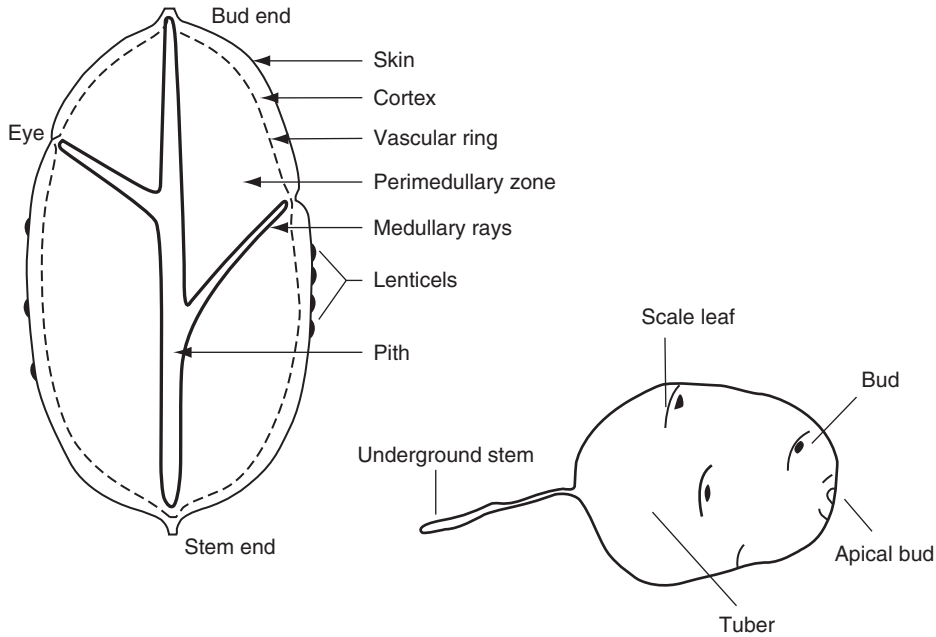


**Figure 16.1** Structure of the potato tuber (Diop and Calverley 1998, with permission of FAO).

### Composition of potato tubers

The composition of potato tubers (see Table 16.2) varies with variety and growing conditions. Dry matter content varies from less than 20% to almost 50%. Starch constitutes 65% to 80% of the dry weight of the tuber. Potatoes are also an important source of protein, iron and riboflavin. In particular potato is a major source of vitamin C (ascorbic acid/ dehydroascorbic acid). Vitamin C levels decrease during the first few weeks of storage, and then more slowly. A single medium-sized potato is said to have about 50% of adult daily requirement (CIP 2008).

### Wound healing of potato tubers and the practice of curing

Like many long-lived plant structures, potato tubers are able to heal wounds. The process involved has been studied for several decades (Priestley & Woffenden 1923). The first stage is that cells at the wound surface become suberized. In this process suberin, a large molecular complex including aromatic and aliphatic components is synthesised in the cell wall. Suberin is an important component of native periderm and suberization is a common response to wounding of plant organs (Kolattukudy

**Table 16.2** Average Constituents of Potato Tubers.

| Constituents | Percentage (by weight) |
|---|---|
| Moisture | 50–81 |
| Protein | 1.0–2.4 |
| Fat | 1.8–6.4 |
| Starch | 8–29 |
| Nonstarch Carbohydrates | 0.5–7.5 |
| Reducing sugar | 0.5–2.5 |
| Ash | 0.9–1.4 |
| Carotene (average) | 4 mg /100 g |
| Thiamine | 0.10 mg /100 g |
| Riboflavin | 0.06 mg /100 g |
| Ascorbic acid | 12 mg /100 g |

Source: From Diop and Calverley (1998).

1983). Suberin acts both as a barrier to pathogen invasion, and due to its characteristic as a highly hydrophobic compound, prevents water loss through the wound. However, there is evidence that it is the waxes associated with the suberin polymer, rather than the polymer itself which constitute the major diffusion barrier in native and wound periderm (Espelie *et al*. 1980; Soliday *et al*. 1979; Vogt *et al*. 1983). Some studies suggest suberin has a directly anti-fungal role (Kolattukudy 1984). This is followed by cell division in a meristematic layer, the phellogen, that develops below the wound, to form a new periderm (wound periderm) or phellem. The process has been reviewed in detail by Thomson *et al*. (1995).

Given that potato tubers tend to get damaged during harvest, successful strategies for storing potato tubers depend on keeping the tubers under conditions that promote wound-healing for a few days immediately following harvest. This process is called curing.

Curing is highly temperature dependent, increasing with temperature, and requires high humidity to prevent water loss which can inhibit the initial suberization stage. At 20°C curing may take three to six days, while at 10°C it will take seven to 14 days. There is variation among cultivars in the efficiency of wound-healing (Wiggington 1974), and it has also been noted that the ability to wound heal decreases with storage time, with final periderm thickness decreasing from 10 cell layers down to to two or three.

**Low-temperature sweetening**

It has been known for decades that potatoes sweeten at low temperature (Burton 1989) with the conversion of starch to sugars. This is generally reversible, except after long-term storage. As a result of low-temperature sweetening, tubers destined for processing into chips and crisps are stored at higher temperatures to avoid the formation of dark brown colouration due to caramelisation on cooking. Thus there is a wide range of storage conditions used depending on final use (Snowden 1991); seed potatoes are stored at 2–4°C and then exposed to warmth and light for "chitting", or sprouting before planting. 5–6°C is used for fresh market potatoes, 6–8°C for chipping potatoes and 7–10°C for crisping potatoes. This has important implications for sprout control (see below).

**Greening of stored tubers**

If tubers are exposed to light, greening occurs in the periderm and in the outer parenchyma cells of the cortex. This is caused by the synthesis of chlorophyll and the formation of toxic glycoalkaloids, including solanin, and results in the development of a bitter taste. The glycoalkaloid content of potato tubers, but can be as high as 210 mg/100 g (fresh weight) (Rastovski *et al*. 1981). The highest levels of glycoalkaloids are found in the periderm and cortex; hence about 60% will be removed by peeling. Potatoes containing amounts greater than 1 mg/100 g are generally considered unsuitable for human consumption.

**Tuber dormancy and sprouting**

When harvested, potato tubers are in a state of dormancy which may last weeks or months depending on the cultivar, until the tubers sprout. In addition to the physical development of the sprouts themselves, tuber sprouting is associated with further quality loss due to an increase in reducing sugar, water loss and an increase in glycoalkaloid content (Burton 1989; Suttle 2004a). For tubers destined for processing, therefore, maintenance of tuber dormancy is a critical aspect of successful potato storage. On the other hand, rapid termination of tuber dormancy is desirable for certain sectors of the potato industry such as for seed certification trials and same-season use of seed potatoes for southern markets.

Although the use of low-temperature storage to extend shelf-life and prolong dormancy for ware potatoes is widespread, the efficiency of this is less where temperatures used for storage must be kept above a certain level to prevent low temperature conversion of starch to sugar and consequent poor processing quality. Further, in some situations (e.g. African highlands, and some parts of Central America) controlled temperature storage is not feasible. Extensive studies of the control of potato tuber dormancy have been undertaken to identify strategies and chemicals (both natural and artificial) for commercial sprout control. More recently, work on the molecular biology of dormancy

has focused on the potential for breeding potato cultivars with extended dormancy.

A number of sprout suppressants have been identified for use with potato. Of these, CIPC (isopropyl N-(3-chlorophenyl carbamates, chlorpropham) is the most effective in current use for ware potatoes. This is an inhibitor of cell division, and requires only a single application. With CIPC treatment early maturing varieties can be stored for 6–10 months, and late maturing varieties for up to 12 months (Kleinkopf *et al*. 2003). However, there are human health concerns relating to CIPC usage. A recent Environmental Protection Agency mandate, from the requirements of Food Quality Act (FQPA) of 1996, resulted in a reduction in allowable CIPC residues on fresh potatoes in the United States from 50 ppm to 30 ppm. (Kleinkopf *et al*. 2003).

For storage of seed potatoes, where sprout inhibition must be reversible the most commonly used commercial sprout suppressants are dimethylnaphthalene (DMN) and Carvone (a natural product that can be isolated from caraway seeds) (*Federal Registry* 1995; Brown *et al*. 2000).

Given the concerns over the use of CIPC, new methods of sprout control using non-chemical methods, or natural chemicals, are being continually sought. Recently continuous ethylene treatment during storage has been used to control potato sprouting. This has been registered for commercial use in the UK since 2003 (Prange *et al*. 2005).

Table 16.3 gives a list (not exhaustive) of sprout suppressant treatments presently used or being investigated for use for potato.

**Table 16.3** Chemicals or Treatments Effective as Suppressants of Sprouting in Potato.

| Treatment | Reference |
|---|---|
| CIPC (isopropyl N-(3-chlorophenyl carbamates, chlorpropham) | Kleinkopf *et al*. 2003 |
| Substituted naphthalenes e.g. 1,4-dimethyl naphthalene (1,4 DMN), 2,6 diisopropylnaphthalene and alpha-naphthalene acetic acid | Lewis *et al*. 1997<br>Suttle 2003b |
| Ethylene | Suttle 2003b |
| Essential oils: carvone, spearmint, peppermint and eugenol | Kleinkopf *et al*. 2003 |
| Hydrogen peroxide | Prange *et al*. 1997 |
| Irradiation | Kleinkopf *et al*. 2003 |

Note: Some references given are reviews and not necessarily the most definitive work on that particular treatment.

Given the economic importance of potato, research into the control of dormancy is much more advanced than for other root crops. Dormancy is considered to begin at tuber initiation (Burton 1989). The buds (eyes) from which sprouts will eventually grow, are present from an early stage. Buds near the apex are dominant (apical dominance) such that lateral buds will only develop if apical buds are removed, or the tuber is cut into smaller seed pieces. The control of dormancy maintenance and dormancy break is very complex. This is illustrated by the observation using methods of Quantitative Trait Loci (QTL) analysis that dormancy is controlled by at least nine distinct genetic loci (van den Berg 1996). As a consequence, the results of scientific research are sometimes confusing and apparently contradictory.

### *Hormonal control of dormancy*

A large volume of work has been conducted to understand the hormonal control of tuber dormancy (reviewed in Suttle 2004a). The role of the different classes of hormones has been studied including: auxins, gibberellins, cytokinins, abscissic acid and ethylene.

The role of auxins is confusing. Early bioassay data suggested that a key auxin, indole acetic acid (IAA) was low in dormant tubers and increased during sprout growth, indicating a role in sprout stimulation, although contrary evidence was presented by Sorce *et al*. (2000). On the other hand, high doses of IAA, or of the auxin, 1-naphthalene acetic acid have been shown to inhibit sprouting. Auxins are therefore postulated to be involved in control of sprout growth (Suttle 2004a). Dimethylnaphthalene, which is used as a commercial sprout suppressant has an auxin-like structure and may bind to auxin receptors.

The identification of hundreds of gibberellins makes interpretation of their role complicated. Suttle (2004b) conducted a study to determine the effects of post-harvest storage duration on the endogenous content and bioactivities of selected gibberellins in relation to the dormancy status in Russet Burbank potatoes. The conclusion from this study was that endogenous gibberellins are not intimately involved with tuber dormancy control, but play a critical role in sprout stimulation at dormancy break. Gibberellins, specifically ($GA_3$) are used to promote sprouting of seed potato for seed certification programmes.

Cytokinins are defined by their ability to release G1 cell cycle blocks, and bud meristematic cells are arrested in this phase. Recent immunological techniques have allowed confirmation of earlier bioassay work, indicating that

cytokinin levels increase at the break of dormancy. This together with findings that potatoes transformed with a cytokinin biosynthesis gene show early sprouting (Ooms & Lenton 1985) suggest that cytokinins are involved in dormancy break.

Abscissic acid, (ABA) is high in dormant tubers and declines during post-harvest storage. Moreover Suttle and Hultstrand (1994) showed that Fluridone, an inhibitor of ABA synthesis, caused premature sprouting in an *in vitro* micro-tuber system, while addition of ABA suppressed sprouting.

Ethylene can have different effects on sprouting. Rylski *et al*. (1974) showed that short-term ethylene treatment can prematurely terminate tuber dormancy, while continuous treatment (at levels of about 5 ppm) results in sprout growth inhibition. Ethylene is induced by auxins, but despite the fact that it is now in commercial use, its precise role in dormancy control is unclear (Suttle 2003a).

The overall picture of dormancy control put forward by Suttle (2004a) is that both ABA and ethylene are required for the initiation of tuber dormancy, but only ABA is needed to maintain the dormant state. Cytokinins are involved in dormancy break. Thus endogenous cytokinins levels are relatively low in highly dormant tubers and tubers are non-responsive to exogenous cytokinins. During dormancy tubers actively metabolise ABA and cytokinins to inactive products. As dormancy weakens, tuber ABA levels decline and tubers become increasingly sensitive to exogenous cytokinins.

In addition to the clear importance of ethylene for commercial dormancy control, and $GA_3$ for promoting sprouting, the possibility of using synthetic forms of plant hormones for sprout control is also being considered (Suttle 2005).

### *Other natural sprout suppressants*

Research on dormancy control in potato has been taken in a number of directions. More than thirty years ago a number of aromatic hydrocarbon volatiles were isolated from potato skin (Meigh *et al*. 1973; Lewis *et al*. 1997) many of which were found to have sprout suppressant effects. One of these was 1-4 dimethylnaphthalene (1,4-DMN), which is now used as a commercial sprout suppressant. 1,4-DMN is naturally present in potatoes at levels between 1 and 10 ppm. It appears that when conditions are optimum for sprouting 1,4-DMN is metabolised to a low level to allow sprouting. Commercially, 1,4-DMN has to be applied repeatedly, as its effect is temporary. Usually four applications over the storage season are necessary to maintain a sufficient concentration in the potato to control the sprouting. (Federal Registry 1995). Several substituted naphthalenes have been tested singly or as mixtures (Lewis *et al*. 1997), and have been shown to control sprouting as effectively as CIPC. As well as DMN, 2,6 diisopropyl-naphthalene has also been commercialized, and may even be more effective than DMN. It is thought that substituted naphthalenes work through a hormonal effect, and it has already by noted that their structure is auxin-like. It has been shown that multiple application of 1, 4 DMN not only inhibits sprouting of seed tubers but can modify tuber yield and size distribution to obtain a tubers of smaller average size which may be desirable for fresh, processing and seed potato industry (Knowles *et al*. 2005).

Several other compounds with sprout inhibitory activity at least of the same order as CIPC have been isolated from potato surface tissues (Filmer and Rhodes 1985). The chemical diversity of these compounds (1,4- 1,6-dimethyl-naphthalene, 1,4,6-trimethylnaphthalene and diphenylamine) suggest that they act by different mechanisms.

### *Essential oils*

S-Carvone is a monoterpene isolated from caraway (*Carum carvi*) or dill (*Anethum graveolems)* seeds, which is marketed as the sprout suppressant, Talent™ (Kleinkopf *et al*. 2003). This chemical also inhibits the formation of wound periderm, and must therefore be applied after the curing process. Extracts from spearmint (*Mentha spicata*) and peppermint (*Mentha pipenta*) have also been successfully used. These essential oils are applied as thermal fogging, cold aerosol application or by forced evaporation. Given their volatility, continuous application is necessary (Kleinkopf *et al*. 2003). Biox-ATM, or engenol is a purified extract from clove (*Sygzygium aromaticum* (L)) which has similar efficiacy and acts through damaging the developing buds (Kleinkopf *et al*. 2003).

### *Hydrogen peroxide*

Hydrogen peroxide can act as a sprout inhibitor and is part of a commercial product marketed as Hydrogen Peroxide Plus (Prange *et al*. 1997). It damages the meristematic tissues once dormancy has broken. Interestingly, hydrogen peroxide has also been identified as a signal for dormancy break in other species such as grapevines (Perez & Lira 2005).

### *Irradiation*

Ionizing radiation is effective at inhibiting sprout development. The University of Idaho has also looked at high-energy electron treatment. The use of irradiation is dependent on its acceptability to consumers, and at this time it is only used commercially in Japan (Kleinhopf *et al*. 2003).

### *The molecular biology of dormancy control*

Advances in techniques of molecular biology have opened new opportunities for understanding biological systems, and have led to a major international effort to increase our understanding of control of dormancy at the molecular level. Major changes in gene expression dormancy progression have been demonstrated (Bachem *et al*. 2000; Ronning *et al*. 2003), and transcripts and proteins unique to either dormant or growing meristems have been identified. Extensive survey of the potato transcriptome using expressed sequence tags (Ronning *et al*. 2003) has facilitated the identification and further study of key genes expressed during dormancy and sprouting (e.g. Faivre-Rampant *et al*. 2004). Discussion of the findings is outside the scope of this chapter. However, these approaches open up the possibilities of genetic manipulation to produce, for example, cultivars with extended dormancy.

## TUBER STORAGE DISEASES AND DISEASE PREVENTION

Potato production was estimated as 320 million tonnes in 2007 and essentially all of this production must be stored for at least a short time. However, this semi-perishable crop is subject to many pests and diseases during both cultivation and storage which threaten its value as a food and as a commodity. Here, we describe some of the major pests and diseases of potato storage and their management.

Storage diseases of potato are not curable so active prevention of diseased tubers from entering storage is a priority. Disease-free seed with best cultural practices and fungicide programmes to manage diseases all reduce the percentage of diseased tubers being stored. In particular, as most of the pathogens are opportunistic and gain entry to the tuber through wounds, careful harvest and handling, with a view to avoiding physical damage to tubers, is particularly effective. Prior to storage, a good drying and curing regime should be followed, to allow wounds to heal effectively. Stores should be clean, free of previous year's debris and perhaps disinfected before tuber loading. Storage conditions must be controlled to minimise conditions under which diseases and pests thrive. Surveillance for potential problems should be maintained throughout the storage period. Problems should be identified quickly and appropriate management strategies to limit pathogen spread and disease development implemented. Early marketing may be the best option available to preserve the value of the crop.

### Pathogen identification

Pathogen identification enables effective store management decisions. Recognising the pathogen, understanding its biology, minimising the storage conditions that favour its growth and limiting the spread from diseased to healthy potatoes are important in preventing any problems becoming worse.

Some diseases, in particular some fungal and bacterial infections, can very quickly cause extremely severe damage leading to the breakdown of an entire pile. Vigilance in monitoring for problems and accurate identification can minimise losses. Knowledge of the diseases in the post-harvest (pre-stored potato) will help direct storage conditions. For example, fungicides and disinfectants may be applied to tubers during store loading to protect against development of some diseases. Other diseases are potentially sufficiently serious to avoid storage altogether.

Below are very brief descriptions to aid identification of some of the major pests and diseases of potato storage, defined here as those organisms whose activity increases to the detriment of the tuber, and store manager, during storage. More detailed information can be obtained from local and national agronomic pathology services and informative websites are listed at the end of this section.

In some cases a very general indication has been given of the general susceptibility of the pests and pathogens to chemical agents. However, given the diverse sets of regulations and licenses that apply in different countries and the local specific resistances to particular chemical agents, further information should be obtained locally.

## MAJOR POST-HARVEST PESTS AND DISEASES

### Bacterial pathogens

#### *Bacterial soft rots*

The most serious of all potato storage diseases are bacterial soft rots and Blackleg caused by a number of closely related bacteria of the genera *Pectobacterium* and *Dickeya*. The principal pathogens include *Pectobacterium carotovorum* and *P. atrosepticum* (formerly *Erwinia carotovora* ssp. *carotovora* and *E. carotovora* ssp. *atroseptic*a respectively) (Gardan *et al*. 2003) and some species in the genus *Dickeya* (formerly *Erwinia chrysanthemi* ) (Samson *et al*. 2005). The pathogens and the diseases are found worldwide and all cultivars are susceptible.

External tuber symptoms include brownish water-soaked areas of squashy tissue usually outlined by brown to black margins. The margin between infected and healthy tissue is sharp (Plate 16.1). Although the rot is initially nearly odourless it typically progresses to a pale, foul-smelling mass. Under advantageous conditions for pathogen

growth, warm temperatures, high humidity and the anaerobic conditions that develop during infection, infected tubers rapidly break down and spread bacteria to adjacent tubers (Plate 16.2) The pathogen can invade healthy tubers, primarily through lenticels particularly when they have swollen in response to moist or wet conditions, or tubers already infected with other diseases. This can result in localized pockets of rot. Infected potatoes generate heat further increasing the rotting process and which can result in an extremely rapid disease progression. A runaway infection can lead to the breakdown of an entire store in days. Other bacterial species, typically of the genera *Clostridium, Pseudomonas*, and *Bacillus*, can be associated with tuber soft rot.

Control measures are to avoid harvesting during wet conditions and minimizing potato damage during harvest and handling. Remove damaged potatoes before loading in clean stores. If harvested when wet, ventilate continually until the potatoes are dry and provide good air circulation in storage. Check the pile temperature at regular intervals and if temperatures are elevated consider additional ventilation or unloading the store.

***Brown rot***

Brown rot or bacterial wilt is caused by the bacterium *Ralstonia solanacearum*. Tubers symptoms include vascular rotting and pitted lesions (Figure 16.2). In the former a distinct, greyish brown discoloration of the tuber surface covers water-soaked tissues. Gray-white droplets seep out when tubers are cut open. Lesions on tubers are produced because of infection through lenticels.

***Ring rot***

Ring rot is caused by the bacterium *Clavibacter michiganensis* subsp. *sepedonicus* and is one of the most damaging diseases of the potato industry. It can be identified from a very characteristic soft cream cheese-like rotting of the vascular ring (Figure 16.3). Some external swellings and cracking may also be visible on infected tubers. Infected tubers of susceptible cultivars almost always rot during storage, as once established the bacteria multiply rapidly and a small initial infection of tubers may result in the total loss of the crop.

**Fungal rots**

***Early blight***

Early blight is caused by fungal species of the genus *Alternaria*, principally by *A. solani* and *A. alternata*. Symptoms are characterised by shallow, gray to black, dry pit-like lesions. Early blight in tubers is often associated with wounding. The fungus can survive over winter in soil

**Figure 16.2** Brown rot of potato. Crown copyright.

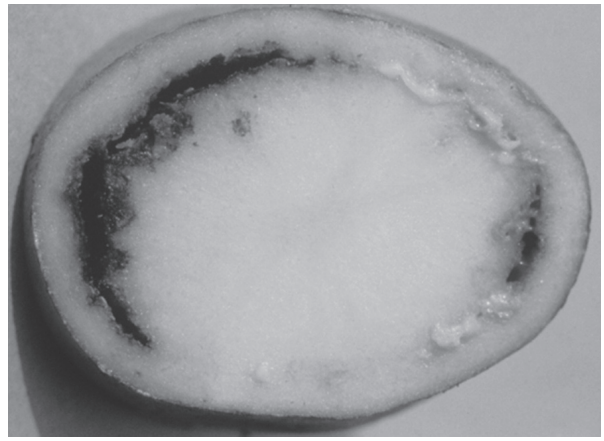

**Figure 16.3** Ring rot of potato. Crown copyright.

or on plant debris and initiate infection in the crop. Lesions on infected potato plants produce spores that spread to healthy plants and cause infection, particularly under warmer growing conditions.

***Dry rot***

Dry rot is caused by four different *Fusarium* spp., *F. avenaceum, F. coeruleum, F. culmorum* and *F. sulphureum,* the latter being the most virulent. A characteristic pattern of concentric, circular wrinkles can often be seen radiating around the initial entry wound and later obvious white mycelial growth. There are differences in the early symptoms of infection by the different species but typically infection progresses to a dry and crumbly tuber decay in which tissue shrinks and collapses. It is often laced with

secondary fungal growth (Plate 16.3). Eventually infected tubers shrivel and mummify. The disease may arise from infected seed or soil inoculum, but wounding at harvest leads to dry rot development in storage. The rot is generally promoted by warm, dry conditions and warmer storage temperatures. Dry rot is minimised by ensuring good skin set before lifting, preventing damage, good store hygiene, promoting wound healing and the application of post-harvest fungicide.

***Gangrene***

Gangrene is caused by *Phoma spp*. in particular *Phoma exigua foveata*, in Europe and Australia and the closely related, less virulent species *P. exigua* var. *exigua* being more widespread throughout potato growing areas of the world. Severe losses can occur during storage, particularly when the potato crop has been harvested during cold weather.

Symptoms on tubers appear as small dark depressions associated with wounds, eyes or lenticels enlarging into sunken areas. Below the superficial depressions there may be extensive internal rotting and well defined infected areas of dark tissue with extensive cavities (Plate 16.4). Infection of tubers occurs mainly through mechanical damage at harvest and grading. Storage at low temperature encourages rot development. Cold and wet conditions during handling encourage disease development, so control of temperature and humidity is important. Treatment at harvest with a fungicide may lessen subsequent disease development in store.

***Late blight***

Late blight, one of the most devastating diseases of potatoes, is caused by the oomycete *Phytophthora infestans*. It is capable of infecting all parts of a potato and tubers can be infected if exposed near the soil surface or if spores are washed from infected aerial tissues into the soil. Infected tubers tend to have a rusty brown, dry rot extending inwards from the skin, the tissues being firm to the touch (Plate 16.5). Generally *P. infestans* survives only in living host tissue although the sexual spore stage can survive dormant in soil. Eventually, the infected tubers become secondarily infected with bacterial rots that can spread, tuber to tuber, in store. Follow a recommended fungicide spray program prior to the arrival of the pathogen. Local or national crop protection agencies should be consulted for registered fungicides.

***Pink rot***

Pink rot is caused by the oomycete *Phytophthora erythroseptica,* a soil living organism which can infect subterranean parts of potato. The pathogen thrives in poorly drained soils and the disease can progress very quickly during warm weather. The disease can spread to healthy tubers during harvest and storage. Infected tubers exude a clear, watery liquid. The skin turns dark, the tissue remains intact with a firm texture. When infected tubers are cut open, a pinkcolour develops within 30 minutes, later turning black. A line demarcates healthy and infected tissue (Plate 16.6). Pink rot in storage is often accompanied by a distinctive odour. Fungicides are available for pink rot control. If pink rot infected areas of fields are identified or suspected, tubers need to be marketed directly after harvest. If this is not possible, they should be stored separately from healthy tubers.

***Pythium "leak"***

Leak is caused by *Pythium* spp., principally *Pythium ultimum*. The description "leak" comes from the extreme wetness of rotted tissues; gentle pressure of a rotten tuber will result in a clear liquid being expelled. In less advanced stages, infected tissue may only be seen when tubers are cut to reveal an internal grey/brown/black rot whereas the outer cortex of the tuber may be intact (Plate 16.7). There is usually a distinct line between healthy and diseased tissue. Frequently the tubers may be secondarily infected particularly by soft rot bacteria. The fungus is present in many soils and can survive over winter in plant debris. Typically tubers become infected through wounds so minimising tuber damage is important to avoid infection. Grading out infected tubers prior to storage reduces spread to healthy tubers.

***Rubbery rot***

Rubbery rot (*Geotrichum candidum*) is a soil borne pathogen. Infected tubers have irregular brown patches on skin with dark margins with occasional white tufts of mycelia. If cut open the flesh has a rubbery texture and turns a dirty pink in about four hours (Plate 16.8). There are no haulm symptoms and usually only a few tubers per plant are affected, which is why the problem is often overlooked until storage. A fishy smell and dark exudates are typical characteristics of infected potato. It is usually only a problem in exceptionally warm and wet conditions. Prevention is best effected by improving field drainage.

**Tuber Blemish Diseases**

Blemish diseases are pathologically minor fungal infections of skin but, where potatoes are sold washed, they affect appearance and therefore impact on crop value.

***Black dot***

*Colletotrichum coccodes*, the fungal agent of black dot is widespread in soil and is a weak pathogen of many plant

species. On tuber surfaces it can develop numerous, tiny black microsclerotia, visible at 10× magnification. The infected periderm usually darkens during storage. Lesions can appear silvery and distinguished from silver scurf by tending to be irregular in shape and without a distinctive margin (Plate 16.9). Disease development is favoured by warm, wet conditions in field or store but it does not spread in store. Control measures are generally cultural with long rotations and avoidance of severely infected seed. Early harvesting, dry curing and cool storage inhibit blemish development.

### *Silver scurf*

*Helminthosporium solani* causes silver scurf, a pervasive blemish disease likely to be present wherever potatoes are grown. Lesions are generally round with dark margins, and often coalesce into larger silvery patches (Plate 16.10). The lesion damages periderm leading to moisture loss. Spores (conidia) can give the lesion a sooty appearance, especially in warm, wet conditions. It is possible for the disease to spread in store as spores are released. Diagnostic features are short, black thread-like conidiophores, seen at 10× magnification. Infection is mainly perpetuated on seed tubers. There are no resistant varieties so clean, or fungicide, treated seed is the first control option. Harvesting early is prudent because the longer mature tubers remain in the ground, the more likely the progeny are to become infected. Dry curing and cool storage will inhibit disease development. Avoid condensation.

### *Skin spot*

*Polyscytalum pustulans* causes skin spot, an unsightly blemish that begins as dark grey spots and can develop into pimples with dark sunken rings. They can be spaced individually or clumped, especially around eyes or scuffed skin (Plate 16.11). Blemishes can penetrate the tuber flesh, especially under cold storage, causing peeling losses. The blemish is not visible on tubers until after six weeks of storage at the earliest. Some thin skinned cultivars are particularly susceptible. The disease is exacerbated by wet harvests and early cold storage. Curing in warm, dry conditions soon after lifting is beneficial. Disease-free or fungicide treated seed reduce disease incidence.

## Virus infection

Potato tuber necrotic ringspot disase (PTNRD), caused by the aphid borne $PVY^{NTN}$ virus is a disease that develops during storage, particularly in Europe and North America. Necrosis, tending to be associated with warm, late growing conditions, is seen as distinctive raised rings on the tuber surface often immediately surrounded by a sunken ring (Plate 16.12). Although they can be superficial, some cultivars are penetrated, sometimes leading to secondary rotting. The disease is best avoided by planting clean seed early and using resistant cultivars. Aphicides have limited affect as the virus is nonpersistent.

## Invertebrates

### *Aphids*

Aphids are mainly a problem for seed storage because they are virus vectors, however where aphid numbers build up on a stored crop they can spoil the appearance of a crop and promote weight loss. Sprouting tissue is particularly at risk. The bulb and potato aphid (*Rhopalosiphoninus latysiphon*), in particular, can build up in store because it is a pest of the underground potato plant. Its close association with potatoes means that it is capable of transmitting Potato Leaf Roll Virus and Potato Virus Y causing significant virus spread.

### *Potato rot nematode*

Potato rot nematode (*Ditylenchus destructor*) has a widespread world distribution but is a relatively minor pest because it is intolerant of desiccation. Subsequently, it is a pest of cool, moist soils. The nematode enters underground tubers, through lenticels, multiplies rapidly and continues to develop in store. Affected tubers have sunken areas with cracked, wrinkled, detaching skin revealing discoloured flesh. The use of clean seed, long rotations (with weed host control) and nematicides are effective.

### *Potato tuber moth*

The potato tuber moth, *Phthorimaea operculella* (Zeller), is a serious pest of stored potatoes in warmer countries. Larvae can tunnel through tubers in storage, leading to secondary rotting. Damaged tubers are unsaleable for either fresh or processing. To limit the problem only crops with low infestations should be stored and, as the larvae are fairly intolerant of cooler conditions, rapid transit into store is beneficial.

### *Wireworms*

Wireworms are the larval stage of "click" beetles in the family Elateridae. Several species e.g. *Agriotes* spp. and *Limonius* spp. can damage in stored potato tubers. Larvae, about 2 mm long after hatching and growing to 40 mm or more at maturity are slender, light coloured with a hard cuticle and have three pairs of small legs near the head. The larvae tunnel into tubers, producing holes about 3 mm in diameter, tunnels can extend throughout the tuber.

These wounds can have a significant impact in the commercial value of the crop and may be the site of entry for pathogens.

### Vertebrates

Animals, particularly rodents and birds, must be excluded from stores to prevent physical damage which can lead to secondary infection and also to prevent contamination by faeces.

### Physiological disorders

There are a number of physiological responses to environmental conditions by the tuber whose symptoms can appear to be the result of disease. In these cases there is usually no external sign of pathogen attack and there has been little or no sign or symptom of infection on the growing crop.

Enlarged lenticels, a response to excessive surface water, can provide entry sites particularly for bacterial pathogens. Jelly end, which superficially resembles a rot, is a breakdown of starch to sugars in response to hot and dry conditions in the early growing season, and can be seen at low temperature storage. Blackheart which superficially resembles an internal rot, is a response to oxygen deprivation, particularly during storage at higher temperatures. Low temperatures or freezing during or prior to storage can cause significant damage, particularly to internal tissues, and leave the tuber more prone to disease. Vascular necrosis, a brownish discolouring of the vascular ring may be a response of the plant to hot, dry conditions during growth and resembles infection by potato leafroll virus or *Verticillium* spp. Pressure bruising causes grey to black discoloration of the flesh as a result of compression due to high potato piles.

### General store hygiene

Diseases can be difficult to control within a store. The long time scales of tuber storage and the particular circumstances of storage can maintain and allow the spread of some damaging diseases. Consequently effort should be expended to ensure that stores are clean and hygienic, for example by annual deep cleaning and perhaps disinfection/sterilisation. Minimize the introduction of diseases brought in on tubers.

## Future prospects for managing post-harvest pest and disease control

A number of issues can be foreseen that will affect the capacity to effectively manage the pests and diseases in store. Climate change will alter the current distribution of pathogens and pests of potato cultivation and storage. Warmer and wetter conditions may extend geographic ranges and breeding seasons, leading to the naturalization of some pests and an increase in the number of generations of current pathogens and pests produced per year. In particular, warmer conditions will extend the range of a number of fungal rots that are not typically a problem in temperate climates. These "new" diseases and pests of field potato will inevitably provide further challenges for storage.

There are currently a limited number of effective chemicals available for disease control on potatoes and even fewer available for use on potatoes destined for human consumption. Almost inevitably the use of these will, because of concerns for environmental and health and safety fears, become more restrictive. Although effort is being expended on the search for new and replacement products there are long lead times for their introduction, meanwhile development of pathogen and pest resistance to current chemical controls is always an ongoing issue and threat.

Currently in the armoury of tools for pest and disease control and management include improved and improving diagnostics and very extensive and accessible web based information and knowledge systems. Our capacity to very quickly and precisely diagnose problems is increasing, for example there are now PCR (Polymerase Chain Reaction), and particularly real-time PCR diagnostics for most significant pathogens. Field based PCR and immunological testing is already possible to inform the status of potato disease brought into store. The development of web pages and networks allows access to the expert knowledge and experience of plant pathologists across the globe. These tools are continuously being refined and updated, and can help redress the balance that problems with climate change and chemical control may bring.

## A summary of the key issues in pest and disease control

The most effective method of minimising pest and disease problems is active prevention and control of diseased potato from entering storage. This requires control of potato production from seed to store. Unfortunately, there are no shortcuts or quick fixes available. To reiterate:

- Use disease-free seed and use best cultural practices to manage diseases and pests in the field
- Harvest and handle carefully to avoid physical damage to tubers
- Use an effective drying and curing regime to allow wounds to heal effectively
- Load carefully into clean and hygienic stores

- Control storage conditions, bearing in mind the desired final tuber quantity and quality and the condition of the tuber on store entry.
- Be vigilant in surveillance for potential problems
- Identify problems quickly and decide on appropriate solutions

The following websites provide further useful information on potato pests and diseases and their control:
http://vric.ucdavis.edu/veginfo/commodity/potato/potato_storage_disease.pdf
http://info.ag.uidaho.edu/pdf/CIS/CIS1131.pdf
http://www.gov.mb.ca/agriculture/crops/potatoes/bda04s07(3–4).html
http://www.potato.org.uk

## TUBER STORAGE

### Storage of tubers for seed

When producing and storing potato seed, the objectives are ultimately to produce a plant that provides uniform, healthy tubers of the size required for the client market, or in some cases the maximum yield of saleable potatoes. Although the type and quality of seed will not ensure that these objectives are reached, if they are not correct it will be impossible.

There are some diseases such as silver scurf which if controlled in the seed can give a good possibility of producing a silver scurf free crop. If the number of sprouts are manipulated the size of the eventual tubers can be altered. If the seed is pre-sprouted or chitted, diseases can, in some cases, be identified. However, it must be stressed that pre-sprouting seed does not always have a consistent effect, for example the dry matter with cv. Maris Piper increased in one season out of four with pre-sprouted seed and with cv. Rooster in two out of four seasons and in the other years there was no difference (Burke *et al*. 2005). Therefore, the management of potato seed post-harvest and pre-planting can make or break a seed production business.

In most cases the storage of potatoes for seed is similar to that for ware or the fresh market but with two distinct differences; no sprout suppressant will be used and there is a greater tendency to use a fungicide prior to storage to reduce the disease loading. At the later stages of storage the crop may be graded and dressed prior to dispatch to the client farm where it may be chitted prior to planting or at least allowed to warm up so that when put on the planter there is no condensation and the tubers are at a similar temperature to the soil so as to avoid any temperature shock.

Within the UK almost 100% of potato seed storage is box storage with traceability being the major issue. This system also provides the potential to store more than one variety in the same store. In a recent survey in the UK on seed storage (BPC 2005) the most common size of seed store was 1000–1250 tonnes (approximately 25% of stores) with a typical loading capacity of 100–200 tonnes per day (approximately 60% of stores) giving a time to fill the store of eight days or less (again approximately 60% of stores). After storage nearly 80% of stores were warmed before grading.

### Chitting stores

The object of chitting is to provide a pre-sprouted tuber which has broken dormancy but does not have a sprout sufficiently developed that will be easily knocked off during handling. Thus the sprout must be short (5 mm or less) and strong which means being green rather than white and thin. Appropriate temperatures can achieve this chitted seed combined with light levels to give a green sprout.

In the UK, traditionally, chitted seed in trayed boxes was produced in greenhouses with high light levels partially compensating for the lack of temperature control (although frost protection has normally been used). In trials carried out by Bishop in eastern England the temperature was found to be in the range of 2.5–7.5°C for around 50% of the time with the remaining 50% being above 7.5°C (Bishop & Maunder 1980). The particular danger of greenhouse chitting has been that if the ground is unsuitable for planting at the time the seed is ready there is no way to hold back the sprouts, which keep growing. Greenhouses are now rarely used for this purpose in the UK.

An insulated store with lights can give better temperature control. Artificial strip lights (around 65 W/t) are hung on the side of the potato trays and rotated on a three day cycle. If the store is ventilated with ambient air at around 0.05 $m^3/s$ per tonne of seed there is the potential for temperature control. As part of the trials mentioned above, the temperature was maintained in the range of 2.5 –7.5°C for around 84% of the time, but above 7.5°C for the rest of the time (Bishop & Maunder 1980). The lights produce heat which will normally be sufficient for any frost protection. An alternative is to have a refrigerated store with lights which can provide the required temperature for the whole of the time in store.

Although producing chitted seed can be advantageous in many cases the desired objective is to have the eyes opened but no more, as this avoids the difficulties of handling and means that the labour involved in placing seed in trays can be avoided.

**Table 16.4** Options for Managing the Curing Period.

| Harvest condition | Curing period |
|---|---|
| Warm/hot (15°C+) and dry soil | Run fans continuously for first day or so and then intermittently; care should be taken with any outside or refrigerated air that the temperature difference is less than 5°C or there is the risk of condensation. Cool slowly. |
| Warm/hot (15°C+) and wet soil | Run fans continuously until all free moisture is removed. Cool slowly. |
| Cool (10–15°C) and dry soil | Run fans intermittently to achieve uniform temperature. |
| Cool (10–15°C) and wet soil | Run fans continuously until all free moisture is removed. and then intermittently to achieve uniform temperature. |
| Cold (below 10°C) and dry soil | Run fans intermittently allowing the temperature to rise through respiration heat. |
| Cold (below 10°C) and wet soil | Run fans continuously until all free moisture is removed and then run fans intermittently allowing the temperature to rise through respiration heat (dry curing). |

**Curing and energy use during storage**

Unlike many other products potatoes can suberise after harvest. This facility to form another skin is obviously very important in preventing moisture loss or disease development. Potatoes are often stored in refrigerated stores for many months which means that the actual energy cost during storage can become an important factor and the author (Bishop) has encountered cases where the energy cost during storage is 10% of the selling price.

**Initial curing period in store**

The first priority when tubers come into store is to dry them as quickly as possible to remove field moisture. Moisture is required for the establishment of all the major storage diseases affecting potatoes. Where a store is filled over several days, the second priority is to ensure that the temperature of the crop already in store tracks the temperature of the potatoes in the ground. This avoids temperature differences between existing and newly lifted stacks of boxes. Differences of 3–4°C can result in convection currents between the two stacks, and increased likelihood of condensation formation on the top of the cooler crop.

The tubers should be allowed a curing or suberisation period on first coming into store so that any wounds can heal. The suberisation process occurs faster at higher temperatures but a balance between disease development and rate of skin development means that normally a target temperature of around 15°C is considered satisfactory. Curing, or wound-healing, is essential to repair any damage to the tuber's protective skin during harvest and store loading. Open wounds increase evaporation, and hence weight loss and provide an easy means of entry for disease-causing pathogens. However, owing to harvest conditions the tubers may arrive at the store in varying states of temperature and "wetness". Table 16.4 summarises the different practical strategies that could be adopted depending on harvest conditions.

In the case of dry curing, continuous ventilation is the key to drying crops rapidly. Positive ventilation systems will dry crops much more quickly than space ventilation systems. However, to maximise airflow around the tubers, attention must be given to using a suitable box type for the positive ventilation system in question. Otherwise, leakage from the boxes will reduce the rate of drying. Large amounts of soil in the boxes will also impede air movement and drying. In such situations it may be preferable to grade into store to remove the soil.

Once the surfaces of tubers are dry, continuous ventilation can stop. Excessive ventilation can lead to weight loss and other problems. It is important to check that tubers are dry throughout the box, rather than just on the top, before ceasing continuous ventilation. Tubers in the section of the box nearest the incoming drying airstream will dry first, while those next to where the air leaves the box may take up to one to two weeks to dry.

Thereafter periodic ventilation will still be required as newly lifted crops will be respiring rapidly and giving off heat. This effect will be greatest in early lifted crops. The heat will tend to cause warm air to rise up the stack, which may condense on the cooler layers of potatoes near the top of each box, and particularly on the top of the top box. Periodic ventilation will reduce temperature differentials and hence the risk of condensation. If outside air is not suitable for ventilation then recirculation can be employed to even out the differentials until the outside air again becomes suitable (Anon 2000).

In large stores the biggest cause for concern in store management during the curing phase is usually with late lifted tubers where damage has occurred. As ambient temperatures are lower, wound healing will take longer and

there can be pressures to lower the store temperature to benefit the product that has been in store for some time.

To monitor the progress of wound-healing, it is suggested that a few tubers are cut and placed on the corner post of boxes and checked daily to see when they have healed over.

**Ambient ventilation**

Although there has been a trend to refrigerated storage in Northern Europe, Storey *et al*. (1994) stated that in a PMB (Potato Marketing Board) survey that over half the storage in the UK was in boxes and 46% had refrigeration. The use of ambient air for maintaining the storage environment is still popular in tonnage terms. The actual ventilation strategy and the ventilation rate varies considerably with geographic areas. In the United States the recommended rates range from 0.005 $m^3/st^{-1}$ (Sparks 1973; 1980) to 0.0075 $m^3/st^{-1}$ (Sawyer *et al*. 1965). In central and northern Europe (e.g. the Netherlands and United Kingdom) they range from 0.019 to 0.0278 $m^3/st^{-1}$ (Rastosky & Van Es 1981) in southern Europe (e.g. Italy) rates as high as 0.0308 + $m^3/st^{-1}$ are suggested (Bertolini & Guarnieri 1990).

Reasons for these variations depend on local climate, market requirements and the condition of the tubers going into store; in northern Europe it may be necessary to dry or partially dry potatoes going into store. The ventilation rate required will also vary depending on whether the potatoes are stored in bulk or in boxes or crates. Also important in the decision of ventilation rate is the expected or potential quantity of soil on the tubers at storage as well as any moisture.

Forbush and Brook (1993) carried out work over three seasons to investigate the influence of airflow rate, in bulk stores, on the temperature, moisture and market quality of process potatoes using the variety Atlantic. The ventilation rate used were 0.016, 0.032 and 0.010 (for one season) $m^3/st^{-1}$. The temperature was maintained in all three cases with also no difference in sugar, fry colour or quantity of defects. There was also no statistical difference in weight loss however "potato loss uniformity was proportional to increased ventilation rates".

In some cases the ventilation may be continuous (Hymlo *et al*. 1976; Grahs *et al*. 1977; Hymlo *et al*. 1979) or it may be variable depending on how much cooling is required. The variation may be achieved by altering the number of fans in operation or by having a variable speed fan.

**Bulk storage systems**

There is only one basic design of forced ventilation bulk store which involves air passing through the crop from below. There are differences in the type of air distribution system used, the size, number and type of fan, the control system, wall design and whether there is refrigeration or a mixer box (blending air from inside the store with ambient air which is in itself too cold by itself) is used The maximum depth of potatoes is 3–5 m depending on the air distribution system (Pringle *et al*. 2009)

The type of air distribution system will depend upon a main duct with smaller ducts or laterals off it. These laterals may be above or below ground. The main duct should be large enough for the store operator to be able to walk down easily when it is necesary to open or close laterals. If the duct is difficult to walk down it does not encourage regular store management, In a number of recorded cases where the store management has not been satisfactory the ease of operation has been cited as an important reason (Holloway 1990). The maximum air speed that should be permitted inside the main air duct is 10 $ms^{-1}$ (0.1 $m^2$ for each cubic metre of fan capacity at the appropriate rating). Preferably the inside surface of the main duct should be free of any projections that could cause turbulence any the cross sectional area of the duct should be measured inside any internal strengthening members.

The smaller side ducts or laterals can be above or below ground. The advantages of below ground ducting is such that the store can be more easily filled without the laterals having to put down as the store is filled or being an obstruction as the store is being emptied. Also with the below ground laterals do allow the building to be used for another use. Above ground ducts are normally of the "A" type, although plastic drainage piping can be used (Bishop 1994).

**Box storage**

The reasons for the popularity of box stores is that they allow for different varieties of potatoes to be stored together, but kept distinct. Traceability is much easier with box storage as each grower/harvest date/field can be seperately labelled. Normally the information on the crop is written on a card and stapled to the box but bar codes are becoming more commonly used. Disease transmission is much slower in a box store and may well be confined to a specific box. Almost all stores are using wooden boxes of nominally one tonne (1.2 m × 1.8 m × 0.9 m) although in practice the capacitty is nearer to 950 kg. Figure 6.4 shows a typical system used to fill boxes.

**Ventilation systems in box storage**

There are four basic methods of ventilating box stores: nonducted, differential ventilation, letterbox or serpentine ventilation and postive ventilation system.

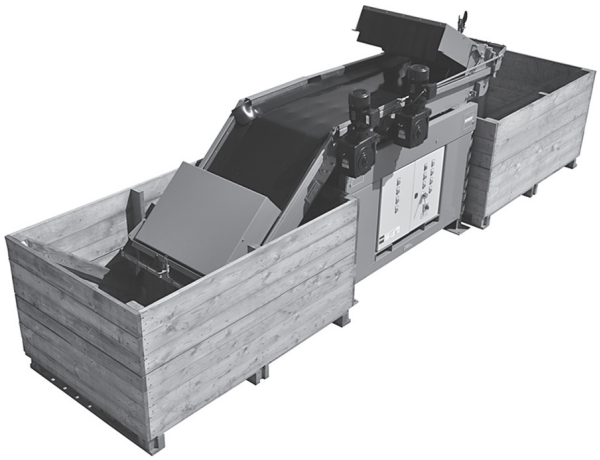

**Figure 16.4** Box filler (courtesy of Herberts).

In all cases the ventilation system can be used with or without refrigeration although for ease of understanding the airflow patterns no evaporator is shown.

The non-ducted system uses boxes with slatted sides and the cool air is blown out at high level and sucked back at low level. The ventilation system works on the principle that the cooler ventilating air drops into the mass of boxes and is then sucked back to a low level intake. It is a low cost system but if the ventilating air is very much cooler or the fan is not powerful enough there is little or no ventilation at the far end of the store from the fan.

The differential system again uses the boxers with slatted sides and the cooler ventilating air is ducted to the far end of the store, sometimes a sheet of plastic is put on top of the boxes instead of actual ducting. The air is then sucked back through the boxes but so as to avoid the air being channeled through some boxes but not others there should be a gap of 350 mm after every five or six boxes. The gap means that the air flow evens out.

The letterbox system uses boxes with solid sides and slatted bases with only one-way entry pallet bases. The arrangement of the boxes is that the pallet base actually forms a duct or lateral and the air is positively ventilated through the boxes. The air comes out of the main duct or plenum chamber and passes down the lateral formed by pallet bases and then through a box of tubers and is exhausted through another set of pallet bases either above or below. This system means that every box is positively ventilated and so a uniform temperature can be maintained, however the system depends on careful stacking of the boxes.

**Energy use minimisation**

The percentage of the total production cost attributed to energy costs can vary from effectively zero with a natuarally ventilated system to over 10% with a sophisticated refrigerated store in a year of low prices. It must be stressed that the total cost of energy, virtually always electricity, and the quantity of energy used are not synonymous as there may be different tariffs. These tariffs may depend on the time of day, time of year or day of the week or all of these factors.

Devres and Bishop developed a computer model for analysis of various factors on total energy use (Devres & Bishop 1995a). The computer model was verified over a two year period against actual energy usage in a 1500 tonne store located in the UK (Devres & Bishop 1995b). The effect of changes in insulation, infiltration and target temperature are given in Table 16.5. The computer model gave an energy consumption of +1.0% in the first year and −2.3% in the second year.

**Low-cost storage structures**

For hundreds of years potatoes were stored in simple low cost structures which often lasted for one storage season. The most basic objectives were to prevent greening, frost damage, damage from rodents or birds and to avoid theft. If a limited number of tubers had sprouted or rotted it may have been possible to remove them. These requirements either involved storing in cellars or caves or protection by straw or soil. Particularly in the case of caves or cellars the extremes of temperature were reduced or eliminated.

**Clamps**

Above ground piles or clamps of potatoes were the traditional method of potato storage in Europe and are still used in various forms in many countries. They have a low capital cost but high labour input. Although there are a number of different types they all require potatoes to be heaped in a long narrow pile of typically 1–2 m in width with a height dictated by the angle of repose of the tubers of 0.4–1 m. Straw of a thickness of 0.3 m or more (a greater thickness of straw will be needed in particularly hot or cold climates) is laid over the top of the tubers to act as an insulant, stop greening and absorb moisture given off by the tubers. The straw is normally then covered with soil or a plastic sheet to protect from rain or strong winds blowing the straw away.

There is a more sophisticated version often referred to as a “Dickie Pie” in which one or two “A” ducts are placed parallel to the long sides. These A ducts are open at each end and can provide some ventilation of the tubers and

**Table 16.5** The Predicted Effect of Changes in Insulation, Infiltration and Target Storage Temperature on Energy Consumption during Potato Storage.

| Design and working conditions | Conventional conditions | Energy consumption difference from conventional % |
|---|---|---|
| Storage temperature 1°C | 4°C | +69.77 |
| Storage temperature 2°C | 4°C | +46.22 |
| Storage temperature 3°C | 4°C | +22.71 |
| Storage temperature 5°C | 4°C | −6.66 |
| Storage temperature 6°C | 4°C | −13.44 |
| Storage relative humidity 85% | 90% | +1.29 |
| Storage relative humidity 95% | 90% | −1.44 |
| Air change, 0.003 empty vols/min | 0.004 empty vols/min | −3.46 |
| Air change, 0.005 empty vols/min | 0.004 empty vols/min | +3.46 |
| Air change, 0.007 empty vols/min | 0.004 empty vols/min | +10.41 |
| Air change, 0.010 empty vols/min | 0.004 empty vols/min | +20.87 |
| Cooling rate to give 5 day half cooling time | 10 day half cooling time | −1.50 |
| Cooling rate to give 15 day half cooling time | 10 day half cooling time | +1.52 |
| Cooling rate to give 20 day half cooling time | 10 day half cooling time | +3.04 |
| 90% Storage capacity | 100% | −7.30 |
| 110% Storage capacity | 100% | +7.32 |
| Ambient humidity −5% | Measured | −2.31 |
| Ambient humidity +5% | Measured | −2.31 |
| Ambient temperature −2°C | Measured | −17.69 |
| Ambient temperature −1°C | Measured | −8.91 |
| Ambient temperature +1°C | Measured | +9.06 |
| Ambient temperature +2°C | Measured | +18.30 |

Note: It is worth noting that the respiration rates taken for the table above were from Burton (1989) and were not the actual measured rates.

Source: Devres and Bishop (1995a) with permission.

allow for a clamp of 4 m width and 1.5 m height. Blocking them with a bale of straw or equivalent can close the A ducts. The cross sectional area of the duct should be a minimum of 0.013 $m^2$ per every ten tonne stored.

**Tropical structures**

The requirements of tropical potato storage can be different to those of more temperate climates. In general in the tropics there are two harvests or more per year which means there can be less demand for storage of more than three or four months. In addition the typical production area and store is smaller with many cases of storage being for the family with the potential to sell any surplus.

There are still examples, such as in the Mexican highlands, of tropical ambient ventilated stores of 3000 tonnes, but in many cases large stores are refrigerated and are used for seed. Most storage is in small low cost stores which have the intention of protecting the potatoes from undesirably high air temperatures and correspondingly, in many cases, low relative humidity, and also reducing the opportunities for predators and pests to aggravate losses. Therefore, there must be some air movement to keep the potatoes as cool as ambient conditions will allow. The mass of potatoes should not be allowed to be large enough to cause self heating and a maximum depth of 1.2 m is traditionally suggested. The storage lots should be reduced if the temperature exceeds 25°C (Hunt 1990).

The most basic store is a traditional woven basket, covered in straw, which may be within the home. The structure of a house that is intended to provide a stabilised environment for the residents and sometimes animals, against the extremes of weather is also of benefit in the storage of potato tubers. The weave of the basket allows for some natural ventilation and thus reduces the likelihood of hot spots or localized deterioration.

The tropical low cost store should, if possible, use any beneficial aspects of the climate and so in addition to some form of insulation and shading to minimise daytime heating there should be a form of ventilation with night air when the temperature is at its coolest and the relative humidity at its highest. (Hunt *et al*. 1982). This store is ventilated by the differences in the density of the air between the warm tubers and the ambient air. The warm air between the tubers will rise bringing in new, cooler ambient air. The materials used will depend on what is locally available, but it is important that the configuration of the roof ensures that the whole store is in shade during the day. It is also important that the walls are lined so that all the air moves in a vertical direction. The simplest system lifts the potatoes off the ground and ensures that air can pass through the tubers all at the time. The night ventilated version has flaps that can be opened to allow ventilation only at night, which can be particularly useful where there is a large diurnal variation such as at altitude.

A further development of the naturally ventilated store with night ventilation is described by Bishop and Stenning (1997) where a solar collector is used, so called solar cooling. Construction of this solar cooling makes use of rocks or similar material that are heated up by the sun during the day and then the flaps are opened at night and the heat of the rocks induces additional nocturnal ventilation. Initial trials carried out in Kenya at sea level near Mombassa gave some temperatures slightly lower than with night ventilation alone but additional development work is required.

### Evaporative cooling

When air carrying less than the total quantity of water possible at that temperature, less than 100% relative humidity, passes through a wetted pad or fine mist it will pick up water thus increasing its relative humidity. At the same time the energy required to vaporise the liquid water (the latent heat of vapourisation) comes from the air and so the air cools. This should mean that evaporative cooling has considerable use in potato storage in warmer and also drier climates as it can reduce temperatures and increase the relative humidity of the air.

Evaporative cooling in naturally ventilated stores with or without solar cooling did not show a significant benefit as the additional resistance to air flow of any damp pad had a negative effect which balanced the cooling potential (Bishop & Stenning 1997; Hunt 1990).

Evaporative cooling can work on forced ventilation stores, in particular in hot, dry conditions, but there have been many examples where this system has not worked as well as it theoretically should because of dry patches in the moist pad, an uneven pad, holes in the pad, or saline deposits clogging up the pad. Although the capital cost of evaporative cooling can be low it requires a high level of management and maintenance.

## POST-HARVEST HANDLING OF POTATOES

### Grading

The objective of the packhouse is to maximise the profit from the incoming product. This may involve virtually no treatment or extensive grading, cleaning and packaging, depending on requirements of the end user.

There are normally a number of different operations involved in a packhouse (often referred to as a grading or packing line) which can simplified as crop cleaning, sorting and inspection (grading), sizing and packing. As well as these operations there are the considerations of supply and removal of the product (and reject/trash) with the ever present concern of damage limitation.

In all countries there are various laws and regulations in place which are relevant to packhouse operation although the range and detail may be different. The legislation may cover aspects of hygiene, operator safety from machines, noise, dust and excessive working hours. Other legislation may involve pollution, disposal of waste and effect on the surrounding area. As well as various regulations and legislation the clients of the packhouse may also have their own additional requirements and it is important to ensure that all these requirements are considered.

### Reception facilities

The objectives of any bulk hopper system is to enable the bulker lorry, trailer, bulk bucket or box tippler to unload easily and quickly without damage to the crop and to provide a continuous supply of potatoes to the packhouse line at an appropriate rate. The size and dimensions of the hopper are therefore dictated by its being wide enough and the correct height for unloading and with a volume which can provide a reserve of tubers so that the line can still work even with intermittent supply. Typical capacities are between 3 and 15 tonnes. Another dimension that can be important is the

operating height above the bulk hopper as it has been known for trailers to have too high a tipping height to be able to use a bulk hopper, although this may be overcome with ramps.

The choice of hopper must fit the range of supply systems and should also avoid having a narrow discharge point as this can cause churning of the tubers and hence damage.

The supply from the bulk hopper must be readily adjustable so as to give optimum supply to the sorting, sizing and packing operation. The normal method of adjusting supply is by a manual operated, variable speed motor but sometimes proximity sensors or electronic eyes are used.

The objectives of a box unloading system are similar to those for bulk hoppers but the supply is in discrete one or half tonne units. The unloading system varies from equipment which will simply empty the box as fast as possible to systems which will gradually tip the box at the rate required to feed the line. Systems that will tip gradually can be controlled manually but more commonly are controlled by an electronic eye or proximity sensor placed before the first piece of operation on the line.

Some box unloading systems have the facility to weigh each box before unloading, count the number of boxes or have a bar code reader and it is anticipated that these facilities will become more common in the future.

Box tipplers or rotating buckets can be fixed to fork lift trucks or tractors and produce a rapid method of moving potatoes. There will always be damage and cut tubers around the bucket edge which may not be high in percentage terms but will need to be graded out at a later stage.

### Cleaners

Except in cases where the potatoes have been harvested soil free or previously cleaned, some form of cleaning is required. There are five main forms of tuber cleaning. In all cases a compromise has to reached between the level of cleaning and the possibility of damage.

The web-type system of soil extraction consists of a series of interlocking rods or rods fixed to a side belt. The webs are normally rubber covered (Huijsmans *et al*. 1990) or hollow (McRae *et al*. 1990) to reduce damage. The cleaning system relies on the web gap and agitation to remove the soil and is similar to that found on a potato harvester. This system will not remove stones or break up clods but can be useful as an intial cleaning system or precleaner.

A star cleaner consists of a series of interlocking rubber stars which revolve on shafts at right angles to the direction of product flow. The soft rubber fingers are backward curving and raise the tubers as they pass onto the next bank of fingers. This action can break up small clods and also in rubbing the surface of the tuber remove lightly attached soil. The use of brushes also can remove lightly attached soil and the quantity of surface abrasion can be changed by the stiffness of the brush used. Brushes are sometimes used with wet cleaning systems often after a soak tank to assist in reducing soil adhesion to the tuber surface. These systems can work well in removing small quantities of soil but can change into mud cylinders if there are large quantities of soil about.

Spools and discs can be used as a method of soil extraction using principles similar to those described above but in this case the forward motion comes from the tubers behind pushing the crop forward.

### Cleaners and washers

Choosing the best time to wash the crop is major element in quality control. Washed potatoes are more attractive to consumers and attract price increases. However, washing also makes them more susceptible to deterioration and loss. Fingers and Fontes (1999) claimed that the average storage life of 30 to 40 days in perfect conditions reduced to 7 to 15 days once potatoes had been washed. Washing is therefore usually dictated by the imminence of conveying them to market.

Particularly for the prepack market, it is a requirement that tubers are washed, and this is normally done using a barrel washer in which they are tumbled around in water inside the barrel. The amount of cleaning depends on the speed of rotation, the inside surface and the time in the washer which is normally altered by changing the angle of the washer to the horizontal. The barrel is typically around 15% under water so that the potatoes keep falling back into the water, which provides agitation and cleaning. It is possible to have a dry barrel cleaner with sides made of bars. There can be a high level of damage to the tubers if they are "thrown" against the sides of the drum but the insertion of a "brake sail" made of a thick plastic material can slow down the movement and reduce the variability of the mechanical load (Geyer & Oberbarnscheidt 1998).

For the disposal of the water from a barrel washer it is normal to use recycled water from both the cost and environmental standpoint. Various methods are used for removing mud, sand and fine organic particles such as sieves, sedimentation and hydro-cyclonic systems (Geyer 1996). There is a variety of machines available on the market suitable for washing and drying potatoes.

Stone seperation or removal is important not just because of the fact that stones are a reject product but because of the potential damage to potatoes and equipment. Most modern

harvesting systems will remove the majority of stones but there is always the possibility that some will remain. Separation methods use the fact that the density of stones is very much higher than potatoes.

### Graders or sizers

The size of a potato can be measured by its dimensions or by its weight. Some sizing can be done by vision grading methods but this is considered under the section on inspection. Traditionally, and still the most common method, is by dimension even though some dimension methods such as screen mesh sizers have an accuracy of +40% as opposed to an optical weight grading system with an accuracy of +9% (Glasbey *et al*. 1988).

The most common form of size grading is with endless screens, when the tubers pass over a series of screens which are rotating like conveyor belts. The size of aperture in the screens increases with each one so that the smallest tubers fall through first onto cross conveyors. There is normally gentle agitation, but the size of aperture through which the tuber falls can very much depend on the orientation of the potato.

A second form of size grading is the riddle system where the seives or riddles can either be stacked with the largest mesh riddle uppermost (this system takes up a limited horizontal space) or the less common jump grade where the tubers gradually "jump" along the sieves falling from one size to another. In the case of the jump or step grader the smallest size goes first. The potential for damage has meant that riddle graders are losing popularity.

Another method of size grading is by weight which is where individual potatoes are passed over a weighing mechanism and then routed depending on weight, as shown in Figure 16.5. This method has been popular in the apple industry for many years. Although a more costly method than tradition size grading this system has become common for specific markets such as for baking potatoes. Weight sizing has the potential to be more precise as the weight increases as a cube of the radius of a tuber.

### Inspection

Almost all potato inspection is still done manually and with most systems the tubers have to be inspected at a rate of 3–6 tubers a second. The inspection takes place on a roller table where the the rotating tubers pass by the operator who has to remove any defects. Some inspection systems can have very low efficiences. A survey by Elstob *et al*. (1988) showed that some inspection systems on farms in the UK had operator efficiencies of 60% to as low as 8%.

Some work has been done on the investigation of speed of the tubers passing the operator, the rotation speed of the tuber and the quantity of defects to be removed. The initial work was done by Malcolm and De Garmo (1953) with artificial (wooden) potatoes with limited field trials. They suggested that each operator should inspect 250–300 tubers per minute at a speed past the operator of 6–9 m/min and a rotation speed of 6–12 revolutions per metre travel. Hunter and Yaeger (1970) carried out field trials with real tubers, artificially blemished, and the conclusions were that the feed rate could be adjusted to give 0.75 t of defects per hour. This was estimated by McRae (1985) as 6250 defective tubers removed an hour assuming a mean weight of 0.16 kg per tuber. In tests 90% efficiency was achieved when there was a 20% defect level and a flow rate of 450 tubers per minute.

**Figure 16.5** Size grading of potatoes where individual potatoes are passed over a weighing mechanism and then routed depending on weight.

The American figures are higher than those recorded in the UK which should give efficiencies of 67% for 0.72 t-h and 33% at 2.26 t-h but this was suggested by McRae (1985) as to be at least partially attributed to the fact that the mean size of tuber meant that there were 36% more in each tonne and that naturally defective potatoes were used.

Work by Bishop and Garlick (1998) also showed that the forward velocity of the tubers can be 20% less at the edge as opposed to the centre of a roller table. Their work also found that the speed of rotation was influenced by the loading level and whether size grading had ocurred prior to the roller table.

Illumination levels for the inspection of potatoes are important factors in the inspection efficiency. In Figure 16.6 the grading line has lights directly above. Both the intensity of illumination and the colour of the light is important.

**Figure 16.6** An inspection line for potato tubers with lighting placed immediately above the conveyor belt.

Zegers and van den Berg (1988) showed that the inspection should be carried out with an illumination of between 500 and 2000 lux with no significant differences of performance within this range. Often the illumination level, in practice, is below this and in work carried out by Hyde (1991) in the state of Washington the levels varied between 350 and 700 lux.

Zegers and van der Berg (1988) also suggested that the colour of the light should be at least 85 on the colour rendering index for effective inspection. The colour rendering index is effectively a measure of whether there is a preponderance of a particular colour in the light used; this could make it more difficult to see certain defects on the tuber surface. Natural light has a colour rendering index of 100. The colour rendering index found to be most common by Hyde (1991) was 62 with a cool-white flourescent tube.

### Vision grading

For a number of years there has been the potential for potatoes to be graded automatically with systems available to sort by size, colour, shape and blemish (Muir *et al*. 1989; Tao *et al*. 1990). Rates of 30–40 tubers per second have been achieved. Although there has been much interest in these systems and one or two have gone into commercial locations there has been no large uptake for potatoes. The initial capital cost and the precise definition of what is acceptable have proved obstacles to their adoption.

Although not directly connected to vision grading the use of acoustic resonance sensing to assess firmness is one of the other areas that could have increased importance in the future (Terdwongworakul *et al*. 1995). This method subjects the tuber to a mechanical vibrational input which then produces a number of characteristic resonance peaks as a response; the second resonance frequency corresponds to the principal mode of vibration for the flesh and this frequency has been observed to fall as the tuber softens.

### Conveyors and elevators

Cushioning is important at many points in the handling system and "any cushioning material must combine high surface wear resistance with retention of resilience over a long period" (McRae 1990). Armstrong *et al*. (1995) summarised the requirements of any cushioning material as absorbing at least 60% of the impact energy to minimise product rebound, the durability and ability to clean must be good and the uniformity between different production lots should be low. Bollen and Dela Rue (1995) evaluated a number of cushioning materials and found that "a closed cell PVC foam was the best material with polyethylene foam and neoprene rubber exhibiting adequate characteristics over the energy range of the tests". For the purposes of testing, the padding materials were impacted by an instrumented sphere (Zapp *et al*. 1989) at six energy levels between 0.3 J and 1.8 J using a pendulum impact device.

Frictional damage is an area which has received only limited interest, the dynamic coefficient has been investigated by Schaper and Yaeger (1992) in 25 kg lots and by Bishop (2007) which both show significant differences in between surfaces and for clean or dirty dry or wet tubers. The potential for frictional damage or scuffing can be further increased if tubers are transferred from one conveyor to another where the tuber is rotating in the opposite direction to the second conveyor giving an increased effective contact velocity (Bishop 1990).

Although all drops during potato handling should be minimized, the size of drop may vary with the level of tubers such as in a holding hopper. Work done by O'Brien *et al*. (1980) on filling systems for fruit and vegetable crops found that an elevator with height sensor was the most effective. In some situations it may not be possible to have a height or proximity sensor and in these cases a method using a telescopic "zig-zag" system may be used, in which the direction of the potatoes is constantly changed and the downward velocity slowed.

The level of dust produced in a potato packhouse can be very much influenced by the design of the handling system and, for instance, large drops of soil from soil extraction systems can greatly increase dust problems. McGovern (1991) describes dust extraction systems for use in grading lines. Increasingly, to satisfy health and safety considerations, air suction points are required at any drops in the

packing line or above any sizing operation which involves agitation such as the use of riddles.

### Damage limitation

Throughout the harvest and post-harvest operations one of the main causes for loss of quality is mechanical damage. A study carried out by Larsen (1962) reported that in the United States 42% of potatoes exhibited blemishes after harvest, 54% after grading and 64% after transport. This study therefore indicated that approximately two thirds of the potatoes bought by consumers had internal or external blemishes. Although the situation has improved since this survey, losses of $125 million were estimated by Preston and Gynn (1995) on a total United States production of $2 billion. A review by Brook (1996) estimated that a 1% reduction in the number of impact related defects in potato tubers was worth approximately $7.7 million in an average year in the United States.

A ware potato chain analysis in the Netherlands (Molema *et al*. 1999) showed that 78% of the total amount of subcutaneous tissue discolouration was caused by impacts.

### Causes of damage

It has been established that potatoes are more susceptible to impact injury at low temperatures such as 4°C, than at higher temperatures such as 15°C. Impact damage caused during grading of susceptible tubers may be reduced by raising the temperature prior to the operation. The results of Wiant *et al*. (1951) on standard experimental bruising of tubers showed a decrease in incidence from 83% at 3°C to 8% at 21°C. McRae *et al*. (1975) found that 77% of a sample of tubers showed signs of splitting when dropped 1100 mm at 5°C whereas this had decreased to 38% at 8°C. It is therefore beneficial to warm potatoes from cold stores prior to grading and although this can often be done by removing the tubers from storage one or two days prior to grading it is sometimes necessary to have a faster response. Pringle (1993) used forced warm air to carry out this operation without condensation and found that the time could be reduced to around 10 h with a ventilation rate of 140 $m^3$/t/h through individual boxes of 0.9 m deep. However, if a high ventilation rate with warmed air is to be used, the system will require double handling and the provision of a separate warming bay. The energy usage for this operation is around 0.7 kWh/t of electricity for air distribution and a further 60 MJ/t of heat to warm the crop. Another method of rapid tuber warming is using radiant heat above the tubers on a reception roller table. Bishop *et al*. (2000) achieved rapid warming in under 2 min with damage reduction using radiant heat but the method involves another operation, further equipment and space.

**Table 16.6** Proposed Names and Definitions of Types of Mechanical Damage.

| Names | Definitions |
|---|---|
| Scuffing | The skin (epiderm) is damaged and removed partly or totally. |
| Cuts | Part(s) of the tuber is (are) sheared, or shearing may be accompanied by loss of tissue. |
| Crushing | Rupture of tuber tissue caused by compressive forces. |
| Splitting | The tuber has splits in the flesh, propagated from the surface. |
| Bruising | Subsurface damage to the tuber tissue which subsequently causes blue/grey to black discoloration of the flesh. |

**Table 16.7** Depths and Surfaces of Damage to Qualify Damage Classifications.

| Classification | Depth mm[1] | Depth cm[2] | Surface %[3] | Surface %[4] |
|---|---|---|---|---|
| None | 0 | 0 | 0 | 0 |
| Slight | 0–1.7 | 0–1 | 0–2 | 0–10 |
| Moderate | 1.7–5.1 | 1–2.5 | 2–5 | 10–20 |
| Severe | > 5.1 | > 2.5 | > 5 | > 20 |

Note: 1 and 2 to qualify cuts, crushing and splitting; 1 and 3 to qualify bruising and 4 to qualify scuffing.

The growing conditions and use of fertiliser and irrigation are also important factors in damage. Thornton and Timm (1990) showed that rain or irrigation a short time before harvesting produced a high water content in the tubers and soil and increased shatter bruising.

### Types of damage

Although there are two basic types of damage which occur with mechanical handling (Jastrzebski 1978), "mechanical damage" and "impact damage", these are very broad classifications. The Engineering Section of the European Association of Potato Research has tried to develop a standardised name and definition of mechanical damage. The proposed classification system is given in Tables 16.6 and 16.7 (Bouman 1996).

Workers at Washington State University have developed a bruise classification system which puts the tuber into one of seven categories: no bruise, blackspot, crush, white spot/white knot, internal shatter, external shatter and external cracking (Baritelle *et al*. 1999a).

**Table 16.8** Factors Affecting the Severity of External Damage.

| Likelihood of splitting | | |
|---|---|---|
| Less | More | References |
| Decreasing drop height | Increasing drop height | McRae *et al*. 1975 |
| Impact flat surface | Impact web rod surface | McRae *et al*. 1975 |
| | | Shimada 1980 |
| Decreasing tuber weight | Increasing tuber weight | Parke 1963 |
| Higher temperature | Lower temperature | Johnsonson and Wilson 1969 |
| Flaccid tubers | Turgid tubers | Hesen and Kroesbergen 1960 |
| | | Finney and Findlen 1967 |
| Mature tubers | Immature tubers | Finney *et al*. 1964 |

The importance of falling distance, conveyor belt speed and materials used has been known for many years and has been well documented since the 1950s (Vollbracht & Kuhnke 1956). In a large packhouse the tubers can pass over up to 100 transfer points during movement from store to retail bag and this can greatly increase the risk of damage (Peters 1996).

The factors that influence the extent of external damage were summarised by McRae (1985) and are given in Table 16.8.

Instrumented spheres have been developed in a number of countries, to measure the level of impact that the tuber experiences. Two examples of the results obtained are given in Figures 16.7a and b (Maunder *et al*. 1990) of grading into store and from a grading and packing line. Instrumented spheres are useful for the assessment of individual grading lines and comparison between packhouses.

**Assessment of damage and susceptibility**

Assessment of damage is the quantification of damage that has already ocurred and the assessment of susceptability is the potential for damage of a specific variety or the potential for damage in a specific situation. In both cases any system should be quick to use, repeatable and not operator dependent.

One damage assessment method was developed by the Scottish Centre for Agricultural Engineering (Robertson 1970). Different levels of damage were categorised as follows:

1. undamaged (0 points)
2. slightly bruised: the tuber may be only scuffed, where a bruise may be detectable after a stroke of a hand peeler, but not after two strokes (to a depth of 1.5 mm) (1 point)
3. moderately bruised: where bruises necessitate peeling to a depth of 4 mm to remove (3 points)
4. severe bruising: where the bruise can only be removed by peeling to a depth of more than 4 mm (7 points)

The method is used for both harvesting and handling operations and the total score for handling operations should be less than 50 per 100 tubers. The two main drawbacks with this system is that it is stepped and does not include bruising damage. There are other methods which give a linear rather than stepped index and include bruising. Evans and McRae (1996) described a system which involved the number of peeler strokes which were needed to remove all damage and bruised areas to give the damage index.

One difficulty with bruise assessment is that bruises take time to develop and the standard method used by many growers and packhouses involves placing the tubers in a high humidity atmosphere for 24 h at around 37°C before bruise assessment. It has been shown that holding the potatoes at a similar temperature but in pressurised oxygen (1.5 bar) will develop latent bruising (Duncan 1973); results could be obtained in seven hours. The system was further developed to give results in five hours with humidified oxygen (Melrose & McRae 1987). However, owing to safety and cost considerations work was then carried out using compressed air at 3 bar which gave similar periods of time to oxygen (McRae & Melrose 1990).

To assess the susceptability of a tuber to impact damage it is necessary to measure both mechanical and chemical properties (Baritelle *et al*. 1999b).

After impact the flesh of the tuber changes colour and Dean *et al*. (1993) suggested that the grey/black colour was caused by both enzymatic and non-enzymatic oxidation of phenolic substances by the enzyme polyphenoloxidase (PPO). This oxidation results in the formation of melanin pigments. Reeve (1968) suggested that PPO mixed with phenolic substances when the cell membranes were disrupted, meaning that damage to the cell wall may not be required for membrane failiure to occur. Baritelle *et al*. (1999b) have developed a method for producing fast results for measuring the chemical properties of the tuber in

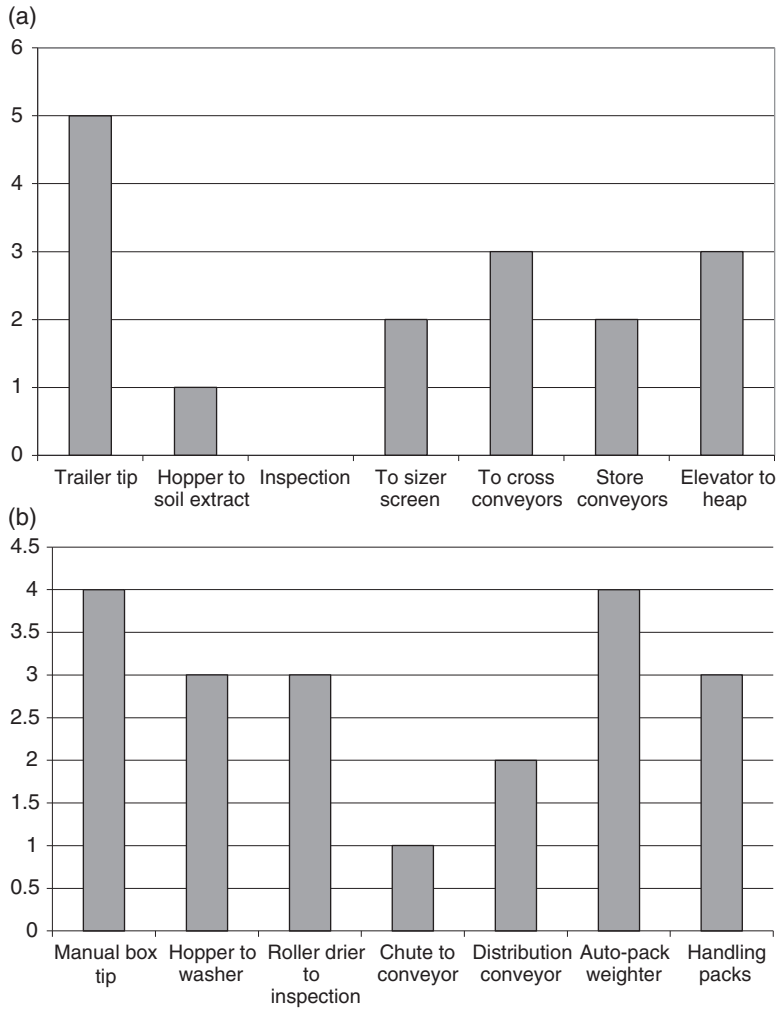


**Figure 16.7** Results obtained from instrumental spheres designed to estimate the level of impact experienced by potato tubers at different stages of handling. Typical maximum impact readings obtained during (a) grading into store and (b) the pre-pack line. Figures given in y-axis are for comparison of the damage level for different operations. (Maunder *et al.* 1990, with permission.)

relation to impact sensivity based on the principle that the majority of the intercelluar space is water. "The procedure consists of the freezing and thawing one-mm thick slices of tubers wrapped in a thin plastic film to retain moisture during the test. After thawing (3 hours approximately) slices can be photographed using a digital camera and directly imported into a computer program, Adobe PhotoShop™, converted into greyscale and the K value from the CMYK system can be measured as a percentage of grey. This procedure takes approximately six hours and can be correlated with the chemical potential reported in the literature." Baritelle *et al*. (1999b).

Quantification of mechanical dynamic failure properties is normally done by a pendulum method. Schippeers (1971) produced a review of the bruising methods used and divided them into methods by which the place and the size of impact can be quantified (drop weight or pendulum methods) and, secondly "bulk bruising methods" where several tubers are used at once and may be no more than running a sample of potatoes over a grader.

There has been extensive use of pendulum systems to give tuber data (Grant & Hughes 1995; Skrobacki *et al*. 1985; Gall *et al*. 1996). In general, the weight of the pendulum used is 76–292 g, the height of fall 100–500 mm and the radius of

the impact weight is 5–10 mm (Martins 1996). The other equipment which has been used for the compression of tissue samples was given by (Bajema *et al*. 1998).

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# 17
# Onions, Shallots and Garlic

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## INTRODUCTION

Onions (*Allium cepa* L.), shallots (*A. cepa* group Aggregatum) and garlic (*A. sativum*) are all plants of the genus *Allium* which produce edible bulbs and leaves. Botanically, the family *Alliaceae* is related to the *Liliaceae* and the *Amaryllidaceae* within the monocotyledons. The majority of species of the large *Allium* genus are distinguished by the presence of sulphur containing compounds which give the typical onion or garlic smell and flavour for which the allium crops are prized. Other important compounds include saponins and flavonols, which also contribute to the flavour and the health benefits from eating alliums. The main storage carbohydrates in onions are complex fructans, especially abundant in pungent onions, while in sweet onions there are higher levels of simple sugars (Davis *et al*. 2007).

Onions and other bulb alliums are important vegetables in world trade since they can be shipped when dormant. Annual figures published by the FAO (Food and Agriculture Organization of the United Nations) show that onion world production has risen steadily in recent years, reaching a total of 64.47 million tonnes in 2007 (FAOSTAT 2008). Estimates of the proportion of onions traded internationally vary from 6 to 10%: for example, the volume exported in 2005 (Tables 17.1 and 17.2) was nearly 5 million tonnes, representing about 7.6% of reported production. However, we should be aware that a lot of 'informal' trade across frontiers is not reported in the official figures (from Tanzania to Kenya for example). In addition to 'dry bulb onions', over 500 000 tonnes of 'green onions plus shallots' were also exported in 2005 (Tables 17.3 and 17.4). For garlic, world annual production is about 15 million tonnes and of this, over two-thirds originate in China, which is also by far the most successful exporter (Table 17.5), while many different countries are substantial importers (Table 17.6) (FAOSTAT 2008).

Major onion producing countries extend from the tropics to temperate regions and onions are produced in countries ranging from the equator to Scandinavia. Since onions are sensitive to photoperiod, a very wide range of onion cultivars has been developed, from 'short day' to 'very long day' adapted, to cover all the latitudes where onions are grown. The highest national onion yields are recorded from temperate countries with long growing seasons (e.g. Ireland and Korea, mean yields 58.0 and 57.0 t/ha respectively in 2007, compared to an average world yield of 18.7 t/ha; FAOSTAT 2008). Temperate climates allow the onion to develop a large vegetative plant before bulbing starts, thereby giving it the capacity to produce a large bulb. In many tropical countries with seasonal climates, onions grow and produce well in the cool season. However, they are more difficult to grow near to the equator in very humid climates and at low altitudes: here, tropical shallots are the traditional alliums produced (e.g. in Indonesia). Traditional garlic production areas are mostly located in Mediterranean climates (including California, Argentina and Chile) and also in India and the East Asian countries.

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**Table 17.1** World Trade in Dry Bulb Onions: Exports, 2005.

| Country | Quantity (mt) | Value ($US million) |
|---|---|---|
| World | 4 868 797 | 1129.0 |
| Argentina | 201 871 | 30.9 |
| Australia | 54 060 | 16.4 |
| Austria | 44 281 | 5.5 |
| Belgium | 88 367 | 23.8 |
| Canada | 58 235 | 24.3 |
| Chile | 54 700 | 15.8 |
| China, People's Republic of | 570 669 | 117.8 |
| Egypt | 300 996 | 31.0 |
| France | 42 825 | 20.6 |
| Germany | 39 128 | 14.5 |
| Guatemala | 21 048 | 3.7 |
| India | 961 806 | 160.9 |
| Iran | 23 471 | 3.3 |
| Italy | 35 252 | 33.5 |
| Kazakhstan | 64 337 | 7.9 |
| Malaysia | 112 727 | 25.9 |
| Myanmar | 39 908 | 8.8 |
| Netherlands | 847 310 | 195.5 |
| Niger | 68 008 | 20.9 |
| Pakistan | 29 597 | 3.7 |
| Peru | 58 400 | 17.3 |
| Poland | 168 051 | 39.9 |
| Saudi Arabia | 24 495 | 5.0 |
| Spain | 203 826 | 63.0 |
| Tajikistan | 31 862 | 6.4 |
| Thailand | 67 713 | 11.8 |
| Turkey | 63 673 | 6.9 |
| United States | 327 904 | 145.4 |
| Uzbekistan | 48 626 | 19.0 |

Note: Only countries exporting >20 000 metric tonnes (mt) are shown. 1 mt = 1000 kg

Source: Data from FAOSTAT (2008).

**Table 17.2** World Trade in Dry Bulb Onions: Imports, 2005.

| Country | Quantity (mt) | Value ($US million) |
|---|---|---|
| World | 4 780 980 | 1428.4 |
| Bangladesh | 332 551 | 69.4 |
| Belgium | 153 547 | 45.7 |
| Canada | 154 504 | 80.3 |
| China, People's Republic of | 39 579 | 16.9 |
| Colombia | 43 990 | 3.2 |
| Czech Republic | 31 737 | 5.5 |
| France | 95 223 | 40.2 |
| Germany | 227 456 | 90.4 |
| Indonesia | 22 133 | 6.8 |
| Ireland | 36 085 | 20.0 |
| Italy | 44 937 | 12.7 |
| Japan | 357 544 | 100.2 |
| Jordan | 20 697 | 4.6 |
| Korea, Republic of (South) | 39 876 | 5.6 |
| Kuwait | 62 909 | 8.5 |
| Malaysia | 420 832 | 100.6 |
| Nepal | 31 876 | 3.8 |
| Netherlands | 87 834* | 27.7 |
| Oman | 36 076 | 8.2 |
| Philippines | 40 323 | 8.6 |
| Portugal | 30 247 | 6.1 |
| Qatar | 24 806 | 4.9 |
| Romania | 42 493 | 6.3 |
| Russian Federation | 500 473 | 113.7 |
| Saudi Arabia | 255 157 | 43.5 |
| Senegal | 107 601 | 13.4 |
| Singapore | 42 527* | 13.5 |
| Spain | 27 847 | 8.7 |
| Sri Lanka | 122 454 | 21.4 |
| Sweden | 29 614 | 17.6 |
| Thailand | 35 870 | 5.1 |
| United Arab Emirates | 142 919* | 26.3 |
| United Kingdom | 304 265 | 117.7 |
| United States | 299 014 | 228.5 |
| Viet Nam | 42 684 | 5.9 |

Note: Only countries exporting >20 000 metric tonnes (mt) are shown.

* Denotes countries which act as important entrepôts for onion trade.

Source: Data from FAOSTAT (2008).

## TRADE IN ONIONS, SHALLOTS AND GARLIC

Both production figures and the import and export figures for dry bulb onions and garlic are recorded annually by the FAO, based on national data (FAOSTAT 2008). The summary tables (Tables 17.1, 17.2, 17.3, 17.4, 17.5 and 17.6) presented here aim to give an idea of the major exporters and importers of the main allium bulb crops. Some big onion producing countries do not export the bulbs (e.g. Brazil), whereas smaller countries such as the Netherlands may export a large percentage of their onion crop (Tables 17.1 and 17.2).

**Table 17.3** Trade in Green Onions and Shallots: Exports, 2005.

| Country | Quantities (mt) | Value ($US million) |
|---|---|---|
| World | 522 033 | 376.4 |
| Afghanistan | 14 807 | 0.9 |
| Austria | 2451 | 0.5 |
| Brazil | 1186 | 0.2 |
| France | 21 111* | 24.5 |
| Germany | 2089 | 2.4 |
| Indonesia | 4259 | 1.5 |
| Italy | 1091 | 1.3 |
| Mexico | 273 193** | 286.4 |
| Netherlands | 34 155 | 11.0 |
| New Zealand | 160 705 | 43.9 |
| Poland | 1169 | 0.9 |

Note: Countries exporting >1000 mt of the combined crops are listed.

*France is an important exporter of dry bulb shallots to other European countries.

**Mexico's exports are mainly of green onions (both *Allium cepa* and *A. fistulosum*) to Europe in seasons which are unfavourable for salad onion production there. Egypt, which exports large amounts of green onions to the United Kingdom in winter, is not listed by FAO in this category.

Source: Data from FAOSTAT (2008).

**Table 17.4** Trade in Green Onions and Shallots: Imports, 2005.

| Country | Quantities (mt) | Value ($US million) |
|---|---|---|
| World | 547 165 | 131.8 |
| Austria | 1051 | 0.7 |
| Belgium | 4937 | 5.3 |
| Brazil | 169 518 | 22.8 |
| Bulgaria | 17 068 | 1.6 |
| Côte d'Ivoire | 58 231 | 13.1 |
| France | 1453 | 1.5 |
| Germany | 6226 | 6.6 |
| Indonesia | 53 071 | 15.4 |
| Italy | 4311 | 4.3 |
| Lesotho | 1250 | 0.4 |
| Mauritania | 2734 | 1.0 |
| Mexico | 49 043 | 15.3 |
| Netherlands | 2294 | 1.1 |
| New Zealand | 1009 | 0.6 |
| Pakistan | 71 205 | 9.9 |
| Paraguay | 65 964 | 10.9 |
| Poland | 1200 | 0.2 |
| Tunisia | 6845 | 0.6 |
| Switzerland | 1002 | 1.5 |
| Trinidad and Tobago | 6305 | 1.8 |
| United Kingdom | 11 371 | 10.6 |
| Uruguay | 1962 | 0.3 |

Note: Countries exporting >1000 mt of the combined crops are listed.

Source: Data from FAOSTAT (2008).

To find satisfactory figures for dry bulb shallots is more difficult, since in the FAO statistical reports they are grouped together with green (spring or salad) onion. Green onion is a perishable leafy crop which is currently traded in considerable quantities, for example from Mexico and Egypt to Europe during the European winter, but does not seem to be reported consistently (Tables 17.3 and 17.4). Within Western Europe, where dry bulb shallots are popular for cooking, France and the Netherlands are important producers, while in the southern hemisphere, Argentina also produces shallots for export. Tropically adapted (short-day) shallots are important in several hot and wet countries such as Thailand and Indonesia: shallots and sometimes the similar but larger multiplier onions are also produced in southern India, Sri Lanka, Thailand, the Philippines, coastal and some mountainous parts of West Africa, Ethiopia and the West Indies. The main advantage of growing shallots in the tropics is that they can be propagated vegetatively to provide an onion-flavoured vegetable in countries where true onion seed is difficult to produce.

**Trade routes**

Trade in onions in Europe and the Mediterranean area traditionally involved the warmer producer countries such as France, Spain and Egypt sending onions to more northerly countries such as Britain and Germany. In Eastern Europe, Poland and Hungary also have cultivars with good keeping qualities which are exported. Several of the ex-USSR republics of Central Asia now figure as exporters (Table 17.1), probably to Russia. In recent years, selection of the Dutch Rijnsburger types of onion and the development of mechanized growing methods together with improved storage technology have allowed onions to be produced more cheaply in northern Europe. However, while technically these countries could be self-sufficient for onion supply, the rise in the power of the supermarkets

**Table 17.5** Trade in Garlic: Exports, 2004 and 2005.

| Country | Quantities year 2004 (mt) | Quantities year 2005 (mt) | Value year 2004 ($ millions) | Value year 2005 ($ millions) |
|---|---|---|---|---|
| World | 1 455 383 | 1 515 814 | 707 158 | 923 862 |
| Argentina | 100 637 | 97 301 | 66.6 | 85.0 |
| Bangladesh | 1484 | 1484 | 0.8 | 0.8 |
| Belgium | 1583 | 2103 | 3.1 | 4.1 |
| Cambodia | 1714 | 1714 | 0.5 | 0.5 |
| Chile | 7535 | 5603 | 7.0 | 5.9 |
| China, People's Republic of | 1 127 833 | 1 158 717 | 419.1 | 563.5 |
| Egypt | 4272 | 1894 | 2.3 | 0.9 |
| France | 12 314 | 12 462 | 29.0 | 33.9 |
| Germany | 1226 | 1288 | 2.8 | 3.3 |
| Hungary | 1334 | 1364 | 1.6 | 1.9 |
| India | 2236 | 32 495 | 0.9 | 8.5 |
| Italy | 10 256 | 8894 | 18.9 | 18.5 |
| Lebanon | 1501 | 177 | 0.1 | 0.1 |
| Malaysia | 50 415 | 42 591 | 9.2 | 8.0 |
| Mexico | 9357 | 10 739 | 10.4 | 14.4 |
| Myanmar | 2918 | 5559 | 0.5 | 1.7 |
| Netherlands | 8945 | 13 279 | 13.0 | 21.1 |
| Niger | 1493 | 383 | 0.2 | 0.1 |
| Philippines | 5094 | 6402 | 1.7 | 5.8 |
| Saudi Arabia | 3732 | 1901 | 0.8 | 0.6 |
| Singapore | 1768 | 1531 | 0.8 | 0.8 |
| Spain | 65 993 | 65 111 | 92.9 | 112.7 |
| Thailand | 514 | 3882 | 0.3 | 2.4 |
| Turkmenistan | 1880 | 1749 | 1.2 | 1.6 |
| United Arab Emirates | 7978 | 16,609 | 2.6 | 5.6 |
| United Kingdom | 2750 | 978 | 3.5 | 2.3 |
| United States | 5605 | 6020 | 7.8 | 9.2 |

Note: Countries exporting >1000 mt of garlic are listed.
Note the large fluctuations between years for volumes exported from some countries.
Source: Data from FAOSTAT (2008).

means that the outward appearance of onions is increasingly important as a selling point. So imports of fresh, attractive onions from the southern hemisphere are preferred by the buyers at times when those out of store in Europe look rather jaded. Onion markets are intensely competitive and supermarkets buyers use this factor to drive down prices to producers.

Within Asia, there are important trade flows of pungent red onions from India and Pakistan to markets in Singapore, Malaysia and the Arabian Gulf states. The special requirements for size and colour of these markets are well known to merchants in the region. In Pakistan, for example, hard pink or red onions produced in desert areas of Sindh province can be stored in the field in sacks for up to eight months: at the merchants' premises in Karachi they are graded for size and then sent to the appropriate regional markets around the Indian Ocean. On a world scale, China is listed as the largest onion producer (FAOSTAT 2008). However, these figures may be questionable, since the leafy species *Allium fistulosum,* or Japanese bunching onion, is consumed on a very large scale in China and may possibly be included in the reports of 'dry bulb onion'

**Table 17.6** Garlic Trade: Imports, 2005.

| Country | Quantities (mt) | Value ($ million) |
|---|---|---|
| World | 1 430 975 | 843 130 |
| Algeria | 12 931 | 4.8 |
| Australia | 8237 | 7.2 |
| Bangladesh | 54 815 | 24.2 |
| Belgium | 5176 | 10.8 |
| Brazil | 132 581 | 73.5 |
| Canada | 11 840 | 13.9 |
| Chile | 5611 | 2.9 |
| Colombia | 22 530 | 6.6 |
| Czech Republic | 7256 | 10.9 |
| Dominican Republic | 7382 | 3.5 |
| Ecuador | 8518 | 4.2 |
| France | 27 498 | 47.4 |
| Germany | 14 357 | 31.2 |
| Haiti | 6483 | 5.7 |
| Indonesia | 283 283 | 66.7 |
| Italy | 26 601 | 40.6 |
| Japan | 30 268 | 24.1 |
| Korea, Republic of (South) | 15 633 | 7.9 |
| Kuwait | 6474 | 2.8 |
| Malaysia | 102 972 | 48.8 |
| Mexico | 16 908 | 21.4 |
| Morocco | 6205 | 3.8 |
| Netherlands | 18 510 | 19.0 |
| Oman | 8414 | 4.0 |
| Pakistan | 51 030 | 18.0 |
| Philippines | 49 925 | 24.6 |
| Poland | 7776 | 8.4 |
| Portugal | 6517 | 10.3 |
| Romania | 9519 | 3.1 |
| Russian Federation | 41 133 | 18.3 |
| Saudi Arabia | 27 670 | 10.0 |
| Senegal | 7471 | 2.8 |
| Singapore | 10 893 | 6.4 |
| Spain | 13 360 | 16.9 |
| Sri Lanka | 18 426 | 4.6 |
| Thailand | 47 803 | 6.3 |
| Tunisia | 6431 | 1.5 |
| United Arab Emirates | 24 832 | 12.7 |
| United Kingdom | 15 290 | 21.9 |
| United States | 69 640 | 74.9 |
| Viet Nam | 72 766 | 17.5 |
| Yemen | 7870 | 2.9 |

Note: Countries importing >5000 mt are listed.
Source: Data from FAOSTAT (2008).

(*A. cepa*) which is still a comparatively recent introduction into China. A close look at the production figures in a country report from 1993 suggested that only about one-tenth of the 'onions' produced in China were actually dry bulb onions (Xu *et al*. 1994), although the situation may have changed in the last few years. Recently a report from an importer into the Japanese market suggested that China may be increasing onion exports in the East Asian region (S. Follen, quoted by Kennington 2003). Japan is a major regional importer and buys large early-bulb onions from tropical countries such as Taiwan, Thailand and the Philippines, and Spanish-type onions from the western United States. Australia and New Zealand are also keen to develop East Asian markets for onions; they already supply onions to islands of the Pacific as well as exporting to Europe. Other competing southern hemisphere exporters include Argentina, Chile and South Africa, all of which have seasonal advantages for selling to Europe, the United States, Canada and Japan.

Mexico is increasingly important as an early onion supplier to the United States. The United States is a major producer with several different seasonal production regions which are exploited in turn by merchants to maintain supplies to markets all year round. Different US regions specialize in producing sweet onions (e.g. Vidalia in Georgia), large Spanish-type onions or pungent winter storage types. The United States exports onions at some seasons and imports them at others. In South America, Brazil is a large-scale producer but cannot meet domestic demand. The shortfall is mostly obtained from Argentina, which has several different onion production regions. Peru is scaling up its onion production and exports sweet onions to the United States in the off-season period.

The Netherlands sells within Europe, acts as an entrepôt and supplies African and other overseas markets, particularly during their off seasons, and also sells to any country which experiences a sudden onion shortage. Within West Africa, Niger and Mali sell onions to the wetter coastal states and well-established trade connections exist between the producers and buyers in coastal cities, mediated by groups of merchants who control this commerce (David & Moustier 1996; 1998). Some big importers such as Singapore and the Emirates in the Arabian Gulf evidently also act as entrepôts for neighbouring states, since they both import and export substantial quantities and (at any rate in the case of Singapore) lack the areas of farmland needed to produce onions.

The world garlic trade is dominated by one producer, the People's Republic of China, which is by far the most prolific producer and successful exporter (Table 17.5).

China has increased garlic production at a rapid rate in recent years and this has had a suppressing effect on production in other countries which are failing to compete on price. Countries such as Argentina are upgrading quality so as to retain traditional markets in Europe. Spain and France are traditional producers which are feeling the effects of competition. Trade sanctions are being used by some countries to restrict Chinese garlic imports in order to protect local garlic producers. However, with greater openness in world trade, this will probably only work in the short term. The demand for garlic continues to rise as new health findings make it more attractive to consumers and new uses are found, such as for the control of diseases (for example, white rot of onions; Crowe *et al*. 2000) or to deter pests. However, temporary bulges in supply, as for all perishable commodities for which demand is relatively inelastic, can lead to price collapse and this can be disastrous for local producers.

## HISTORICAL REVIEWS AND KEY FINDINGS

A compendium of information on vegetables by Messrs Vilmorin-Andrieux of the famous French seed company, in the mid-nineteenth century, mentions the keeping qualities of about 30 European and US cultivars of that time. In William Robinson's English translation of this book (1885), the Brown Spanish, or Oporto onion, or Oignon Jaune des Vertus (the French name of a similar onion), is stated to be the main storage onion supplying Paris and a great part of Europe in the winter. Vilmorin noted that very early varieties (i.e. overwintered onions) in general did not keep well. Some of the varieties trialled in the United States in the 1930s can be traced back to lines mentioned in Vilmorin's book. Robinson (1885) mentioned that very large onions were sent to British markets during the winter from Spain, Italy and Africa.

Some of the earliest detailed accounts of onion post-harvest performance came from experiments made on US onion cultivars during the 1930s (e.g. Wright *et al*. 1935). Varieties current at the time were grown in several different parts of the United States (Magruder *et al*. 1941a) and their post-harvest performance was studied at seven different locations, under ambient and cold storage (Magruder *et al*. 1941b). Results agreed well across the country and the cultivars were reliably classed into storage categories as poor to very good. Many of the forebears of today's onion varieties were described at that time. In the same era, a study made in India allowed the main effects of temperature on local red onions from near-freezing up to 40°C to be identified (Karmarkar & Joshi 1941), effects which were later found to hold true across a range of widely genetically different onions by Stow (1975a). Abdalla and Mann (1963) made the first detailed records of what happened to two contrasting onion cultivars when the freshly harvested bulbs were placed on damp peat and allowed to sprout; these authors wrote a classic paper which set a high standard for subsequent work on onion dormancy and dormancy breaking.

Once onions started to be transported for long distances in the twentieth century, defects which had occurred before or during transport were noticed at city markets. Ceponis and Butterfield (1981) listed onion defects found in New York supermarkets and by consumers in bulbs from various production regions in the United States. Losses of 6–9% from multiple causes were found. From extensive surveys by Ceponis *et al*. (1986) of wholesale market information, the higher occurrence of neck rot (*Botrytis allii* and other *Botrytis* species) in Spanish-type storage onions from the western United States and of black mould (*Aspergillus niger*) on Grano/Granex-type onions from warmer regions was clear. Much work in storage pathology has concentrated on these damaging species.

Jones and Mann (1963) included a chapter on onion post-harvest in their book *Onions and Their Allies*: they described examples of several methods of storage in use in different countries. Fairly crude field storage in clamps or heaps was common in Europe and the United States for long-storing onions at that period. However, methods changed greatly during the next two decades, as scientists and growers experimented with better ways to control environmental conditions during drying, curing and long-term storage (Maude *et al*. 1984). At the same time, the biology and epidemiology of many storage diseases were also elucidated, and treatments developed led to marked improvements in onion storage life. Extension literature produced in the 1970s and 1980s (e.g. Maude *et al*. 1984) established a framework for the 'direct harvest' methods which are still being refined today in temperate countries where large-scale storage is practised (O'Connor 2002).

Problems of onion storage in the tropics were reviewed several times from the 1970s to the 1990s by scientists from the Natural Resources Institute in the United Kingdom, in response to many requests for advice (Thompson *et al*. 1972; Thompson 1982; Currah & Proctor 1990; Brice *et al*. 1997). Experimental studies were made on the reactions in storage of a range of cultivars to different levels of temperature and humidity (Stow 1975a, 1975b). Later, the biology and control of black mould (*A. niger*) and other onion storage fungi were investigated on onions in the Sudan and in the United Kingdom (Hayden *et al*. 1994a,b; Hayden & Maude 1997). Since only short-day (SD) onions

are normally grown in the tropics, a survey was made to find out more about the nature of tropical landrace and popular imported types of SD onions. Information was obtained on cultivars and their yields and storage performance, seed sources, growing methods and methods of curing and storage. Several different genetically distinct types of short-day onions were being grown, and their storage performance was related to their ancestry and traditional uses (Currah & Proctor 1990).

Biological aspects of onion post-harvest have also been thoroughly reviewed in recent years. Komochi (1990) gave a good summary of biological findings on onion dormancy up to that date and Maude (1990) reviewed storage diseases and their control. Storage and transport diseases and disorders of onions were illustrated and described by Snowdon (1991). Brice *et al*. (1997) presented the options for choosing various types of storage installations and provided decision trees to help readers to define their needs and the choices which would be feasible for their own environments and economic situations. Gubb and MacTavish (2002) reviewed recent literature on the biological aspects of storage. The findings on bacterial diseases of onions were reviewed by Mark *et al*. (2002). For garlic, Messiaen *et al*. (1993) dealt briefly with garlic storage from the European perspective after consulting growers in France. However, garlic storage has not been as extensively reviewed as the onion story, and many of the most useful papers published are in French or Spanish, with many from Latin America.

## ONION ANATOMY AND PHYSIOLOGY FROM A STORAGE VIEWPOINT

The cultivated onion is a biennial and forms its storage organ, the bulb, at the end of the first season of growth. The bulb stores water and nutrients for the next season of growth, when the onion would naturally mobilise its reserves to sprout rapidly and produce flowering shoots and eventually seeds. In its initial season of growth, the onion first produces a substantial vegetative (leafy) plant and then switches into 'bulbing' mode under the influence of several factors, most notably photoperiod (day length). The onset and rate of bulbing are also influenced by a number of other factors such as temperature, spacing, nutrient status, and biotic and abiotic stresses (Brewster 1994, 1997, 2008). Bulbing is the process by which water and assimilates from the foliage leaves are stored in the fleshy leaf bases and in special bladeless storage scales which are formed at the heart of the bulb after bulbing is initiated.

The dry bulb onion of commerce is therefore a simple layered structure formed by the swelling of the initially cylindrical leaf bases, which enclose a number of fleshy bladeless leaves or bulb scales. All the thin and swollen scales alike are joined at their lower ends to the 'base plate', a flattened disc-like stem which provides all the vascular connections between the different layers of the bulb and the roots. 'Dormancy' is the term used to refer to the state of the onion at harvest time, when there is little cell division taking place, inhibitory growth substances have been exported from the leaves to the bulb and biological activity is at a low ebb. The art of the store manager is to keep the onion in a dormant state for as long as possible, until the time is right for it to be sold. Dormancy normally wears off gradually and is replaced by a stage known as 'rest' (period of sprout suppression) in which the onion can resume internal activity under the influence of suitable temperatures and in the presence of water or of high atmospheric humidity, eventually producing visible shoots.

Shallots are a morphologically distinct subgroup of *A. cepa*: instead of a single bulb, they form a cluster of relatively small dry bulblets which remain attached together at the base when they are mature. Traditionally, shallots have been multiplied vegetatively by separating and planting out the small bulblets, each of which produces a new shallot cluster in the next growing season. Intermediate forms between shallots and onions, known as potato onions or multiplier onions, are grown in countries such as Russia, Finland, southern India and Sri Lanka. A review of literature on shallots, including some experimental results, was published by Rabinowitch and Kamenetsky (2002).

The outer scales of onions and shallots, formed from the lower parts of leaf sheaths which expand actively around the inflating fleshy scales during the bulbing process, dry out during bulb maturation and curing, to produce one or more layers of dry papery scales. These dry or semi-dry scales (the 'skins' of the onion) tightly envelop and protect the bulbs during the dormant period. Their integrity is important for maintaining bulb dormancy (Apeland 1971), and at least one undamaged layer of skin over the bulb is also needed when the onions are prepared for sale, since the presence of the intact skin is an important quality feature of the onion (Hole *et al*. 2000). During 'curing', an important stage in preparing onions for long-term storage, simple compounds present in the skins polymerize: some produce chemicals with antibiotic properties which are effective against some fungi attacking onion bulbs (Takahama & Hirota 2000). It may be that the gradual process of the withdrawal of water from the skins underlying the outermost dry one contributes to keeping the bulb turgid. However, little research has been done to trace the exact changes which take place at this time. Both

the genetic make-up of the cultivar and the conditions of storage affect the length of dormancy.

Whereas onions are propagated by seed, set or transplant the situation for shallots is changing. Many traditional and selected clonal shallot cultivars were developed and maintained by vegetative propagation, but recently, commercial firms have started to offer shallot cultivars which can be propagated by seed. This method avoids the necessity for storing large quantities of propagating material, and also frees the crop from viruses which reduce yields, but growth from seed requires a longer season than growth from bulblets. The prized culinary qualities of the French 'Jersey' and 'Grey' shallot cultivars are not always found in the seed-propagated types (Bufler 1998). In the tropics, where the short growing season of the shallot is a useful character, vegetative propagation may retain its usefulness. Some types of multiplier onion (e.g. certain cultivars in Sri Lanka and north east Brazil) are already propagated locally by seed (Currah 2002). In the Côte d'Ivoire, local seed-propagated shallots have been proposed as a substitute for imported onions (David *et al*. 1998).

## GARLIC ANATOMY AND PHYSIOLOGY

Garlic is another important edible bulbous allium. It differs in several ways from onions and shallots. Garlic is an ancient cultivated crop which has long been propagated vegetatively, and until recently it was generally thought to be infertile by seed. The garlic bulb of commerce differs in structure from onions and shallots because it is formed in a different way. All the leaf bases of the plant become papery at maturity, rather than the inner ones becoming fleshy as in *A. cepa*: meanwhile, within the leaf axils, one or more whorls of buds develop which give rise to discrete fleshy garlic bulblets or 'cloves', all joined together by the basal plate. Many varieties of garlic also produce a central flower stalk which may be fully or partially developed at bulb maturity. The different garlic groups were described and illustrated by Messiaen *et al*. (1993), and the day-length responses of these groups are also discussed. Etoh and Simon (2002) also reviewed garlic from the evolutionary point of view and presented the recent achievements of breeders who are working to develop sexually propagated garlic.

Each edible garlic clove consists of an outer papery membrane, one inner fleshy scale (which is considerably higher in dry matter and pungency than those of the onion), and at its centre, an internal leaf bud with shoot initials which is the germ of the next season's leafy sprout (Takagi 1990). The garlic 'bulb' is therefore a compound structure which is held together by the outermost papery scales. Usually it is separated into cloves both for consumption and to provide propagating material to plant for the next year's crop. Selection of large, good quality cloves for planting is desirable in order to maintain quality. In countries where virus-free, or more accurately, virus-tested material is produced, specialist growers carry out the production of the early generations cleaned-up by meristem culture under pest-proof covers, and release them to be multiplied in 'low-pest' zones for one or two generations before they are bulked up sufficiently to be sold to growers (Salomon 2002). In several countries, such as France, China and Argentina, enterprises specializing in the production of virus-tested propagating material have been established during the past 20 years.

In terms of physiology, garlic is affected by cool treatment of the bulb during the dormant period; storage temperatures which are very low (near 0°C) affect the quality of the bulbs in the subsequent season by leading to the production of 'rough' (irregularly shaped) bulbs. Therefore, storage conditions for 'seed' garlic should be quite distinct from those which best preserve the commercial bulb crop for sale. However, since so many different clonal varieties exist, their exact temperature responses are still being determined. Studies on this topic have been reported from France (Messiaen *et al*. 1993), Argentina (Pozo *et al*. 1997), Canada (Bandara *et al*. 2000) and Italy (Miccolis *et al*. 2000). Commercial storage of garlic for sale can be successful at either warm (about 25°C) or cool (−3°C to 0°C) temperatures. Garlic has a higher dry matter content than onion (about 40–43% in recent Indian studies; Singh & Gupta 2002); even so, storage at −4°C or lower is not regarded as safe, and many studies suggest that temperatures of about 0°C are best suited for long-term storage. Some cultivars with very long dormancy can be stored at atmospheric temperatures for several months, for example the 'northern' type of garlic grown in Korea (J.K. Lee, personal communication, 2003) which is dried and safely stored in barns.

## FACTORS AFFECTING THE POST-HARVEST PERFORMANCE OF ONIONS AND GARLIC

### Pre-harvest factors

These were recently reviewed by Gubb and MacTavish (2002) in the context of post-harvest biology and by Bosch-Serra and Currah (2002) in terms of field agronomy. Some of the key factors affecting onion quality are the choice of appropriate long-storing varieties for the production area; careful timing of sowing and (if used) transplanting, so as to avoid environmental conditions which may lead to

bolting or to splitting and doubling of the bulbs; careful use of fertilizers such that nitrogen is not scarce in the early growth stages but is mostly used up by the plant by the time of harvest; care with the application of irrigation so that the bulbs are encouraged to dry down fully by the time of harvest; and the use of a sprouting inhibitor (usually maleic hydrazide or MH) during the last stages of leaf die-down but while the foliage is still green. A recent report of the effect of nitrogen on sweet onions confirmed the need to keep this element to low levels to reduce rots in storage (Díaz-Pérez *et al*. 2003). There are also indications that soil texture can influence storage life: for example, in the United Kingdom onions from sandy soils seemed to store better than those from peaty (muck) soils, possibly because the bulbs dried out more rapidly and thoroughly once irrigation was withdrawn. In other countries, trace elements such as copper have been shown to influence skin quality and hence storage life. It is also important that sulphur nutrition should be adequate so that full pungency (if desired) and the correct texture of the cell walls can be developed (Randle *et al*. 1999; Lancaster *et al*. 2001).

### Maleic hydrazide

An important pre-harvest chemical treatment of onions to prevent early sprouting in store was developed in the 1950s: this was maleic hydrazide (MH) (Isenberg 1956). The chemical must be applied to the maturing plants before the foliage has died down and correct timing is crucial – application at 10% tops down is now recommended in the United Kingdom (O'Connor 2002) – since the active ingredient must be absorbed and translocated to the internal growing points before the foliage has dried up completely. The chemical acts to prevent cell division at the growing point by inhibiting cell division – it prevents spindle formation during mitosis. Eventually during prolonged storage, the growing points darken and the onions lose quality by loss of water. MH treatment is routinely applied to storage onions in the United Kingdom and the United States. In Germany, however, its use is not permitted. The use of MH in foodstuffs has been questioned as studies have shown links between MH and the production of tumours in mammals (Ribas *et al*. 1996). It has been estimated that the average adult ingests approximately 630 mg of MH a day from potatoes, onions and tobacco from cigarette smoke (USEPA 1999). The use of MH on onions has been banned by many retailers as it is the only chemical used on onion that leaves a detectable residue. Typically, levels of MH in onion bulbs lie between 4 and 6 mg $kg^{-1}$ with the maximum residue level (MRL) at 10 mg $kg^{-1}$ (Johnson 2006). Additionally, MH could be detrimental to the environment as there are concerns over the risk of leaching into drinking water (Sorensen & Grevsen 2001). Pressure from retailers and consumers has led to a need for new methods to extend storage.

### Genetics

The genetic component of a cultivar is crucial to its storage life. Genetically controlled factors which are involved include the length of dormancy, dry matter content, number and thickness of outer dry scales after curing and bulb colour (which can influence susceptibility to disease). The history of the cultivar in terms of its traditional role (or that of its immediate open-pollinated progenitors) in the farming system is important to understand: for example, in Spain there are traditional onions for several different seasonal markets, some of which are grown for sale fresh (the earliest overwintering onions) while others (summer-grown onions) have been selected as suitable for storage. The choice of suitable cultivars is therefore an essential part of the system of storage onion production.

Seed companies provide valuable information on the storage aspect of cultivars for particular production areas, but in new areas where onion storage has no local tradition, experimental validation of storage performance under local conditions is essential. This should be carried out as replicated trials on healthy samples of onions which are examined at regular intervals to check losses from evaporation and respiration (physiological weight loss) as well as visible losses from rots, sprouts and rooting. Two accounts by Ko *et al*. (2002a, 2002b) from Taiwan provide good examples of a multidisciplinary study of this type on short-day onions, including observations on varietal differences in black mould resistance.

Currah and Proctor (1990) found that different genetic groups of short-day onion could be differentiated by their storage performance. For example, Creole onions stored longer than Grano and Granex types, while in Egypt very long storage (up to ten months) was reported under dry hot conditions with local cultivars. In Europe and Japan, the majority of storage onions are usually pungent yellow-brown types, though milder onions of the Spanish summer storage types are also grown in several countries (western United States, Argentina and Chile). The physical characters of the bulbs, and particularly their hardness (which is related to resistance to stacking damage), may determine what storage method is best chosen for a particular group. Softer onions are often stored in bins to limit stacking damage, whereas hard cultivars can be stored in bulk, sometimes to a height of 3 or even 4 m.

The genetics of onion storage performance, which involves the study of quantitative trait loci (QTLs), have been studied (e.g. Galmarini *et al*. 2001). The performance of progenies from crosses between contrasting onion lines showed that there were significant genotypic and phenotypic correlations between the traits soluble solids concentration (SSC), dry matter, pungency, and *in vitro* anti-(blood) platelet activity. A chromosome region on the onion linkage group E seemed to account for a substantial amount of the phenotypic variation for these traits. However, Havey *et al*. (2003) later discovered that when analyzing family means adjusted to average dry weights (DW), linkage group E showed no significant effect on these traits. This region may therefore be related to onion water content. Havey *et al*. (2003) found QTLs on linkage groups A and D associated with fructose and sucrose concentrations which Galmarini *et al*. (2001) had previously associated with SSC or DW. The close genetic association of these characters may explain why the linkages between them are fairly hard to break in practical breeding terms.

Garlic genetics is more obscure, since no well-known clones have been characterized genetically, and crossing between them for experimental purposes is not yet possible. However, the ancestral origins of garlic (*A. sativum* L.) and its relationships to other species of *Allium* are gradually being explored using the methods of molecular biology (Etoh & Simon, 2002; Klaas & Friesen 2002). However, these studies have not yet contributed to our understanding of post-harvest performance in garlic and much remains to be discovered about this species in the future. Different clones of garlic certainly do differ in their storage ability: for example, in Korea, 'northern' types store well for many months at ambient temperatures while 'southern' lines introduced from China more recently have shorter dormancy and require storage at low temperatures to keep for several months (J. K. Lee, personal communication, 2003). In Argentina, 13 clones were compared and the influence of temperature, photoperiod and cold storage on them was defined (Pozo *et al*. 1997). In India, several clones were recently compared for dehydration potential and significant differences were found (Singh & Gupta 2002). In Syria, mutations induced by gamma irradiation have been used to try to improve resistance of garlic to the fungal disease white rot (caused by *Sclerotium cepivorum*) and its storage performance, with encouraging results (Al-Safady *et al*. 2000); some lines from the mutation breeding scheme showed reduced storage losses. Work on the genetic transformation of garlic is beginning to be reported (Park *et al*. 2002).

## HARVESTING TECHNIQUES

In areas where onions can be stored with minimal structures or even out of doors, methods of harvesting tend to be rather rough and ready. Simply by giving better instructions to the labourers who harvest the onions, mechanical damage and other unnecessary losses can be reduced. For example, it is often poorly understood by the workers that a substantial neck (minimum about 4 cm) should be left on the onion before curing. Often, labourers trim onions at the easiest level, that of the neck, causing wounds to the not yet dry fleshy tissues which can lead to pathogens becoming established.

If onion sowing or the planting of sets is slightly mistimed, this may result in too many doubled and split bulbs which are unsuitable for storage. Hence, a whole-crop approach which emphasizes optimum timing, appropriate choice of variety, a fertilizer regime to avoid excessive N being present in the crop at maturity, and good control of pests and diseases, all contribute to the production of a storage crop at harvest time with what Guerber-Cahuzac (1996) described as 'quality capital'. The art of the store manager is to retain this quality capital for as long as is needed until the time is right to sell the crop at a profit.

While many onions are still harvested by hand, either where labour is cheap or where holdings or individual fields are too small to allow a mechanized approach, in northern Europe and other areas of extensive farming, modified potato or carrot lifters have long been used to mechanise the harvesting of hard storage onions. In the 'direct harvest' system the onions are topped, allowed to dry for a short time then lifted and transported immediately to bulk stores where the drying process begins immediately. However, studies progressed in the United States to develop an understanding of the physical factors, and to improve the mechanisation of harvesting and handling of sweet, soft onions (e.g. Maw *et al*. 2002a, 2002b). It has been known for many years that it is important to treat onion bulbs gently throughout the harvest and handling processes (Isenberg 1955), and recent work using a 'synthetic' onion in Germany has helped to define the points at which stresses and potential for damage occur during harvesting and grading (Herold *et al*. 1998). The addition of padding to equipment, and attention to distances that onions fall during store or bin loading all count towards reducing damage and hence later losses. Novel handling methods involving the use of very large bins containing up to 18 t, to minimise handling, are now being used commercially in the United Kingdom (P. Garrod, 2003, personal communication).

## CURING

The curing process in onions and shallots essentially consists of a drying of the outer scales until they reach a 'rustling dry' stage when they have become papery: this is accompanied by internal changes, as the neck of the bulb dries up and closes tightly, a process which slows down gas exchange with the atmosphere and reduces water loss. It may be that the corky layer around the base plate also thickens up, but this aspect has been little studied. Curing forms a complete skin which helps to prevent water loss from the flesh and obstructs pathogens from entering the bulb. Within the outer thin scales, chemical processes take place which produce compounds with antifungal activity, and the skin colour may also deepen, producing a more attractive colour and improving skin finish. In general terms, onions can lose up to about 5% of their weight at harvest during the curing period. But their storage life willbe extended if this drying, which chiefly affects the outer inedible parts of the bulb, is carried out correctly. In Europe and the United States this usually means a 6-week period at about 28°C during which the drying of the outer layers goes ahead but the temperature is just cool enough to discourage harmful fungi from developing. It is therefore important that the bulbs are not left at too high temperatures (above 30°C) for more than a few days at the start of the drying process. A study on the effect of curing on the physiology and biochemistry of onion bulbs was conducted at Cranfield University (Bedfordshire, United Kingdom) as part of a larger UK Government-sponsored Horticultural Link Project (HL0182).

## ONION STORAGE IN COOL CLIMATES: TECHNICAL ADVANCES AND CURRENT RECOMMENDATIONS

During the 1960–1970s, onion storage technology in northern Europe was modernised to take advantage of novel technology including computer control of temperature and humidity. Gradually, methods were evolved to control the temperature, humidity and ventilation rates to do specific jobs at certain stages in the process, in order to prepare the damp, uncured onions lifted from the field for long storage through controlled drying, and by varying airflow and temperature in order to partially control the processes which need to take place to make the onion bulbs suitable for long-term storage ('curing'). Four stages are distinguished:

Stage 1. Immediately after lifting, the onions have the surface moisture removed and are also heated in a process which helps to control neck rot by preventing latent infection from moving down the neck tissues into the fleshy scales. This stage needs a temperature of about 26–28°C and air flow rates through the bulbs in bulk storage of at least 250 cfm (cubic feet per minute). As the store is usually still being loaded while the drying process starts, it is important to note that each batch that is added should be surface dried before another is placed on top of it. In a large bulk store, the drying front needs to reach the top surface (shown by the difference in temperature between air entering the heap and air leaving being only about 1.5°C) before more onions are added to the stack.

Stage 2. After surface drying, the main curing stage follows, in which the outer scales become dry and the neck dries up. Experienced managers now recommend that this stage should last for six weeks at a temperature of 28°C and at a high airflow rate but with intermittent, not continuous, ventilation. At this stage, the neck closes up and the underlying moist skins also dry down gradually, possibly by transfer of water into the fleshy bulb tissues, to allow the neck to close properly. The time spent at this temperature should not be excessive since some pathogens such as basal rot (caused by *Fusarium oxysporum* f. sp. *cepae*) may be favoured. However, 25°C is too cool for *A. niger* or for storage bacteria to be very damaging to the bulbs.

Stage 3. After the onions are fully cured, they are gradually cooled to the long-term storage temperature. The air relative humidity (RH) is kept at between 65% and 75% or so by partial recirculation within the store, and the airflow rate can be reduced, since the onions should now be fully dormant and therefore at the lowest requirement for air. For ambient low temperature storage, slow cooling is advocated, while for refrigerated storage, a faster cooling rate of about 1°C per day is now recommended (O'Connor 2002). Where mild, low-pungency onions (e.g. Granex and SS1) are being stored, controlled atmosphere treatment has now begun to extend the period of sprout suppression.

Stage 4. To prepare the onions for sale, their temperature is gradually raised towards ambient, to prevent condensation from forming on the cold bulbs when they are removed from the store. In some packhouses a special warming chamber is used to heat up the bulbs before they are again put through the graders. If left moist, bulbs pick up dust and dirt and if left damp, may even start to sprout roots. The bulbs are usually graded out of

storage so that skinned or deteriorated bulbs can be removed before the saleable ones are sacked up ready for market. Usually they are packed in labelled mesh bags and stacked on pallets for transport to the wholesaler or retailer.

**Shallot harvesting, curing and storage**

Specific information about this aspect of shallot culture is not easy to find, as the crop attracts less research attention than onions. Messiaen and his colleagues consulted researchers and growers in France to collect the following information, which is taken from their 1993 book (Messiaen *et al*. 1993).

Shallots for storage are lifted by hand when the foliage is fallen and two-thirds yellowed, and are usually field-cured on top of the beds for five to eight days before being taken to the storage site. Sometimes grading is done and if leaves and roots are removed at this stage, good ventilation in storage is more easily achieved. On a small scale, the bulbs are simply placed on trays or in crates in a naturally well-ventilated shed or barn. Forced ventilation methods are also used, sometimes with temperature control. The following data are quoted: one cubic metre of storage holds about 450 kg of bulbs, an airflow rate of 240 $m^3$ per hour and per $m^3$ of storage (500 $m^3$/h.t of bulbs and a static pressure equivalent to 30 mm of water column are needed for a layer of bulbs 2 m thick), the air distribution channels should be of the correct dimensions, heating should be capable of being adjusted appropriately and the regulation of heating should be precise and reliable. Various types of systems can be used: shallow trays or shelves with all-round air circulation, bulk storage with under-floor air channels, or bin storage in which the air is forced up through each bin by selective blockage of exit channels at the base. All of these methods are similar to those used for onions. Also as in onions, a drying phase starts the controlled drying process, in which the temperature is gradually raised to 35°C and the RH is allowed to adjust to 70% by an increase in the amount of air recirculated within the store from 50% to 90% over time. This phase is considered complete when the difference in temperature between air entering and leaving the store is not more than 1°C to 1.5°C. Then follows a phase of controlled heating or 'thermotherapy' to use the French term, the aim of which is to deter the spread of neck rot. However, as Messiaen *et al*. (1993) point out, this phase may actually favour the activity of the basal rot organism, *Fusarium oxysporum* f. sp. *cepae*, if this fungus is present. The mass of the bulbs is kept at 35–36°C for four days, and the RH at >70% so that not too many skins are lost. As with stage 3 of onion storage, the temperature of the bulk shallots is then gradually lowered by adding more cool and dry external air until a low temperature is reached. If no refrigeration is possible, it is important to limit ventilation to times when the outside air temperature is more than 2°C and the air is reasonably dry (<90% RH). It is advisable to avoid too rapid changes in temperature, long periods without ventilation, or to allow air to enter that is much warmer than the bulb temperature, because of the risks of condensation.

If refrigerated storage is to be used, it is advisable to dry the bulbs rapidly and place the bulbs into the cold store as soon as possible after harvest, and in any case within ten days of lifting. The temperature is first brought down by ventilation with cool outside air, then further by adding refrigeration, until the bulbs reach a temperature of 0°C or better still, –2°C, provided that the temperature controls are very precise and also reliable. At this temperature, the air RH should be maintained at 70% and the air should be changed at least once per day. Such a regime should allow shallots to be kept from autumn to May with losses of around 8% (rather than of 70–75% as would be expected from using ordinary ambient storage).

With forced ventilation but no refrigeration, shallots can be kept until only February-March without sprouting. After storage, the shallot bulbs are if necessary separated, trimmed and graded before being packed for sale (Messiaen *et al*. 1993).

Recent research on shallot storage include an Ethiopian study, which concluded that sacks were inferior to both mesh bags and boxes as containers for stored shallots (Jemal 2000), and a Polish study on the changes in flavonols during growth and storage (Horbowicz & Kotlinska 2001): they reported that quercetin content increased during the late maturation period in the field and continued to rise during the first two months in storage, after which it remained stable for a time and then decreased slightly. The shallots in the trial were four Polish landraces and the first four months of storage were at about 4°C. Quecetin is of interest as an antioxidant and contributes to the 'nutraceutical' aspect of edible alliums.

## GARLIC HARVESTING, CURING AND STORAGE

Garlic is also often hand harvested and allowed to dry out on beds in the field. Messiaen *et al*. (1993) in France recommended harvesting the bulbs before they are perfectly mature, in order to avoid contamination with the fungus *Helminthosporium allii*: they suggested that the bulbs

should be harvested when about two-thirds of the foliage has yellowed. Total soluble solids (TSS) can be used to indicate readiness; if it exceeds 25, the bulbs are ready (Llorens *et al*. 1989). If the garlic is to be dried artificially, the pseudostems can be cut at this stage. Otherwise, if field curing is practised, the bulbs are laid out in the field with the foliage covering them for protection against sunburn. Some garlic is harvested mechanically in the United States and in parts of France. Some cleaning may be done in the field. Garlic which is to be marketed in strings needs to retain its foliage for plaiting. In California, most garlic for the dehydration industry is harvested mechanically, topped and conveyed in bulk onto trucks for transport to the factory (Cantwell 2002). Böttcher (1999), in Germany, established that the best time to harvest garlic for optimal storage quality was when 30–70% of the leaves were dried.

The drying or curing of garlic takes longer than that of onions, as considerable amounts of water need to be removed from the internal skins in order to make storage safe: all the leaf bases and also the skin surrounding each individual clove need time to dry out. Water probably migrates from the skins into the cloves at this time. Experiments in south-west France (cited by Messiaen *et al*. 1993) showed that garlic could be dried effectively in pallet boxes ('pallox') of about 1 $m^3$ in capacity, following a pattern of heated ventilation (35°C) for the first three days, during which at least 6% loss in weight should be achieved, followed by intermittent ventilation at the same temperature. Costs could be saved by using a lower temperature of 29°C intermittently, which allowed limited growth of *H. allii* to take place. By the end of one month of storage, a weight loss of about 20% had taken place, indicating that the internal skins had dried to a safe level for long-term storage.

Following curing, commercial garlic, like onions, can be stored at either a cold (–3°C to 0°C) or warm (25°C) temperature, the latter being practical only if the bulb mite *Aceria tulipae* is absent (Messiaen *et al*. 1993). In the case of high-temperature storage, the RH of the circulating air should be kept under 80%. Layers of bulbs should be no thicker than 1.5 m so as to allow good air flow to all the bulbs. Intermittent ventilation can be used, meaning that the bulbs are aerated for a period during each day, so as to remove products of respiration and to keep the bulb temperature even throughout the store. Some speciality producers plait and smoke garlic (for up to eight days) to give a gourmet product which keeps well (Messiaen *et al*. 1993). In the dry climate of Mendoza, Argentina, the garlic is usually stored in bulk after drying and is then cleaned and packaged into a variety of market packs which include small wooden crates as well as sacks and plastic sleeves.

## THE PHYSICS OF ONION AND GARLIC STORAGE: INFLUENCES OF TEMPERATURE AND RELATIVE HUMIDITY

It is clear from the preceding accounts of practical storage methods that two major environmental factors have very important effects on the storage life of onions, shallots and garlic. These factors are temperature and the RH of the air (see Devereau *et al*. 2002 1:75). In studying storage environments, consideration is given to the RH of the air, not the absolute humidity (i.e. percentage moisture in the air), since the amount of water vapour which air carries is related to the air temperature: warm air can carry much larger volumes of water vapour than cold air. When warm damp air cools to below the 'dew point', it deposits the water it can no longer carry as dew, or condensation, on the product or on container or building surfaces. Psychrometric charts can be used to calculate the dew points for various combinations of temperature and RH of the air. At one time, wet and dry bulb thermometers had to be used to take the necessary readings, but these days well-calibrated electronic equipment can be used to monitor air temperature and wetness (Morrish 1999). However, the store manager must have a good understanding of both factors, since the choice of when to ventilate a store using air from the outside, and when to recirculate air within the store can be critical for preserving onion quality. These factors were explained well by Matson *et al*. (1985). Further details on the practical aspects of the choice of air and temperatures for onion ventilation in the United Kingdom, particularly at the initial drying stage, were discussed by Morrish (1999). The chief point to grasp is that air carrying enough water to condense on the cold product when it reaches the lowered temperature of the store should not be allowed to enter the store. Therefore, air which is either cool already (i.e. holding little moisture) or dry (e.g. because of the choice of the driest time of day) is best suited to ventilate stores.

Relative humidity is important for several reasons; it has immediate effects on onion quality (Hole *et al*. 2000, 2002; Hole 2001) because dry onion skins are hygroscopic and take in water until they reach a state of equilibrium with the RH of the atmosphere. It is desirable to keep the skins at a moisture content which allows them to retain some flexibility, so that they will withstand cracking when handled. Excessively low air RH (below about 65% RH) allows the outer bulb skins to become brittle and to split

and fall off when the onions are disturbed at store unloading and during grading, so that the fleshy bulb surface is left unprotected: onions are immediately downgraded if this occurs. Skin loss may also lead to a shortening of the dormant period (Füstos 1997). Conversely, at a high atmospheric RH of over 80%, pathogens already present on the skin of the bulbs can start to develop and will eventually attack the edible tissues. Interestingly, at high moisture contents, more water is also lost from the fleshy parts of the bulb, due the increased permeability of the outer skins, as studied in Brazil (Matos *et al*. 1997; 1998). This feature of onion storage is another good reason for trying to keep the circulating air within the relatively 'safe' band of 65–75% RH.

Since onions under damp conditions can actually lose more water from the interior fleshy scales than those which are kept dry, this has important implications for onions and garlic sent for export by sea and for their treatment once they arrive. At the port of arrival, the bulbs may need to be dried out to a safe RH to prevent disease development, but also need to retain enough flexibility in the skins to stop the clean dry inner skins from being shed. In fact, water does not transfer easily across from one onion scale to another since they are only joined physically at the base plate. Therefore, even if the outermost fleshy scale starts to dry down on being exposed, the neighbouring scale within the bulb may still be in good condition. Thus, even a batch of outwardly unattractive bulbs which have partly lost their skins may be used for industrial processing or for catering uses, although prices paid are substantially lower for such uses.

### 'Biological' water in stored alliums

While ambient temperature can only be modified by adding cooling or heating capacity within a storage or drying structure, usually with forced ventilation, onions themselves can create higher relative humidity within the stack or heap by virtue of the fact that they are living, breathing organisms which produce $CO_2$ and water vapour by respiration. Some water is also lost by evaporation through the outer skins, though more may escape through the neck and the basal plate areas; hence the importance of the curing process applied prior to storage, during which the neck closes up and the outer scales are well dried. Pre-harvest treatments right back to treatment of the seed for disease control can affect onion post-harvest quality (Gubb & MacTavish 2002). Methods of storage which work well at a small scale can lead to problems if they are scaled up without taking into account the need to manage the humidity produced by respiration from the bulbs in bulk.

### Temperature effects on dormancy and sprout suppression

The influence of temperature on the storage life of the edible alliums is rather complex, since onions can be stored successfully for extended periods at two completely different temperature ranges: at low temperatures, around 0–2°C, and also at warm temperatures of around 27°C. Temporary high temperature treatments are useful to dry the bulbs and to discourage neck rot from developing. It is at the intermediate temperatures of about 7–20°C that the bulbs lose dormancy more rapidly, sprout growth begins and as a result the onions lose quality and soon become unsaleable. This adaptation of onions to remain dormant at both cold and warm/hot temperatures can perhaps be understood when considering their original mountain origin in Central Asia, where only the milder times of year, spring and autumn, are favourable for growth. Storage temperature is important because of its effect on the natural physiological responses of the onion bulb. It can be manipulated in order to keep onions dormant for several months. (Conversely, putting onions into a domestic refrigerator at about 5–7°C can lead to rapid sprouting.) Refrigeration to near zero temperatures, and if necessary, the addition of controlled atmosphere (CA) storage using suitable percentages of oxygen and carbon dioxide, are other possible methods of retaining long dormancy.

At the higher storage temperatures, bulbs naturally tend to lose much more water by evaporation and probably also by respiration than when kept cold with their internal activity at a minimum. Therefore practical limits exist as to the length of time that onions can be stored, and these also depend to some extent on the bulb characteristics of the different varieties, such as number of skins, skin thickness and resistance to storage pathogens. In the case of cold storage, using refrigeration in the spring can extend the dormant period. With long-storing onions, CA has been reported to prevent onion growth for as long as a year (Tanaka *et al*. 1996). However, whether this is economic or not is another matter. So far it has been demonstrated as a possibility rather than being widely adopted. In the United Kingdom, O'Connor (2002) estimated that CA could add another month to storage life by extending it into the early summer (May–June) when combined with refrigeration.

### Other methods of extending onion dormancy

Dormancy can also be extended artificially by treating the bulb in the field, prior to harvest, with a sprout suppressant such as maleic hydrazide (MH), as mentioned earlier. By inhibiting sprout regrowth, MH consequently slows the mobilisation of water and nutrients from the outer scales,

**Table 17.7** Summary of Controlled Atmosphere Storage and Shelf Life Experiments on Onions.

| Cultivar | $CO_2$–$O_2$ | Storage duration | Marketable bulbs after storage duration | Shelf-life duration | % sprouting after shelf-life duration | Physiological and biochemical differences[3] | Reference |
|---|---|---|---|---|---|---|---|
| Boñska, Dinarof, Sochaczewska | 2–0.75 | 33 weeks 0 °C | 93.9 | 21 days 20°C | 25 | n/a | Adamicki & Saltveit (1997) |
| | 2–1 | | 86.3 | | 25 | | |
| | 5–1 | | 90.5 | | 55 | | |
| | 2–2 | | 86.9 | | 38 | | |
| | 5–3 | | 74.2 | | 55 | | |
| | Air | | 4.2 | | 85 | | |
| Rumba | 3–0.5 | 36 weeks 0 °C | 86.1 | 21 days 20°C | 2 | n/a | Adamicki (2005) |
| | 3–1 | | 83.4 | | 3 | | |
| | 3–2 | | 81.7 | | 10 | | |
| | Air | | 29.7 | | 39 | | |
| Sherpa | <0.3–0.5% <0.3–1.0% <0.3–21% | 36 weeks, 2 °C | n/a | n/a | n/a | ↑ water soluble carbohydrates in 0.5% $O_2$ ↑ sucrose in low $O_2$ storage ↑ fructans in low $O_2$ | Ernst *et al.* (2003) |
| Granex | 5–3 | 5 months 27 °C | 50 | 14 days 27°C | 10 | ↑ pungency in low $O_2$ | Smittle (1988) |
| | Air | | 25 | | 25 | ↑ fructose, glucose and sucrose in low $O_2$ | |
| | 5–3 | 5 months 5 °C | 83 | | 13 | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 10–3 | | 86 | | 9 | | |
| | Air | | 28 | | 94 | | |
| | 5–3 | 7 months 1°C | 99 | | 2 | | |
| | Air | | 89 | | 36 | | |
| Walla Walla | 0.1–20.5% | 6 months 0°C | 0[1] | 14 days 20°C | 5 | ↓ neck rot in 0.7% $O_2$ | Sitton *et al.* (1997) |
| | 0.05–1.4% | | 29 | | 20 | ↓ ethylene in 0.7% $O_2$ | |
| | 0.05–1.1% | | 20 | | 25 | | |
| | 0.04–0.7% | | 80 | | 55 | | |
| Sherpa | <0.3–0.5% | 27 weeks 2°C | 100[2] | 21 days 18°C | 29 | ↑ dry matter in 0.5% $O_2$ | Praeger *et al.* (2003) |
| | <0.3–1% | | 100 | | 41 | ↓ respiration rate in low $O_2$ | |
| | <0.3–21% | | 53 | | 94 | ↓ weight loss in 0.5% $O_2$ | |
| | <0.3–0.5% | 36 weeks 2°C | 100 | | 31 | | |
| | <0.3–1% | | 100 | | 24 | | |
| | <0.3–21% | | 0 | | 100 | | |

[1] Marketable bulbs category was taken as 100% – % of decayed bulbs.
[2] Marketable bulbs category was taken as 100% – % of sprouted bulbs.
[3] ↑ ↓ = Higher and lower than control at end of storage period.

a process which normally causes deterioration at the time of sprout growth initiation. So although MH does not directly affect the disease loading of the bulbs, they tend to remain healthy for longer than usual: when bulbs age normally, the outer scales rapidly become senescent when sprouts start to grow and hence become susceptible to pathogens. Kubilius and Bushway (1998) recently developed a new, sensitive method for detecting MH in onion tissues capable of detecting levels as low as 2 µl $l^{-1}$.

**Irradiation**

Another means of slowing bulb degeneration is to use controlled gamma irradiation prior to storage. The World Health Organization permits gamma radiation up to a strength of 0.15 kGy to preserve onions and garlic (Kobayashi *et al*. 1994). This technique has repeatedly been shown to reduce bulb storage losses and is being adopted in preference to MH in some countries, such as Algeria (Benkeblia 2000). Toxicological tests have concluded that irradiation of onion bulbs is not detrimental to eating quality or harmful to humans (Brewster 1994). Irradiation can be used in conjunction with other methods of maintaining quality such as controlled temperature or atmosphere conditions. Irradiation is expensive and is therefore often only used for processes such as sterilisation when there are no alternative methods (Andrews *et al*. 1998). Irradiated food is also not acceptable to consumers in some countries; however, there seem to be few reasons for refusing food treated in this way. Certainly it has been shown to be effective in assisting onion storage over long periods, and may have the advantage of killing off certain pathogens and pests (mites) which can attack the stored crop (Ignatowicz 1998).

Irradiation is also very effective in extending the life of stored garlic (reviewed by Iglesias & Fraga 2000). Scientists in Argentina have developed methods to elucidate whether garlic has been irradiated or treated with MH, using the appearance of the bulbs at 120 days after harvest in order to distinguish which of the treatments was applied (Pellegrini *et al*. 2000). Onions and garlic from Chile, imported into Cuba, were irradiated before transport and this allowed them to retain quality substantially better than the nontreated bulbs, even after six months of storage at the destination (Iglesias *et al*. 2001).

**Ethylene**

Recently, systems have been introduced which produce a continuous supply of ethylene to suppress sprouting of stored onions and potatoes (10 µL $L^{-1}$ and 4 µL $L^{-1}$ respectively) reviewed by Chope and Terry (2008). Continuous ethylene treatment (10.6 µl $L^{-1}$) for 4 or 9 months storage at 18°C delayed 50% initial sprouting by 1 or 2 weeks respectively although the mechanism by which ethylene inhibits sprout growth in onion is still unknown (Bufler 2008). Benefits of ethylene treatment include the elimination of detectable residues caused by MH, the use of low concentrations (10 µL $L^{-1}$) which pose no hazards to workers and the potential integration of ethylene treatment with controlled atmosphere, low- or high-temperature storage (Johnson 2006).

The ethylene binding inhibitor 1-methylcyclopropene (1-MCP) is approved for use on a range of produce in several countries (Watkins 2006). Sprout growth inhibition has previously been shown in onions cv. SS1 treated after curing with 1 µl $l^{-1}$ 1-MCP as a single 24 h treatment as compared to the control when stored at 4°C and 12°C (Chope *et al*. 2007c). However, when stored at 20°C, Chope *et al*. (2007c) found treated onions cv. SS1 had longer sprouts than the control although this was not significant. This agrees with Bufler (2008) who found onions cv. Copra sprouted earlier when treated with 0.25 µl $l^{-1}$ 1-MCP for 5 h (20°C) then stored at 18°C suggesting sprout suppression using 1-MCP may only be effective prior to low-temperature storage.

**Controlled atmosphere**

For a long time, studies of changed atmospheric concentrations of oxygen and carbon dioxide on onions were only of theoretical interest (Chawan & Pflug 1968; Adamicki & Kepka 1974). Studies on the effects of changing the gas concentrations of $O_2$ and $CO_2$ during storage began to be translated into practice in the past 15 years, first to extend the marketing season of very sweet onions in the United States (Smittle 1988) and more recently to try to find methods of extending long-storage of onions (Adamicki & Saltveit 1997; O'Connor 2002). However, recent work by Chope *et al*. (2007a) suggested that removal from CA storage (5 kPa $CO_2$, 3 kPa $O_2$) caused a stress-related increase in respiration rate which in some short-storing, mild cultivars such as cv. SS1 could be sufficient to initiate sprouting, and thus reduce shelf-life. The usual recommendation for onions is to reduce oxygen to 3% and allow $CO_2$ to rise to 5% (higher levels may be damaging) and to store at near zero (1–2°C) temperatures (Smittle 1988). Stores are fitted with sensors to control temperature, RH and gas levels, and the gas mixture is circulated through the onions. In some seasons, losses may be experienced in store because the onions in the fields were already infected by bacterial or fungal diseases which can continue to grow at low temperatures. Table 17.7 summarises studies on the effect of CA on storage and shelf life.

Some novel developments in storage methods are still commercially sensitive, for example the adoption of ozone ($O_3$) treatment of the air in stores. In Canada, experiments showed that raising $O_3$ levels in the storage atmosphere was quite an effective way to control the growth of storage pathogens: *Penicillium* was one of the more susceptible genera (Hildebrand *et al*. 2001; Fan *et al*. 2001). Numbers of fungal spores in the store atmosphere were reduced following $O_3$ treatment. This technology is available commercially in North America.

## CHEMICAL CONSTITUENTS OF ONIONS, SHALLOTS AND GARLIC

The water-soluble storage carbohydrates in onions are glucose, fructose, sucrose and a series of fructans. Fructans are fructosyl polymers based on sucrose, which show varying degrees of polymerization (DP) with fructose elongations up to 19 units on both sides of the sucrose (Vågen & Slimestad 2008). Sweet onions have higher concentrations of the simple sugars, while storage onions show a series of oligofructans of differing degrees of polymerization (Davis *et al*. 2007). During storage, the fructans are gradually converted to simple sugars, particularly when dormancy is broken and growth resumes (Suzuki & Cutriffe 1989). The flavours for which onions are most valued, however, are the sulphur-containing compounds, known as the *S*-alk(en)yl cysteine sulphoxides (ACSOs), which impart the well-known onion and garlic flavours. These flavours are released by enzymatic processes which start when the tissues are cut or otherwise wounded. Pyruvate, ammonia and a series of highly reactive compounds are released when this happens; these account for the strong volatile odours released by cut onions and garlic. Otherwise, the reactive compounds (flavour precursors and the enzyme alliinase) are segregated within the cell, the ACSO precursors in the cytoplasm and the enzyme in the vacuole. The chemistry of these compounds and other sulphur compounds present in smaller quantities was reviewed by Randle and Lancaster (2002).

Pungency can be measured in terms of pyruvate concentration which has been shown to differ spatially. Pungent cv. Renate has been found to contain the highest pyruvate concentrations at the beginning of storage in the outer two scales whereas the sweet cv. SS1 showed the highest concentrations in the central scales at the end of storage (31 days, 4°C, 3 kPa $CO_2$ and 5 kPa $O_2$) (Abayomi & Terry 2009).

During storage, changes take place in the chemical constituents: the fate of the fructans and oligosaccharides has been studied in Spain (Jaime *et al*. 2001a, 2001b, 2002). Increases in fructose in the course of storage were attributed to fructan hydrolysis. Cultivars with relatively high dry matter content (>16%) or 15% soluble solids content were capable of storage for six months at 0°C and 60–65% RH (Jaime *et al*. 2001a). Studies to identify good fructan sources within bulbs of cv. Hysam concluded that the two outermost fleshy layers were the most productive (Jaime *et al*. 2001b). More detailed studies on potential sources of dietary fibre showed that the ratios of soluble to insoluble dietary fibre increased from the inside to the outside of onion bulbs, with the greatest proportions of fibre in the outer skins of the bulbs (Jaime *et al*. 2002). Additionally, in sweet onion cv. SS1, higher glucose concentrations were found in the two outermost scales. However, pungent cv. Renate had the highest glucose levels in the central scales (Abayomi & Terry 2009). Sweet onion cultivars contain higher concentrations of fructose and glucose compared to pungent, long-storing onions which in taste panels were positively correlated with likeability and sweetness, respectively (Terry *et al*. 2005; Chope *et al*. 2007a). Studies on the chemical constituents of onions, with a view to developing saleable by-products, have also been made in the United Kingdom recently (reviewed by Waldron 2001).

Shallots, which are valued in cooking for their intense flavour, tend to have higher levels of dry matter than most onions, and their contents of fructans, sugars and sulphur compounds are more concentrated than those of onions (16–33% dry matter compared to 7–15% in onions, cited by Rabinowitch and Kamenetsky 2002). Bufler (1998) found that dry matter of seed-grown shallots was lower and pyruvate content higher than in vegetatively-propagated shallots, suggesting that these may have a harsher flavour. For the 'French grey' shallot cultivar Griselle, however, the dry matter content can be as high as 30% (Cohat & Le Nard 1998). This distinctive cultivar is now believed to be an interspecific hybrid predominantly derived from *Allium oschaninii* (Friesen & Klaas 1998.) Flavonols such as quercetin which are valued for their anti-oxidant properties are also present in shallots (Horbowicz & Kotlinska 2001), perhaps at greater concentrations than in onions.

Garlic contains much higher percentages of dry matter than onions and shallots; in a survey in India, 40–43% dry matter was found. Of this, about 28–40% consisted of sugars (Singh & Gupta 2002). Recent studies identified a novel higher fructan of garlic (Baumgartner *et al*. 2000). Lawson (1996) listed all the sulphur compounds so far found in garlic. The main sulphur compound, alliin (2-PeCSO), is found in greatest abundance in the storage mesophyll cells of garlic cloves, with none near to the bundle-sheath fibres (G.S. Ellmore, unpublished data, in

Lawson 1996). Garlic also contains steroidal sapogenins which may be of interest for their health benefits in terms of prevention of cardiovascular disease (Matsuura 2001). Ariga and Seki (2000) listed the flavour components of garlic and their multiple functions in benefitting human health, while Keusgen (2002) has also reviewed this topic. During garlic storage in India, 'rubberisation' was the term used to describe the loss of texture associated with garlic ageing (Selvaraj *et al*. 1998).

**The effects of storage on the quality of bulbous alliums**

Several studies on onions in store have shown that the pungent compounds tend to increase over time before showing a decline just before sprouting, presumably at a time when they are finally mobilised to construct new shoots of the flowering plant. Levels of fructans also decrease after a while, as these act as storage carbohydrates in onion bulbs. Water content declines over time as a result of slow evaporation from the bulbs; loss is quicker following damage or loss of the outer dry scales. Deterioration resulting in leathery or watery outer scales may be caused by poor timing of harvest, overheating during curing, or by improper nutrition during the growing season: these factors have been extensively investigated in Hungary and in Scandinavia in recent years (e.g. Füstos 1997; Solberg & Dragland 1998; Füstos & Solberg 2000). As storage progresses, pungent onions tend to decrease in pungency, whereas sweet onions tend to become more pungent (Kopsell & Randle 1997); in both cases, these changes can make them less typical of freshly harvested samples and therefore less attractive to consumers.

The physical processes that go on during storage in terms of airflow and moisture removal from bulbs were studied in detail in many different countries from the 1970s onwards (e.g. Neale & Messer 1976; Matos *et al*. 1997, 1998). These findings allowed a more complete picture to be built up of what really goes on at the different levels from cellular and chemical level through bulbs up to bulk crop level. The fate of, and changes in, the sulphur-containing chemicals which account for the most noticeable onion flavours have been studied over the storage period (reviewed by Randle and Lancaster 2002). Methods to estimate fungal and bacterial loading at the time of harvest have been developed in order to provide tools to estimate storage potential of onion batches before they are loaded into store.

While onions are in storage at low temperatures and apparently dormant there are still changes going on, although slowly, which lead eventually to regrowth of the vegetative shoots and to vernalization which allows flower shoots to be initiated. After two to three months in storage, a surge in gibberellins was found at a time when the new shoots were being initiated. Then, after a few more weeks, cytokinins increased, indicating that cell division was taking place in the growing point, followed by gibberellin production which accompanied the extension growth of the shoots (Isenberg *et al*. 1987). These processes are slowed but not totally prevented at low temperatures. They can only be halted if the onions are treated before storage with either sprout suppressant chemicals such as MH or by irradiation. Both of these methods prevent the shoot regrowth which triggers further physiological and physical changes to the onion bulb.

Abscisic acid (ABA) concentrations have been shown to decrease in onions during storage (Chope *et al*. 2006). The initial ABA concentrations were higher in long- and intermediate-storage cvs. Renate and Ailsa Craig (288 and 298 ng $g^{-1}$, respectively) than short-storing sweet onions cv. SS1 (116 ng $g^{-1}$) which agreed with Chope *et al*. (2007b) who found sprouting occurred later in cultivars with high pre-storage ABA concentrations. The decrease in ABA concentration during storage appeared to be negatively correlated with sprout tendency during controlled atmosphere storage (3.03 kPa $CO_2$ and 5.05 kPa $O_2$) at 1°C (Chope *et al*. 2006). Chope *et al*. (2007b) measured ABA in six onion cvs. SS1, Carlos, Dinaro, Renate, Red Baron and Hysam stored in air at 4°C, 12°C and 20°C and witnessed an increase in the last days of storage coinciding with sprout onset. They hypothesised that the increase of ABA may have been due to its synthesis in the growing sprout as ABA has been linked with both dormancy and leaf organogenesis (Barrero *et al*. 2005).

Well before the new shoots emerge, a visible swelling and elongation that changes the bulb shape can be seen above the old base plate area: this can crack and dislodge the dry outer skins and cause them to be lost more easily than earlier in the storage period, especially if they have already loosened due to bulb shrinkage (Tanaka *et al*. 1985). Cutting the bulbs across reveals advanced shoot growth as yellow or greenish shoots which can easily be seen. Bufler (2001) investigated methods of monitoring the progress of dormancy breaking, using measurements of the very small (<5 mm) leaf-sheath and leaf lengths within the bulbs, together with confidence limits which indicate when the onions have ceased to be dormant. Two contrasting cultivars were compared and the test was able to detect when sprout growth started. The test will be used

to study the effects of pre- and post-harvest factors on onion bulb dormancy.

## GARLIC STORAGE EXPERIMENTS

Several garlic storage experiments have recently been reported, mostly from Europe, Argentina and East Asia. In Poland, a study on the effect of storage up to nine months of local garlic ecotypes and the cv. Mera was carried out. Most of the ecotypes showed an increase in dry matter with storage duration. Total sugars increased until the middle of the period and then declined again. Storage at 4°C was most effective in retaining dry matter content and total sugars, but losses of L-ascorbic acid occurred in low temperature storage (Nurzynska-Wierdak 1998).

In Argentina, recent work in Mendoza province, which has a dry climate (about 50% RH), established that for short-term storage (three months or less) storage in the field or in store was probably adequate for garlic cv. Colorado, whereas for longer periods, a cold store at 0°C or –3°C gave superior quality for up to nine months of storage, with no sprouting when the lower temperature was used (Giménez *et al.*1998). Another group in Argentina studied the effect of irradiation on garlic bulb quality and reported that treatment at 0.4 Gy/s at 30 days post-harvest had beneficial effects on quality through its influence on water content and the movement of solutes between organs during storage (Pellegrini *et al*. 2001). In Taiwan, experiments on a wide range of storage temperatures determined that at 5°C, 10°C or 15°C, garlic sprouted early and losses were severe, whereas at 35°C or at 1°C the garlic could be stored for ten months. However, shelf life after storage was shorter when the garlic had been stored at the lower temperature, due to rapid sprouting, whereas storage at 35°C was followed by an acceptable shelf life of ten days at 20°C (Wang & Horng 2001). Park *et al*. (2000) in the Korean Republic investigated different clipping treatments (no clipping, or trimming at 5 or 10 cm above the neck) and ambient versus 0°C storage temperatures on garlic cv. Eusung. Nonclipped bulbs stored under ambient conditions lost the most weight after 7.5 months in storage. The low-temperature storage treatment resulted in less weight loss and sprouting. Clipping treatments also reduced sprouting. Ambient conditions, however, were satisfactory for short-term storage (Park *et al*. 2000). J.K. Lee (personal communication, 2003) in the Korean Republic reported that computer-controlled cold stores are commonly used now for storing 'southern' types of garlic. Korean consumers use a lot of garlic for the production of the salted vegetable pickle *kimchi*, as well as in cooking many other popular dishes. Annual consumption is about 8 kg per year per person.

## DIVERSITY OF STORAGE METHODS

How onions, shallots and garlic are stored varies enormously with local conditions, and every situation from domestic storage in bunches in a warm kitchen to industrial scale bulk storage holding thousands of tonnes of onions, with controlled temperatures and humidity and even with CA, can be found somewhere among onion-producing nations. Currah and Proctor (1990) found that in many tropical countries, onions were usually marketed at once after harvest, and that on-farm storage was not practised at all; in other places, onions may be stored out of doors in sacks or under trees, or even left in the ground during the hot dry season. When onions are to be stored, they are often first lifted and field cured (i.e. left to dry in the open or under a leafy covering in the field, or in sacks) if the weather is suitable (i.e. dry and warm), or may be dried further under cover of a shed or barn before being put into storage on the farm. Many types of tropical on-farm onion storage are illustrated or described in Brice *et al*. (1997).

The prices obtainable at a particular time affect onion marketing strategies: very high prices encourage onion farmers to lift a crop early or even green so to take advantage of prices which they know will fall rapidly once the maincrop comes in. In areas such as the Mount Elgon region in Kenya, for example, farmers leave the onions in the ground and only lift them when prices are right. The onions then have their tops cut off, are very roughly dried in the open, after being collected from the field in sacks, and are sold as rapidly as possible. Such onions are not expected to keep beyond a month after lifting, since they have received virtually no curing and have been cut across a fleshy region of the neck, allowing pathogens to enter freely. Many start to sprout again at once. Even normally good storage varieties do not withstand such rough treatment. But as onions are produced all year round in Kenya from rain-fed as well as irrigated regions, the main job of the marketing authority is simply to ensure consistent supplies to the cities at a reasonable price.

In areas where onion storage is traditionally practised, the storage crop usually consists of maincrop onions which come in at a time when the price has gone down to uneconomic levels due to temporary oversupply. In economic terms, the market for onions is inelastic, with a constant requirement from consumers for the product throughout the year, and the market cannot absorb more than a small excess over normal demand without the price falling fast, often to less than the cost of production. Therefore, farmers, grower cooperatives, marketing boards or onion merchants make arrangements to take the onions

out of circulation for a time until prices rise to levels which make sales worthwhile. Traditional storage systems can easily be disrupted by changes in other parts of the agronomic system: for example, if high-yielding hybrids are substituted for traditional long-storing varieties, this can lead to storage problems, particularly if the stores are comparatively simple and lack forced ventilation, temperature and humidity control. The efficiency of the curing process in preparing the bulbs for storage becomes very important in such circumstances. Unfortunately, this is not always appreciated by farmers and store managers; sometimes marketing circumstances even act as disincentives for farmers to cure onions correctly (for example, if the onions are bought by weight, with no premium for quality).

## TECHNOLOGY OF ONION STORAGE

### Simple systems for dry climates

Some storage systems can use outdoor storage, provided that the climate is dry enough to allow this. For example, in Mendoza province, Argentina, onions are often stored in heaps in the fields after being pulled with green leaves; they cure naturally in the dry air and can be cleaned and packed out in the field. But as market requirements for quality increase, these methods are being superseded by others which allow better control of conditions, using conventional packhouses with grading tables and with regular inspection by export control authorities. If onions are not sold on at once, it may be advisable to circulate hot air through the bulk boxes or bins to remove the products of respiration.

In the tropics, where onions can be stored at ambient high temperatures, better stores are also coming into use in which ventilation is given a higher priority in order to keep the bulbs dry and to discourage diseases from developing. Various types of stores with layers of shelving or new types of storage arrangement which allow most of the bulbs to be dried by the wind are being developed in many parts of the tropics where forced ventilation is still too expensive for the onion crop. For example, in Brazil, a plastic tunnel drier was found to be superior to drying onions in a conventional barn (Sampaio *et al*. 1999). Plastic tunnels protect onions from rain and allow them to dry out in a warm dry area under good ventilation, especially where seasonal winds can be relied on to blow through the tunnels. Additional drying by air heaters can assist the process and keep the onions warm if necessary (e.g. at high altitudes) so as to delay sprouting. However, it must be said that some of these methods are only economic in situations where there are trade restrictions on imports, thus 'artificially' extending the marketing season for locally produced onions into periods when externally sourced onions might well be cheaper to consumers. Since the general movement in international trade is towards the removal of such restrictions, methods which may have been useful in the past could have limited utility in the future. Countries where the production costs are low because labour is cheap are likely to succeed in expanding their export markets in future.

### Buildings and facilities for onion storage in bulk

For onion storage in bulk, buildings with load-bearing walls are needed: either steel-framed structures or stout masonry walls are suitable. Matson *et al*. (1985) gave very good guidance on construction details, while Brice *et al*. (1997) summarised many of the points to be taken into account when constructing and managing onion stores. Bulk onion stores for the 'direct harvest' management system are usually constructed with slotted false floors or with underfloor ventilation via a main duct serving laterals, such that onions loaded into the store can be ventilated from below, using warmed air at the drying and curing stages, and with the capacity for rapid air flow at the early stages. Later, the warmed air is gradually replaced with cooler and then cold air over several weeks so that there are no rapid changes of temperature which might lead to cool air condensing on the bulbs. Once the bulbs are thoroughly dry the air flow rates can be reduced, though the onions should be ventilated for at least part of each day so that the products of respiration are removed and the temperature remains even throughout the heap. Hard onions can be piled up to a height of 3 m or more. The loading of the store is done in stages, such that each additional load is dried at least on the exterior of the bulbs before the next one is added. The elevators used are placed so that the bulbs do not fall very far, to avoid bruising. Studies on the loads which onions undergo during the harvest and storage periods have shown that it pays to treat the onions as gently as possible, since even if bruises do not show up at first, they can develop over time and lead to the onions being downgraded when the store is unloaded. Experienced managers emphasise the need to avoid patches of earth or trash in the store which will impede ventilation and lead to the formation of 'hot spots' that may be give trouble caused by high humidity, with root growth and disease development later on. Ideally, onions should be examined, and damaged or substandard bulbs be removed as they move along belts into the store.

A common storage system used for sweet Grano/Granex cultivars and very large Spanish onions is based on the use of large, stacking bins. These are now available in plastic

form so that sharp corners are avoided. Large bins need to be handled by fork-lift trucks, and require special physical planning of the store. For ventilation of bin stores, a plenum chamber, formed like a narrow room, runs down one side of the main store, and 'letter box' slots for ventilation are provided, which can be lined up with the bins at different levels. With this system the air passes up through the onions in each bin (Schouten 1987). Normally such systems are for cool climates or are used with refrigeration. However, in warm climates which are not humid for prolonged periods, it may be possible to combine bin or bulk storage with intermittent forced ventilation using ambient air of the appropriate temperature and RH at certain times of day: the development and management of such systems is discussed in detail by Brice *et al*. (1997). Farmers in Zambia and Zimbabwe independently developed heated air onion stores in the 1980s, often making use of tobacco drying barns equipped with heaters (Currah & Proctor 1990).

Where onions are still largely hand harvested, sacks may be filled in the field and stacked on pallets in ventilated stores. In this case an open area should be left in the centre of each pallet so that each sack is aerated from both sides. Failure to do this invites trouble, as the onions in the centre of each palleted mass will tend to get damp and may sprout and eventually rot. Other storage arrangements include using shelves to store bulk onions, using small crates arranged on shelving, or stackable trays with permeable sides and bases, or storing onions in bunches or in strings. In all storage set-ups, however, it should be emphasised that air needs to circulate freely around the onions and that if it is impeded, trouble will follow. The same advice can be given about shallots and garlic. Traditional stringing methods are still in use in some places, such as Korea for 'northern' garlic (J.K. Lee, personal communication, 2003).

## ONION PEST AND DISEASE PROBLEMS IN STORAGE AND DURING TRANSPORT

### Pathogens

A range of fungal and bacterial pathogens feed on and damage onion bulbs. Usually these are organisms which are common in the field or may even be seed-transmitted, as was found with *Botrytis allii* and certain bacterial pathogens. Each pathogen species has its own temperature requirements for development, while all are encouraged to grow by high humidity (>80% RH) during storage. They include low temperature pathogens such as neck rot, and those needing high temperatures (most of the bacteria, black mould or *Aspergillus niger*, and some other fungi). Some fungi preferentially attack coloured cultivars; others prefer white cultivars. Red onion skins contain phenols, protocatechuic acid and catechol, which are not found in the outer scales of brown onions (Walker *et al*. 1929; Link & Walker, 1933). Both phenolic compounds are toxic to the fungus *Colletotrichum circinans* responsible for the disease smudge (Link & Walker 1933). However, not all fungi are affected by these phenols including *B. allii* which is thought to suppress or degrade the onion bulb's natural defences known as tsibulins which are cyclopentane phytoalexins that accumulate in bulb scales at the site of infection (van Baarlen *et al.* 2004). In general terms, onions with high dry matter and high pungency are more resistant to pathogens, and softer, juicy onions are more susceptible and therefore less suitable for long-term storage. But by breeding for good skin quality and higher pungency, even onions with quite low dry matter content can be obtained which can withstand long storage. Traditionally, for example, Egyptian and Spanish storage onions fit this category.

The use of high-temperature (>25°C) drying to discourage neck rot has already been mentioned. Several bacterial and fungal diseases can be hard to control if the infected onions are not detected before they are stored. Mechanically or biologically damaged onions are a menace in store since they give off more water vapour than normal through their raised respiration rate, and their damaged flesh can develop disease infections. Many of the diseases which onions can suffer in storage were illustrated by Snowdon (1991), who also depicted some of the other conditions which can lead to onion downgrades, such as skin staining by water during transport.

Some of the more serious storage pathogens of onions and the conditions which favour them are shown in Table 17.8.

The development of fungi on irradiated onions in store was studied by Benkeblia and Selselet-Attou (1997) in Algeria. The highest ionising treatment, at 0.31 kGy, was most effective in reducing fungal loads on onions. Fungal loads fell at first during storage on the control samples but after a time in store (more rapidly at ambient than at 4°C) they gradually increased again until they reached the original levels after several weeks of storage. After the most severe ionising treatments plus cool storage, the original microflora levels were not regained. However, onion rotting in store could not be correlated the numbers of onion fungi present, and it is suggested that other less specialised organisms are also involved.

In the Korean Republic, novel methods of controlling fungi on onions by biological means have shown promise (Lee *et al*. 2001). The most prevalent diseases were basal rot, black mould and neck rot. A number of antagonistic

**Table 17.8** The Most Economically Important Storage Diseases of Onions.

| Name of disease and organism | Symptoms | Biology and spread | Conditions favouring disease | Control methods |
|---|---|---|---|---|
| Neck rot *Botrytis allii* (*B. byssoidea and B. squamosa* can cause similar damage but are less common in storage.) | Grey-brown rot of flesh often starting in neck area, not usually detected at harvest but shows up within 3 months of storage. Grey mould on the surface followed by large black sclerotia. | Seed transmitted and may also survive in field rubbish and cull piles to infect subsequent crops. Latent in onion plants in field; develops after harvest. Can survive unnoticed from the seedling stage. | Untreated seed; cool wet field conditions especially before and at bulbing. Failure to cure bulbs using heat. Coloured cvs are more resistant than white skinned ones. Can develop at low temperatures but storage at 0°C and 65–75% RH slows development of the fungus. | Seed treatment with benomyl + thiram. After harvest, a relatively short heat treatment at >25°C to dry neck and kill latent fungus in the bulbs is effective. Good ventilation and low RH in storage discourages sporulation. Grow resistant cultivars if possible. |
| Basal rot *Fusarium oxysporum* f.sp. *cepae* | A slowly spreading rot infecting the base plate in the field, later shows as white mycelium and a watery rot that spreads upwards from the base in the bulb. | Soil-borne disease which may also be carried on seed. Often associated with pink root rot, *Pyrenochaeta terrestris*. May survive on weed hosts. | Warm conditions (14–32°C) in soil and in store favour the disease, with optimum temperature at 26–28°: more severe in Mediterranean countries than in cooler ones. Lack of rotation of onion crop. | Remove infected bulbs before storing. Cool storage at <15°C slows disease development. |
| Black mould *Aspergillus niger* (*A. fumigatus*, blue-green mould, and *A. alliaceus*, yellow mould, also occur at even higher temperatures.) | A black powdery mould on or between outer bulb skins after a few days or weeks. More common on veins than between them. Can lead to soft rot of the bulb under hot humid conditions. | Partly seed-borne and can survive in plants until harvest. Very common as a saprophyte on field debris and rubbish around stores especially in hot countries. May be more severe on coloured than on white bulbs. | Favoured by high humidity and temperatures of 27–35°C, and can develop on bulbs if curing stage lasts too long at high temperatures. Commonly develops on stored onions in the tropics if curing and ventilation are inadequate. | Seed treatment may help to reduce seedling damage and storage problems. Proper curing and good ventilation in store help. Cold storage should prevent it from becoming troublesome. |

| | | | | |
|---|---|---|---|---|
| White rot *Sclerotium cepivorum* | A white mycelium affects the roots and base of the bulb, followed by small pin head size black sclerotia. | A long-lasting soil-borne fungus requiring very long rotations once established. However some fields may have some natural biological control agents. Easily spread by workers, machinery or animals. | Favoured by moderate temperatures of 10–20°C, can kill plants in field or start rotting infected bulbs in store. | Long rotations; use of special preparations to induce germination of the sclerotia has shown some promise. Some protective chemicals available. |
| Blue-green fungus *Penicillium* spp. | Fluffy coating of blue-green of greyish fungus on the outer damp skins of onion bulbs especially after transport in damp conditions. | Very common saprophytic fungi which can attack outer skins of onions if they are damp for a prolonged period. | High RH of the air and lack of ventilation favour these fungi. | Drying and shedding of the outer skins usually gets rid of the unsightly fungus coating. |
| Bacterial rots of onion: several species including *Burkholderia (Pseudomonas) alliicola, B. (Ps). cepacia, Ps. aeruginosa, Ps. viridiflava, Erwinia spp., Lactobacillus spp., Pantoea ananatis, Xanthomonas spp.* | Symptoms of the various bacterial infections are soft rots called 'slippery skin', 'sour skin', 'brown rot,', 'bulb rot' 'centre rot' etc. Often only the outside fleshy rings or certain inner rings are affected by the rots. May be accompanied by odours which can be diagnostic.<br>Sometimes bulbs in store rot then dry and shrivel. | Some species suspected to be seed-borne. Often spread between plants by rain splashing, may enter through surface wounds including at harvest and by topping blades. Some species are harboured by common field weeds. | Some bacteria can spread at a wide range of temperatures (5–41°C) but in general warm or hot (>25°C) and damp conditions favour bacterial rots. Under very hot climates, other normally saprophytic bacteria and yeasts can also attack onion tissues. Care to avoid damage, rotations, cleanliness in field operations are all recommended. Overhead watering should be avoided in the run-up to harvest. | Copper fungicides, sometimes with antibiotics (if permitted) have been used, but bacterial diseases are hard to control especially in wet seasons. Less of a problem in dry climates and dry season crops. If possible, allow foliage to dry completely before trimming, to prevent spread. Good weed control removes the alternative hosts.<br>Cool storage slows development of bacterial infections. |

Sources: Chupp and Sherf (1960), Anon. (1986), Maude (1990), Snowdon (1991), Hayden and Maude (1997) and Mark *et al*. (2002).

micro-organisms were applied to the onion rhizoplane at transplanting in order to identify those most effective against storage rots and the best time for application. *Trichoderma harzianum* strain TM was effective in reducing basal rot infection from 16% to 4%. When the antagonists were applied to onion necks at top cutting, both *T. harzianum* TM and *Bacillus amyloliquefaciens* strain BL-3 completely suppressed neck rot in one test.

### Pests

Some pests can become a nuisance in onion stores. In Egypt, a number of mites found on onions have been shown to transmit *Aspergillus* spp. and other moulds between onions or garlic in storage, either on the outside of their bodies or via the digestive tract (Abdel-Sater & Eraky 2002). Stores which are not kept clean can also harbour other pests such as beetles which can damage onion bulbs; stores should also be well protected against rodents and should be checked regularly for signs of the gnawing damage to the structure which will allow them to enter (Brice *et al*. 1997).

## GARLIC PATHOGENS AND PESTS IN STORAGE

A somewhat different collection of pests and diseases can attack garlic: these include storage mites (Abdel-Sater & Eraky 2002), which are less often a problem on onions, and *Penicillium* spp. moulds which can attack individual cloves and dry them out or reduce them to powder. Studies in Poland found that garlic was infected by species such as *P. viridicatum* and other *Penicillium* species. These species were also found on the roots before harvest, as was *Fusarium oxysporum* (Machowicz-Stefaniak *et al*. 1998a, 1998b). In Botucatu, Brazil, fungi present on or in garlic bulbs were identified as *Penicillium* spp., *Fusarium* spp., *Aspergillus* spp. and *Embellisia allii*: various fungicides were tested for efficacy against them (Soares & Kurozawa 1998, 1999). In Maharashtra, India, *A. niger* was the most important pathogen found on garlic bought in local markets (Guldekar *et al*. 1999), whereas in Khorasan, Iran, *F. oxysporum* was the most damaging fungus (Mahmoody 1998). In Egypt, several other fungi were also found, including *A. niger*, *A. versicolor*, *P. chrysogenum*, *P. funiculosum* and several 'field fungi' and the three mites species found were capable of moving these fungi from one plant to another within the store (Abdel-Sater & Eraky 2002). In Jiangsu, China, bacterial diseases caused by *Erwinia*, *Bacillus spp*., and *Rhodococcus* spp. were identified on garlic, as were the fungi *P. chrysogenum*, *A. niger* and *F.oxysporum* (Ge & Xu 2001). A bacterial disease, 'café au lait' of garlic, caused by *Pseudomonas fluorescens*, was found in several European countries (Jacques *et al*. 2000).

Mites which attack garlic in storage include *Aceria tulipae*. Courtin *et al*. (2000) studied its biology to identify the environmental conditions which most favour the pest. They found that a temperature of 25°C was ideal for rapid multiplication. The mite's development was arrested by low-temperature storage, but it was not completely killed.

## LONG-DISTANCE TRANSPORT BY SHIP

Onions are often transported in steel shipping containers: for preference, these should be temperature controlled and have the possibility of being ventilated with ambient or recycled air *en route*, particularly if the journey will take several weeks. Onions from Australia and New Zealand go through several climatic zones before reaching Europe and the use of 'fantainers' or refrigerated ('reefer') containers is recommended to keep the onions in good condition. Failure to take care of onions in transit can lead to expensive losses, for example through condensation water falling on the bulbs and staining the skins, or by the development of severe surface moulds (usually *Penicillium* spp.). Delays in tropical ports can be disastrous if the ventilators cannot be kept running. On arrival at the destination port, the onions will probably be damp skinned and should be unloaded and dried out as rapidly as possible, so as to stop further water losses. Once the skins have dried out to a safe moisture content but are still flexible, the onions can be put over a grader and packed for market into mesh bags. The poorer quality external scales are usually lost at this stage so the appearance of the bulbs improves when the brighter underlying dry skins are revealed. Onions showing signs of damage, staining, sprouting and so on make the batch unsuitable for the higher-quality classes but the lower grades may still have a value for processing where surface-quality criteria are less important. The problem of maintaining quality after shipping was studied by Dean and Patil (1995) in the north-western United States in connection with exports of sweet onions to Japan.

## MARKETING ONIONS AND GARLIC TO CONSUMERS

Plastic mesh sacks holding 12 to 25 kg are commonly used to transport onions from packhouses to commercial outlets (in the United States, 50 pound (22.7 kg) bags are commonly used). In less-developed countries, very large jute or hessian sacks containing over 100 kg may be used for onion transport (David & Moustier 1998): these are not ideal since they can crush the onions and also allow people to walk or lie on the bags when being transported by truck.

Onions for retail sale may be sold loose or be packaged into smaller mesh packs or in plastic bags, though these are not ideal due to their limited ventilation. Well ventilated bags are a better option. Often certain types of onions are sold in recognisable packs, such as large Spanish-type onions in 'in-line' packs of three in the United Kingdom. The consumer tends to assume that these onions will be mild, though surveys in the United Kingdom have shown that this is not always true (B.M. Smith, personal communication, 2001). Similarly, there seems to be an assumption here that red onions are usually mild, and again this generalisation is not justified since red onions can show a wide range of pungency levels. Developments in onion selling are the use of ready-peeled and cut onions for catering uses. Some research has been done on the use of modified atmospheres to retain quality in such packs (Blanchard *et al*. 1996).

In the United Kingdom, there is little attempt at marketing onions for specific uses and consumers are usually left to find the best uses for themselves. However, in the United States, with its large and distinct production areas, speciality crops such as seasonal sweet onions (e.g. Vidalia onions from Georgia), or large mild onions, are well publicised by state or regional grower groups which can obtain funds through federal marketing orders (i.e. levies on crops sold). In many countries, it is noticeable that the growers themselves show little interest in the marketing aspect of onion production, an omission which leaves them open to having their market share taken by more enterprising exporters. The need to educate consumers in how best to store onions and garlic in the home is ignored, leading to complaints that onions do not keep well and that garlic sprouts rapidly when kept in the refrigerator; in fact, traditional methods of keeping bulbs under warm dry conditions are as effective as ever, but often they have not been put over to younger consumers.

Garlic tends to be treated as a speciality crop or a condiment and its high value allows it to be marketed in a range of units, from single bulbs through sleeved or boxed pairs of bulbs up to strings, small wooden crates or sacks. Treatment by smoking is sometimes used to add value. For the catering trade, 'peeled' garlic is a valuable commodity since the preparation work can be omitted at the factory. Chinese peeled garlic can be shipped to markets such as the United States, which can be reached within 18 days of peeling the bulbs. 'Fresh' garlic (i.e. bulbs sold with their green tops) is also seasonally popular in European markets. In East Asia, special green leaved varieties are grown for the leaves which are traditionally used in cooking, as well as the dry bulb varieties. As well as fresh garlic for culinary uses, other uses such as dietary supplements (including 'aged' garlic, no-odour garlic etc.), pest repellents and so on are being rapidly developed. Novel time-saving preparations such as ready-crushed frozen garlic are being developed (J.K. Lee, 2003, personal communication.). The health-giving properties of garlic are of great interest, since it can also serve as an antiseptic in cases where antibiotics are not effective. Health aspects of garlic were reviewed by Milner (2001), Keusgen (2002) and Corzo-Martínez *et al*. (2007).

### Research on prepared allium products

The increasing use of prepared onions and garlic, usually for the catering trade, is bringing a need for research on methods of conservation of these products. Lee *et al*. (2000) investigated the dynamics of internal atmosphere and humidity in perforated plastic packages of peeled garlic. These workers developed a mathematical model which can predict the changes that take place in the package atmosphere over time: however, they found that hermetic packaging, which produced a water-saturated atmosphere with nil $O_2$ and 5% to 15% $CO_2$, performed better than perforated plastic in maintaining the freshness of the peeled cloves.

Diced yellow onions packaged in a range of modified atmospheres were studied by Blanchard *et al*. (1996) in France. The work included studies on microbial development in the packs. The conclusions were that high $CO_2$ and low $O_2$ delayed both the rise in respiration and the reduction in sucrose content. The levels of reducing sugars and total sugars were not affected during the 12-day experiments at 4°C. The data obtained will be used to develop the safest methods to package cut onion products.

## WASTE DISPOSAL

The problems associated with waste disposal from allium storage and processing is presenting increasing problems, especially where laws on waste disposal are becoming more stringent. Allium waste is not suitable for animal feed or landfill as it rapidly produces phytopathogens and cannot be reintroduced into the soil due to the high levels of sulphur compounds. Work is therefore being commissioned on ways to make constructive use of waste products from alliums. In California, Zhang and Zhang (1999) developed a method of anaerobically digesting garlic waste to produce biogas. After the digestion process, 51% of dry matter and 62% of volatile solids in the garlic waste were converted to biogas. It was planned to develop this to pilot plant scale. Roldán *et al*. (2008) investigated methods of processing onion by-products to produce a safe product which retained

its antioxidant properties and could be used as a food ingredient. They concluded that pasteurisation (100°C, 11–17 min) was superior as it developed a safe food ingredient which retained its high antioxidant capacity and showed no adverse effects such as caramelisation.

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# 18
# Tropical Root Crops

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## INTRODUCTION

Root and tuber crops provide the dietary base for 500–700 million people in the world. FAO statistics indicate that root and tuber crops are particularly important in the tropical countries of the world (Lancaster & Coursey 1984). Cassava (*Manihot esculenta* Crantz), sweet potato (*Ipomoea batatas* (L.) Lam) and yam (*Dioscorea* spp.) are the major tropical root crops grown in developing countries and will be the main focus of this chapter. They play a vital role in the food security and economies of many countries, and their importance to poor people makes them key targets for making an impact on poverty world-wide. There is, however, a wide range of lesser known root and tuber crops, many of which are of key importance to populations in specific regions. Some of these crops are listed in Table 18.1. Organisations such as the Global Facilitation Unit for Underutilized Species (www.underutilized-species.org) and the International Centre for Underutilised Crops (www.icuc-iwmi.org) work to maintain genetic diversity and therefore to preserve these crops.

World production data estimates for 2005 (FAOSTAT 2006) for the major root crops are shown in Table 18.2. Some of the main points to note are the importance of cassava, particularly in Sub-Saharan Africa (54% of world production), China's dominance of sweet potato production (83% of world production) and the importance of yam in Africa (97% of world production), particularly in Nigeria (68% of world production). The figures may even underestimate the importance of cassava; Cock (1985) estimated that cassava was a staple food crop for 500 million people in 24 countries. In the Democratic Republic of Congo, the Republic of Congo, Central African Republic, Mozambique and Angola cassava provides over one third of the calories in the diet (FAO 1990). Cassava takes on an importance of its own in times of civil unrest and war when it remains available while other crops have to be abandoned.

Root crops have become so important in tropical developing countries because of their agronomic advantages and limited requirement for inputs. For example, cassava gives a high yield of carbohydrates even on poor soils, has good tolerance to drought, is relatively resistant to pest infestation and disease and can be stored in the ground until required. Sweet potato produces the highest quantity of energy per hectare per day of any of the major tropical crops (194 MJ/ha/day compared to 149 for rice, 145 for maize and 101 for sorghum) (Woolfe 1992). Yams need more agricultural inputs than the other root crops (for example, in terms of labour requirements; 45 working days/tonne of yam, in comparison to 21 for cassava, 121 for maize and 145 for rice). Nevertheless yams are an important source of household income and they have great cultural significance, especially in West Africa (Coursey 1967).

These crops also have a role in world trade and in developed countries. The international trade in fresh cassava is small but growing with the movement of populations from Latin America, the Caribbean and Africa

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**Table 18.1** Underutilized Tropical Root Crops.

| Latin name | Common names | Distribution |
|---|---|---|
| *Alocasia macrorhiza* | Yantua-it, giant taro, elephant ear, ape flower | SE Asia, Australia, Pacific |
| *Amorphophallus campanulatus* | Elephant foot yam, dziwadlo, pungapung, telingo potato, suran | Madagascar to Asia, Polynesia, N Australia |
| *Arracacia xanthorrhiza* | Apio, arracach | Northern South America |
| *Canna eduli* | Achira, edible canna | Peru |
| *Colocasia esculenta* | Taro, coco yam, kalo, taro de chine, chinese potato, malanga | |
| *Cyrtosperma chamissonis* | Giant swamp taro | SE Asia, W Melanesia |
| *Maranta arundinacea* | Arrowroot, obedience plant | Florida, W Indes, Australia, SE Asia, S and E Africa |
| *Oxalis tuberose* | Oca, 0oa | Andes, New Zealand |
| *Pachyrhizus erosus* | Jicama | Mexico, Central America |
| *Plectranthus esculentus* | Livingstone potato, kaffir potato | Africa |
| *Smallanthus sonchifolius* | Ycon, Mexico potato, potato bean, yacurna | Andes |
| *Tropaelum tuberosum* | Mashua, anu mashwa | Andes |
| *Ullucus tuberosus* | Ulluco | Andes |
| *Xanthosoma sagittifolium* | Badoo, Chinese taro, macabo, cocoyam | W Indes |

Source: Information collated from http://www.underutilized-species.org/species/roots_tubers.asp.

**Table 18.2** Production of Major Root Crops (Million Tonnes per Annum) in Selected Regions and Countries.

| Region | Potato | Cassava | Sweet potato | Yam | Total roots and tubers |
|---|---|---|---|---|---|
| Total World | 321 | 203 | 129 | 40 (68%) | 712 |
| Sub-Saharan Africa | 7 | 110 (54%) | 11 | 38 (97%) | 179 |
| South America | 14 | 36 | 1 | 0.6 | 52 |
| Asia | 132 | 58 | 114 | 0.2 | 306 |
| North and Central America | 27 | 1.6 | 1.5 | 0.6 | 31 |
| Europe | 131 | | | | 131 |
| Australia | 1.3 | | | | 1.3 |
| China | 73 | 4 | 107 (83%) | | 186 |
| Brazil | 3 | 27 | 0.5 | | 30 |
| DR Congo | | 15 | | | 16 |
| Nigeria | 0.7 | 38 | 2.5 | 27 | 72 |

Note: Figures in parentheses indicate percentage of world production.
Source: 2005 estimates from FAOSTAT (2006).

to developed countries. Most international trade in cassava is as dried chips and pellets for animal feed, with Europe as the main importer and Asian countries, especially Thailand as the main exporters. The size of this trade depends critically on the grain prices (IFAD FAO 2000). Approximately 15% of the overall cassava trade is as flour and starch, in which case the main importers are Japan, Taiwan and China (IFAD FAO 2000). Sweet potato is a popular commodity in the United States, and is growing in popularity in Europe. As for cassava, trade in yams from Africa to Europe is increasing with the size of the African immigrant population.

## POST-HARVEST PHYSIOLOGY OF FRESH ROOT CROPS

Although cassava, sweet potato and yams are all subterranean storage organs which accumulate starch, they have different botanical origins. A yam is a tuber, but although the harvested part of cassava and sweet potato are also often referred to as tubers, they are in fact lateral roots in which starch has accumulated.

Harvested root crops are living parts of the plant that continue to metabolise and respire after harvest. Cassava roots are used by the plant to store energy while sweet potato roots and the yam tuber not only act as an energy store, but are also reproductive organs. Despite their agronomic advantages over grains, which are the other main staple food crops, root crops are far more perishable. Out of the ground, and at ambient temperatures these root crops have shelf lives that range from a couple of days for cassava (Wenham 1995), two to four weeks for sweet potato, to between four and 18 weeks for the natural dormancy of yams (Knoth 1993). There are two main approaches to overcoming this problem of perishability: the breeding of varieties with longer shelf-lives; and the use of improved storage techniques to optimise storage environment. Breeding is a long-term strategy, whereas improved storage is likely to have a more immediate impact, although in this case the extent of the improvement will still be limited by the roots inherent perishability.

The ability of plant tissues to heal wounds is important to prevent excessive water loss and pathogen invasion. Thus the ability of roots and tubers to wound heal has important implications for shelf-life, and is usually exploited by a process termed curing, in which they are placed in an environment to promote healing of wounds incurred during harvesting and handling. The ability of each of the major root crops to wound-heal will be discussed within the individual sections below.

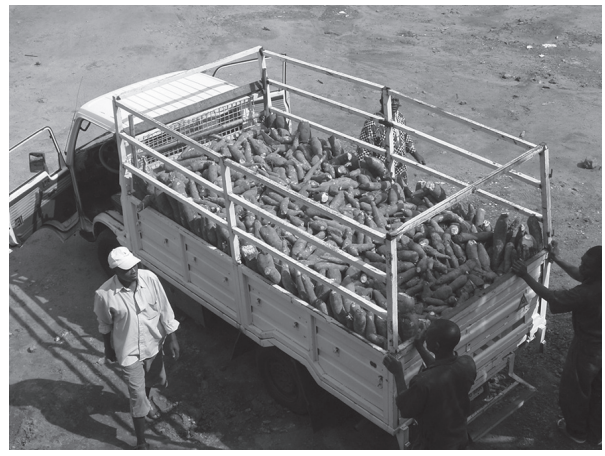

**Figure 18.1** Cassava roots being transported by truck in West Africa.

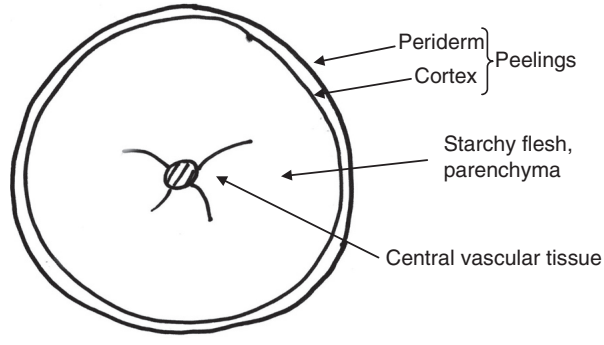


**Figure 18.2** Cross section of cassava root. (Adapted from Diop and Calverley 1998, with permission from the FAO.)

## BOTANY AND PHYSIOLOGY OF CASSAVA

Cassava is known by many names, including tapioca, manioc, mandioca and yuca. Although the genus *Manihot* has about one hundred species, *Manihot esculenta* is the only one cultivated (Alves 2002) (Figure 18.1). It is grown in tropical and sub-tropical regions. There are two plant types; erect and spreading. Harvest time ranges from six to 24 months, and roots can be left in the ground until needed, making cassava a very useful food security crop (Cardosa & Souza 1999). As a perennial shrub, the plant can grow indefinitely, alternating vegetative growth with periods of carbohydrate accumulation and near dormancy at times of stress. Cassava germplasm is very variable; the largest germplasm collections are maintained by the International Center for Tropical Agriculture (CIAT) in Columbia and the Empresa Brasileira de Pesquis a Agropecuaria (EMBRAPA), Brazil.

The harvested cassava roots are generally adventitious roots that have developed into storage roots, although if propagated from seed, the tap root can also become a storage root. Unlike sweet potato, the cassava root is a 'true' root rather than a tuberous root, and as such cannot be used for vegetative propagation (Alves 2002).

The root structure (Figure 18.2) consists of the outer periderm, which is a few cells thick and constitutes about 3% of the total root weight. Underneath this is the cortex, which consists of the sclerenchyma, cortical parenchyma

**Table 18.3** Composition of Cassava Roots.

| | % in whole roots | % in peel (8–15% of the root) |
|---|---|---|
| Dry matter | 35 | 30 |
| | % of dry matter (DM) | |
| Carbohydrate (mainly starch) | 89 | 75 |
| Lipid | 1 | 2 |
| Protein | 2.5 | 4 |
| Fibre | 4.5 | 12 |
| Ash | 3 | 5 |
| Calcium | 0.125 | — |
| Phosphorus | 0.1 | — |
| Thiamine | 0.125 mg/100g DM | — |
| Iron | 2.2 mg/100g DM | — |
| Ascorbate | 0.39 | — |

Source: Adapted from Balagopalan *et al*. (1988) and Silvestre (1989).

and phloem (11–20% of total root weight). The innermost tissues, constituting about 85% of the total root weight are the parenchyma, made up of starch containing cells and the xylem vessels (Alves 2002).

### Cassava root composition

Table 18.3 summarises the typical composition of a cassava root. Despite its high starch content cassava is low in protein and key micronutrients (zinc, iron and vitamins). When disrupted the root tissues may produce toxic hydrogen cyanide which can have very important implications for human health (see below)

### Cassava root deterioration

Of the main starchy root crops cassava has the shortest shelf life. Two types of post-harvest deterioration are recognised in cassava; primary physiological deterioration which involves internal discolouration and the initial cause of loss of acceptability, and secondary deterioration due to microbial spoilage (Booth & Coursey 1974). Physiological deterioration is thought to be a physiological response to tissue damage during harvesting. In most cases it is seen as a blue-black discolouration of the vascular tissue which is generally called vascular streaking. These initial symptoms are followed by a more general discolouration of the tissue. Where cassava is harvested and consumed locally this is not a great problem, but it is a serious constraint for the development of marketing, where the distance between production and consumption increases (e.g. Westby 2002). The whole process has been the subject of considerable investigation as an improved understanding is perceived as key to extending cassava shelf life and hence its potential to improve food security.

### Post-harvest physiological deterioration in Cassava

Post-harvest physiological deterioration (PPD) in cassava has been identified as an enzymatically driven response that occurs throughout the root as a result of wounding and oxidative stress incurred at harvest. The first symptoms involve a discolouration of the vascular tissues that spreads from the wound sites, and then into the storage parenchyma (Plate 18.1). The pattern of fluorescence observed when tissues are exposed to UV light indicates the production of phenolic compounds including scopoletin and tylose. The blue/black vascular streaking has been attributed to the peroxidase-mediated oxidation of scopoletin (Wheatley & Schwabe 1985). Reilly *et al*. (2003) support this hypothesis by demonstrating the presence of both reaction components and peroxidase activity. Coloured occlusions and tyloses appear to block xylem vessels. Other symptoms related to PPD include increases in respiration and mobilisation of starch to sugars by the activity of acid invertase, changes in lipid composition and increased synthesis of phenols, diterpenes and catechins as well as increased synthesis of ethylene.

PPD appears to be a continuous cascade of wound response spreading through the root. It is interesting that when roots remain attached to the plant they are capable of normal wound repair (Mwenje *et al*. 1998), it is only after harvest that wound repair and down modulation appear to be inadequate, leading to this cascade response. This response is not found in the other main root crops for which the storage roots/tubers are reproductive.

Thus, PPD is not considered to be degenerative, but an active response of the cassava root involving gene activation, protein synthesis and secondary metabolite accumulation. Inhibition of protein synthesis by chemical inhibitors or heat treatment slows the process (Uritani *et al*. 1984). CDNA-AFLP analysis indicates that genes expressed during PPD include defensive compounds such as antimicrobials, antioxidants and, cell wall components. Up-regulation of genes related to defence and wound healing is observed such as phenyl alanine ammonia lyase (PAL), b-glucanase and hydroxyproline-rich glycoproteins and of proteases, protease inhibitors and other genes implicated in senescence or programmed cell death responses in other plant systems

(Beeching 2001, Han *et al*. 2001, Huang *et al*. 2001, Reilly *et al*. 2001, Taylor *et al*. 2001a.)

Beeching and co-workers postulate that in common with many stress defence pathways in plant tissues (Scott *et al*. 1999) reactive oxygen species are central to the PPD response. Thus PPD is associated with peaks of reactive oxygen species and increased activity of enzymes that modulate reactive oxygen species. (Reilly *et al*. 2001, 2003) as well as the accumulation of secondary metabolites, some of which show antioxidant properties, and the altered regulation of genes related to the modulation of reactive oxygen stress. This is consistent with the observations that decreasing oxygen levels by controlled atmospheres, modified atmospheres or waxing, all slow the PPD response. It has also been observed that the content of the carotenoids, which have antioxidant activity, above a certain threshold (5 mg/Kg fresh weight) reduces PPD response (Chavez *et al*. 2000, Sanchez *et al*. 2006). Both β-carotene and ascorbate levels decrease during PPD.

It is known that cassava cultivars differ in their susceptibility to PPD, opening the possibility of breeding for reduced PPD either through conventional methods or by transformation. This is a major objective for the Cassava Biotechnology Network, organised through CIAT. It has been shown that there is a genetic contribution, (PPD is a complex multigenic trait), but that there is also a strong environmental interaction (Cortes *et al*. 2002). Molecular information can provide valuable information and tools such as quantitative trait loci (QTL) mapping and marker-assisted selection could assist and accelerate breeding programmes. Several transformation systems are now available and have been applied for research purposes (e.g. Taylor *et al*. 2001b).

The biochemical events during deterioration in a range of cassava varieties showing differential deterioration responses have been studied, as well as the phenomenon that cassava shows less PPD when plants are pruned a few days before harvesting (van Oirschot *et al*. 2000). Low PPD by variety and due to pruning have been shown to be associated with increased catalase activity. Less susceptible cultivars or pruned plants may efficiently utilise catalase to scavenge $H_2O_2$ produced after wounding, resulting in the formation of $O_2$ and $H_2O$ (Reilly *et al*. 2003). Where catalase levels are relatively lower and peroxidase levels relatively higher, a significant proportion of $H_2O_2$ scavenging could occur via peroxidase mediated reactions requiring the participation of cellular components including scopoletin, as an electron donor. Thus relatively higher levels of peroxidase would lead to increased oxidation of scopoletin observed as vascular streaking. In support of this hypothesis, pruned cassava with lower PPD show higher levels of the MecCAT1 transcript suggesting higher catalase levels.

### Wound-healing of cassava roots

Cassava roots are able to wound-heal, but less efficiently than the other tropical roots crops. At relative humidities of around 80% to 90% periderm formation occurs in seven to nine days at 35°C and 10 to 14 days at 25°C (Rickard 1985).

### Cyanogenic compounds

Cassava contains cyanogenic glucosides, which together with their breakdown products (cyanohydrins and free HCN) formed during processing, can cause health problems. Acute intoxication, manifested as vomiting, dizziness or even death can occur under rare conditions. Such poisoning occurs when food shortage and social instability induce shortcuts in established processing methods or when high cyanogen varieties are introduced into an area lacking appropriate processing techniques (Bokanga *et al*. 1994). It is well established that thiocyanate resulting from dietary cyanide exposure can aggravate iodine exposure deficiency expressed as goitre and cretinism (Bokanga *et al*. 1994). There is also strong evidence for a causal link between cyanide and the paralytic disease konzo (Tylleskar 1994) and tropical ataxic neuropathy (Osuntakun 1994).

The cyanogenic glucosides present in fresh cassava roots are linamarin (93%) and lotaustralin (7%) (Nartey 1978). These are hydrolysed to the corresponding ketone (cyanohydrin) and glucose by the endogenous enzyme, linamarase, when cellular damage occurs (de Bruijn 1973, Nartey 1978). Cyanohydrins breakdown non-enzymically at a rate dependent upon pH and temperature (Cooke 1978) with their stability increasing at acidic pH values. The removal of cyanogens from cassava during processing is achieved through this chain of reactions. The development of an assay method for the different cyanogenic compounds (Cooke 1978, modified by O'Brien *et al*. 1991) allowed scientists to start to understand the mechanisms of cyanogen reduction during processing. (See section on cassava processing).

## BOTANY AND PHYSIOLOGY OF SWEET POTATO

Sweet potato is a dicotyledonous plant belonging to the Convulvulaceae family. A large number of sweet potato cultivars exists, with a variability that is greater than for most other tropical root crops. Cultivars have arisen through systematic breeding as well as natural hybridization and mutations. In East Africa alone, 2000 clones have been identified (Jana 1982).

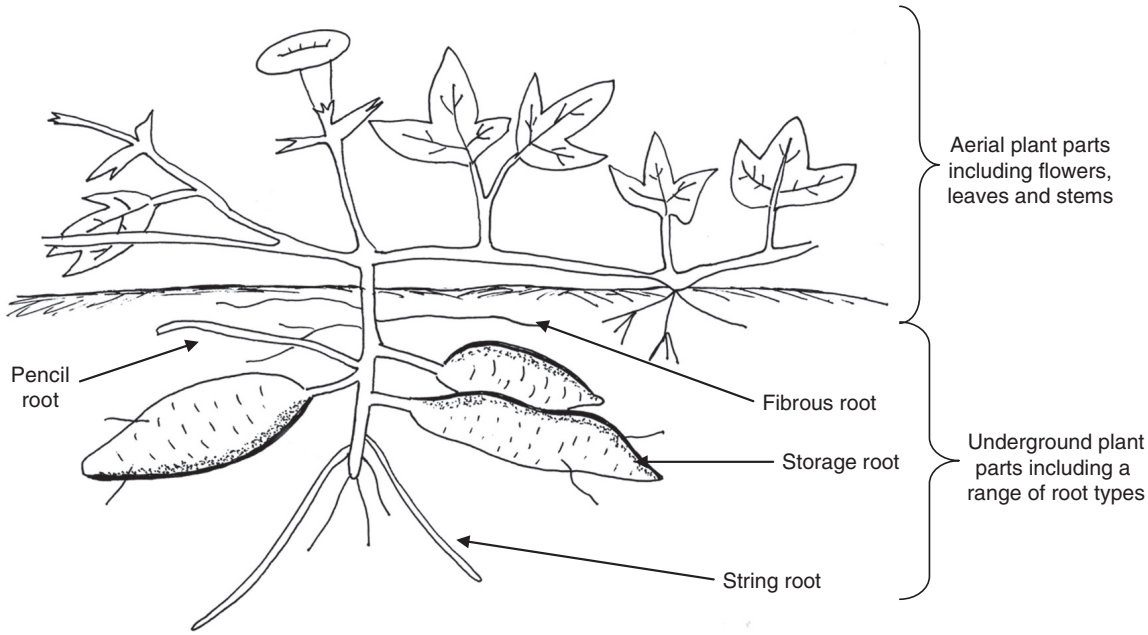


**Figure 18.3** Morphology of the sweet potato plant. In practice, the proportion of foliage to root is somewhat greater than that shown here. (Adapted from Woolfe 1992.)

Sweet potatoes are grown from 40°N to 32°S of the equator. On the equator they are grown from sea level to 3000 m. Growth is best at or above 24°C and when temperatures fall below 10°C it is severely retarded. The crop is damaged by frost and this restricts its cultivation in temperate regions to areas with a minimum frost free period of 4 to 6 months (Onwueme 1978).

Like cassava, the storage organ of the sweet potato is a root, although unlike cassava it can be used for vegetative propagation (Figure 18.3). This is in contrast to potatoes, which are tubers originated from the stem (Kays 1985).

Sweet potato is a perennial plant, but it is normally grown as an annual. Under cultivation it is usually propagated from vine cuttings, although in some countries such as the USA it is common to obtain growing material from roots. The growth occurs in three more or less distinct phases. In the first phase fibrous roots grow extensively and there is only moderate growth of vines. In the second phase the vines grow, the leaf area increases and the growth of storage roots is initiated. In the third phase the bulking of the storage roots takes place (Kays 1985).

Sweet potato storage roots are ready to harvest after 4 to 5 months, but sometimes, depending on the cultivar, this can be longer. The number of storage roots produced per plant varies but is generally from three to ten roots (Woolfe 1992).

Sweet potato roots vary enormously in characteristics among cultivars. The basic structure consists of starch storing parenchyma, an outer cortex, and the surface periderm. The colour of the flesh can be uniform or multicoloured, with colours ranging from white, cream, yellow, orange and even purple. The colour of the skin is likewise very variable; cream, orange, dark red.

### Sweet potato root composition

Typical ranges in composition are given in Table 18.4. Sweet potato is high in carbohydrates and can produce more edible energy per hectare per day than wheat, rice or cassava. The protein content (generally about 5% by dry weight) is too low to provide a balanced diet on its own, and is lower than found in staples such as potato, yam and cereals, but higher than crops such as cassava and plantain. More than 80% of the protein is the storage protein sporamin (A and B) (Maeshima *et al*. 1985). Digestibility of this protein by humans is not high, suggesting that there is some component within sweet potato that affects protein digestion (Woolfe 1992).

Some varieties with orange flesh are particularly high in pro-vitamin A, and have been the subject of a range of initiatives to combat vitamin A deficiency focused on sub-Saharan Africa (Tomlins *et al*. 2010). While most sweet

**Table 18.4** Typical Composition of Sweet Potato Roots.

| Component | Levels in storage root (units as indicated) |
|---|---|
| Dry matter (%) | 14.7–39.9 |
| Total sugar (% DM) | 5.6–46.8 |
| Starch (%DM) | 12.3–70.8 |
| Protein (% DM) | 2.7–10.4 |
| Protein (% FW) | 0.5–2.4 |
| Fat (% FW) | 1.8–6.4 |
| Carotene (mg/100g) | 0–13.3 |
| Ascorbic acid (µg/g fresh tissue) | 68–284 |
| Crude fibre (g dry fibre/g fresh tissue) | 0.04–0.35 |

Source: Adapted from Collins (1989).

potato presently consumed in sub-Saharan Africa is white or yellow fleshed, orange fleshed varieties biofortified with pro-vitamin A are becoming more widespread. More than three million children under the age of five in the region suffer from vitamin A related blindness, and vitamin A deficiency is one of the leading casues of early childhood death and a major risk factor for pregnant women. Adding 100 g of orange fleshed sweet potato to the daily diet can prevent vitamin A deficiency in children, dramatically reduce maternal mortality and lower the risk of mother-to-child transmission of HIV/AIDS (van Jaarsveld *et al*. 2005). Ex –ante impact assessment study indicated that introducing the new high-beta carotene varieties that meet local preferences would benefit an estimated 50 million children under the age of six who are currently at risk in addition to significant benefits for childbearing women (Kapinga *et al*. 2005, Low *et al*. 2001, 2007).

The root is also an important source of ascorbic acid (Vitamin C) with some cultivars containing more than 30 mg/100 g (Visser & Burrows 1983).

### Storability of sweet potato

Sweet potato roots do not exhibit the post-harvest physiological deterioration described above for cassava, and even without temperature control can, with care, be kept for weeks rather than days. Thus in East Africa sweet potatoes have a shelf life of one to two weeks during marketing (Rees *et al*. 2001). In storage trials carried out under simulated marketing conditions in Tanzania, it was found that rates of root weight loss and rotting both varied considerably among cultivars. This has been attributed to variation in wound-healing efficiency. Sweet potatoes are able to wound-heal more efficiently than cassava, and thereby reduce both water loss and pathogen entry through wounds.

### The process of wound-healing in sweet potato and its role in determining storability

The healing response of surface tissues in root crops such as sweet potato is very important for the protection of damaged roots against water loss and pathogen invasion, and is key to ensuring good keeping quality. It has been demonstrated that a wide range in shelf life of sweet potato cultivars is associated with variability in the efficiency of wound-healing (van Oirschot *et al*. 2006); Although sweet potato cultivars are generally all able to heal wounds efficiently when placed at high humidity, they differ significantly in their ability to heal wounds when kept at low humidity (Van Oirschot *et al*. 2002, 2006). Wound-healing of roots and tubers, notably potatoes, has been studied extensively under controlled high humidity conditions (Walter & Schadel 1983, Burton 1989, St Amand & Randle 1991). However, tissue response at low humidity, which is generally more relevant for plant tissues, both under natural conditions and notably marketed commodities wherever the commodity is handled in the absence of temperature/humidity control, has been largely overlooked. Given its importance for sweet potato shelf life this has recently become a focus for investigation in sweet potato.

Descriptions of the process of wound-healing in sweet potato date from the 1920s when Weimer and Harter (1921) described how moisture and temperature affect the wound periderm formation and the efficiency of the wound cork in preventing infection. Artschwager and Starret (1931) distinguished three stages of healing: (1) desiccation of several cell layers of parenchyma, (2) thickening of cell walls (lignification) in underlying cell layers and (3) formation of the wound periderm. The desiccation of cell layers in which the cells on the surface dry out and die is the first response after wounding. At low humidity, poor wound-healing is associated with a thick desiccated layer and slow or incomplete lignification (Van Oirschot *et al*. 2006). Continuity of the lignified layer is vital for effective wound-healing, presumably to act as an effective barrier to water loss and pathogen invasion (Van Oirschot *et al*. 2006). A method for assessing efficiency of wound healing based on assessing the continuity of lignified layers by phloroglucinol staining (lignification score) was developed by Van Oirschot *et al*. (2002, 2006), and has been used as a tool for screening sweet potato germplasm.

A relationship of sweet potato root dry matter content both with shelf life (Rees *et al*. 2003) and with wound-healing efficiency, has been reported previously (Van Oirschot *et al*.

2002, 2006). Low dry matter content is associated with longer shelf life and more efficient healing at low humidity. In order to understand the basis for this association, van Oirschot *et al*. (2002) carried out a screening of a wide range of sweet potato germplasm originating from many regions of the world. Cultivars from different regions tended to cluster both by wound-healing efficiency and dry matter content. Thus African cultivars tended to be both poor healers and have high dry matter content. Evidence has been obtained suggesting that there is a direct link between carbohydrate levels (sugar and starch) and sweet potato tissue response to water stress, which thus affects wound healing efficiency (Rees *et al*. 2008). However, there appear to be additional cultivar factors controlling wound-healing efficiency and more work is needed if it is to be possible to breed for better storing cultivars.

### Respiration and chilling injury in sweet potato

During long-term storage, respiration rates can be a good indication of storage life, and respiration can contribute significantly to weight loss in sweet potato roots. High rates of metabolism, can be detrimental to quality, by changing the carbohydrate composition, or in the extreme case, by metabolising so much starch that air spaces form, and the texture of the root becomes spongy. Most work on carbohydrate metabolism and respiration has been carried out on North American or Japanese cultivars under the temperature regimes used in refrigerated stores (typically 13–15°C) (e.g. Woolfe 1992 and references therein, Takahata *et al*. 1992). These have generally shown that sugar levels increase during storage (Woolfe 1992). However, the metabolic rate is temperature dependent, and the cultivars can vary significantly in their metabolic characteristics (e.g. Ahn *et al*. 1980), so that there is a need to determine how cultivars behave under tropical conditions. Storage roots are more sensitive to temperature than the rest of the plant. Whereas the Q10 (increase in respiration rate over 10 degrees) of whole plant is 1.6, that of storage roots is 2.5 (Kays 1985).

Sweet potato roots are sensitive to chilling injury below about 12.5°C. Symptoms of damage include flesh discolouration, internal breakdown, increased decay, off-flavours, hard core when cooked (Wang 1990).

### The control of sprouting of sweet potato roots

The sweet potato storage root can be used for vegetative reproduction, and thus it will sprout easily. There appears to be no dormancy period, so that harvested roots can generally be induced to sprout by being placed under appropriate conditions (20°C and above, and high humidity). There is no evidence of preformed eyes, as found in potato. The role of plant growth regulators has not been studied as extensively as potato, but appears to have certain similarities. Thus sprout growth is stimulated by gibberellin and inhibited by continuous ethylene (Cheema *et al*. 2010).

Sprout production is an important economic consideration in commercial sweet potato cropping. At planting time, vigorous and plentiful sprout production is required to minimise the cost of propagation material. However, sprout growth decreases the quality and value of roots for fresh market sales. Sprouting is generally controlled by manipulating the temperature and humidity under which the crop is stored. Sprout suppression would be useful for produce in transit as export to the northern hemisphere requires shipping through equatorial conditions that promote sprouting. Control of sprout production in sweet potatoes has been examined using a number of treatments. For sweet potato roots, isopropyl N-(3-chlorophenyl) carbamate (CIPC) (Kushman & Wrights 1969), gamma irradiation (Bonsi & Loretan 1988), naphthalene acetic acid (Paton & Scriven 1989) all suppressed sprouting to some degree.

## BOTANY AND PHYSIOLOGY OF YAM

The yams are members of the genus *Dioscorea* in the section Enantiophyllum. They belong to the monocotyledonous plant class Liliposida, the subclass Liliidae that comprise the orders Orchidales, Pandanales, Liliales and Dioscoreales (Ayensu & Coursey 1972). Members of the genus *Dioscorea* have an underground tuber which is an annually renewed organ as in the case of all edible yams, or may be perennial, becoming larger and progressively more lignified from year to year to form a rhizome. In certain species, bulbils (aerial tubers) are formed in the leaf axils. The plants are dioecious with white, green, or red flowers arranged in clusters or spikes. The aerial stem may be smooth, thorny or hairy and may be round or square in section with alternate or opposite leaves which are usually heart shaped and may be smooth or hairy. Many of the cultivated forms have become sterile as a result of centuries of vegetative propagation. In the southern United States the name yam is used for sweet potato (*Ipomea batatas*, L. Poir) and in other places the edible tubers of the aroids but more generally and in this chapter the term yam is confined to plants of the genus *Dioscorea*.

Yams are predominately grown in three regions; West Africa, South America and Asia. About 600 species has been identified world-wide (Burkill 1960) of which only 20 are consumed with eight specifically regarded as a source of staple carbohydrate and medicinal compounds (Degras 1993). Pre-eminent among these are: *D. alata* L. (water yam), *D. cayenensis* Lam. (yellow or guinea yam),

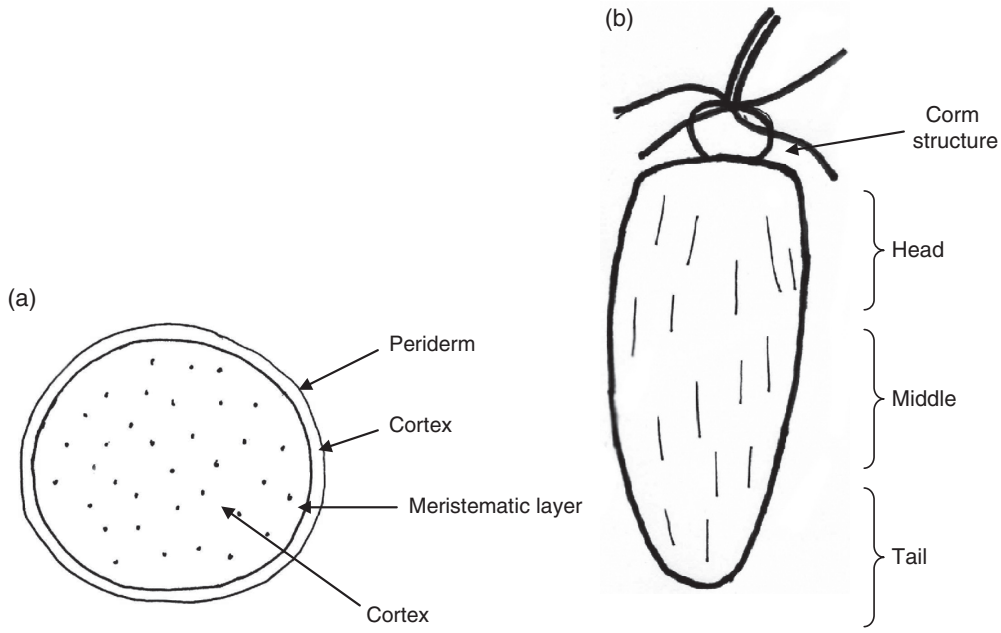


**Figure 18.4** Structure of the yam tuber. (Adapted from Diop and Calverley 1998, with permission from the FAO).

*D. dumentorum* (Kunth.) Pax. (trifoliate yam), *D. esculenta* (Lour.) Burk (chinese yam) and *D. rotundata* Poir (white yam). *D. cayenensis* and *D. rotundata* are sometimes pooled into the *D. cayenensis-rotundata* complex due to their morphological and molecular relatedness. Also of importance are *D. batatas* Decne, *D. bulbifera* L (aerial yam) and *D. trifida* Lam (cush-cush yam). Yams have many varieties compared to other crops, with some having slight morphological differences generally recognized only by farmers. There is therefore much confusion in naming the cultivated forms, which in most parts of the world have never been properly scientifically classified.

Unlike other tropical root and tuber crops yams normally produce a single large tuber each year, often weighing 2–10 kg The tuber shape and size can vary greatly due to genetic and environmental factors. However, cultivated forms of yam generally produce tubers that are more or less cylindrical in shape and 3–5 kg in weight with a dry matter content ranging from 20–40%. The yam tuber grows from a corm-like structure at the base of the vine. Occasionally this corm remains attached to the tuber after harvest, in which case when sprouting occurs, the sprouts will develop from it. More normally, when the corm separates from the tuber, sprouting occurs from the tuber near to the point at which the corm was attached.

The structure of the tuber is illustrated in Figure 18.4. The outermost layer is a corky periderm which is a thick layer of cork cells, which although often cracked provides a barrier against water loss and pathogen invasion. Immediately below the periderm is the cortex, which is a layer of thin-walled cells only a few millimetres thick, with very little stored starch. Below this is a meristematic layer, of elongated thin-walled cells. Sprouts are initiated from this later. The central portion of the tuber is the parenchyma, composed of thick-walled starchy cells, with large inter-cellular spaces, interspersed with vascular bundles (Degras 1993, Diop & Calverley 1998).

The composition of the main yam species is summarised in Table 18.5.

**Table 18.5** Tuber Composition for a Range of Species of Yams.

| | | % fresh weight | | |
|---|---|---|---|---|
| Species | Moisture content | Carbohydrate | Fats | Crude Protein |
| *D. alata* | 65–73 | 22–29 | 0.1–0.3 | 1.1–2.8 |
| *D. rotunda* | 58–80 | 15–23 | 0.1–0.2 | 1.1–2.0 |
| *D. cayenensis* | | | | |
| *D. esculenta* | 67–81 | 17–25 | 0.1–0.3 | 1.3–1.9 |
| *D. bulbifera* | 63–67 | 27–33 | 0.1 | 1.1–1.5 |

Source: Information from Knoth (1993).

**Table 18.6** Environmental Conditions Determined for Curing of Yam Tubers to Prolong Shelf Life.

| Species | Temperature (°C) | Humidity (%) | Duration (days) | Reference |
|---|---|---|---|---|
| *D.alata* | 32 | 90 | 4 | Gonzalez and Rivera (1972) |
| *D.rotundata* | 25–30 | 55–82 | 5 | Adesuyi (1973) |
| *D. esculenta* | 26–28 | high | 5–7 | Martin (1974) |
| *D. dulbifera* | | | | |
| *D. rotundata* | 25–40 | 95–100 | — | Been *et al*. (1976) |
| *D. caynensis* | | | | |
| *D.rotundata* | 26 | 92 | 11–15 | Nnodu (1986) |
| *D. caynensis* | 36–40 | 91–98 | — | Thompson *et al*. (1977) |

**The process of wound-healing in yam**

As for sweet potato and cassava roots, yam tubers are able to wound-heal. Passam *et al*. (1976) examined the physiological processes involved and concluded that a layer of suberin formed under the wound, below which a wound periderm was formed. This process is accompanied by an increased metabolic rate. Several workers have reported the advantages of storing cured tubers over uncured tubers. Table 18.6 summarises the findings of a number of studies to determine the optimum conditions for curing for a range of species. There seems to be agreement on the use of high humidity (>70°C) but there is still a wide range in suggested optimum curing temperature (25–40°C) and curing duration (2–15 days).

Much is still to be discovered regarding the mechanisms that control wound healing in yam, in particular how the process may be influenced by factors such as tuber maturity at harvest and duration of storage of tubers. The optimum age at harvest for tubers to be stored for a long period is an important factor for yam production. The time of maturity varies considerably between cultivars (Degras 1993) but little is known about the effect of maturity at harvest on curing and therefore on the storability of yams. It is also important to investigate if yams stored over a period of time but later sustain some damage due to transportation and handling can be cured before export. The physical effects of curing on tuber skin strength, toughness and fracture (skin strength, skin elasticity and tissue integrity) is also worth studying as this impacts on the level of damage on cured tubers as they are transported or inspected in storage.

**The control of sprouting of yam tubers**

Storage of yams tends to be limited by natural dormancy (ranges from 4–18 weeks depending on variety/species). Not only does sprouting directly affect yam quality, but it has been observed that dormancy break is associated with an increased susceptibility to rotting. The rate of respiration is also very dependent on the state of dormancy. It has been observed that the rate of respiration at harvest (15 and 29 ml $CO_2$/Kg fresh wt/h at 25 and 35°C respectively) drops to 20–30% with the onset of dormancy, but returns to harvest levels at dormancy break. During ambient storage these rates of respiration would lead to significant loss. Thus extension of dormancy is important to improve storability. On the other hand, for breeding programmes it is important to find ways to break dormancy in order to speed up improvement programmes.

**Table 18.7** Dormancy Periods of the Major Edible Yams.

| Yam species | Locality | Length of dormancy (weeks) |
|---|---|---|
| *D. alata* | Caribbean | 14–16 |
| | West Africa | 14–18 |
| *D. rotundata* | West Africa | 12–14 |
| *D. cayenensis* | West Africa | 4–8 |
| *D. esculenta* | West Africa | 12–18 |
| | Caribbean | 4–8 |
| *D. trifida* | Caribbean | 4 |

Source: Information from Passam (1982).

The dormancy period can be defined as a period of reduced endogenous metabolic activity during which the tuber shows no intrinsic or bud growth, although it retains the potential for future growth. Length of dormancy varies considerably by species and variety. It is also affected by temperature moisture, oxygen and $CO_2$ content of the storage atmosphere (Diop & Calverley 1998). Table 18.7 shows the dormancy period for the main species of yam. The length of dormancy almost certainly depends on the length of the dry season in the region of evolution. Thus

*D. cayenensis*, which originates from the West African forest zone where the dry season is very short, shows almost continuous vegetative growth. In contrast, *D. alata* and *D. rotundata*, originating respectively in Asia and Africa, appear to be adapted to climates where there is a longer dry season during which the plant survives as a resting tuber.

Lower storage temperatures reduce the metabolic activity of roots and tubers and prolong their dormancy. Temperatures of 16° to 17°C have been used to prolong the storage period for *D. alata* tubers for up to four months, provided the tubers were properly cured prior to storage in order to control infection by wound pathogens.

Sprout suppressants have almost all proved to be quite ineffective on yams (Diop & Calverley 1998). This is probably because yam tubers are unusual amongst plants propagating vegetatively in not having pre-formed buds. Many sprout suppressants, such as Isopropyl N-(3-chlorophenyl) carbamate (CIPC) which is used extensively on potato, affect the growing meristematic cells of the sprouting loci. In yam sprout initials are formed only just before the end of dormancy and then rise from beneath the periderm. When a sprout inhibitor is applied on the yam tuber just after harvest there are no sprout loci on which the chemical can act. Once sprouting has been started, the application of sprout suppressant may then inhibit further growth of the sprout initials. Ile *et al*. (2006) have defined three phases of dormancy, and postulate that chemicals may only be effective once the meristem starts to form foliar primordia; phase II by their definition. A number of studies have looked at the concentrations of endogenous plant growth regulators (PGRs) during the phases of dormancy and the effects of exogenous PGRs (Ile *et al*. 2006). Chloroethanol and thiourea can shorten dormancy, while gibberellins prolong dormancy (e.g. Nnodu & Alozie 1992), (which is contrary to their effect on potato where they promote sprouting). Tschannen (2003) carried out a detailed study of Ga3 effects on *D. alta* and *D. cayenensis-rotundata*. He showed that if applied immediately after harvest Ga3 would prolong dormancy and also slow respiration at the point of sprouting. It was postulated that its action is actually to promote multiple sprouts over the whole surface of the tuber. Tschannen devised treatment methods using soil paste or gelatinised starch instead of dipping. It is not clear whether this method is used practically as a strategy to extend dormancy at this time Attempts to induce sprouting by the use of gibberellin inhibitors (uniconazole-P, prohexadione-Calcium) has had some success when inhibitors are applied as a foliar treatment prior to harvest (Shiwachi *et al*. 2006).

## STORAGE, HANDLING AND PROCESSING OF CASSAVA

### Cassava storage and handling

As described in previous sections cassava roots are very perishable, as they are prone to post-harvest physiological deterioration (PPD). Fresh cassava is most important in regions of developing countries where resources are very limited, so that in most cases appropriate handling and storage methods must require few inputs. In-ground storage where the crop is just left in the ground unharvested until needed is one of the most practical storage methods used in developing regions. This works particularly well for cassava as it suffers from relatively few pests and diseases. There is, however, a loss in quality as the roots lose starch through metabolism and tend to become progressively more fibrous after their optimum harvest date (Lancaster & Coursey 1984). There is also the obvious disadvantage that land is taken up by this strategy.

Traditional methods of post-harvest storage have been reviewed by a number of authors such as Knoth (1993) and Westby (2002). Methods include burying roots in the soil, which is claimed to keep roots for months. In West Africa and India harvested roots may be stored in heaps which are kept moist by daily watering. Coating with loam paste is said to extend shelf life by 4–6 days. Trench silos are claimed to be the most successful traditional method of storage (Westby 2002). For all these methods the quality of the roots after harvest is critical. As most rots develop from the stem end of the root, some people recommend leaving 2–3 cm of stem attached (Diop & Calverley 1998). Pre-harvest pruning (cutting of above ground stems) three weeks before harvest has been shown to reduce harvest damage, although the effect is not great (van Oirschot *et al*. 2000).

All the traditional methods of storage involve maintaining a high humidity, suggesting that environments conducive to wound-healing are important. This is confirmed by work that has been carried out by the Centro Internacional de Agricultura Tropical (CIAT) and the Natural Resources Institute (NRI) since the 1980s to develop improved storage methods. With appropriate handling, even in the absence of temperature control it is possible to keep cassava for up to 4–8 weeks. This requires very careful harvesting, sorting to remove damaged roots and a storage environment with high humidity. Where roots are able to wound-heal, it has been shown that this slows or stops the development of PPD (Wenham 1995). This is confirmed by work in India where it has been shown that cassava can be stored for two months with less than 20% losses using pits with sand or soil at 15% moisture content (Balagopalan 2000).

A number of storage methods were tested by CIAT/NRI (Diop & Calverley 1998, Westby 2000), Conical heaps or clamps with 300–500 kg roots were constructed with a layer of straw on the base and another layer of straw covering the roots, with an additional layer of soil. Openings were left at the bottom of the heap to provide ventilation. Although this storage method could successfully store roots for more than four weeks, it was found to be difficult to adapt to changing seasons, in terms of ventilation and the risks of water damage. There was also had a high labour requirement.

Another method tested was to use wooden crates with alternate layers of sawdust and cassava roots, starting and finishing with a layer of sawdust. Wood shavings and, peat and other packing material could also be used as long as the material was moist but not wet. Physiological deterioration occurred if the material was too dry so that wound-healing was impaired, while microbial decay accelerated when it was too wet. With this method 75% of the roots remained acceptable after four weeks in store, provided the roots were packed immediately on the day of harvest. With a delay of only one day only 50% of the roots were rated as acceptable. The costs of this method make it suitable for export but not domestic trade.

Probably the most practical method of storing cassava roots for domestic (usually urban) markets is the use of airtight plastic bags. When also treated with a fungicide such as thiabendazole, the roots can be kept for two to three weeks. This method was successfully introduced to Ghana (Crentsil *et al*. 1995) where it was shown that household bleach (0.95% active chlorine) was almost as effective as thiabendazole. In practice most people used no fungicide, but sprinkled the roots with water, and often used woven rice or cocoa sacks. Even with these adaptations wound-healing can occur and storage of 7–10 days is possible

More expensive methods of storage such as freezing and waxing have been used for export markets primarily for export markets to Europe and America. Low temperature storage is also feasible taking into account that as a tropical product cassava is likely to be susceptible to chilling injury.

**Cassava processing**

The processing of cassava into more storable forms offers an opportunity to overcome the perishability of the fresh root. Processing is also important for the removal of cyanogens to produce a safe product. In the case of cassava, a wide variety of products are produced; especially in Africa and South America. The full range of products has been reviewed elsewhere; for example the Collaborative Study of Cassava in Africa (COSCA) supported by the Rockefeller Foundation has studied the range of products in Africa, covering Cote D'Ivoire, Ghana, Nigeria, Democratic Republic of Congo, Uganda and Tanzania (NRI 1992). Only a brief summary will be given here.

Products may be separated into dry or moist. Dry products, including chips, *gari*, *farinha*, *cassava bread* are generally less time-consuming to produce and the most practical processed form, with a longer storage shelf life. Moist products, such as *attieke*, *chikwangue*, *batons* can take a long time to prepare, and their shelf life is relatively short (Diop & Calverley 1998).

For many products fermentation is an important part of the process. This essentially refers to all moist products and many of the dry products. Fermented products can be divided into three types depending on type of fermentation (Westby & Twiddy 1992):

1. Products that are fermented in grated form include *gari*, where roasted granules are fermented in sacks, *attieke* from Cote d'Ivoire, where steamed granules are fermented, and fermented pastes such as *agbelina* from Ghana and *placali* from Cote d'Ivoire. These products undergo a lactic acid fermentation associated with a decrease in pH.
2. Processing using underwater fermentation is practised across Africa e.g. *akpu*, *fufu*, *chikwangue*. In this case at the start of fermentation a wide mix of flora is found, but this is later dominated by lactic acid fermentation and yeasts.
3. The third method involves fermenting whole roots in a heap as in the case of *udaga* produced in Tanzania. The main fermenting organisms in this case are *Rhizopus, Mucor, Penicillium, Fusarium*.

In many cases when products are dried, where the drying process is slow, for example when sun-drying is used out of the dry season, fermentation occurs, even though it is not intended. This is usually not a problem, but can lead to contamination with mycotoxins.

Processing is important for removal of cyanogens. Breakdown of cellular structure is key to this process. As described previously, the cyanogenic glucosides present in fresh cassava roots are linamarin (93%) and lotaustralin (7%) (Nartey 1978). These are located in the cell vacuole. During processing if the cells are broken the cyanogenic glucosides can be hydrolysed to the corresponding ketone (cyanohydrin) and glucose by the endogenous enzyme, linamarase, which is located in the cell wall (de Bruijn 1973, Nartey 1978). Cyanohydrins will then break down

**Table 18.8** Main Rotting Pathogens of Fresh Cassava Roots.

| Pathogen | Occurrence | Symptoms | Control |
|---|---|---|---|
| Botryodiplodia theobromae | Columbia, Costa Rica, Brazil, Nigeria, India | Discolouration of internal tissue, grey mould on cut surfaces. | Roots may be infected prior to harvest via growth cracks or due to harvest damage. Can be controlled by post-harvest fungicide or low temperature storage. |
| Fusarium solani | Columbia, Costa Rica Nigeria, India Puerto Rico | Dry rot, discoloured flesh. White surface mould in humid conditions. | Roots may be infested prior to or during harvest. Can be controlled by post-harvest fungicide. |
| Other rotting pathogens that are significant post-harvest: *Aspergillus*, bacterial soft rot (primary rot usually due to *Erwinia* spp.), *Mucor*, *Phytophthora*, *Rhizopus*, *Sclerotium*, *Sphaerostilbe*, and *Trichoderma*. | | | |

Source: Collated from Snowdon (1991).

non-enzymatically at a rate dependent upon pH and temperature (Cooke 1978) with their stability increasing at acidic pH values.

Several studies have been undertaken to examine the rate of cyanogenic glucoside breakdown at different stages of processing. Grating, sun-drying and roasting all contribute to cellular breakdown, as does the fermentation process itself. (Mlingi & Bainbridge 1994, Jones *et al*. 1994, Bainbridge *et al*. 1998). Dissemination of information on the relative efficiency of different processes is very important, especially in regions where new cassava varieties with higher cyanogenic potential have been introduced. This has happened, for example, where varieties with increased resistance to African Cassava mosaic virus have been released (Bockett 1997, Bainbridge *et al*. 1997).

### Cassava processing for international trade

In many countries cassava is dried for export. The principal markets for cassava products are in Europe – the European Union being the most important for dried roots – and for cassava starch the United States, the United Kingdom and Japan. Although complete statistics of world trade in cassava products are not available, thus making it difficult to estimate the total quantity entering international trade, the import statistics of the EEC and the United States show a substantial increase in recent years, particularly for dried cassava roots. Cassava starch is used as a raw material for a wide range of food products and industrial goods, including paper, cardboard, textile plywood, glue and alcohol (Tonukari 2004).

### Cassava Post-harvest Pests and Diseases

As indicated above where fresh roots rot it is often an indication of the onset of post-harvest physiological deterioration. The most common rots are summarised in Table 18.8. As storage of the fresh root is relatively short-term, insect pests are only really significant for the dried products. Losses of dried cassava products of up to 75% have been reported in Tanzania as a result of infestation by Larger Grain Borer (*Prostephanus truncates*) (Hodges *et al*. 1985).

## STORAGE HANDLING AND PROCESSING OF SWEET POTATO

Sweet potato is a commodity which is handled and stored in both temperate and tropical countries and in situations covering a wide range in the availability of resources. Where facilities are available for temperature controlled storage sweet potatoes can be stored for more than 6 months, however, in the absence of temperature control storage life is generally restricted to a few weeks.

### Handling and storage in developed countries

In the United States, storage temperatures of 12.5°C to 15°C and a relative humidity of 85% or higher are recommended (UC Davis 2008). Under these conditions storage is possible for 6–10 months. Sprouting may occur after 6 months, but it is not common practice to use sprout suppressants. Chilling injury may occur at lower storage temperatures. Curing is standard practice for which roots are placed at 25–32°C with relative humidity greater than 90% for up to one week. Minimising root damage during harvesting and subsequent handling is considered very important for successful storage. Thus roots are not washed before storage. Irrigation may be stopped 2–3 weeks before harvest to allow the tops to start drying, and this may lead to some toughening of the root periderm as seen in potatoes.

### Handling and storage in developing countries

In developing countries where roads may be rough, packaging to cushion damage and temperature controlled

storage are too expensive, sweet potato roots rarely keep for more than 2–3 weeks (Rees *et al*. 2001, Tomlins *et al*. 2002). In this case a wide range in keeping quality of different varieties has been observed, and one approach to extending shelf life would be the introduction of cultivars with better keeping qualities, an approach that would cause no additional cost to farmers and traders (Rees *et al*. 2003).

In-ground storage is practiced, but not as widely as for cassava. The main problem is that at the onset of the dry season infestation by the sweet potato weevil (*Cylas* spp) becomes significant and damages the crop (see below).

Traditional storage technologies for sweet potato roots have been reported in tropical countries such as Bangladesh (Jenkins 1982), India (Prasad *et al*. 1981, Ray & Ravi 2005), Tanzania (Tomlins *et al*. 2007) and Kenya (Karuri & Ojijo 1994, Karuri & Hagenimana 1995). The success of these storage technologies, however, has been variable (Ray & Ravi 2005). A review of storage methods (Ray & Ravi 2005) has highlighted the need for further assessment of the factors affecting storage because an understanding of these factors remains incomplete. In Tanzania, a study located at a research station investigated stores that varied by store type (pit or heap), cultivar and ventilation by measuring $O_2$ and $CO_2$ levels, relative humidity, temperature, root condition and weight loss (Van Oirschot *et al*. 2007). The findings indicated that the main factors that improved storability of fresh sweet potato under tropical conditions were the use of good-quality roots free of damage and disease, not lining the stores with grass, and avoiding temperature build-up in the stores. The type of store (pit or heap), cultivar and ventilation were all found to have minimal effect on root keeping qualities. The study concluded that fresh roots could be stored for up to 12 weeks and that, by this time, stored roots may taste sweeter than freshly harvested ones (Tomlins *et al*. 2007). The design of two stores that were tested in Tanzania are shown in Figure 18.5.

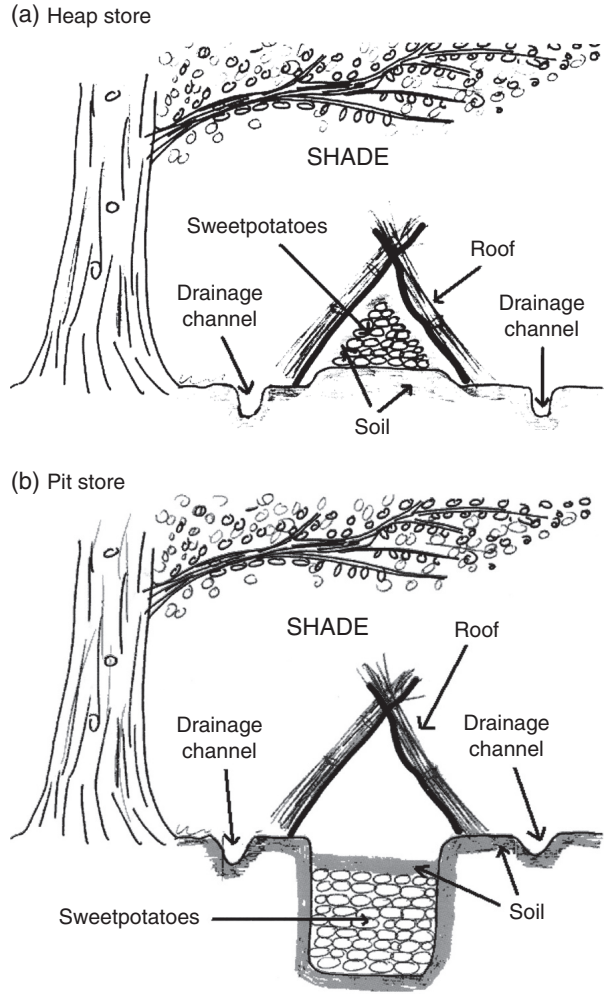


**Figure 18.5** Construction of heap and pit stores in the Lake Zone of Tanzania.

### Processing of sweet potato

In countries where sweet potato is a staple, one strategy to ensure the availability of sufficient food, especially during the lean seasons and where sweet potato cultivation is limited to only one season in a year, is to process the roots into dried chips and store them in this form (Owori & Agona 2003). The dried chips are either reconstituted by boiling or are ground into flour which may or may not be mixed with millet/sorghum flour for making porridge. Sweet potato processing for human consumption in many countries is not yet commercialized. Studies in some countries have, however, investigated the feasibility of sweet potato as a partial substitute for imported wheat flour in snack products (Owori & Agona 2003). Substitution of wheat flour, either with fresh, grated roots or sweet potato flour, is gaining a foothold in the snack product market in Kenya and Uganda and bread containing biofortified sweet potato in Mozambique (Tomlins *et al*. 2009). Promotion of commercial processing of primary products would increase the utilization of sweet potato flour as an ingredient in snack product processing. There is great variation in the processing characteristics of sweet potato cultivars but generally dry matter is an important characteristic.

While many new sweet potato products have been developed in Africa, the priority is still predominantly in the improvement of the quality of the flour after drying and storage (van Hal 2000). Recent initiatives have focused on the

retention of retention of carotenoids in processed products made from orange fleshed varieties because of the potential benefits to health and nutrition. Bechoff *et al*. (2010) found high losses in carotenoids during drying and storage. They showed that total carotenoid retention during drying varies more with variety than type of dryer (solar or sun). Carotenoid loss was generally correlated with high initial moisture content and high carotenoid content in fresh sweet potato roots. Hot air cross flow drying however retained significantly more provitamin A than other drying methods tested. However, while some provitamin A is lost during drying, much greater losses can occur during storage (about 70%) and this was not affected by the packaging (storage at ambient temperature). For low cost storage of sweet potato chips at ambient temperature, the losses of carotenoids during storage are therefore considered to be more of a constraint to the utilisation of dried orange fleshed sweet potato than losses occurring during drying (Bechoff *et al*. 2009).

## PESTS AND DISEASES OF SWEET POTATO

### Sweet potato weevil

Damage to sweet potato storage roots by insect pests, even when it occurs before harvest, can be considered a post-harvest problem as it reduces both the nutritional and economic value of the storage roots and can reduce shelf life.

The most important insect pest of sweet potato storage roots worldwide is the sweet potato weevil (*Cylas* spp., Coleoptera: Apionidae). In certain areas of East Africa, the so-called rough weevil (*Blosyrus* spp.), which damages the surface of the root, is also starting to gain economic importance.

Sweet potato weevils constitute a major constraint to sweet potato production and utilization worldwide (Villareal 1982, Sutherland 1986, Chalfant *et al*. 1990, Lenne 1991). Yield losses as high as 60–97% have been reported (Ho 1970, Subramanian *et al*. 1977, Mullen 1984, Jansson *et al*. 1987, Smit 1997). Even low levels of infestation can reduce root quality and marketable yield because the plants produce unpalatable terpenoids in response to weevil feeding (Akazawa *et al*. 1960, Uritani *et al*. 1975) and consumers will pay only reduced prices for roots damaged by *Cylas* spp. (Ndunguru *et al*. 1998). Sweet potato weevils are a particularly serious problem under dry conditions, because the insects, which cannot dig, can reach roots more easily through cracks that appear in the soil as it dries out. In much of East Africa, the sweet potato crop matures after the end of the rains, and root bulking, which has a tendency to shift the soil, often exposes roots providing easy access for *Cylas* spp. It is for this reason that during the dry season, unlike cassava, sweet potato roots cannot be stored in-ground for any significant period of time. Surveys of root quality in the markets of Tanzania have shown that, at certain times of the year, 15–20% of roots that are sent to the market may be spoiled by infestation (Kapinga *et al*. 1997). This is an underestimation of the total levels of loss, since farmers usually leave infested roots in the field.

There are a number of species of sweet potato weevil; *Cylas puncticollis* and *C. bruneus* are the most prevalent species in East Africa, while *C. formicarius* is the most abundant in North America and the Far East. The female sweet potato weevil lays eggs singly in cavities excavated in either the vines or exposed/easily accessible roots. The developing larvae tunnel while feeding inside the vine or root and are the most destructive stage. Pupation takes place within the larval tunnels and adults emerge after a few days. Plants may wilt or even die as a result of extensive stem damage, and damage to the vascular system can reduce the size and number of storage roots. While external damage to roots can affect their quality and value, internal damage can lead to complete loss.

Several attempts have been made to breed for resistance to *Cylas* spp. Variation in susceptibility to infestation among sweet potato cultivars has been reported (Mullen *et al*. 1985, Stathers *et al*. 2003 and references therein). Breeding programmes have lead to the release of cultivars in the United States with a degree of resistance to *Cylas formicarius*. The most likely resistance mechanisms include: escape via deep rooting (as weevils can only burrow short distances); or early maturity (enabling farmers to harvest roots before the onset of the dry season and the subsequent increase in *Cylas* spp. populations); or non-preference related to the chemical composition of the roots of different cultivars. However, the rate of success in breeding for non-preference has been slow, leading some breeders to conclude that an adequate source of resistance may not exist within the sweet potato germplasm (Talekar 1987). Nevertheless, there are numerous reports of variation among varieties in susceptibility to weevil attack. Stathers *et al*. (2003) have related reduced susceptibility to deeper rooting. There is some evidence of resistance based on chemical composition of the root surface. The levels of two triterpenoid components; boehmeryl acetate and boehmerol, which are known ovipositional stimulants (Wilson *et al*. 1990), differed significantly in sweet potato cultivars that differed in susceptibility to the *C. formicarius elegantulus* (Summers). Selecting varieties with low levels of these components may be a route to the selection of less preferred and therefore less susceptible cultivars. However, considerable chemical variation within a cultivar was also reported

suggesting that simple selection based on the presence of these compounds was not so straightforward (Marti *et al*. 1993). More recently, Stevenson *et al*., 2009 identified chemical compounds in one Ugandan sweet potato variety New Kawogo that are directly toxic to weevils and increase mortality although development was not hindered for those larvae that survived. These findings suggest that potential for breeding improved African varieties with resistance to *C. puncticollis* and *C. brunneus*.

**Post-harvest rots of sweet potato**

Many of the rotting pathogens are present in the soil, and infect through wounds made during harvesting. Thus, harvesting practices to minimise damage, curing, and fungicide treatment immediately after harvest are all effective ways to reduce losses.

Low temperature storage reduces rot incidence. The main post-harvest rots of sweet potato are described by Snowdon (1991), and these are summarised below.

Black rot of sweet potatoes is caused by *Ceratocystis fimbriata* and this is an important rot of sweet potatoes in most regions of the world. The main symptoms are slightly sunken brown/black circular lesions, and a bitterness throughout the flesh due to phytoalexin production. Crop rotation is a good preventative measure as the pathogen does not attack many other crops.

*Fusarium* rot is caused for example by *F. oxysporum* or *F. solani*. The type of decay is variable, either a dry decay from the ends or a surface rot of pale brown circular lesions. Some cultivars exhibit resistance, and therefore there is potential in breeding for resistant varieties.

Java black rot caused by *Botryodiplodia theobromae* was first observed in roots imported to the USA from Java. This disease is common throughout the tropics. Infected tissue is yellowy-brown and firm, later darkeningto black. It is important to make sure that any roots used for planting material are free from infection, as the infection can spread to progeny roots. Thus dipping seed roots in fungicide before planting is a recognised practice. Some cultivar resistance does exist.

*Rhizopus* rot can be caused by several species of *Rhizopus* but mainly *R. stolonifer*. This is characterised by soft watery lesions, and copious development of coarse white mould with globular sporangia, turning from white to black. In store the infection spreads fairly rapidly to adjacent roots creating 'nests' of rotting. This pathogen is both soil and airbourne.

Other important rots include Sclerotium rot caused by *Corticium rolfsii,* Soil Rot/Pox caused by *Streptomyces ipomoeae* and Scurf caused by *Monilochaetes infuscans* (Snowdon 1991).

## STORAGE, HANDLING AND PROCESSING OF YAMS

The yam tuber is prone to mechanical damage during harvest from the soil when simple traditional tools such as cutlass and hoe are used as these readily cut or injure the large-sized tubers. Any rupture of the tuber caused by damage or injury leads to deterioration and dehydration. Despite its obvious advantages curing does not appear to be widely practised in West Africa. Research undertaken in Ghana, Cote d'lvoire and Nigeria has estimated that 10–50% of yams produced and harvested are lost in storage (Amusa *et al*. 2003, Rees & Bancroft 2003).

Ideal storage conditions for most species are 15–16°C and 70–80% relative humidity (Anon 1982). Under these conditions storage for 6–7 months is possible. In West Africa where most yams are grown temperature control is not an option, and ambient storage leads to shorter dormancy and more rapid sprouting. Storage structures used range from pits or mounds of tubers placed directly on the ground to constructions where shade is provided, the tubers are off the ground and have a degree of ventilation. A simple classification of types of storage is given in Table 18.9. The maturity

**Table 18.9** Simple Classification of Yam Storage Structures and Their Characteristics.

| Storage structure | Characteristics |
|---|---|
| Mounds/clamps | Prone to insect, nematode damage – maintain tubers at high humidity. |
| Pits | Prone to insect, nematode damage – maintain tubers at high humidity. |
| Mounds/clamps/pits + Shade (tree or built shelter | Prone to insect, nematode damage – maintain tubers at high humidity, lower temperature. |
| Structures that raise tubers above the ground (wooden or bamboo shelf). | Protect tubers from pests – maintain tubers at lower humidity. |
| Structures that increase ventilation (yams tied to poles or hung, yam barns). | Protect tubers from pests, and maintain tubers at lower humidity. Labour intensive. Allow easy inspection of tubers for rots and sprouting. |

of yams at harvest affects the post-harvest behaviour of the tubers, so that the optimum storage methods may differ. It appears that less mature tubers may store better with less ventilation (higher humidity) (Rees & Bancroft 2003).

**Processing**

By far the greater part of the yam crop in West Africa is consumed fresh. Fresh tubers are prepared for eating as boiled or pounded yam, mashed, fried or baked. The preparation of pounded yam involves peeling, boiling and pounding the yam tissue until a sticky, elastic dough is produced. This is called pounded yam or yam fufu. Some small-scale processing of yam occurs notably in South West Nigeria and in Benin, the processing is mainly to utilise damaged tubers at harvest.

Given the problems of storing fresh tubers, drying of tubers, especially those that have been damaged, soon after harvest and converting them into dried slices or milling into flour for *amala* or *fufu* is an effective strategy for extending availability.

Yam flour is generally regarded as an inferior substitute for freshly pounded yam because it is often made from damaged tubers. Nevertheless, consumption of products such as amala made from yam flour is becoming more popular in urban centres.

The most common method of drying yam is to cut it into sticks and sun-dry it. Drying of sticks of yam for example is practiced in central and northern areas of Benin (Dossou, R.A. *Pers. Comm.*). Tubers are sliced to a thickness of about 10 mm, more or less, depending on the dryness of the weather. The slices are then parboiled and allowed to cool in the cooking water. The parboiled slices are peeled and dried in the sun to reduce the moisture content. The dried slices are then ground to flour in a wooden mortar and repeatedly sieved to produce a uniform texture. Small, hand-operated or engine-driven corn mills or flourmills are used in some areas.

The blanching/parboiling stage reduces discolouration (oxidation of phenolics) during drying, and can also reduce subsequent damage by insects and fungal pathogens. Treatment with sodium bisulphate may also be used to prevent phenolic oxidation. Parboiling can also change textural properties. Higher temperatures make the resulting dried sticks softer and gives a lower temperature of gelatinization.

The yam flour is rehydrated and reconstituted into *fufu* or *amala* and eaten with a soup containing fish, meat and/or vegetables.

Industrial processing is increasing, especially in Nigeria (Akaroda M. *Pers. Comm.*). The most important industrially processed yam product found in the market is the pounded yam flour. As the major cities in southwest Nigeia sell amala in the public restaurants, amala is becoming widely consumed. Thus, the demand for yam flour is on the rise.

Studies in Benin and Nigeria have indicated that there is a significant problem of aflatoxin contamination due to poor drying and storage (Adeleke 2009). According to surveys carried out in Benin by Bassa (2000), 98% of the analyzed dried sticks had an aflatoxin content higher than the European limit of 4 ppb and 6% of dried sticks beyond the OMS standard of 20 ppb. These results were supported by those obtained subsequently by Fagbohoun (2001). The use of preservatives to inhibit mould, possibly using traditional herbs, during the processing of amala should be investigated as a means of control.

**Post-harvest pests and diseases of yam**

It has been reported that insect pest attack in storage can result in as much as 20% losses (Okoedo-Okojie & Onemolcase 2009). However, of the range of factors that precipitate losses of marketable tubers, rots are the most immediately apparent causing both primary and secondary damage. An extensive list of fungal and some bacterial organisms have been isolated from decaying yams (e.g. Coursey 1967; GTZ 1995; Nwankiti *et al*. 1988; Ogundana 1982; Thompson *et al*. 1977). The main spoilage microrganisms responsible for rotting are listed in Table 18.10. *Aspergillus, Lasiodiplodia, Fusarium.*

**Table 18.10** List of Micro-organisms Isolated from Yam Tuber Rots.

| |
|---|
| *Aspergillus* sp. |
| *Aspergillus niger* van Tiegh. |
| *Aspergillus flavus* Link ex Fr. |
| *Chanephora cucurbitarum* (Berk and Fac.)Thax |
| *Erwinia carotovora*. |
| *Fusarium sp*. |
| Fusarium culmorum (W.G. Smith) Sacc. |
| *Fusarium solani* (Mart.) Sacc. |
| *Fusarium oxysporium* Schlecht. |
| *Lasiodiplodia theobromae* Pat. |
| *Mucor* sp. |
| *Pencillium sp*. |
| *Pencillium brevi-compactum* Dierckx |
| *Pencillium oxalicum* Currie and Thom. |
| *Rhizopus* sp. |
| *Rhizopus stolonifer* (Ehrenb) Lind |
| *Trichoderma* sp. |

Source: Rees and Bancroft (2003).

*Penicillium* and *Rhizopus* are the genera frequently isolated from diseased tubers. It is thought that many of these infections originate from the seed yam in the field (Rees & Bancroft 2003) while in other cases gain entry into the cortical tissues of the yam via natural openings, cracks, punctures caused by various insect pests and nematodes and wounds resulting from mechanical damage and poor handling (Thompson & Bancroft 1996). Incidence of rots may be influenced by the nature of the storage environment and whether tubers have been cured or treated with biocides or lime and/or ash preparations, and varietal differences. Development of rots by *Aspergillus niger*: showed that *D. alata* was more resistant than *D. rotundata* and *D.esculenta* (Otusanya & Jeger 1996).

Destructive analysis of apparently sound yams has also revealed high levels of chronic disease deep within the yam tubers suggesting that a significant proportion of infections may be initiated pre-harvest and may even stem from the original planting material.

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# 19
# Cut Flowers

*Daryl Joyce and John Faragher*

Cut flowers and foliage represent an important international industry, with an estimated world trade of approximately $US4.6 billion per year (Staby & Robertson 1982; Behe 1993; Wills *et al*. 1998; Laws 2002). Their farmgate value is high and they are utilised in value-adding operations, such as bunching in bouquets. Aesthetically, cut flowers contribute to the general quality of life through their natural beauty. They are the subject of fashion and the articles of design (Figure 19.1). Cut flower types and colours are associated with social trends (e.g. sunflowers have regained popularity in recent times). Cut flowers are used to convey special messages (e.g. on Mothers' Day and St Valentine's Day).

Flowers are often transported long distances, under adverse conditions, from the place of production to markets (e.g. from southern hemisphere and tropical countries to Europe, United States and Japan). This makes good post-harvest handling imperative, but often difficult. Post-harvest losses during marketing of cut flowers within the United States have been estimated to be 20% (Hardenburg *et al*. 1986).

The ornamentals industry covers a broad range of product types, including fresh and preserved (e.g. dried) cut flowers and foliage and potted seedling, foliage and flowering plants (Gross *et al*. 2004; Wills *et al*. 1998; Reid 2002). This overview focuses on fresh flowers, but also considers preserved flowers (Joyce 1998).

## BIOLOGY

The optimal application of post-harvest technology benefits from an understanding of product biology (Wills *et al*. 1998). Commercial cut flowers are often complex, compound structures, including stems, leaves, flowers and sometimes bracts and fruit. Each of these parts may develop and age differently after harvest. Cut flower longevity is often expressed as 'vase life', the time in which flowers are in the vase before they display some characteristics that make them unacceptable (e.g. petal wilting or drop; Figure 19.2). This is usually measured under standard conditions of 20°C and 60–70% relative humidity (RH) (Reid & Kofranek 1980; Joyce 1996).

Genotype is a fundamentally important factor determining cut flower longevity (Ashman & Schoen 1994). Different genera vary widely in their vase lives (e.g. from a few days for Dutch iris to several weeks for spray carnations). Vase life can also vary markedly among genotypes within species and genera. Vase life of cut grevillea flowers ranged three-fold, from three days for *Grevillea wickhamii* Meisn. to nine days for *G. whiteana* McGill (Joyce *et al*. 1996). Ferrante *et al*. (2002) reported a range in foliage longevity for cut alstroemeria flower stems from five to 18 days.

Post-harvest longevity can also vary with phenotype, which is the interaction of genotype with environment and management factors. These factors include cumulative light energy, production temperatures, water and nutrients

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**Figure 19.1** Flower arranging demonstration in Tokyo, Japan.

(Halevy & Mayak 1979). For example, provision of supplementary irradiation increased the vase life of cut roses (Fjeld *et al*. 1994).

The processes of flower development and senescence are highly variable in terms of morphology and physiology among genotypes. Flower initiation, which can be temperature and/or photoperiod sensitive, is typically followed by bud development, flower opening, pollination and senescence. Bud and flower abscission are associated with reduced longevity in some species (Reid & Goszczynska 1985; Joyce & Poole 1993; Macnish *et al*. 1999; Reid 2002). Senescence is often characterised by colour change (fading) and water loss (wilting) in flowers and/or leaves (Figure 19.2). Cut flower senescence usually has some of the characteristics of ageing on the plant (e.g. biochemical changes, flower opening and petal death) and some additional characteristics, particularly water loss.

### Physiological changes after harvest

Profound changes in metabolism occur throughout flower development, ageing and senescence (Mayak & Halevy 1980). Multiple pathways of ageing and senescence go on in the flower at the one time. Most of these processes appear to be under tight genetic control. Thus, marked changes in gene expression, nucleic acid levels and types, and protein, including enzyme, synthesis take place (Woodson 1991). The later processes of senescence are similar in flowers where senescence is controlled by ethylene and in ethylene insensitive flowers.

There is an increasing record of genes and enzymes that are up- or down-regulated during ageing and senescence. They include up-regulated genes for synthetic enzymes (e.g. ethylene and amino acid synthesis), hydrolytic and degradative enzymes (e.g. proteinase, nucleases, lipase, glucosidase), enzymes that alter fatty acid metabolism and cell walls and genes associated with signalling and transport (Woodson 1991; Jones *et al*. 1995a; Jones & Woodson 1999; Rubenstein 2000; Eason *et al*. 2002; Hunter *et al*. 2002). Rubenstein (2000) and Hunter *et al*. (2002) point out that while these genes are part of the ageing process, they are not necessarily the genes that initiate the senescence cascade. The ways in which the senescence-associated genes are regulated are not clear, though some are ethylene induced and/or mediated. The trigger that initiates senescence in cut flowers, before increased ethylene synthesis and before many of the processes described above, is still not established. The role of signals in senescence is discussed by Rubenstein (2000).

In addition to the genetic analysis, many other enzyme changes have been observed, including those associated with increased pigment synthesis, decreased phospholipid synthesis and lipid oxidation and breakdown (Borochov & Woodson 1989; Thompson *et al*. 1997; Rubenstein 2000). Treatment with cycloheximide, an inhibitor of protein synthesis, generally delays flower ageing.

Flowers show some of the characteristics of programmed cell death, including increased proteinases, nucleases and DNA fragmentation (Rubenstein 2000; Eason *et al*. 2002; Hunter *et al*. 2002). Senescence of ethylene insensitive sandersonia, daylily and daffodil flowers and ethylene sensitive carnation flowers is characterised by increased proteinase activity, a key regulator of cell death in animals (Jones *et al*. 1995a; Rubenstein 2000; Eason *et al*. 2002; Hunter *et al*. 2002; Figure 19.3).

It is not clear whether some of the processes in ageing petals may be more like a breakdown of cell function and structure than programmed cell death, e.g. the lipid oxidation that ultimately leads to membrane leakiness (Borochov & Woodson 1989; Thompson *et al*. 1997). In other words, full understanding of the interacting set of ageing processes has yet to be realised.

Cut flower development and senescence are at least partly controlled by plant growth regulators, including ethylene (Halevy & Mayak 1979, 1981; Mayak & Halevy 1980; Reid & Goszczynska 1985; Mayak 1987; Borochov & Woodson 1989; Woodson 1991; Wills *et al*. 1998; Reid 2002; Eason 2006).

Cut flowers can be loosely categorised as either climacteric, such as carnations, or nonclimacteric, such as roses, according to whether or not, respectively, ethylene plays a pivotal role in coordinating their senescence (Wills


**Figure 19.2** Time series (0, 3, 6, 9, 12 and 15 days) of chrysanthemum senescence in the vase.

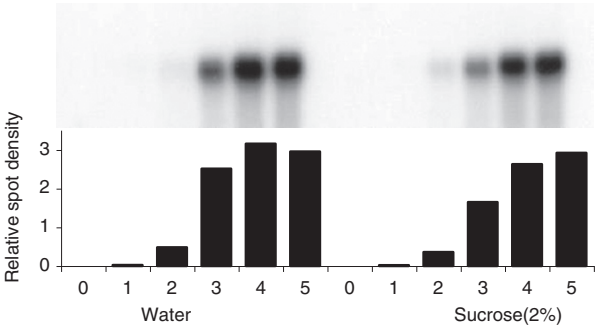


**Figure 19.3** Expression (RNA probe hybridisation and relative spot density) of cysteine protease PRT5 in senescing sandersonia flowers (Eason *et al.* 2002). The experiment was conducted for five days (*x*-axis) and the flowers were stood into either water or 2% sucrose vase solution (Eason *et al.* 2002, courtesy of CSIRO publishing).

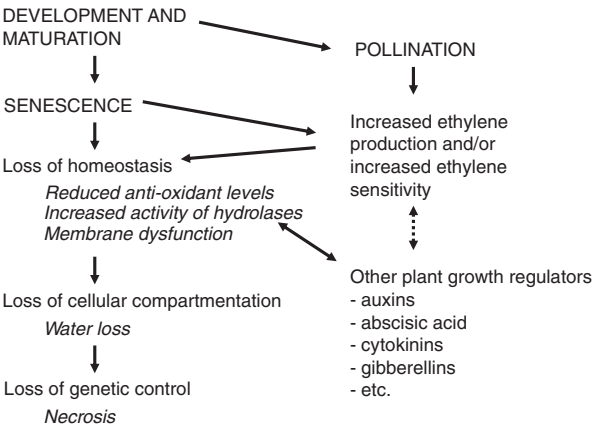


**Figure 19.4** Interacting factors influencing cut-flower senescence in the absence of over-riding stress effects (e.g. stem plugging by vase solution microbes).

*et al.* 1998; Figure 19.4). Climacteric flowers may also have an increase in respiration during senescence. Prominent ethylene sensitive flowers include carnations, some orchids, gypsophila and some roses. Common insensitive flowers include iris, tulip, gerbera and chrysanthemum. For comprehensive lists of ethylene sensitive and ethylene insensitive flowers, see Nowak and Rudnicki (1990), Woltering and van Doorn (1988), Nell and Reid (2000) and van Doorn (2001). However, among genotypes of carnation, for example, there are marked differences in both ethylene production and sensitivity (Wu *et al.* 1991a, 1991b).

In flowers where ethylene plays a pivotal role in senescence, the genes and enzymes responsible for ethylene synthesis are turned on, ethylene is produced and its action leads to a range of gene expression, enzyme activity and degradative processes. These processes include decreased membrane phospholipids, increased membrane leakage and hence flower wilting and closing (Thompson *et al.* 1982; Borochov & Faragher 1983; Woodson & Lawton 1988; Woodson 1991; Jones & Woodson 1999). Inhibitors of ethylene production, including aminooxyacetic acid (AOA) and aminovinylglycine (AVG), and inhibitors of ethylene action, including silver thiosulphate (STS) and 1-methylcyclopropene (1-MCP), inhibit many ageing and senescence processes in these flowers (e.g. see Figure 19.9). When carnations are genetically engineered to inhibit the genes for either ethylene synthesis (viz. 1-aminocyclopropane-1-carboxylic acid (ACC) oxidase) or the ethylene receptor (viz. *etr1-1*), ageing is dramatically inhibited (Savin *et al.* 1995; Bovy *et al.* 1999). The sensitivity of flower petals (e.g. carnations) to ethylene generally increases with age (Borochov & Woodson 1989).

Pollination can induce senescence of flowers, including carnation, petunia and orchid. This effect is often mediated by increased ethylene production (Whitehead *et al.* 1984; Larsen *et al.* 1995; Porat *et al.* 1995). As flowers are generally comprised of a number of individual organs, such as the lip of orchid flowers, inter-organ signalling can have a role in whole flower senescence. In orchids, the soluble ethylene precursor ACC and gaseous ethylene appear to be involved in signalling between floral organs (Woltering 1990; O'Neill *et al.* 1993).

The role of other endogenous hormones in senescence is less clear (Borochov & Woodson 1989). Applied cytokinins delay flower and leaf senescence. Flower ageing is often accompanied by decreased endogenous cytokinins (Eason 2006). Applied abscisic acid (ABA) advances senescence. Endogenous ABA increases during rose, carnation and daylily petal senescence and after stress, possibly mediated by ethylene. Abscisic acid has been used experimentally to reduce water use and leaf crisping of roses (Halevy & Mayak 1981; Markhart & Harper 1995; Pompodakis & Joyce 2003) and to extend the vase life of Geraldton waxflower foliage (Joyce & Jones 1992). Applied auxins can increase (via ethylene) or decrease senescence. The role of endogenous auxins as possible anti-senescence agents remains to be properly examined. Applied gibberellic acid (GA) can delay leaf chlorosis and increase the vase life of some flowers, including roses (Goszczynska *et al.* 1990).

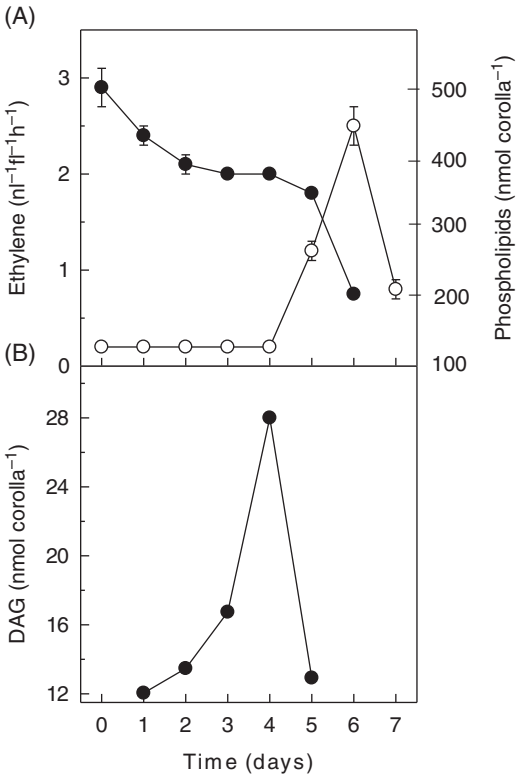


**Figure 19.5** Ethylene production rates (top panel (A), ○), microsomal membrane phospholipids (top panel (A), ●) and plasma membrane diacylglycerol (phospholipid breakdown product; bottom panel (B), ●) levels during cut petunia flower senescence (Borochov *et al.* 1997). (Reproduced with permission from the authors and the publisher.)

Senescence is associated with membrane-based changes that culminate in loss of cellular compartmentation and increased water loss. Decreases in membrane phospholipids and increases in oxidation products, such as free fatty acids, lead to decreased fluidity, increased presence of gel phase lipid, increased membrane permeability and decreased activity of membrane proteins (Mayak 1987; Paliyath & Thompson 1990; Borochov *et al.* 1997; Thompson *et al.* 1997; Figure 19.5). The loss of protective antioxidants and membrane attack by free radicals and lipoxygenases are important parts of these processes (Behera *et al.* 1987; Droillard *et al.* 1987; Fobel *et al.* 1987; Rubenstein 2000). Ethylene causes some of the changes leading to increased permeability in carnation and rose petals (Thompson *et al.* 1982; Borochov & Faragher 1983; Faragher & Mayak 1984; Faragher *et al.* 1987). However, some changes in membrane properties have been observed before any rise in ethylene production (Thompson *et al.* 1982, 1997; Faragher *et al.* 1987; Paliyath & Thompson 1990; Borochov *et al.* 1997). Perhaps the enzymic processes leading to membrane changes (phospholipase, decreased phospholipid synthesis, increased lipoxygenase), loss of protective antioxidants and membrane attack by free radicals, are some of the critical early events in senescence, leading to a cascade of subsequent degradative processes.

The green pigment chlorophyll and the chloroplast organelles that contain it are usually degraded during flower development and senescence (Halevy & Mayak 1979; Mayak & Halevy 1980). Orange and yellow carotenoids may accumulate in lipid chromoplast organelles that arise from chloroplasts. Water-soluble red and blue anthocyanins accumulate in vacuoles. Co-pigments and pH can influence the shade of anthocyanin-based colours. Blueing of senescing red cut flowers is thought to be associated with a pH shift from more to less acid due to the release of free ammonium from proteins during their catabolism (Halevy & Mayak 1979; Mayak & Halevy 1980).

Respiration rates tend to be high in young developing buds and flowers and then fall, often to be followed by a further, climacteric increase in association with senescence (Halevy & Mayak 1979; Mayak & Halevy 1980; Wu *et al.* 1991a). The respiratory climacteric may be associated with a more or less co-incident ethylene climacteric.

Carbohydrates and other respirable substrates (e.g. organic acids) provide energy for flower development and senescence (Halevy & Mayak 1979; Mayak & Halevy 1980). Some flowers, such as rose, accumulate starch reserves (Gorin & Berkholst 1982; Berkholst & Navarro Gonzales 1989; Shellabear *et al.* 1993). In roses, starch is hydrolysed during petal expansion, which is presumably driven by the osmotic potential of the released sugar (Evans & Reid 1988). Other flowers, like gladiolus and other harvested spike flowers, may depend relatively more upon the continuous import of sugars from vase solutions to maintain vase life (Reid 2002). Sugars are also important as osmotically active molecules to maintain water balance and as components of cell walls. There is also increasing evidence for sugars acting as signalling molecules in senescence (O'Donoghue *et al.* 2002b; Eason 2006).

Changes in petal cell walls after harvest have not been extensively studied, despite the fact that wilting is an important visual result of ageing. There are significant alterations in cell wall enzymes and polymers during flower growth and ageing (e.g. in sandersonia and daylily) (Rubenstein 2000; O'Donoghue *et al.* 2002a). However, O'Donoghue *et al.* (2002a, 2002b) believe that wilting is not governed by those events alone.

Certain cut flower species suffer physiological disorders, some of which are caused by ethylene, low temperature, gravitropic bending and phenol oxidation (Halevy & Mayak 1981; Wills *et al*. 1998; Reid 2002, 2004). Exposure to ethylene often results in bud and flower abscission or accelerated senescence (Cameron & Reid 1981; Mor *et al*. 1984; Woltering 1987; Woodson & Lawton 1988; Reid *et al*. 1989; Joyce *et al*. 1990; Joyce 1993; Sexton *et al*. 1995; van Doorn 2001; Plate 19.1). Ethylene is also involved in the gravitropic tip bending response of cut flowers, including snapdragon and gladiolus (Woltering 1991; Philosoph-Hadas *et al*. 1996a; Philosoph-Hadas *et al*. 1999; Reid 2002).

Exposure to low temperatures above the freezing point of flower tissues can cause chilling injury (Wills *et al*. 1998; Reid 2002). Flowers of tropical and subtropical origin (e.g. anthurium; Paull 1987) tend to be most susceptible to chilling. The severity of chilling injury is a function of increasing exposure times and/or falling temperatures. Symptoms, which may only express upon return to ambient temperatures, include tissue discolouration (i.e. blueing, browning and blackening) and reduced vase life (Paull 1987; Joyce & Shorter 2000; Miranda *et al*. 2000; Plate 19.1).

Gravitropic bending occurs when actively growing regions of the cut flower grow upwards away from gravity (e.g. in gladiolus, gerbera and snapdragons). The mechanism appears to involve auxin redistribution, asymmetric ethylene synthesis and changes in calcium levels (Philosoph-Hadas *et al*. 1996a; Philosoph-Hadas *et al*. 1999).

Phenol oxidation, leading to black leaves, is a major problem in some protea species after harvest, particularly when the flowers are kept in the dark. It is associated with a loss of sugars from the leaves. It is probable that if sugars are hydrolysed from phenolic glycosides the remaining phenolic molecules are rapidly oxidised (Jones *et al*. 1995b). Blackening can sometimes be inhibited by feeding glucose to the cut stems (Stephens *et al*. 2001).

Some flowers are damaged by fluoride in the water supply (approximately 1 ppm). Fluoride accumulates in the petal margins and kills those cells, as found in gerbera, gladiolus, freesia and roses (Halevy & Mayak 1981; Tjia *et al*. 1987).

Ultrastructural changes accompany the physiological changes after harvest, such as tonoplast invagination and breakdown, chloroplast and chromoplast breakdown, disappearance of ribosomes and lipid phase separation in membranes (Halevy & Mayak 1981; Thompson *et al*. 1997; Rubenstein 2000). While some of these changes may be late events in cell death, there are some cases where these changes occur before climacteric ethylene production and before flower opening (Rubenstein 2000).

**Water relations**

All cut flowers can suffer from water deficit both in the vase and beforehand (Halevy & Mayak 1981; Mayak 1987; van Doorn 1997; Wills *et al*. 1998; Reid 2002, 2004). Water loss is via stomata and trans-cuticular diffusion from leaves and floral organs. The lower the vapour pressure of the surrounding atmosphere, the steeper the diffusion gradient for water loss (Wills *et al*. 1998). High airflow rates favour water loss by disturbing the otherwise unstirred water vapour boundary layer around the stems.

For flowers in vases, factors that limit water flow up through the stem contribute to development of tissue water deficits (van Doorn 1997). These factors can include: (1) Blockage of stem ends and xylem elements by microbes (Zagory & Reid 1986; van Doorn *et al*. 1989, 1991b); (2) blockage due to physiological plugging (Parups & Molnar 1972; Lineberger & Steponkus 1976; van Doorn *et al*. 1991a; van Doorn & Cruz 2000; van Doorn & Vaslier 2002; Williamson *et al*. 2002; He *et al*. 2006); (3) blockage caused by physical plugging from organic (e.g. dead microbes) and inorganic (e.g. clay) particles in the vase water; and (4) blockage by air bubbles formed in the xylem system (i.e. cavitation), including at the stem ends (i.e. emboli) (Dixon *et al*. 1988; van Meeteren 1992; van Doorn & Otma 1995; Williamson & Milburn 1995). Air emboli and xylem cavitation can also occur in flower stems held out of solution, such as during storage and/or transport.

Cut flowers lose water through stomata and cuticles. In some flowers, stomata close after cutting. Post-harvest light increased water loss in roses, presumably due to stomatal opening (Halevy & Mayak 1981). The difference in vase life between a short and a long-lived rose cultivar was attributed to stomatal closure and reduced transpiration in the long-lived cultivar (Mayak *et al*. 1974).

Water deficit stress experienced either prior to harvest or during storage, transport and vase life can enhance senescence processes in cut flower tissues (Mayak & Halevy 1971; Mayak *et al*. 1974; Spikeman 1986; Hinesley 1988; Drory *et al*. 1992; van Doorn & Suiro 1996).

**Pests and diseases**

Insect pests of cut flowers include those that visibly damage flowers, detract from the appearance of flowers and/or constitute a quarantine risk (Seaton & Joyce 1988; Hansen & Hara 1994; Wills *et al*. 1998). The larvae of many lepidopterous (moth and butterfly) species eat bud and flower tissues. Early infestations of sucking insects, such as mites, aphids, scales and mealy bugs, result in flower spotting and/or deformation. Later infestations tend to be less damaging to the flowers, but detract from their


**Figure 19.6** Out-turn examination of cut boronia flowers by plant quarantine inspectors following a trial sea shipment from Perth, Australia to Yokohama, Japan.

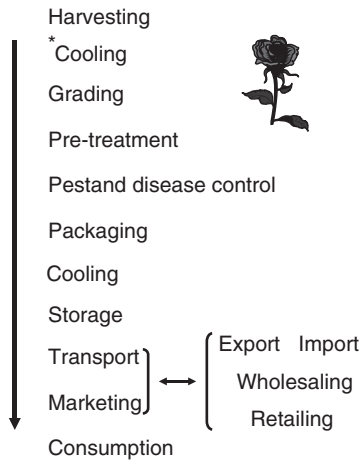


**Figure 19.7** Generic cut-flower handling chart.
* indicates removal of field heat; a vitally important step, where practical, within the context of post-harvest handling chain logistics.

appeal. Most infestations occur during growing, but there is evidence of insects moving into flowers, bunches and packages after harvest and during transport. Almost any live insect in international cut flower consignments can result in rejection or fumigation by plant inspection services (Figure 19.6).

Grey mould or botrytis blight, caused by the fungal pathogen *Botrytis cinerea* (de Bary) Whetzel, is the major disease of a wide range of cut flowers, including carnation and rose (Orlikowski 1991; Wills *et al*. 1998; Reid, 2002; Plate 19.2). This pathogen can colonise dead or dying tissue, such as the senescing anthers or stigmas on Geraldton waxflower (Beasley & Joyce 2002). Botrytis spores can also directly penetrate healthy tissue, including gerbera, rose and freesia petals (Pie & De Leeuw 1991; Salinas & Verhoeff 1995; Darras *et al*. 2006). Spore germination typically requires free water, such as condensate at high humidity (Hammer & Marois 1989; Darras *et al*. 2006). Necrotic flecking on petals may be symptomatic of direct penetration. Most fungal infection occurs during flower growth. Latent infections can remain quiescent until changes in host physiology and/or environmental conditions trigger pathogen growth and development. For example, after harvest, inadequate cooling, high humidity, condensation, tight packing and slow marketing can all contribute to massive fungal growth. Development of tan lesions and/or superficial growth of white mycelium with grey spore masses typify active botrytis infection. Compared with other fungal pathogens, botrytis is relatively active at low and intermediate temperatures. *Alternaria alternata* (Fr.) Keissl. is another significant cut flower pathogen (Taylor *et al*. 1998).

## POST-HARVEST HANDLING PRACTICES

Figure 19.7 depicts the generic post-harvest operations for cut flowers (Halevy & Mayak 1981; Wills *et al*. 1998; Reid 2002, 2004). Because of their wide variety, no single flow chart suits all flowers. It is important for people involved in post-harvest operations to gain an appreciation of the product that they are handling. In this context, training of personnel is desirable. Experience in one fresh flower distribution centre in California was that losses were markedly reduced when workers were told of the delicate nature of, and actually shown, the produce within the cartons that they handled on a day-to-day basis! Losses were reduced through better cool chain management and less physical damage. Moreover, distribution centre workers assumed more ownership of the product, took greater pride in their work and contributed useful suggestions for improved workplace practices.

### Production factors affecting post-harvest quality

It is wise to grow popular flower species and varieties that have inherently long life. Quality, including longevity, is the result of sound production practices. Optimum water, fertiliser, pesticide and management lead to healthy and vigorous growth. It is particularly important to reduce pest and disease infestation during production.

## Harvesting and handling

Cut flowers are harvested at various bud development stages. For example, single daffodil blooms are typically harvested at a tight bud stage. Geraldton waxflower, which is a spray-type bloom, is harvested at a stage when 25% of flowers have opened (Beal *et al*. 1998a). Bud-stage flowers must be of sufficient horticultural maturity that they have the inherent capability to open in the vase.

Ideally, flowers should be harvested during a cool part of the day so that their metabolic rate is low and removal of field heat is less difficult. Harvesting is most often by hand with the aid of secateurs (Figure 19.8). Harvested blooms need protection from dehydration. Protection is usually afforded by shading with covers and use of handling solutions, such as chlorinated water. Flowers also need protection from physical damage and thus careful manipulation. Transport to the packing shed should be rapid and gentle. Hampers and conveyors are useful aids. In some circumstances flower are prepared for sale and packed in the field.

## Cooling

Cut flowers have relatively high metabolic rates and therefore benefit from rapid cooling to their optimum holding temperature (Joyce 1988; Nowak & Rudnicki 1990; Nowak *et al*. 1991; Wills *et al*. 1998; Reid 2002, 2004; Tables 19.1 and 19.2). Cooling from 20°C to 0°C decreases respiration rate of carnations to about 4% of that at 20°C (Table 19.1).

Flowers can be cooled soon after harvest, to remove field heat, and/or after grading, post-harvest treatments and packaging (Figure 19.7). Most flowers are cooled to close to 0°C, except tropical flowers and foliage such as orchids, ginger, anthurium and bird of paradise (Table 19.2). Once flowers have been cooled, it is advantageous to keep them cool wherever this is practical.

Room cooling is suitable for cut flowers since they have a high surface area to volume ratio and can be stood in water to prevent drying out. However, pressure or forced-air cooling is best for packaged flowers provided that airflow among the blooms in not obstructed (Figure 19.8). Again, because of their high surface area to volume ratio and ability to rapidly rehydrate, vacuum cooling is a good method for cut flowers. For details of cooling methods see Gross *et al*. (2004) and Kader (2002).

## Grading

Culling is often the first of the packinghouse operations, whereby defective blooms (e.g. bent stems) are rejected. Grading is usually to length, although other quality attributes also need to be considered. These attributes include maturity, bud and flower form, leaf condition and pest and disease damage (Figure 19.8). Grading can be assisted with mechanical and electronic devices such as photocell-based stem length graders. Image analysis is also being investigated for grading.

Bunching can either be of single or mixed varieties of one or more species. Length-graded flowers are usually bunched on the basis of stem numbers (e.g. five- or ten-stem bunches). Weight can also be used, either alone or along with stem numbers. Uniformity of bunches is an important consideration. Conveyors are used widely in the preparation of large numbers of mixed-flower bunches. Flowers are added incrementally to the bunch as it moves along the packing line. Mechanical or electronic balances are used to check bunch weights. Bunches are very often tied with rubber bands. Tying machines that use elastic string are also used.

Bunches are trimmed to length using a guillotine or saw. Frequently, especially for high-value flowers and mixed bouquets, bunches are sleeved. Sleeves are usually printed plastic and are sometimes perforated. They are typically used with a chute feed-type dispenser.

## Pre-treatments

Pre-treatments are treatments applied to cut flowers, by growers, wholesalers or exporters, prior to storage or dispatch with the objective of maximising post-harvest longevity.

### *Hydration*

Maintenance of a high water vapour pressure in the atmosphere surrounding cut flowers reduces their propensity for water loss. The vapour pressure deficit (VPD) is the difference in vapour pressure over free water inside cut flower tissues and the vapour pressure in the surrounding atmosphere (Wills *et al*. 1998). VPD is largely a function of relative humidity and temperature. A low VPD is usually achieved by keeping flowers at high RH (e.g. >95%) and low temperature (e.g. *ca*. 2°C). High RH in the immediate vicinity can be achieved using low water vapour transfer wraps, such as polyethylene shrouds and sleeves, placed over individual bunches or groups of bunches. Atmospheric RH may be increased by steam or mechanical humidifiers. Wet coil rather than conventional dry coil refrigeration systems are particularly suitable in cold rooms for cut flowers (Wills *et al*. 1998). However, high RH can also be achieved by selection of a dry coil refrigeration system that has a large surface area evaporator coil and which therefore operates at a low temperature differential. Maintaining a low airspeed over cut flowers also reduces water loss






**Figure 19.8** Post-harvest operations for cut Geraldton waxflower: harvesting (top left image), sorting and grading (top right), bunching (second row left), dipping in a fungicide and insecticide mix (second row right), STS pulsing (third row left), packaging (third row right), and forced air or pressure cooling (image on following page) (Beal *et al.* 1998b). ©The State of Queensland (Australia), 1998.

**Figure 19.8** *Continued*

**Table 19.1** Temperature Effects on Respiration and Heat Production by Carnation Flowers.

| Temperature (°C) | Respiration rate (mg $CO_2$/kg/h) | Heat production (kW/t) | $Q_{10}$ |
|---|---|---|---|
| 0 | 10 | 0.026 | — |
| 10 | 30 | 0.079 | 3.0 |
| 20 | 239 | 0.632 | 8.0 |
| 30 | 516 | 1.364 | 2.2 |
| 40 | 1 053 | 2.784 | 2.0 |
| 50 | 1 600 | 4.245 | 1.5 |

$Q_{10} = (R2/R1)^{10/(t2-t1)}$ is the factor by which reactions, in this case respiration, increase with a 10°C increase in temperature (Wills *et al*. 1998).

Source: Maxie *et al*. (1973), Hardenburg *et al*. (1986) and Reid (2002).

because moisture vapour in the thin boundary layer of high humidity air in and around bunches is not swept away.

Cut flowers that have lost water can generally be rehydrated by standing them in water (Halevy & Mayak 1981; van Doorn 1997; Wills *et al*. 1998; Reid 2002). Cutting 2 to 3 cm from stems held under clean water can remove air emboli blocking the xylem ends. However, cutting stems under water is often not practical in large-scale operations. Where water quality is poor (e.g. on-farm), rain rather than dam water, removal of particulates (by flocculation and filtering of clay) and disinfection to kill microbes (by chlorination; Dychdala 1983; Haynes *et al*. 1990) are desirable. It is generally recommended that flower water contains a germicide (biocide) or a commercial post-harvest solution containing a germicide (Damunupola & Joyce 2008). Flower containers such as buckets need to be kept clean. Water temperature can affect water uptake. Cold water has greater capacity to dissolve gasses and may be less likely to give rise to air bubbles blocking the xylem (i.e. cavitation) (Van Meeteren 1992; van Doorn 1997). Conversely, warm water can facilitate water uptake, possibly as a result of lower dissolved gas content and / or reduced viscosity. Adjuvants that facilitate water flow in stems include wetting agents (surfactants such as Agral at 0.01% to 0.1% v/v; Table 19.3), acids (e.g. citric acid; about pH 3.5) and germicides (Halevy & Mayak 1981; Faragher 1986; van Doorn 1997; Williamson & Milburn 1995; Nell & Reid 2000; Reid 2002; Damunupola & Joyce 2008). Commercial post-harvest solutions usually contain germicides and acid, and sometimes wetting agents, to improve water uptake. However, care should be taken to avoid reactive constituents, such as chlorine with citric acid (Xie *et al*. 2008).

***Anti-ethylene treatments***

Pre-treatments to inhibit abscission and senescence are commonly applied to ethylene-sensitive species (Halevy & Mayak 1981; Wills *et al*. 1998; Reid 2002). A number of ethylene sensitive flowers are listed in Table 19.4. Sources of ethylene, such as ripening fruit and gas-powered forklifts should be avoided. Ventilation with fresh air (more than one room volume exchange per hour) is an effective and inexpensive solution to ethylene contamination problems.

Inhibitors of ethylene production include AOA and AVG. Inhibitors of ethylene action (i.e. binding) include STS and 1-MCP (Figure 19.9). AOA can be used on species that are affected by endogenous ethylene and which tolerate this chemical, such as carnation. STS is widely used, for example, on carnation, gypsophila, Geraldton waxflower, sweet pea and solidago (Tables 19.5, 19.6 and 19.7). With the exception of 1-MCP, which is a gas, anti-ethylene chemicals are usually applied as pulse treatments. However, STS can be applied as a spray; for example, to potted plants (Figure 19.9). A higher concentration of STS is used for short (e.g. 15 minutes at 4 mM $Ag^+$) versus overnight (e.g. 0.5 mM $Ag^+$) pulse treatments (Reid & Farnham 1980; Joyce 1992; Faragher *et al*. 2002). It is sometimes difficult in practice to ensure the flowers take up the correct amount of STS. Because silver compounds are toxic, STS requires careful handling and disposal. It has been banned in most European countries (EC 2002) and is not available in many states of the United States. 1-MCP is very effective at low concentrations and is relatively easy and safe to apply and dispose (Nell & Reid 2000). In some flowers 1-MCP protects against ethylene

**Table 19.2** Storage Conditions for Selected Cut Flowers.

| Cut flower type | Temperature (°C) | r.h. (%) | Storage life (days) | Short-term storage temperature (°C) |
|---|---|---|---|---|
| alstroemeria | 0–4 | 90–95 | 6–10 | 1 |
| anthurium | 12–16 | 90–95 | 3–10 | 15 |
| bird-of-paradise | 7–10 | 85–95 | 3–28 | 7.5 |
| carnation | 0–7 | 90–95 | 3–42 | 1 |
| chrysanthemum | 0–8 | 90–98 | 7–42 | 1 |
| delphinium | 0–5 | 90–95 | 1–2 | — |
| freesia | 0–4 | 90–95 | 1–14 | 1 |
| ginger | 7–10 | 90–95 | 5 | — |
| gypsophila | 0–5 | 98 | 1–21 | 1 |
| iris | 0–4 | 90–95 | 4–28 | 1 |
| liatris | 0–5 | 90–95 | 3–14 | — |
| lily | 0–5 | 90–95 | 4–28 | 1 |
| lisianthus | 1 | 90–95 | 7 | 1 |
| narcissus | 0–2 | 90–95 | 7–21 | 1 |
| orchid | 0–15 | 90–95 | 7–28 | — |
| protea | 2–4 | — | 7–21 | 2 |
| rose | 0–4 | 90–98 | 4–14 | 1 |
| snapdragon | 0–5 | — | 3–28 | 1 |
| statice | 2–4 | 90–95 | 14–42 | 2 |
| tulip | 0–2 | 85–95 | 3–42 | 1 |

Source: Adapted from Wills *et al*. (1998).

**Table 19.3** Vase Life of Cut Rose cv. Sonia.

| Treatment | Vase life (days) |
|---|---|
| (i) 48 h in water | 12.1 |
| (ii) 24 h in aqueous solution and then 24 h dry storage | |
| no surfactant | 4.3 |
| Tween 20 (0.1 g/l) | 5.4 |
| Tween 80 (0.1 g/l) | 9.1 |
| Triton X-100 (0.1 g/l) | 15.3 |
| Non-oxynol-8.5 (0.5 g/l) | 15.8 |

Note: Sonia blooms kept (i) in water for 48 h prior to assessment of longevity or (ii) in water or various surfactant solutions for 24 h and then dry-stored for 24 h at 20°C and 60% RH before return to water.

Source: Compiled from van Doorn *et al*. (1993).

for a relatively long time (e.g. 12 to 15 days in carnations; Sisler & Serek 1997). In other flowers, protection is conferred for four to seven days (Nell & Reid 2000). In yet other flowers, protection is short-lived (e.g. low concentrations of 1-MCP protected grevillea for two days; Macnish *et al*. 2000).

***Other pre-treatments***

Some cut flowers benefit from pulsing with exogenous carbohydrate compounds, such as sucrose, to supplement endogenous levels (Halevy & Mayak 1981; van Doorn 1997; Wills *et al*. 1998; Reid 2002, 2004; see Table 19.7). This pre-treatment is particularly useful for cut flowers harvested at the bud stage, such as lilies and gladioli. A typical bud opening solution treatment is composed of a high concentration (e.g. 2 to 20%+ [v/v]) pulse for a short (e.g. 0.5 h at room temperature) to a relatively long (e.g. 16 h or overnight at room or cold room temperatures) period of time. Pulsing at a moderate VPD, not at high humidity, can enhance uptake by maintaining transpirational demand. Pulsing some proteas with glucose, but not sucrose, inhibited leaf blackening (Stephens *et al*. 2001).

Plant growth regulators (PGRs) are applied to help maintain the post-harvest longevity of certain cut flowers. Auxins have been used to reduce flower abscission from Geraldton waxflower and other flowers, but they are not

**Table 19.4** Cut Flower Lines Reported to be Ethylene Sensitive.

| Name | Sensitivity | Comment |
|---|---|---|
| agapanthus | yes | |
| anenome | yes | |
| anthurium | low | |
| alstroemeria | high | |
| asparagus fern | low | |
| gypsophila | yes | |
| bouvardia | yes | |
| carnation | high | |
| daffodil | high | |
| delphinium | high | |
| euphorbia | high | |
| freesia | high | |
| grevillea | high | |
| gerbera | low | |
| holly | yes | |
| iris (bulbous) | high | |
| lisianthus | low | |
| mistletoe | high | |
| nerine | low | |
| oriental lily | high | |
| orchids | yes (high)/no | varies with genus |
| rose | yes | varies with cultivar |
| snapdragon | high | |
| statice | yes | |
| stock | yes | |
| sunflower | low | |
| sweet pea | high | |
| sweet William | yes | |
| tuberose | low | |
| tulip | low | |
| verticordia | yes (high)/no | varies with species |
| waxflower | yes | varies with genotype |

Source: Nowak and Rudnicki (1990), and Nell and Reid (2000); see also Woltering and van Doorn (1988), and van Doorn (2001).

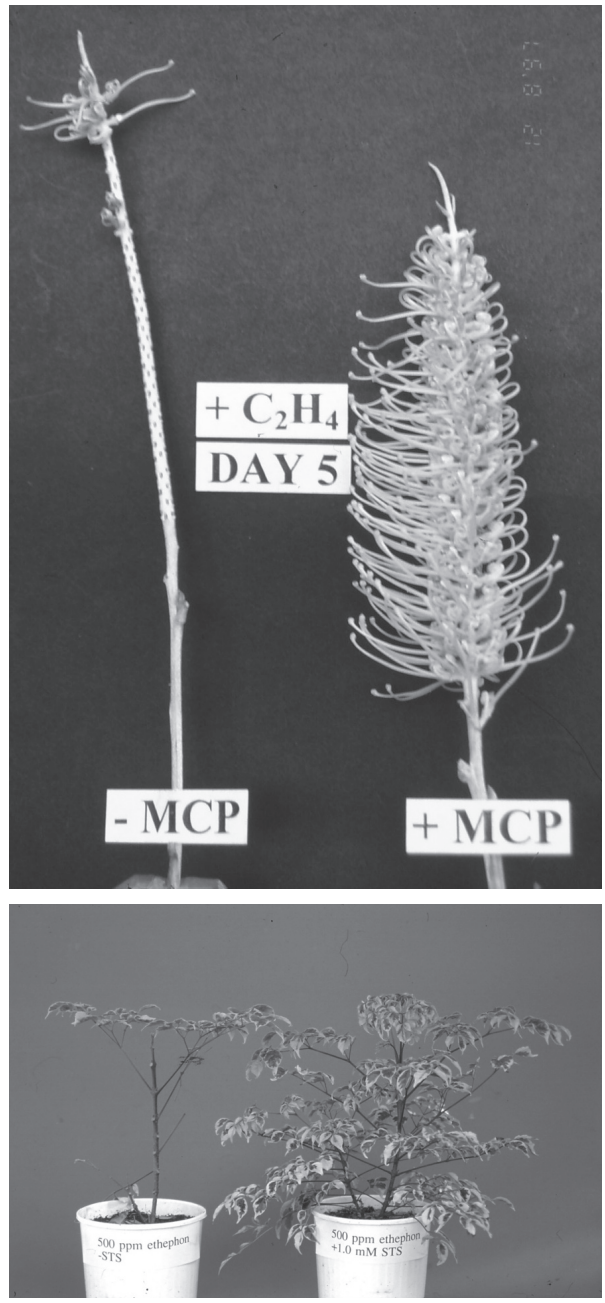


**Figure 19.9** Protection against ethylene-induced abscission conferred by pre-treatments of cut *Grevillea* cv. Honey Gem inflorescences with 1-methylcyclopropene gas (Top image) and potted *Radermacheria* cv. Crystal Doll plants with silver thiosulphate spray (Bottom image). Controls on left and treated on right in both images. Reproduced with permission of the authors and publisher.

always effective (Table 19.5) (Halevy & Mayak 1981; Joyce 1989). Gibberellin and cytokinin treatments retarded alstroemeria and Easter lily leaf chlorosis (Hicklenton 1991; Han 1995), and increased the foliage vase life of goldenrod (Table 19.6). Pulse treatment of cut *Alstroemeria* cv. Diamond stems with the cytokinin-like compound thiadiazuron (TDZ) increased leaf longevity from ≤18 days to over 60 days (Ferrante *et al*. 2002). Applied GA

**Table 19.5** Effect of Pre-Treatments with Auxin (Naphthalene Acetic Acid, NAA) versus STS on Relative Fresh Weight, Visual Appearance Scores (1 = Excellent, 3 = Good, 5 = Fair, 7 = Poor, 9 = Very Poor) and Vase Life of Cut Flowering Geraldton Waxflower Stems Exposed to 5.6 µl Ethylene/l for 24 h on Day 0.

| Treatment | Weight (% initial) | Appearance score | Vase life (days) |
|---|---|---|---|
| Control | 50.8 | 8.8 | 1.0 |
| 4 mM STS, 15 min pulse | 94.9 | 2.4 | 5.4 |
| 0.5 mM STS, overnight pulse | 100.3 | 1.2 | 7.4 |
| 40 µg NAA/ml, 30 sec dip | 59.8 | 7.2 | 1.0 |

Source: Compiled from Joyce (1989).

**Table 19.6** Effects of Pre-treatments with STS and the PGRs NAA, Gibberellic Acid ($GA_3$) and Benzyladenine (BA; Cytokinin) on the Vase Life (Days) of Cut Goldenrod *Solidago* cv. Yellow Submarine Stems.

| Treatment | Inflorescence vase life (days) | Foliage vase life (days) |
|---|---|---|
| Control | 9.7 | 6.0 |
| STS (200 µM) | 13.3 | 11.0 |
| NAA (200 µM) | 9.8 | 7.4 |
| $GA_3$ (100 µM | 8.5 | 7.2 |
| BA (10 µM) | 9.8 | 8.2 |
| STS + BA | 13.7 | 15.0 |
| $GA_3$ + BA | 7.8 | 10.5 |

Source: Compiled from Philosoph-Hadas *et al*. (1996b).

can increase the vase life of some roses (Goszczynska *et al*. 1990).

There is a broad range of other pre-treatments that have been researched, including nitric oxide (Lesham 2000). For more information, see Halevy and Mayak (1981), Nell and Reid (2000) and Reid (2004).

**Pest and disease management treatments**

Early pest infestation (e.g. mites) or pathogen infection (e.g. botrytis) can result in malformed flowers. For example, pre-harvest infection with botrytis can result in

**Table 19.7** Vase Life at 23°C of Cut Sweet Pea Florets and Spikes Held in Sucrose with or without Pre-treatment with STS.

| | Vase life (days) | |
|---|---|---|
| Treatment | Florets | Spike |
| water (control) | 1.7 | 2.5 |
| sucrose (100 g/l) | 3.0 | 5.9 |
| STS (0.2 mM) | 4.4 | 7.2 |
| STS + sucrose | 6.0 | 8.7 |

Source: Compiled from Ichimura (1998).

hard green lumps that distort lily petals when they grow and expand. Thus, insects and diseases affecting cut flowers should be controlled prior to harvest. In the context of international trade, post-harvest infestations can constitute a quarantine problem (Figure 19.6). With a view to managing resistance, alternating use of active ingredients from different chemical families should be practised prior to harvest. Another chemical from a different group can be reserved for post-harvest treatment. Adherence to the principles of integrated pest (and disease) management will reduce reliance upon chemicals (Hansen & Hara 1994; Flint & Gouveia 2001). Pre-harvest adoption of biological control measures (e.g. *Trichoderma* for botrytis management) merits consideration (Elad *et al*. 1993). Use of packaging materials and methods and handling conditions that allow ventilation, minimise the risk of condensation and maintain low temperature will assist in post-harvest disease management (Hammer & Marois 1989; van der Sman *et al*. 1996; Taylor *et al*. 1997, 2001).

***Insects***

Control of insect levels during production is the best way to reduce post-harvest insect problems. Post-harvest infestations can be removed manually, such as in the course of a detergent wash (Seaton & Joyce 1988; Hansen & Hara 1994). Chemical control is effected by dips and sprays with either insect specific or broad spectrum insecticides, such as dimethoate and deltamethrin (Seaton & Joyce 1988; Hansen & Hara 1994; Figure 19.8). Certain insecticides, for example synthetic pyrethrins, can be applied in aerosol form. However, complete coverage of the surfaces of bunched flowers may be difficult to achieve. In contrast, gas fumigants like methyl bromide and phosphine can be extremely effective, but the risk of phytotoxicity demands

**Table 19.8** Effects of Post-harvest Treatments with Pyrimethanil and Iprodione on *Botrytis cinerea* Inoculation-Induced ($1 \times 10^4$ Spores/ml) Disease Severity (Scores: 1 = None, 2 = Trace of Mycelium, and 3 = Mycelial Matting), Flower and Leaf Abscission (Debris, as % Initial Stem Weight) and Flower Vase Life of Geraldton Waxflower cv. CWA Pink Packaged and Kept at 20°C for Six Days

| Treatment | Disease Severity | Debris (% initial Score weight) | Flower vase life (days) |
|---|---|---|---|
| water (control) | 3.1 | 24.5 | 1.7 |
| iprodione (1.0 ml Rovral/l) | 1.4 | 2.7 | 3.5 |
| pyrimethanil (1.5 ml Scala/l) | 1.4 | 5.7 | 3.0 |
| pyrimethanil (2.0 ml Scala/l) | 1.7 | 6.2 | 3.3 |

Source: Compiled from Taylor *et al*. (1999).

care in application. Methyl bromide is being banned from many uses because it depletes ozone in the atmosphere. Dichlorvos has a degree of vapour-phase activity. In addition to concentration, the efficacy of insecticide treatments is strongly influenced by the time by temperature interaction. That is, control is generally enhanced at higher temperatures and upon longer exposure to insecticides. Physical treatments, such as hot-water dips, may prove useful for tolerant cut flowers (Seaton & Joyce 1988; Hansen & Hara 1994). Irradiation is attractive as it leaves no pesticide residues, but the doses needed to kill insects also damage flowers. Even the lower doses needed to sterilise insects cause damage (Seaton & Joyce 1992; Nell & Reid 2000).

### *Disease treatments*

Disease control is usually achieved using fungicides, such as iprodione or pyrimethanil for botrytis control (Wearing *et al*. 1995; Taylor *et al*. 1999; Table 19.8). Fungicides are applied as dips or sprays (see Figure 19.8). Biological control agents may have commercial potential for botrytis management (Hammer & Marois 1989), as may treatments with compounds (e.g. methyl jasmonate) that enhance natural defence processes (Meir *et al*. 1998; Darras *et al*. 2005; Dinh and Joyce 2007). Calcium treatments may also help restrict botrytis (e.g. roses; Volpin & Elad 1991), albeit not for all flowers (e.g. Geraldton waxflower; Taylor *et al*. 2003). GA treatment inhibited botrytis development in some rose cultivars (Shaul *et al*. 1995).

The regulations covering the use of specific insecticides and fungicides vary between jurisdictions. Thus, the relevant governing rules must be read and understood before pest and disease management programs can be implemented. It is similarly important to adhere strictly to product use advice and other information on the label.

### Miscellaneous treatments

Fresh dyeing or tinting of some cut flowers, such as carnations, is practised to extend the product range (Wills *et al*. 1998; Reid 2002). Light-coloured (e.g. white) blooms are pulsed with food-grade water-soluble dyes. Blue dye is often used (Plate 19.3). With a view to reducing the risk of physical damage during packing and transport, kangaroo paw inflorescences may be pre-wilted. Provided that the treatment is not excessive, rehydration is readily achieved later. Hygiene is an important issue with all cut flowers. Good hygiene involves washing and disinfection of containers and other equipment (e.g. secateurs) with an approved chemical (often chlorine based). Light after harvest is important for the quality of some flowers. For example, some protea species suffer leaf blackening in darkness. Supplementary lighting equivalent to bright room or office lighting conditions ($30\,\mu mol/m^2/s$) markedly reduces blackening (Jones *et al*. 1995b). Leaf blackening of protea can also be reduced by only growing species that are not prone to blackening, watering before picking, cooling, avoiding water condensing on leaves, glucose pre-treatments, and rapid marketing (Jones *et al*. 1995b; Stephens *et al*. 2001; Faragher *et al*. 2002). Gravitropic bending can be reduced by holding flowers vertically and keeping them cold. Fluoride injury can be avoided by using rain, good quality bore or dam water, or deionised water. Some flowers cause allergies to people handling them. For example, the hairs on kangaroo paws

can cause skin irritation. Some mimosa (acacia) growers in Europe have become allergic to acacia pollen. These risks can presumably be avoided to some extent by using gloves and protective clothing, including breathing masks.

### Efficient handling and process control

Post-harvest handling is expensive, at least where labour costs are high. Thus, it is important to use efficient methods of handling. These include minimising the number of handling steps, using mechanical aids, automating to give an even flow of flowers through the handling chain, and achieving economies of scale. It is also wise to ensure that staff are well trained and have comfortable and safe working conditions.

The reliable supply of high-quality cut flowers is important in maintaining customer satisfaction. Towards this end, careful and regular monitoring of product quality (e.g. vase life) and of treatments (e.g. STS uptake) and handling conditions (e.g. temperature) is important (Wills *et al*. 1998). Thus, cut flower enterprises can benefit from adoption of quality management protocols including Total Quality Management and Hazard Analysis and Critical Control Point (Forsythe 2000). Increasingly, customers such as wholesalers and retailers, consumers and legislators are requiring documented and third party-certified evidence of quality assurance. They are also interested in demonstration of sound chemical, environmental and ethical management practices.

### Vase life measurement and prediction

Cut flower quality is conventionally gauged by subjective vase life assessment under standardised conditions of temperature 20°C, 60–70% RH and 12 h light per day (Reid & Kofranek 1980; Joyce 1996). Subjective vase life criteria, such as days to first signs of wilting, can be supported by objective measures, such as weighing the flowers daily and plotting relative fresh weight (i.e. proportion of initial fresh weight) as a function of time in days. A degree of prediction of vase life may be obtained from more sophisticated objective measures, such as starch–iodine staining status (Berkholst & Navarro Gonzales 1989; Shellebear *et al*. 1993), chlorophyll fluorescence (Joyce & Shorter 2000; Miranda *et al*. 2000) and water uptake (Buys & Cours, 1980). Both subjective and objective measures can facilitate predictive modelling of post-harvest performance (Hansen *et al*. 1991; van Doorn & Tijskens 1991; Hoogerwerf *et al*. 1994).

### Packaging

#### *Primary package*

Plastic buckets are widely used in cut flower handling. In wet-handling systems, buckets are used from the point of harvest through to the point of sale. Buckets can be arranged on sturdy wheeled trolleys that are returned to the seller. There is increasing use of special boxes that contain water in the base for transporting flowers. For larger scale operations wheeled tubs or troughs of water can be used. In dry-handling systems, a variety of natural (e.g. fibreboard cartons; Plate 19.4; McGregor 1987) and synthetic (e.g. polystyrene caskets) materials are used as primary packages. Dry handling is particularly appropriate for international airfreight and/or for storage for periods in the order of weeks or months. Wet handling is more appropriate for road freight and/or for storage for a matter of days. To prevent stem bending, vertical packaging can be adopted for gravitropic flowers such as gladiolus and snapdragons (Halevy & Mayak 1981; Reid 2002).

#### *Secondary packaging*

A wide variety of secondary packaging options offers physical protection to delicate cut flowers. These include carton liners of plastic or paper sheets; padding by shredded paper, wood or synthetic wool; bunch sleeves of perforated printed plastic; supports in the form of cleats, perforated cards, plastic boxes; and vase solutions provided in flexible or rigid vials or in a saturated cotton wool plug (Plate 19.4; McGregor 1987). In addition, ice or freezer packs can afford in-package cooling, particularly if the flowers and ice are insulated from external heat. Holes in cartons can provide ventilation, and scrubbers (e.g. permanganate-coated particles in sachets) can help to remove ethylene. Insulation, such as reflective foils and thermal blankets, can be applied to cartons, groups of cartons and/or pallets to restrict incoming heat.

### Cold storage and transport

Cut flower storage is usually only for a relatively short period of time, with stems in water (Table 19.2). Longer term storage is possible for some flowers, but requires picking at an early bud stage, pre-treatments, tight packing to prevent water loss, low temperatures, and special rehydration and bud opening processes after storage (Goszczynska & Rudnicki 1988; Nowak & Rudnicki 1990; Nowak *et al*. 1991). Long-term cold storage practices can be used for shipping flowers by sea. This is done, for example, from South America to North America and Israel to Europe. However, in-transit loss of

quality and vase life has meant that shipping over longer distances has not been practised widely.

Flowers can benefit from controlled atmosphere (CA) cold storage (e.g. daffodil/narcissus and carnations; Nowak & Rudnicki 1990; Macnish *et al*. 2009). However, normal low-temperature cool storage rooms are typically used. Similarly, hypobaric (reduced pressure) cold storage has been shown beneficial, but is not currently economically feasible (Halevy & Mayak 1981; Nowak & Rudnicki 1990; Macnish *et al*. 2009). Modified atmosphere packaging (MAP), which encloses flowers in a semi-permeable plastic film, has received limited use on flowers. MAP extends the life of some flowers (e.g. carnations) as long as temperatures are maintained at low and constant levels. However, this condition is often not possible in commercial practice, particularly in air transport.

Ethylene removal from cold rooms by ventilation at about one air change per hour and, less successfully, by scrubbing with activated charcoal or permanganate is perhaps warranted for cut flowers (Halevy & Mayak 1981; Nowak & Rudnicki 1990; Reid 2002). However, effective protection of ethylene sensitive flowers is best achieved by STS or 1-MCP.

### *Transport*

Road and air are the main modes of transport for cut flowers (McGregor 1987; Nowak & Rudnicki 1990). Sea and rail transport are comparatively rare. Nonetheless, sea shipment of cut flowers and foliage is routine on the major trade route from South to North America. Trucks fitted with mechanical refrigeration units are used to move cut flowers within regions and between regions and countries, such as throughout Europe and North America. In contrast, air transport is more typically used for intercontinental shipping, such as from Australia to Japan. Refrigeration is usually not possible during the air transport, though it is now being introduced by at least one airline. However, ice or other cryogenic compounds such as dry ice can be included in packages and/or in the air container to remove incoming radiation heat and vital heat of respiration, particularly if the flowers and ice are insulated to minimise incoming heat (Wills *et al*. 1998). For this approach to be effective, the latent field heat must have been removed prior to shipment. In the absence of provisions for in-transit cooling, ventilation of cut flower cartons may help to limit both the heat load from respiration and ethylene accumulation. Some ventilation can be achieved by leaving the pressure cooling holes open. Thermal blankets and reflective foils may also be of use in restricting incoming heat and hence flower warming during nonrefrigerated shipping. Where rail transport of cut flowers is a viable option, refrigerated boxcars should be used. Refrigerated sea containers are similarly useful. These can be fitted with equipment to generate and/or maintain CA conditions. CA shipping by sea might be appropriate for comparatively durable cut flowers, which respond positively to CA, like bud stage carnations (Macnish *et al*. 2009).

Re-cooling of cut flowers at various steps in the handling process can be helpful in maintaining the post-harvest cold chain. For example, cut flowers may need pressure cooling upon arrival at an importer's premises following non-refrigerated air transport. Similarly re-hydration of cut flowers may be useful after shipping or storage. This process involves re-cutting the stems and standing the cut flowers in clean water containing germicide, acidifier and/or surfactant, or a commercial post-harvest solution. Re-hydration can be facilitated by high RH and low air velocity, and is ideally done at low temperature. For instance, with the cut flowers standing under loose plastic shrouds in buckets of re-hydration solution arranged in a cold room.

Flowers need to be handled gently during transport to avoid physical damage. Above all, transport needs to done as quickly as possible to ensure maximum flower life and quality in the hands of the consumer.

### Costs and benefits of post-harvest practices

The benefits that are likely to result from post-harvest treatments include reduced losses due to wilting, flower drop and poor flower opening; increased sales as a result of customer satisfaction; and savings in labour and time because there are fewer problems to deal with.

The greatest costs of post-harvest handling are labour for picking; labour for grading, treating and packing; transport to market; and cartons. In relative terms, the cost of post-harvest chemicals and pesticides is very small (Faragher *et al*. 2002).

## MARKETING AND CONSUMPTION

### Marketing

Cut flower trading occurs at local (farm gate), regional (farmers' market), national (central market) and international (export-import) levels. The sales and distribution process can be complex. For example, flowers grown in Kenya may be sold at auction in Holland and used in bouquets for sale at a supermarket in the United Kingdom. Some markets have adopted the Dutch auction clock system, where as the initially high price falls the buyers bid to stop the clock at the price they are willing to pay (Plate

19.5). The purchaser who bids first obtains the consignment. Despite the traditional and general popularity of central market systems, direct sourcing of cut flowers is practised widely. Thus, large volumes of cut flower lines used in bouquets are obtained directly from growers. Wholesalers that prepare bouquets typically mix-and-match component flower types to achieve a colour or seasonal theme at an agreed price and with a vase life guarantee of one or two weeks. High volume retail outlets include supermarkets, petrol stations and cut flower stands. The use of refrigerated display areas or cases helps to slow cut flower development and senescence processes. Increasingly, florists specialise in floral art that involves a wider variety of materials than fresh cut flowers, including dried and dyed floral material, balloons and ribbons, and services such as greeting cards and delivery. Internet marketing is a relatively recent and lucrative variation of the traditional florist trade.

**Consumption**

Fresh cut flowers are often sold with ingredients (e.g. sachets of sugar and citric acid crystals) to make up a vase solution. Consumer advice is usually printed on sachets, flower sleeves or labels. This advice typically covers trimming to remove dead and damaged flowers and leaves, and removal of leaves that will be below the vase solution surface. Re-cutting under water to remove 2 to 3 cm from stem ends is recommended. Other common and sound advice includes keeping flowers in cool places, out of direct sunlight, away from ripening fruit (i.e. sources of ethylene) and in draught-free areas (Joyce 1986).

**Vase life**

The vase life of most cut flowers can be extended by the use of a suitable vase solution. These are similar to the pulsing and re-hydration solutions mentioned above. They can be made up by the user or purchased as commercial products.

***Water***

The water used for vase solutions should be free of inorganic (e.g. clay) and organic (e.g. live or dead microbes) particles that can block transpirational water flow via the xylem. Aluminium sulphate can be used to flocculate clay. The use of water that is warm (40–50°C) or cold (about 2°C), deep (Valle *et al*. 2001; Table 19.9), acidic (pH 3–4) and/or contains a surfactant (Table 19.3) can facilitate uptake (Halevy & Mayak 1981; van Doorn 1997; Reid 2002, 2004). Fluoride in tap water at about 1 ppm can be highly toxic to some flowers, like gerberas, gladioli, freesias and roses (Halevy & Mayak 1981; Tjia *et al*. 1987). Using rain, deionised water or clean bore or dam water can avoid this problem.

**Table 19.9** Effects of Shallow and Deep Vase Water on Vase Life of Leptospermum and Acacia (Mimosa) Flowers.

| Flower | Vase life (days) | |
|---|---|---|
| | Shallow water (5 cm) | Deep water (20 cm) |
| *Leptospermum obovatum* | 3 | 8 |
| *L. polygalifolium* | 2 | 7 |
| *Acacia baileyana* | 7 | 11 |

Source: J.D. Faragher and V.G. Williamson (unpublished data), and Williamson *et al*. (2002).

**Table 19.10** Effects of a Selection of Germicides, in Citrate-Glucose Solution (0.2 and 10 g/l, Respectively), on Longevity Indices of Time to Decline in Fresh Weight (Life) and Maximum Gain in Fresh Weight (Gain) for Cut Rose cv. Classy.

| Treatment[a] | Life (days) | Gain (%) |
|---|---|---|
| Water (negative control) | 7.0 | 5.0 |
| Citrate-glucose (positive control) | 7.0 | 8.3 |
| CPC (0.05 g/l) | 9.5 | 5.1 |
| Dantogard (0.05 g/l) | 8.0 | 10.3 |
| DICA (0.2 g/l) | 8.5 | 5.1 |
| HQC (0.2 g/l) | 9.4 | 9.1 |
| Isocil (0.05 g/l) | 9.6 | 8.7 |
| Physan (0.05 g/l) | 9.4 | 10.0 |

[a] CPC = cetyl pyridinium chloride;
DICA = dichloroisocyanurate, sodium salt;
HQC = hydroxyquinoline citrate.
Source: Compiled from Knee (2000).

***Microbes***

Bacteria and fungi, including yeasts, proliferate rapidly in vase solutions (Halevy & Mayak 1981; van Doorn 1997; Reid 2002, 2004). Their growth is fuelled by substrates that leak from submerged stems. Germicides such as chlorine and quaternary ammonium compounds are used to slow their growth (Table 19.10). Acidification with citric acid to about

pH 3 also suppresses microbial development, but should not be used in combination with chlorine (Xie *et al*. 2008).

### *Food*

Sugar, 0.5% to 2.0% sucrose, can be provided in vase solutions to sustain flower development processes (Ichimura 1998; Halevy & Mayak 1981; Reid 2002, 2004). Optimum concentrations vary with the genotype and flower development stage. Bud opening typically requires higher concentrations, up to 5%, to meet respiratory and osmotic demands.

### *Ethylene*

Ethylene can cause flower fall or senescence of sensitive cut flowers (Halevy & Mayak 1981; Reid 2002; Reid 2004). These flowers should ideally have been pre-treated with either inhibitors of ethylene-mediated processes (e.g. auxin), ethylene production (e.g. AVG, AOA) or, preferably, inhibitors of ethylene action (e.g. STS, 1-MCP). Inhibitors of ethylene synthesis (AOA, AVG) have been used in some vase solutions for flowers that produce their own ethylene, such as carnations. However, they are generally less effective than STS or 1-MCP. Sources of ethylene, such as ripening fruit and car exhausts, should be avoided. Ventilation with fresh air is an effective and inexpensive solution to ethylene contamination problems.

### *Plant growth regulators*

PGRs can be used to help maintain the post-harvest longevity of certain cut flowers (Halevy and Mayak 1981). In laboratory experiments, cytokinins extend the life of carnations, roses and iris and delay leaf yellowing. Gibberellins also delay leaf yellowing. Abscisic acid has been used to reduce water use and leaf crisping of roses and to extend the life of Geraldton waxflower foliage (Halevy and Mayak 1981; Joyce & Jones 1992). In commercial practice, most vase solutions do not contain plant growth regulators. However, a small number contain cytokinins and/or gibberellins specifically to delay leaf yellowing.

### *Other treatments*

A number of lesser known treatments have been tested or advocated for specific cut flowers (Halevy & Mayak 1981). For example, ethanol in the vase solution can enhance the vase life of carnations (Wu *et al*. 1992). Dipping stem ends of Iceland poppy into boiling water can coagulate latex that might otherwise block xylem uptake of vase water (Stirling 1950, cited by Halevy & Mayak 1981).

## PRESERVATION

Cut flowers and foliage are often processed from fresh to more durable forms for use in the florist trade (Plate 19.6). The processes are generally simple and include drying, sulphuring, bleaching, dyeing and treatment with humectants (Joyce 1998).

### Drying

Dried cut flowers are called ‘everlastings’ in some parts of the world. A number of approaches can be taken to drying cut flowers and foliage (Knap 1975; Petersons 1981; Dubois & Joyce 1989a; Joyce 1998). A very common method of drying is simply to suspend bunched cut flowers upside down from rafters or racks in an airy shed. Ventilation of black plastic-covered tunnel houses, with air piped through a matrix of vented plastic drainage pipes, is an inexpensive means of drying on a commercial scale. Air can be de-humidified to speed the dehydration process. Freeze drying (lyophilisation) is also possible, but is expensive relative to the low unit value of the product. Physical support for the material being dried can be provided with a view to minimising distortion. On a limited scale, plant material can be dried in a bed of dry sand or silica gel. Microwave oven drying in a bed of pre-dried silica gel also offers physical support. The pressing of cut flowers between sheets of newsprint that are regularly changed has long been practised.

### Sulphuring

Sulphuring of fresh cut flowers can be achieved by exposure in a confined space to $SO_2$ gas or the fumes from burning sublimed sulphur powder (Joyce 1998). This treatment bleaches some pigments like chlorophyll and fixes others such as anthocyanins. In addition, sulphuring speeds drying and helps prevent mould growth. Sulphuring is particularly effective for red roses, where the red of the petals and green of the leaves become lighter. Sulphur is both toxic and corrosive and so care must be taken in selection of application protocols and treatment facilities.

### Bleaching

Through bleaching, plant pigments are degraded or altered leaving the tissue light and even white. Oxidative (chlorite) and/or reductive (sulfite) bleaching can be used for cut flowers (Dubois & Joyce 1988, 1992a; Joyce 1998). Brittleness and yellowing may be reduced by multistep bleach processing in which peroxide is followed by chlorite. The pH of bleach baths needs to be adjusted to optimise the process in terms of the rate of release of active

compounds. For example, hypochlorite bleaching is most efficient at pH 8.5 to 9.5. Interesting effects can be obtained by allowing bleach solution to be taken up in the transpiration stream via the stem (Plate 19.7). Bleaches are caustic and so care must be taken with them, including the use of protective clothing, respirators and ventilation.

### Dyeing

Preserved cut flowers are typically immersed in textile dyes, such as cationic aniline dyes, after initial processing by bleaching (Dubois & Joyce 1989b; Joyce 1998). Dyes are transparent, making prior bleaching particularly important for darker plant materials. As dye compounds generally do not bind specifically to plant material, the degree of staining is a function of the plant material, dye concentration and immersion time. Pure dyes can be mixed to obtain different colours. However, they must be compatible. For example, if anionic and cationic dyes are mixed, they will precipitate. Dyes are usually toxic and so appropriate material handling and safety literature must be obtained.

### Humectifying

Humectants are compounds, including polyols such as glycerol, sugars, salts and quaternary ammonium compounds that absorb water from the atmosphere. As a result of their hydration, they maintain treated plant tissue in a supple (plasticised) state (Paparozzi & McCallister 1988; Dubois & Joyce 1990, 1992b; Joyce 1998; Campbell *et al*. 2000). Glycerol (glycerine) is the most widely used humectant. Humectants are applied either by uptake or immersion. For immersion, the plant tissue can be pretreated with a strong alkali to strip the waxy cuticle and thereby facilitate penetration. Treatment concentration, time and temperature can affect the degree of humectification achieved. Under-treatment can leave the tissue brittle. Over-treatment can result in a greasy product predisposed to mould (Plate 19.7). Compounds that are less water-attractive (e.g. low molecular weight polyethylene glycol) may be blended with glycerine to moderate the degree of humectification. Humectification should be undertaken with the typical temperature and RH conditions of the intended marketplace in mind. Product packaged in moisture-proof sealed bags is less likely to sweat during transport to market.

Preserved cut flowers and foliage can be of lower unit value than their fresh counterparts. Nonetheless, the supply of uniform high quality preserved material is important. Process monitoring and optimisation for each individual item is also important in reaching and maintaining high standards. Transport costs for dried flowers can be relatively low if surface, rather than air, transport is used.

## CONCLUSION

This chapter presents a general overview of the post-harvest physiology and technology for cut flowers and foliage. For the most part, each individual species has particular characteristics that merit investigation if optimum post-harvest longevity is to be realised (Halevy & Mayak 1981; Reid 2004). The reader is therefore encouraged to research the substantial published literature on cut flowers. The following reference section contains relevant review articles that cite numerous original publications on the many different cut flower and foliage species.

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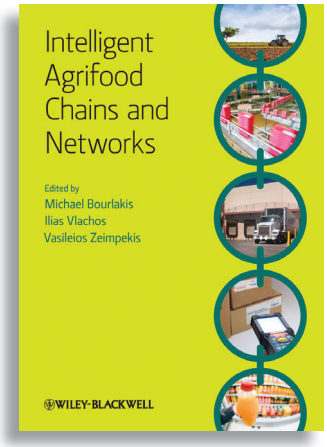


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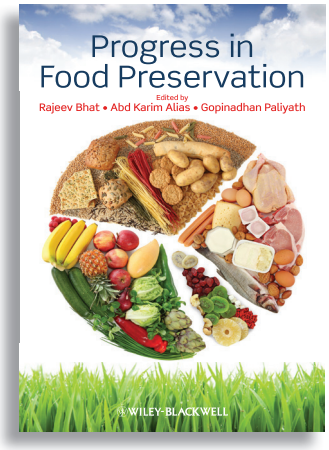


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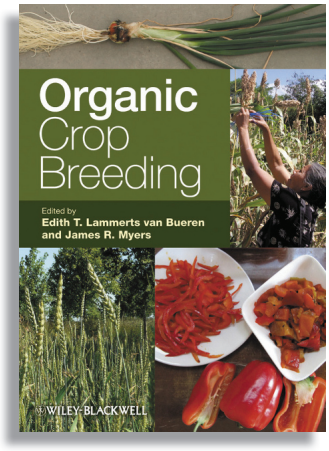


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