



Crop Post-Harvest: Science and Technology

PERISHABLES

EDITED BY

DEBBIE REES, GRAHAM FARRELL AND JOHN ORCHARD

 WILEY-BLACKWELL


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Crop Post-Harvest: Science and Technology

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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).

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.

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

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).

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 aminoethoxyvinylglycine (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

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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 Matthioli 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



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

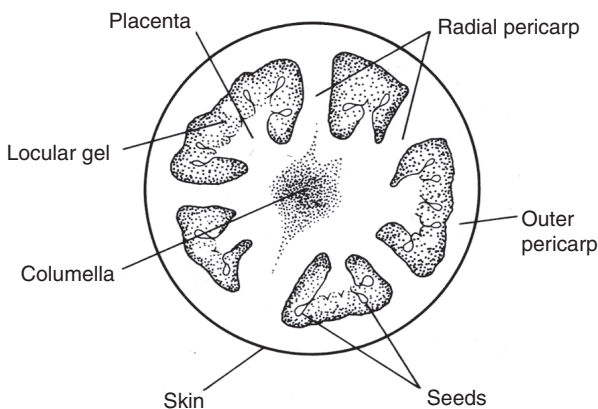


Figure 2.2 Anatomical structure of a tomato fruit. Photo credit: J.K. Brecht, University of Florida.

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 $0.05 \text{ nl g}^{-1} \text{ fruit h}^{-1}$) during later fruit growth but increases significantly during ripening. At the onset of the respiratory climacteric, production is around $2\text{--}10 \text{ nl g}^{-1} \text{ fruit h}^{-1}$ (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 $>0.05 \mu\text{l l}^{-1}$ (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 $0.1 \mu\text{l l}^{-1}$ ethylene was substantially delayed by exposure to 1-MCP in the concentration range $0.1\text{--}100 \mu\text{l l}^{-1}$. The delay was directly related to the concentration of 1-MCP and the exposure time. Exposure to $5 \mu\text{l l}^{-1}$ 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 $5\text{--}100 \mu\text{l l}^{-1}$ resulted in an increase in post-harvest life based on fruit appearance, with exposure to $20 \mu\text{l l}^{-1}$ 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 CO₂ accumulation. The latter is because CO₂ 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 $>30^{\circ}\text{C}$ 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 CO₂ 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 C₁₂–C₁₆ 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 (LDL) 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 40mg of lycopene was enough to substantially reduce LDL 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 LD₅₀ 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 LDL 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 CO₂ 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

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

fruit are held for longer than two weeks at 10°C, but in just 6–8 days if fruit are held at 5°C.

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 O₂ and high CO₂ to improve tomato eating quality have not been successful (Ratanachinakon *et al.* 1997). Atmospheres with ≤1% O₂ and/or >3–5% CO₂ 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 CO₂ 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 CO₂ and low O₂ concentrations inhibited yeast and mould growth without off-flavour development. The overall tomato slice quality was better at 5°C than at 0°C under high CO₂ (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*,