INFLUENCE OF CROP MANAGEMENT DECISIONS ON POSTHARVEST QUALITY OF GREENHOUSE TOMATOES

ELHADI M. YAHIA1*, XIUMING HAO AND ATHANASIOS P. PAPADOPOULOS2
1Faculty of Chemistry, Autonomous University of Queretaro, Queretaro, Qro., 76010, Mexico.
*e-mail:yahia@uaq.mx. 2Greenhouse and Processing Crops, Research Centre, Research Branch, Agriculture and Agri-Food Canada, Harrow, ON., Canada N0R 1G0

1. Introduction

Tomatoes are one of the leading produce items in the market in terms of value and volume consumed (Figs 1-13). The fruit is very sensitive to improper handling, storage and shipping conditions. Proper postharvest handling is critical for high product quality, a prerequisite to successful marketing. Postharvest fruit quality is strongly influenced by preharvest factors.

2. Nutritional and Health Values

Tomato and tomato-based foods are considered healthy foods because they are low in fat and calories, cholesterol-free, and a good source of fibre, vitamins A and C, β-carotene, lycopene, and potassium. The interest in the nutritional and health benefits of tomato fruit and their products has increased greatly. Vitamin C content in tomato (23 mg/100g) is not as high as in several other fruits, but its contribution is very important due to the common use of tomato in the diet of many cultures. A 100-g tomato can supply about 20% and 40% of the adult U.S. 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, but 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. 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. Although lycopene has no provitamin A activity, as is the case with carotenoids, 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. The serum level of lycopene and the dietary intake of tomatoes have been inversely correlated with the incidence of cancer. Protection for all sites of digestive-tract cancers (oral cavity and pharynx, esophagus, stomach, colon, rectum) was associated with an increased intake in tomato-based foods, and an increased supply of lycopene. 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. 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. Older subjects who regularly ate tomatoes were found to be less likely to develop all forms of cancer. A study at the Harvard School of Public Health done on 48,000 men for 4 years reported that men who ate 10 or more servings of tomato products (such as tomatoes, tomato sauce, pizza sauce) per week had up to 34% less chance to develop prostate cancer. Lycopene had a protective effect on the oxidative stress-mediated damage of the human skin after irradiation with UV light. 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; the daily consumption of tomato products providing at least 40 mg of lycopene was enough to substantially reduce LPL oxidation. Lycopene is recognized as the most efficient singlet oxygen quencher among biological carotenoids. Lycopene has also been reported to increase gap-junctional communication between cells and to induce the synthesis of connexin-43. Fresh tomato fruit contains about 0.72 to 20 mg of lycopene per 100 g of fresh weight, which accounts for about 20% of the total carotenoids in plasma. 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 at the end of the maturation period, and almost exclusively in the external part of the fruit. Other tomato components that can contribute to health include flavonoids, folic acid, and vitamin E.
3. 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, no green shoulder, (2) uniform shape depending on type: round, globe, flattened globe, Roma, (3) freedom from defects such as: stem-end scars, growth cracks, sunscald, catfacing, insect injuries, bruises, mechanical injury.

Proper quality tomato should include 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. Jelly formation in the locules of the tomatoes is important for good flavour.

Although appearance quality is important, increasing attention is given to 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 postharvest handling.

3.1. Colour

Colour is one of the most important quality components of horticultural crops. Tomato fruit is available in different colours including red, pink, yellow and orange. External colour in tomato is the result of both flesh and skin colours. A pink tomato is due to colourless skin and red flesh, while a red tomato is due to yellow skin and red flesh. Chlorophyll in green fruit is replaced by oxygenated carotenes and xanthophylls during ripening. The most abundant pigments in ripe tomatoes are lycopene (red) and phytoene (colourless). Lycopene is important for human health due to its antioxidant activity. Therefore, its degradation is important from the standpoint of 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. Isomerization converts all-trans isomers to cis-isomers due to additional energy input, and results in an unstable, energy-rich state. The amount of lycopene in fresh tomato fruit depends on variety, maturity stage, and environmental conditions under which the fruit matured. Fresh tomato fruit usually contains about 3-5 mg lycopene/100 g, while deep red varieties contain more than 15 mg/100g, and yellow varieties contain only about 0.5 mg/100g. Higher concentrations of lycopene and other carotenoids were found in the stem than in the blossom-end of the fruit. Lycopene concentration in tomatoes was higher in summer than in the winter. Tomatoes picked green and ripened in storage had less lycopene than vine-ripened fruit. High temperatures (38ºC) inhibited lycopene production, while low temperatures inhibited both lycopene production and fruit ripening. Lycopene formation is promoted by ethylene and inhibited by ethanol. Lycopene content in tomato can also be enhanced by fertilisers and proper harvest time and varietal selection, but a reduction in the activity of polygalacturonase did not affect its synthesis. Several subjective scales and colour charts have been developed to classify ripeness according to fruit colour, including the six classes of tomato ripeness stages used almost all over the world (Table 1, Figs 3, 8). Objective measures of tomato colour are also available, including light reflectance and light transmittance techniques and pigments 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.

Table 1. Ripeness classes of tomatoes.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immature-green</td>
<td>The surface is completely green, no jelly-like material in any of the locules, and seeds are cut upon slicing of fruit with a sharp knife.</td>
</tr>
<tr>
<td>Mature-green</td>
<td>Seeds are fully developed and 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 harvesting maturity.</td>
</tr>
<tr>
<td>Breaker</td>
<td>Tomatoes at this stage are characterised by a break in the colour from green to tannish yellow with pink or red skin covering not more than 10% of the surface.</td>
</tr>
<tr>
<td>Turning</td>
<td>More than 10% and up to ≤ 30% of the surface, in the green aggregate, shows a change in colour from green to tannish, pink, red, or a combination of these colours.</td>
</tr>
<tr>
<td>Pink</td>
<td>More than 30% and up to ≤ 60% of the surface, in the green aggregate, shows pinkish red or red colour.</td>
</tr>
<tr>
<td>Light-red</td>
<td>More than 60% and up to ≤ 90% of the surface, in the green aggregate, shows pinkish red or red colours.</td>
</tr>
<tr>
<td>Red</td>
<td>More than 90% of the surface, in the green aggregate, shows red colour.</td>
</tr>
</tbody>
</table>

* all percentages refer to both colour distribution and intensity.
3.2. Size and shape

Fruit size is also important, but preference for different sizes varies among cultivars, among consumers and the intended use of the fruit. Fruit shape varies among 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. Shape defects are commonly due to poor pollination and irregular development of some locules. These defected fruits are commonly discarded during selection. Minor defects that would not detract from eating quality are commonly considered as acceptable. However, serious defects can detract quality, cause shrivelling and enhance susceptibility to decay. Some of the defects that are known to occur before harvest include sunscald, insect damage, puffiness, catfacing, goldfleck/pox syndrome, radial and concentric growth cracks and irregular ripening. Several defects can occur in postharvest due to mishandling such as scuffing, cuts and punctures, vibration and compression injuries, abrasions and decay development. Physical damage can also increase ethylene production and therefore can accelerate fruit ripening and decay development.

3.3. Dry matter content

Dry matter represents about 5 to 7.5% of tomato fruit, of which about 50% are reducing sugars while protein, pectins, celluloses, hemicelluloses, organic acids, pigments, vitamins, lipids and minerals represent the remaining half. Fruit with high dry matter content usually also have higher content of sugars and acids, higher soluble solids, and thus have better taste and flavour.

3.4. Firmness

Tomato firmness is closely related to quality and ripeness and it is important in determining shipping ability and postharvest-life. Tomato fruit that can maintain good firmness beyond the table-ripe stage will permit the picking of the fruit at more advanced stage, and therefore can develop better flavour. Tomato is preferred to be firm, without tough skin and not losing too much juice upon slicing. 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 degradation of pectins and in fruit softening. Polygalacturonase (PG) is one of the important enzymes thought to be involved in cell wall degradation and in fruit softening. However, despite gene repression and inhibition of accumulation of PG mRNA and its enzyme activity, fruit softening still occurs. This suggests that PG is not the only factor involved in fruit softening. Pectinases are responsible for most of the demethylation of cell wall pectins, and are thought to facilitate cell wall hydrolysis by PG. β-Galactosidases are other enzymes that can contribute to fruit softening. Several factors can affect tomato firmness including cultivar, ethylene, water content and turgor, cell wall composition and integrity, 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. A non-destructive 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.

3.5. 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. High sugar content and relatively high acid content are required for best flavour; high acids and low sugar contents will produce a tart tomato, and high sugars and low acids will produce a bland taste; a tasteless, insipid flavour is the result of low sugars and low acids. 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. The sugar content, mainly in the locule walls, reaches a peak when the fruit is fully ripe, malic acid decreases quickly as the fruit turns red, while the citric acid content is rather stable throughout the ripening period. Fruity flavour, which best
Figure 1. Cluster cherry tomatoes, Rotterdam, July 2003.

Figure 2. Greenhouse hydroponic tomato plant.

Figure 3. Different maturity indices.

Figure 4. Tomato greenhouse.

Figure 5. Greenhouse hydroponic tomatoes.
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Figure 6. Tomato, Rotterdam, July 2003.

Figure 7. Greenhouse tomato harvesting.

Figure 8. Tomatoes at different maturity stages.

Figure 9. Tomatoes.

Figure 10. Tomato greenhouse station.
Figure 11. Tomato genetic diversity.

Figure 12. Tomato from Agros, Queretaro, 2003.

Figure 13. Tomato packhouse, Agros, Queretaro, 2003.
describes tomato flavour, was linked to increased levels of reducing sugars and decreased glutamic acid content. It has been suggested that changes in acid and sugar levels in ripening tomato is independent of ethylene and CO₂ production.

Aromatic (volatile) compounds are numerous in tomato fruit. 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. Hayase et al. 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 the oxidative carotenoid breakdown, deamination and decarboxilation of amino acids, and lipid oxidation. Aroma volatiles in tomato are affected by several factors including cultivar, growing conditions, management practices and postharvest handling conditions.

A relation exists between tomato fruit colour and its volatile composition, especially those formed by the oxidation of carotenoids. Several other correlations were made between taste descriptors and other fruit components. Off-flavours are formed in tomatoes picked green and ripened off the plant, and were related with higher concentration of some volatiles such as 2-methyl-1-butanal. Bruising and physical damage was found to cause more off-flavour and less “tomato-like” flavour.

### 3.6. Safety factors

Tomatine, a steroidal glycoalkaloid, is accumulated in developing tomato fruit in all tomato genotypes, and causes bitterness when fruit is harvested immature. However, during ripening its concentration declines to about 0.04% (FW), which is considered to be below the LD₅₀ value of 0.5 g/kg body weight. Dehydrotomatine is another glycoalkaloid found in tomato at a concentration of 0.05 to 0.42 mg/kg (FW) in red fruit, and 1.7 to 45 mg/kg in green fruit. These glycoalkaloids are considered as defensive mechanisms to protect the plant against insects and pathogens. It has been suggested that low concentration of some of these alkaloids might have health benefits. For example, Friedman et al. reported that feeding commercial tomatine to hamsters induced significant reduction in plasma low-density lipoprotein cholesterol, and this reduction was higher using high-tomatine green tomato than low-tomatine red tomato diets.

### 4. Preharvest Factors Affecting Quality

Many preharvest factors can influence the composition and quality of tomatoes. Some of these factors include cultivar, environmental conditions, plant water and nutrients, and crop management.

#### 4.1. Environment and climate control

##### 4.1.1. Light

Light is the driving force for plant photosynthesis. As the light intensity increased, the leaf photosynthesis of tomato increases until it reaches the light-saturation point. Stronger light irradiance (both intensity and duration) increases the transportation of photoassimilates to fruit and thus can have large influence on tomato fruit growth and development and fruit quality. Indeed, increasing solar radiation has been shown to increase fruit dry matter and soluble sugars content, ascorbic acid, and pigments (lycopene). The soluble sugar concentration of tomato fruit follows the pattern of solar radiation. Fruit grown under strong light irradiance usually has better flavour because of high content of soluble sugars. Low light irradiance reduces pigment synthesis, resulting in uneven fruit colouring and low fruit soluble sugar content which results in a ‘watery’ taste. Fruit grown under strong light also has a well-developed cuticle and thus longer shelf-life.

On the other hand, too high light irradiance, especially direct light on fruit, may reduce fruit quality. Strong solar radiation in summer causes various fruit disorders such as sunscald, uneven ripening or colour, soft fruit, fruit cracking, russetting and blossom-end rot (BER). Most of the negative effects from strong solar radiation may be due to its side effects on fruit temperature. High temperature (˃30°C) inhibits normal fruit ripening and the synthesis of lycopene. When fruit is exposed to strong solar radiation, it can be expected that the exposed area would have higher temperature than the area not exposed to direct solar radiation. This uneven fruit temperature could induce uneven ripening and
colouration of the fruit. High temperature also tends to favour pulp expansion towards the interior of the fruit and weakening of the cuticle. We have observed large increases in fruit cracking and russetting in greenhouse tomato production toward summer (Hao and Papadopoulos, 2002, unpublished data). Similarly, Peet and Willits also observed a linear increase of fruit cracking at the upper clusters of tomato fruit with high solar irradiance and fruit temperature.

The light available to plants is mainly determined by the level of natural solar radiation. However, it can also be affected by the greenhouse cover material, supplemental lighting, shading/white-washing, plant density and canopy architecture management. In northern Europe, where light is a limiting factor, 1% light reduction has induced approximately 1% fruit yield loss, and thus the glass is the dominant greenhouse cover in greenhouse tomato production because of its higher light transmission. In Canada and United States, shading or whitewashing are usually applied on greenhouses in summer to reduce the solar radiation and air temperature for minimising fruit quality problems. Low plant density is used to make more light available for each plant in the winter, and laterals are allowed to develop in the summer to increase plant density and provide shading to fruit when the solar radiation is strong. Where it is economically feasible, such as in some northern countries, supplement lighting at 200 W m\(^{-2}\) installed capacity and with up to 18 hours each day can also be used to improve tomato fruit quality and yield.

4.1.2. Temperature

Temperature affects plant growth balance, flower development and pollination, fruit growth and development, thus has substantial influence on fruit quality. Low temperature (<13ºC) reduces pollen viability while high temperature (>30ºC) favours an excessive growth of the style, both of which cause poor fertilisation and uneven development of locules, and thus result in misshapen fruits such as ‘catfacing’ and roughness. High temperature increases photoassimilate distribution to the fruit at the expense of vegetative growth; increasing air temperature increases fruit growth rate by approximately 5 µm h\(^{-1}\) C\(^{-1}\). However, the final size of tomato grown under elevated temperature decreases because high temperature reduces the duration of fruit development (from fruit set to harvest); i.e. the reduction in duration is greater than the increase in fruit growth rate. Papadopoulos and Hao found that the reduction in tomato fruit size to average air temperature was mainly due to day air temperature, not night temperature. Therefore, they proposed a temperature management strategy, which uses high night temperature to achieve the desired 24-h temperature and to avoid the negative effect of high temperature on tomato fruit size. This strategy is more feasible in greenhouses equipped with thermal screens. Too high air temperature increases the number of hollow fruit in the winter and the miscoloured and soft fruit in the summer. As mentioned in the previous section (4.1.1), high air temperature should be avoided by shading, whitewashing of the greenhouse or other temperature reduction measures such as roof-sprinkler cooling and evaporative cooling pads, depending on the greenhouse location and available equipment.

Increasing air temperature in the range of 17 to 23ºC improves organoleptic quality (taste) of greenhouse tomato because it increases fruit dry matter content and reduces soft and mealy fruit. However, this fruit also has a less resistant cuticle, which makes it more vulnerable to physical injury. The combination of high temperature and high electrical conductivity (EC) of nutrient solution in the winter and early spring greatly improves tomato flavour without weakening fruit cuticle, because high EC can promote a resistant cuticle as discussed later (4.2.2).

Sudden temperature changes or high day/night temperature variation will favour the cracking of tomato fruit. Low night temperature causes a negative pressure in fruit, whereas high day temperature increases both gas and hydrostatic pressure of fruit pulp on the epidermis, resulting in a wakening or cracking of the cuticle. Changes from night to day temperature setting need to be made before sunrise and ramping the temperature at no more than 1ºC per hour to avoid water vapour condensation on fruit, which increases incidence of fruit russetting.

4.1.3. Humidity (vapour pressure deficient, VPD)

Under high humidity, fruit is generally smaller, softer and has a shorter shelf-life. High humidity (VPD, 0.1-0.3 kPa) affects fruit colour (marbling) and increases gold specks incidence. Also, high humidity, in combination with low light, such as the environment experienced in winter and early spring, leads to fruit cluster kinking, which then affects the photoassimilate transport to fruit and causes rough and small fruit. At high humidity (0.1 to 0.2 kPa), yield can also be reduced due to the small leaf size resulting from calcium deficiency. High humidity reduces leaf transpiration and calcium transport to foliage. A yield reduction between 18-21% at 0.1 kPa VPD has been observed in comparison to 0.5 kPa VPD. High humidity also causes an increase in root pressure, which favours fruit cracking. Under low humidity, the fruit produced
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is firmer, juicer, less mealy, more tasteful (high soluble sugars) and has better colour and longer shelf-life due to a tougher and well-developed epidermis and cuticle 24,111,118. However, a low humidity increases the incidence of BER 55. Low humidity reduces root pressure and increases the competition between foliage and fruit for calcium, and thus induces BER 10.

In modern greenhouses, the humidity is reduced by ventilation, in combination with heating, if necessary. Reducing and maintaining the humidity to below 0.3 kPa, especially in cold winters, may not be economically feasible 24,81. However, pre-night de-humidification should be practiced to avoid condensation on fruit. Leaves close to the ripening clusters can be removed to improve air circulation and reduce humidity close to fruit. Cluster brassing/supports should be used in the winter or early spring to prevent cluster kinking.

4.1.4. CO2 enrichment

High concentration of CO2 increases fruit number, yield and average fruit size 157. As the CO2 concentration increases from 340 ppm (ambient) to 1000 ppm, photosynthesis rate increases by 50-70%, and thus high CO2 increases the photoassimilates available to fruit. CO2 enrichment increases fruit soluble sugars, soluble solids and dry matter contents 29. The fruit grown with high concentration of CO2 also ripens slowly, has low respiration and ethylene production rates, and thus, longer shelf-life. In summer CO2 application, high CO2 in combination with high humidity, may limit the calcium transport to the apex and cause short leaf syndrome, which reduces leaf shading to fruit, and may have negative effects on fruit quality 159. High CO2 causes partially closure of stomata, which reduces transpiration and calcium transport to leaves 40,181. In general, CO2 up to 1000 ppm may be applied during winter and early spring, when the greenhouse is closed; whereas, a concentration of 300-400 ppm of CO2 should be maintained during summer tomato production.

4.2. Root environment and fertigation

Greenhouse tomato may be grown in soil, soilless media such as rockwool slabs, peat or sawdust bags and pure hydroponic systems such as the Nutrient Film Technique (NFT). In soil, nitrogen and potassium fertilizers are usually applied to improve fruit yield and quality. In soilless and pure hydroponic production, all the essential nutrients need be supplied continuously. Fertilizers are supplied to plants with irrigation water in a form of a nutrient solution, a technique called fertigation. The nutrient solution is usually supplied to the plants through a drip irrigation system or as a shallow stream. If managed properly, the growth media generally do not have any significant effects on fruit quality 63. However, the volume and frequency of fertigation, electrical conductivity (EC), and concentration of nutrients and their ratios have a profound influence on postharvest fruit quality. The pH of the nutrient solution does not directly affect fruit quality, but it can have significant effects through its influence on the availability of nutrients. A pH 5.5-6.0 is usually recommended for the greenhouse tomato 192.

4.2.1. Irrigation

Restriction in water supply (deficit irrigation) can improve tomato taste (organoleptic quality). Fruit water content decreases while fruit soluble solids, sucrose, hexoses, citric acid and potassium contents increase under water deficit conditions 4,154,179. The increase in the content of soluble solids, sugars and acids is mainly due to reduced water content (increased content of dry matter), not because of high dry matter production 4,154. Fruit size is reduced under deficit irrigation 4. Under severe water deficiency, plant growth and fruit yield may be substantially reduced 4,154,196. Fruit produced under water limiting condition also tends to have more intense colour, higher rate of CO2 production and a shorter shelf-life 38,170. Water deficit stress increases ethylene production 13,28, which stimulates synthesis of carotenoids and lycopene, and the ripening process 112,170.

In contrast to deficit irrigation, a high irrigation supply increases fruit yield and reduces fruit quality due to high fruit water content 1,184. Excessive water application causes poor root aeration and health 28. Nutrient uptake is reduced when the oxygen level in the nutrient solution is below 3 ppm 101. Poor root health and nutrient uptake can induce various physiological disorders and negatively affect fruit quality. Excessive water supply also increases root pressure and fruit cracking 2,172. Irrigation should be managed based on climatic conditions (solar radiation, temperature, humidity), plant growth stage and the characteristics of growth media 167. Irrigation may be stopped 1-2 hours before sunset to avoid high root pressure and to prevent fruit cracking and russetting 163.
4.2.2. Electrical conductivity (EC)

High EC, if not excessively high (i.e. < 9.0 mS cm\(^{-1}\)), generally improves tomato organoleptic quality (taste) by increasing dry matter content (\%, dry weight/fresh weight), sugar and organic acid contents \(^{3,134,201}\), prolongs shelf-life and reduces fruit cracking and russetting \(^{80,201}\). Furthermore, increasing the EC of the nutrient solution results in higher concentration of vitamin C and total carotene, and firmer fresh tomato fruit \(^{175}\). However, the improvement in tomato fruit quality by high EC is usually accompanied by a reduction in yield and fruit size, although the reduction may be smaller than the common experimental error if the EC level is just above the salinity yield reduction threshold \(^{8,90}\). A recalculation of fruit dry matter based on mg per fruit reveals equal total fruit dry matter per fruit although the fruit grown under a moderately high EC is smaller and has a higher dry matter content (\%, dry weight/fresh weight) \(^{8}\). Thus, it seems reasonable to conclude that the effect of moderate EC (just above the yield reduction threshold) is a reduction in fruit water accumulation due to a low water potential of the nutrient solution with a high EC \(^{120}\). The yield reduction threshold ranges from 2.3 to 5.0 mS cm\(^{-1}\), depending on cultivar and growing environment such as humidity and light intensity \(^{64}\). An EC of 3 to 8 mS cm\(^{-1}\) reduced fruit yield because of a reduction in fruit size, whereas an excessively high EC (>10-12 mS cm\(^{-1}\)) not only reduced fruit size, but also reduced fruit number, whole fruit sugars and acids \(^{5,80}\) and fruit shelf-life \(^{155}\). The number of fruit affected by BER generally increases with high EC \(^{9,53,100,102}\). In commercial greenhouse tomato production, a moderate EC (salinity)(2 to 5.0 mS cm\(^{-1}\)) is usually applied because the improvement of fruit quality is much more than compensated for the small yield loss under such EC condition \(^{64,192}\).

It is well known that climatic conditions such as air humidity \(^{135,204}\) and light intensity \(^{96}\) have a strong interaction with EC levels (salinity). Thus, the EC of nutrient solution needs to be managed according to climate. As a general rule, the EC should be lowered at high temperature, strong light intensity and very low humidity as the growing season progressed \(^{165}\). Variable EC has been tried to maximise the positive effect of high EC on fruit quality while minimising the negative effect on fruit yield and size. A day/night EC of 1/9 mS cm\(^{-1}\) has increased the yield by 20% and reduced BER incidence in comparison to constant EC treatment (day/night EC 5/5 mS cm\(^{-1}\)) with the same 24-h average EC (5 mS cm\(^{-1}\), \(^{216}\); however, the fruit dry matter content (\%) was slightly reduced by the variable EC treatment (day/night EC 1/9 mS cm\(^{-1}\)). Nederhoff \(^{158}\) found a day/night EC 2/8 mS cm\(^{-1}\) can be used under the greenhouse conditions of New Zealand to improve tomato fruit quality without significant yield loss. In a recent study on summer greenhouse tomato grown on rockwool \(^{90}\), varying the feeding EC from 1 to 7 mS cm\(^{-1}\) (24-h average 3.82 mS cm\(^{-1}\)) according to solar radiation (high EC in early morning, late afternoon and night, and low EC in the late morning and around noon) achieved all the fruit quality improvement of a constant high EC (3.82 mS cm\(^{-1}\)) treatment (increase in fruit dry matter content, soluble solids, fruit firmness and decrease in fruit cracking and russetting) while avoiding the negative effects (reduction in fruit yield and size) of the high EC treatment in a summer tomato crop. The variable EC treatment (24-h average 3.82 mS cm\(^{-1}\)) had higher leaf photosynthetic rates and a higher total biomass production \(^{90}\).

4.2.3. Nutrients and their ratios

Both the nutrient concentrations and their ratios have significant influence on tomato growth, fruit yield and quality. In greenhouse nutrient management, distinction should be made for optimum feed concentration, root zone concentration and nutrient uptake concentration (uptake of nutrients/uptake of water). The optimum concentration in root zone for growth and development may not be the same as the uptake concentration. The uptake of bivalent nutrient ions such as Ca\(^{2+}\), Mg\(^{2+}\), and SO\(_4\)^{2-} is more difficult than that of monovalent ions, and thus they require a root zone concentration higher than their uptake concentration to achieve desired uptake \(^{54,219,222}\). The objective of nutrient management is to achieve and maintain the optimum nutrient concentrations in the root zone. In open hydroponic systems, the plants can easily be fed with a nutrient solution of optimum concentration; the quantities of nutrients corresponding to the excesses between feed solution and nutrient uptake can leach in the drain solution. In the closed systems, the plants can be fed with the optimum concentration of nutrient solution for the root zone in the beginning, but later, the concentration of the feed solution needs always be equal to the nutrient uptake concentration to maintain the optimum nutrient concentration and proper nutrient balance in the root zone. Various standard nutrient solutions have been proposed \(^{57,203}\) and nutrient uptake concentrations (ratio between the quantity of nutrients and water taken by the plants) \(^{222}\) have been calculated.
4.2.3.1. **Cations and their ratios**

Inside the cell, calcium linked to pectic acids of the middle lamella maintains cell wall and tissue rigidity \(^{145}\). High calcium has been shown to reduce BER incidence, fruit cracking and russetting \(^{89,100}\). However, the high levels of calcium affect negatively tomato fruit organoleptic quality and shelf-life \(^{54}\). Calcium salts have been used extensively in the tomato processing industry to maintain tissue integrity \(^{17}\). However, high calcium in the nutrient solution has reduced fruit firmness and thus high Ca may increase tissue elasticity rather than rigidity \(^{89}\). High calcium may induce gold specks, calcium oxalate crystals in fruit wall \(^{56}\). Calcium is taken up passively, with water \(^{145}\). Therefore, any environmental factors, which affect water uptake and transportation, can have an influence on calcium uptake and distribution in tomato plants. Supply of Ca, for a winter crop starting in an environment of low light and high humidity, needs to be higher because Ca accumulation is necessary for achieving desired uptake; late in the growth season, the supply can be reduced because of previous accumulation and an environment favourable to its uptake (strong light, higher temperature and lower humidity).

High potassium has a positive effect on improving fruit shape, reducing fruit ripening disorders such as uneven or blotchy ripening and green shoulders, and increasing fruit acid concentration and lycopene \(^{7,58,80,144,213}\). The increase in acid content under high potassium has been linked to improved organoleptic quality (taste). Potassium plays an important role in the maintenance of electrical neutrality of the organic acids in the fruit \(^{49,154}\).

The antagonism between calcium and potassium uptake is well known \(^{100,101}\). A high K:Ca ratio improves tomato fruit firmness and acidity and reduces the number of fruit affected by gold specks \(^{160,218}\) while it reduces sugar content \(^{116}\) and increases BER incidence \(^{214}\). To maintain the balance between calcium and potassium, the supply of potassium should not be excessive. A potassium concentration of 400 ppm is sufficient to achieve high fruit quality \(^{100}\). A K:Ca molar ratio of 3.7 has been recommended by Voogt \(^{219}\) while a molar ratio of 2:1, 3:0:1 and 4:1 has been recommended by Nukaya et al. \(^{160}\) for cultivars susceptible, moderately susceptible and resistant to BER, respectively. The uptake of potassium is closely linked to fruit load. At 8 weeks after planting, the uptake of potassium increased considerably \(^{221}\), when the plants had the highest fruit load, and thus the supply of potassium should also be increased accordingly. There has been very limited information on the direct effect of magnesium (Mg) on fruit quality. Recently, Hao and Papadopoulos (2002, unpublished data) found that high Mg increased fruit firmness. The incidence of BER linearly increased with Mg concentration at low concentration of calcium (150 ppm) but not at high concentration of calcium (300 ppm). An increase in the K and Mg activity ratios over Ca or a reduction in Ca activity in the root environment favours BER occurrence \(^{230}\).

4.2.3.2. **Anions**

High nitrogen favours leaf area development and vegetative growth. A very high nitrogen concentration reduces photo-assimilate distribution to fruit, negatively influences fruit colour, delays fruit ripening and reduces fruit soluble solids and vitamin C contents \(^{136}\). High NH\(_4\)-N increases fruit sugar content but decreases fruit calcium concentration \(^{99}\), thus resulting in high BER incidence \(^{176}\). Generally, nitrogen supply in the form of NH\(_4\)-N needs to be lower than 10% of total nitrogen to minimise the incidence of BER. In order to obtain high quality tomato fruit, the N:K ratio should be 1:1.2 (weight basis) for young plants (until the first inflorescence) and 1:2.0-2.5 when the 9th cluster is in flower \(^{6,101}\).

Phosphorus (P) is essential to the development of flowers and fruit \(^{151}\). High P in the nutrient solution stimulates the uptake and distribution of calcium to fruit \(^{55,202,223}\), and thus reduces the incidence of BER in favour of the occurrence of gold specks \(^{56}\). Sulphate accumulation generally occurs in closed systems. High sulphate concentration in the nutrient solution generally does not affect fruit quality directly, unless it causes high EC and nutrient imbalance \(^{137}\).

4.2.3.3. **Other nutrients**

Sodium chloride has been added to the nutrient solutions to increase the EC for improving tomato fruit quality. Chloride raises the cell osmotic pressure and, as a result of the hydrophilic nature of the ion, increases the hydration of plant tissue \(^{110}\). Chloride ions can replace nitrate ions in their colloid-chemical functions and thus may be used to prevent excessive nitrogen in plant tissue \(^{30}\). Substituting NO\(_3\)-N with KCl, NaCl or CaCl\(_2\), does not affect fruit yield if the minimal concentration of nitrogen is maintained at 120 mg L\(^{-1}\) and the K:N ratio is kept between 2 and 4 \(^{62,101}\). High Cl concentration (8-13 mM in comparison to 3 mM) stimulates Ca uptake and reduces BER incidence but increases the number of fruit affected by gold specks \(^{54,56,161,162}\). The Cl threshold in the root zone is around 7.5 mM \(^{220}\).
Boron has a stabilising effect on calcium complexes of the middle lamella and is essential to the maintenance of cell wall structure. Foliar boron spraying can reduce fruit russeting 65. Some studies have shown that addition of biocarbonate to nutrient solution improved tomato fruit quality by increasing sugar and organic acid content 33. The beneficial effect of bicarbonate on fruit quality is more profound when used in combination with high EC 70.

4.3. Crop management

4.3.1. Plant population density

Plant density affects the light intercepted by each plant. Generally, a moderate increase in plant density may increase fruit yield per unit area but also reduce fruit size 168. Increasing in plant density during high light period by allowing the development of lateral stems may optimize the light usage, fruit yield and size 46. The extra shoots may also provide shading for fruit avoiding fruit sunscald or injury and other associated ripening disorders.

4.3.2. Deleafing and fruit pruning

The distribution of assimilates between vegetative and generative parts is mainly determined by fruit load 98,109. Generally, if fruit pruning is moderate, the fruit size increases as the number of fruit per plant is reduced. Removing the fruit from the distal end of the first three clusters in winter increases the average fruit weight of the remaining fruit and the yield of top clusters 46. In summer tomato production, the limit for production was the insufficient sink for assimilates and fruit pruning increased fruit affected by russeting (Papadopoulos et al., 2002, unpublished data). Proper deleafing can improve the air circulation around fruit and fruit quality in terms of taste and shelf-life, but severe deleafing reduces assimilate supply to fruit, which leads to ‘boxy’ fruit in winter and to fruit sunscald in the summer (due to exposure to strong solar radiation).

4.4. Physiological disorders

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

4.4.1. Blossom-end rot

Blossom-end rot is a physiological disorder that causes extensive losses in production 63. This disorder develops as a visible external depression of black necrotic tissue affecting the distal end of the placenta and the adjacent locular contents as well as the pericarp 230. In internal BER, also called ‘black seeds’, black necrotic tissue presents in the adjacent parenchyma tissue around young seeds and the distal part of the placenta 9. BER is believed to be caused by fruit Ca-deficiency or stress 191. Fruit susceptibility is related to lack of co-ordination between accelerated cell enlargement and insufficient supply of calcium. The development is also positively correlated with the leaf K:Ca ratio, but is weakly correlated to the K:Ca ratio in mature fruit 27. 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 63, including: 1) 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) use of low EC, 5) optimizing irrigation frequency, 6) avoiding high root temperature (>26°C), avoiding excessive canopy transpiration by deleafing, shading, roof sprinkling and greenhouse fogging, 8) maintaining proper fruit: leaf ratios that can provide adequate fruit growth rate, 9) spraying of young expanding fruit with 0.5-0.65% calcium chloride solution.

4.4.2. Blotchy ripening

Blotchy or irregular ripening is characterized by green, green-yellow areas on apparently normal red fruit. It is usually confined to the outer walls, but in extreme cases radial walls can also be affected. Blotchy areas of fruit walls contain less
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Inorganic acids, dry matter, total solids, starch, sugars and nitrogenous compounds. Low potassium \(^{7}\) and high fruit temperature (>30ºC temperature affects pigmentation, see 4.1.2) are believed to be related to blotchy ripening.

4.4.3. Cracking and russeting

Tomato cracking can cause up to 35% losses in North American greenhouses \(^{63}\). Greenhouse tomatoes are more vulnerable to fruit cracking compared to field-grown tomatoes because greenhouse tomato is usually harvested at the pink stage or later, and most greenhouse tomato cultivars lack cracking resistance. Fruit cracking not only reduces fruit appeal and marketing, but can also increase fruit susceptibility to decay and shorten shelf-life. Cracking and splitting of tomatoes are usually initiated before harvest, generally about 7 weeks after fruit set \(^{23}\). Several types of cracking are known to affect tomatoes, including cuticle cracking (russetting), fruit bursting, radial cracking and concentric cracking. Cuticle cracking, fine cracks on the skin, which impairs quality and reduces shelf-life, is the most common type in greenhouse tomatoes \(^{63}\). Cuticle cracks are usually initiated as small fissures in the outer epidermis and occur at right angles to the direction of expansion of the epidermis cells. In later stages the complete epidermis and part of the underlying collenchyma tissue break down. Russetting was suggested to occur because the expansion of the epidermis could not keep pace with the fruit enlargement. Higher number of fruit per plant decreases 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 russetting \(^{63}\).

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 \(^{63}\); there are differences in cutinability susceptibility, but the problem can be reduced by adequate calcium nutrition and avoidance of drought stress \(^{89}\). 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 the imbalance between the supply and loss of water, and therefore cultivars with highly developed system of vascular tissue are more resistant to cracking \(^{48}\). Gibberellic acid application was reported to reduce tomato fruit cracking \(^{172}\). This effect is probably due to alteration of the calcium dynamics at the level of the pericarp \(^{41}\), and an increased elasticity of the cuticle \(^{131}\).

4.4.4. Greenback/green shoulder

This is a different disorder from blotchy ripening. The symptom is characterised by a firm green area around the calyx-end, while the rest of the fruit is ripe and red in colour. The green area may turn yellow and thus 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 \(^{82}\).

4.4.5. Gold flecks and gold speckles

These are tiny yellowish spots of less than 0.1 mm across, associated with the formation of calcium oxalate crystals, and usually affect the shoulders and calyx-end of the fruit \(^{56}\). This disorder affects the external appearance of the fruit \(^{79}\), and reduces its shelf-life \(^{114}\). Symptoms are commonly affected by cultivar and the nutrition and greenhouse environment which are favourable to the calcium transport to fruit.

4.4.6. Hollowness, puffiness, boxiness

This is the lack of part of the pulp surrounding the seeds, and the existence of open cavities between the outer walls and the locular contents in one or more locules \(^{82}\). The affected fruit tends to be light in weight, becomes soft and can be detected by flotation in water. The symptoms are commonly developed in early spring greenhouse crops, mostly due to low light intensity and inappropriate mineral nutrition which reduce the carbohydrate supply to fruit.
4.4.7. Solar injury (sunscald 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. If the fruit temperature exceeds 30°C for a long period, the affected part of the fruit becomes yellowish and remains so during ripening. When the temperature of an exposed fruit portion exceeds 40°C, it becomes white and sunken (sunscald, sunburn, or sunscorch). Tomatoes at the mature-green stage are especially susceptible. Affected areas may later develop Alternaria and Cladosporium rots.

4.4.8. Watery fruit

This disorder results from a massive influx of water into the fruit, due to an excessive root pressure, which can increase the volume of the cells and may even damage them. 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 reduction of root pressure by maintaining a plant leaf area index at a reasonable level during summertime.

5. Harvesting Factors Affecting Fruit Quality

5.1 Fruit maturity at harvest

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

A 6-class classification of tomato fruit maturity (Table 1) has been widely adopted. For greenhouse tomato, the earliest stage for harvest is the mature-green stage. Tomatoes harvested at the mature-green stage will ripen adequately. Immature green fruit will ripen very poorly, and will have poor quality in postharvest. Mature green tomatoes are somewhat difficult to detect (difficult to distinguish from immature-green fruit). Besides the characteristics listed in Table 1, its identification 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) appearance of brown corky tissue on the stem scar in some cultivars.

Tomatoes harvested later than the mature green-stage 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. Tomato harvested at breaker stage was superior in flavour to fruit harvested in mature-green 127. Vine-ripened tomatoes will accumulate more sugars, acids and ascorbic acid, and will develop better flavour than mature-green tomatoes ripened off the plant 31,35,188,205. Tomato harvested over-ripe was shown to have lower ascorbic acid content and higher ascorbate oxidase activity 232. Intensities of sweetness, saltiness and “fruity-floral” flavour were higher in tomatoes harvested at the table-ripe stage than at earlier stages 225. Early harvesting is a practice for obtaining firmer fruit suitable for transport and to attain a longer marketable period 22. However, trade journals recommended that fruit should be harvested at a late ripe stage to satisfy consumer’s demand for better flavour 117,227. Therefore, tomatoes for distant markets can be picked at the “mature-green” or “breaker” stages whereas tomatoes for near outlets can be picked at the “breaker”, “turning”, “pink” or “light-red” stages. The cluster or vine-ripe tomatoes are harvested at the “light-red” to the “table-red” stage.

5.2. Harvest

Tomatoes destined for fresh market are harvested by hand and usually in the morning to avoid the heat of the day. For beefsteak tomatoes, the fruit is picked from the vine by gentle twisting, without tearing or pulling. For cluster or vine-ripe tomato, the whole fruit cluster is cut off from the plants. Tomatoes should not be kept in the sun for an extended period of time. Greenhouse tomato fruit is usually harvested with the calyx and a short stalk for distinguishing from field tomato. The freshness of the calyx is used as an indication for freshness and quality of the fruit. Care must be taken to avoid the stalk puncturing other fruit, especially for tomatoes picked at a later stage, because they are much more susceptible to physical injury. 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.
6. Postharvest Factors Affecting Fruit Quality

Post-harvest factors such as fruit physical handling during grading and storage, transportation and ripening conditions have important influence on tomato fruit quality.

6.1. Fruit handling (washing, waxing and packaging)

Rapid cooling to 12.5°C immediately after harvest is important to remove heat, retard ripening and prolong storage and shelf-life. Pre-cooling can also reduce 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 stages of maturity. Optimum method of pre-cooling is forced-air cooling. However, room cooling can also be used. Room cooling 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.

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 drawing water and microorganisms into the fruit 197. The wash water may be chlorinated (125 ppm chlorine) to disinfect fruit surface and prevent microbial inoculation 187. The pH of the chloride water should be maintained at about 7.0. Disinfection of tomatoes with sodium hypochlorite before packaging greatly reduced subsequent microbial spoilage 12. However, chlorination has no residual effect 193, and therefore, tomato exposed to pathogens after treatment remains susceptible to reinfection. Chlorination using sodium hypochlorite may lead to physiological and textural change of tomatoes 108. A naturally derived plant compound, trans-cinnamaldehyde has been shown to be an effective fungicidal agent, especially when applied as an aqueous solution 198,199. 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 minutes, respectively. With the tomatoes treated for 30 minutes, visible mould growth was delayed by 7 days during storage under modified atmosphere condition at 18°C. After washing/disinfection, the fruit is 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 luster of the fruit 15. Fungicides may be added in the wax for protecting against fruit rot pathogens 87.

After washing and disinfection, fruit is then sorted/graded and packaged. Automatic systems for fruit sorting based on weight and colour are widely used in large commercial greenhouse or packaging houses. Tomatoes are packed in a variety of packages, depending on type of the fruit, maturity stage and type of market and 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. They are commonly constructed from double wall-corrugated fibreboard with at least 2.75 MPa bursting strength. Cluster/vine-ripe tomatoes are usually cleaned by air blow and then directly packaged with a plastic net bag and other packages. The package should be designed in such a way that minimises fruit physical injury during transport. Physical injuries such as cuts, punctures, scuffs and abrasions are not only 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 C₂H₄ production rates of the mature-green tomatoes 143.

6.2. Storage, shipping and ripening

Temperature affects several aspects of tomato quality, such as fruit firmness and colour development. Cold storage has a negative effect on fruit aroma and consequently on its organoleptic quality 130. During short-term storage, Janse 115 and Peters et al. 174 observed a decrease of titratable acid content. Storage-ripened green tomato usually has much lower levels of carotene than the vine-ripened fruit 84.

The optimum air temperature for storage varies with fruit ripening stages (Table 2). Fruit in advanced ripening stages can tolerate lower temperatures. Mature-green tomatoes are sensitive to low temperature and there is a risk to develop chilling injury if held for 2 weeks or longer below 13°C 91. Sensitivity to chilling injury will depend on temperature, length of exposure period, maturity of fruit and variety. For example, chilling injury symptoms and increased decay may appear in tomatoes kept below 10°C if fruit is held for longer than 2 weeks, or at 5°C if fruit is held for 6-8 days. Fruit in advanced maturity is less sensitive to chilling. Symptoms of chilling injury include failure to ripen or uneven ripening, ion leakage, surface pitting, premature softening, failure to develop characteristic flavour and colour, mealiness when ripened and increased decay 169. Alternaria and Cladosporium rots are usually associated with chilling injury. Expression of symptoms
is usually delayed until after exposure of fruit to room temperature for 2 days or longer. Tomato fruit stored for 7 days at
5°C and ripened at 20°C had acidic taste and low flavour 125. Tomatoes will freeze at about –1°C (30°F) depending on
soluble solids content. Symptoms of freezing include water soaked appearance, excessive softening and tissue breakdown,
and desiccated appearance of the locular gel 82. Optimum relative humidity during storage and transport is 85 to 95%.

Postharvest heat (prestorage) treatments have been pursued to delay ripening and to enhance resistance to low
temperature and to disinfect fruit 138. Exposed tomato to air at 38°C for 3 days (72 h) can reduce the detrimental effects
of low-temperature storage of mature-green tomatoes 86,140-142. Tomatoes exposed to either a short-term heated water
treatment (42°C for 1 h) or a long-term heated air treatment (38°C for 48 h), stored at 2°C and then transferred to 20°C,
ripened normally; the short-term heated air treatment extended the storage life equally as well as the long-term air heat
treatment, but altered some volatile profiles 148,149. Prestorage heat treatment of mature-green fruit (treated in water for
42°C for 1 h) can effectively reduce fruit decay with only minimal adverse effects on tomato fruit quality 150. However, the
effect of heat treatments on tomato fruit is variety-dependent. Heated forced air (38°C at 50% RH for 24 h) injured
mature-green ‘Trust’ tomatoes prevented the development or red colour, increased weight loss and decreased the production
of ascorbic acid 233. Some pigments, especially lycopene, and some antioxidants in tomato fruit are very sensitive to heat
 treatments (Yahia et al., 2002, manuscripts in preparation).

Tomato ripening is commonly done at 18 to 21°C. Tomatoes will not ripen normally at higher temperatures 82. Tomatoes
ripened at temperatures higher than 25°C will be soft and poorly coloured, as high temperature will hinder 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 82. 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 207. The production of volatile compounds associated with fruit taste depends on the final ripening temperature
rather than the initial storage temperature 207.

Quality and shelf-life of tomatoes can be improved by intermittent warming 19. In comparison to continuous storage at
6 or 9°C, intermittent warming during two or three cycles of 6 days at 6 or 9°C and 1 day at 20°C, enhanced surface colour
and encouraged ripening after the fruit was allowed to ripen for a period of 3 days at 20°C and 75-80% relative humidity.
The fruit quality and shelf-life by intermittent warming during three cycles of 6 days at 9°C and 1 day at 20°C was better
or as good as the continuous storage at 12°C 20. In Canada, it was recommended that mature green tomato 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 50. The optimum relative
humidity during storage is 90-95% while the optimum relative humidity for ripening is 75-80% 50. Higher relative humidity
will promote infection of fungi and the development of decay.

Table 2. Temperatures and storage duration of different classes of tomatoes

<table>
<thead>
<tr>
<th>Class</th>
<th>Temperature °C</th>
<th>Storage duration, days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mature-green</td>
<td>12.5-15</td>
<td>Up to 28 days</td>
</tr>
<tr>
<td>Pink</td>
<td>10-12.5</td>
<td>7-14 days</td>
</tr>
<tr>
<td>Light-red</td>
<td>9-10</td>
<td>4-7 days</td>
</tr>
<tr>
<td>Firm-ripe</td>
<td>7-10</td>
<td>3-5 days</td>
</tr>
<tr>
<td>Pink-red, firm-red or vine-ripen</td>
<td>7</td>
<td>2-4 days</td>
</tr>
</tbody>
</table>

6.3. Ethylene and fruit ripening

Tomatoes 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 15,133. Ethylene 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. Its
production increases significantly during maturation and ripening. At the onset of the respiratory climacteric, the production
is around 2-10 nl g⁻¹ fruit h⁻¹ 82. The transition of ethylene production feedback mechanism from negative to positive, which
occurs in tomato fruit only with ripening initiation and progress, may be responsible for the climacteric behaviour of tomato
fruit 21. Ripening of mature-green tomatoes is accelerated by exposure to ethylene at concentrations >0.05 µl 1⁻¹ 229.
However, at the breaker stage and later stages of maturity, fruit is not affected by ethylene exposure as it produces enough
ethylene for ripening. Therefore, ethylene removal is effective at the mature-green stage for delaying ripening. Tomatoes
should not be stored or shipped with other products that are maintained at lower temperatures 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 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 \(^{211}\). Therefore, interfering with ethylene biosynthesis or perception may affect the progression of any stage. Indeed, 1-methylocyclopropane (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 \(^{105}\). Ripening of mature-green tomatoes held at 20°C in air containing 0.1 \(\mu l l^{-1}\) ethylene was substantially delayed by exposure to 1-MCP in the concentration range 0.1-100 \(\mu l l^{-1}\). The delay was directly related to the concentration of 1-MCP and the exposure time. Exposure to 5 \(\mu l l^{-1}\) 1-MCP for 1 h resulted in about a 70% increase in the time to ripen, and is a good potential commercial treatment \(^{228}\). 1-MCP treated fruit showed a reduced loss of titratable acid on ripening, which resulted in a lower brix/acid ratio compared to untreated fruit. 1-MCP applied to ripe tomatoes for 2 h at 5-100 \(\mu l l^{-1}\) resulted in an increase in postharvest life based on fruit appearance; with exposure to 20 \(\mu l l^{-1}\) giving a 25% increase in postharvest life \(^{228}\).

Greenhouse tomatoes are usually harvested at breaker or later maturity stages. Ripening with supplemental ethylene does not usually lead to any benefits because the ripening process will initiate with ethylene produced by the fruit. However, the process of ripening can be accelerated. Ripening of “mature-green” tomatoes may be done with postharvest application of ethylene to ensure uniformity in ripening and in colour development. 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 \(^{125,226}\). Maximum ethylene concentration should be between 100 and 150 ppm, for rapid and uniform ripening. Duration of ripening period is 24 to 48 hours, depending on ripening temperature, ethylene concentration and desired speed of ripening \(^{36}\). Good air circulation is needed to insure uniform temperature throughout the room and to prevent CO\(_2\) accumulation. CO\(_2\) at \(\geq\) 2% will inhibit ethylene action and therefore will slow-down or inhibit ripening (see 6.4). Adequate air exchange in ripening rooms is important to reduce the development of “off flavours” \(^{82}\).

6.4. Modified/controlled atmospheres (MA/CA)

MA refers to atmospheres that are different from ambient air, whereas CA refers to strictly controlled atmospheres \(^{122,200}\). Modified atmosphere packaging (MAP) refers to the development of a modified atmosphere around the product through the use of permeable polymeric films \(^{126}\). Low O\(_2\) reduces respiration and ethylene production, and increases the tolerance to low temperature, and thus extends tomato shelf-life \(^{71}\). Also, it reduces the loss of chlorophyll and the synthesis of lycopene, carotenoids and xanthophylls, and delays ripening \(^{126}\). Elevated CO\(_2\) also retards ripening. An atmosphere of 3-5% O\(_2\) + 0-3% CO\(_2\) is used to delay ripening and to retard fungal growth. Tomatoes can be kept at this atmosphere at 12.5°C for up to 6 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 to 10% carbon monoxide and 4% O\(_2\) reduce postharvest decay incidence and severity without adversely affecting tomato flavour \(^{124}\). Nitrous oxide was found to be effective against fungus growth and fruit decay \(^{180}\). Mature-green tomatoes were stored for up 7 weeks at 12.8°C at 4% O\(_2\), 2% CO\(_2\), and 5% CO\(_2\), with acceptable quality. Atmospheres with \(\leq\) 1% O\(_2\) and/or \(\geq\) 3-5% CO\(_2\) can cause uneven ripening, uneven colour development, discoloration, softening and off flavours \(^{125}\). However, attempts to use low O\(_2\) and high CO\(_2\) to improve tomato eating quality has not been successful \(^{82}\).

Fresh cut produce sales have increased spectacularly during the last decade in Europe and northern America, mainly due to changes in consumer demand but also due to improvement in the cool chain and processing technology, including MAP. Quality and marketability of tomato slices deteriorates rapidly after cutting compared with other vegetables and a long-life cultivar has been used for fresh cut to slow ripening and extend storage life \(^{18}\). The effects of slicing on the postharvest behaviour of fresh cut tomato slices includes a rapid rise in CO\(_2\) and C\(_2\)H\(_4\) production which reduces shelf-life \(^{18,152,153}\). Controlled atmosphere is a good supplement to cold storage in extending the shelf-life of fresh cut tomato \(^{152}\). Atmosphere of 3 kPa O\(_2\) + 0 kPa CO\(_2\) or 3 kPa O\(_2\) + 3 kPa CO\(_2\) reduces C\(_2\)H\(_4\) production in tomato slices and delays ripening \(^{152}\). Moreover, surface sterilization of whole fruit with sodium hypochlorite as well as the use of potassium bicarbonate, calcium chloride and calcium lactate extend the shelf-life of fresh-cut tomato \(^{74,108}\). Most of the defects of fresh-cut tomatoes observed during processing and storage, such as juice accumulation, seed germination and moisture condensation, have been overcome. A water-absorbing paper in the trays avoided juice accumulation \(^{74,153}\). Ripening slices at either 20 or 25°C in humidified atmospheres containing either 9 or 20 \(\mu l l^{-1}\) C\(_2\)H\(_4\) reduced seed germination and radicle growth \(^{152}\). Lowering storage temperature was more critical factor than MAP in reducing microbial counts. High CO\(_2\) and low O\(_2\) levels 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\(_2\) \(^{71}\). After 10 days of storage, the quality attributes of tomato slices were...
maintained better at 2 than at 10°C. When slices were stored at 10°C, both the 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 18.

7. Pathological Disorders

Tomatoes are sensitive to attack by several decay organisms. Organisms can enter the fruit through openings such as wounds, cracks, cuts, stems, stem scars, etc. Therefore, tomatoes with such defects should be separated from good quality fruit. Decay can also be initiated in the packing line. Tomato losses at the retail and consumer levels in the New York area were estimated at 11.4 to 14.2%, and were mostly due to diseases, principally Alternaria, Rhizopus, grey mould and bacterial soft rot 44. Most postharvest decay problems commonly originate during cultivation. Physical damage and chilling injury augment the incidence and severity of decay. These problems are minor in tomato production in modern greenhouses with good climate control but quite severe in low-tech greenhouses and field production. The most common decay problems in tomatoes are described as follows.

7.1. Black Mould

Caused by Alternaria alternata: fruit becomes susceptible when exposed to <10°C (50°F) for one week. 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 temperatures lower than optimum and avoidance of mechanical injury.

7.2. Grey mould

Caused by Botrytis cinerea, mostly on greenhouse tomatoes and especially if film-wrapped. The affected tissue is usually firm, dry, and brown to black in colour. Preventive measures include the use of adequate storage temperature, avoidance of chilling and physical injuries, and the use of appropriate fungicides.

7.3. Sour rot

Caused by Geotrichum candidum. Symptoms on mature-green fruit appear as pale lesions, dull and water-soaked, with sour odour. On ripe fruit the infected tissue is usually dark, soft and watery. Symptoms usually start at the stem scar due to wounding. Avoiding mechanical injury is an important preventive measure.

7.4. Hairy or Rhizopus rot

Caused by Rhizopus stolonifer and characterised by soft, water-soaked and discoloured lesions with fermented odour. A coarse white mould may appear which then turns black. Preventive measures include the use of adequate level of hygiene in the greenhouse and packing line, and avoidance of fruit injury. The fungi grow very slowly at around 10°C.

7.5. Phoma rot

Caused by Phoma destructera Plowr 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, avoidance of fruit injury, use of optimum temperature during storage and shipping, and ensuring hygienic practices.
7.6. Early blight rot
Caused by *Alternaria solani* Sorauer. 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 chemical treatment of seeds before planting.

7.7. Late blight rot
Caused by *Phytophthora infestans* (Mont.). 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.

7.8. Bacterial speck
Caused by *Pseudomonas syringae* pv. Tomato (Okabe) Young, Dye & Wilkie. 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.

7.9. Phomopsis rot
Caused by *Diaporthe phaseolarum* var sojae is in 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.

7.10. Pink mould rot
Caused by *Trichothecium roseum* Link 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 temperature.

7.11. Pleospora rot
Caused by *Pleospora herbarum* (Pers.) Rabenh, 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.

7.12. Ring rot
Caused by *Myrothecium roridum* Tode ex Fr., 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 avoidance of mechanical injury.

References


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