14 Postharvest Physiology

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14.1 Introduction

Successful postharvest handling of mangoes requires knowledge of the postharvest physiology of the fruit and how the fruit physiology determines the best handling practices to maintain and develop high fruit quality. For example, mango, like banana, tomato and avocado, is a climacteric fruit, which means...
that it may be picked when mature but before ripening has commenced, and subsequently ripened postharvest. As mango fruit mature on the tree and begin to ripen, eating quality improves, but potential marketable life decreases due to the difficulty of controlling the ripening changes once they have been initiated, increased bruising susceptibility and increased decay. Susceptible mango cultivars tend to develop more internal breakdown (jelly seed, soft nose and stem-end cavity) the longer that harvesting is delayed (Raymond et al., 1998; see Galán Saúco, Chapter 9, this volume). As a tropical species, mangoes are subject to chilling injury (CI), which limits the use of refrigeration to maintain postharvest quality. Mangoes are also subject to other physiological disorders, physical damage and decay, the symptoms of which may make the fruit unmarketable (Yahia et al., 2006a).

Mangoes harvested at a mature but unripe stage of development (‘mature-green’) can be stored in the unripe state as long as the initiation of ethylene production and hence ripening is avoided. The initiation of ripening can be avoided by prompt cooling and storage at a low temperature at which ripening does not occur or, more effectively, by changing the composition of the storage atmosphere so that the oxygen (O₂) level is reduced and carbon dioxide (CO₂) level is raised. This latter approach is called either modified atmosphere (MA) or controlled atmosphere (CA) storage, depending on the degree of control. These technologies slow fruit metabolism and specifically inhibit the initiation of ethylene production. With MA or CA transport or storage, mangoes can typically be maintained in a firm, green condition for several days longer than can be achieved with normal refrigerated air storage. However, there are limits to the levels of O₂ and CO₂ that can be tolerated by mangoes and these limits are affected by several factors, including cultivar, maturity or ripeness stage, storage temperature and storage time (Yahia, 1998).

Mango postharvest physiology and technology have been described in previous reports, book chapters and reviews (Subramanyam et al., 1975; Lakshminarayana, 1980; Ledger, 1986; Peacock, 1986; Lizada, 1991; Coates and Johnson, 1993; Johnson and Coates, 1993; Lizada, 1993; Heather, 1994; Jacobi et al., 1994; Johnson et al., 1997; Mitra and Baldwin, 1997; Tharanathan et al., 2006).

14.2 Contribution of Mango Fruit to Human Nutrition and Health

Consumers are becoming aware of the nutritional and health benefits of fresh fruits and vegetables. Mango fruit are a rich source of vitamin C (Table 14.1), although the content decreases during ripening (Thomas, 1975; Vinci et al., 1995). ‘Raspuri’ mango is rich in vitamin C (300 mg/100 g fresh fruit) during the early stages of development, but the concentration is less (39.1–69.5 mg/100 g) at maturity (Siddappa and Bhatia, 1954). The content of vitamin C was between 13 and 178 mg/100 g in the ripe fruit of 50 cultivars surveyed by Singh (1960). The vitamin C content in fully grown mango fruit of cultivars in Puerto Rico ranged between 6 and 63 mg/100 g (Iguina de George
Table 14.1. Composition of the edible portion of mango fruit (Source: USDA/ARS, 2007).

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Unit</th>
<th>Value per 100 g edible portion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>g</td>
<td>81.71</td>
</tr>
<tr>
<td>Energy</td>
<td>kcal</td>
<td>65</td>
</tr>
<tr>
<td>Energy</td>
<td>kJ</td>
<td>272</td>
</tr>
<tr>
<td>Protein</td>
<td>g</td>
<td>0.51</td>
</tr>
<tr>
<td>Total lipid (fat)</td>
<td>g</td>
<td>0.27</td>
</tr>
<tr>
<td>Ash</td>
<td>g</td>
<td>0.50</td>
</tr>
<tr>
<td>Carbohydrate, by difference</td>
<td>g</td>
<td>17.00</td>
</tr>
<tr>
<td>Fibre, total dietary</td>
<td>g</td>
<td>1.8</td>
</tr>
<tr>
<td>Sugars, total</td>
<td>g</td>
<td>14.80</td>
</tr>
<tr>
<td>Minerals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcium</td>
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<td>10</td>
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<tr>
<td>Iron</td>
<td>mg</td>
<td>0.13</td>
</tr>
<tr>
<td>Magnesium</td>
<td>mg</td>
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<td>Potassium</td>
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<td>Sodium</td>
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<tr>
<td>Zinc</td>
<td>mg</td>
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</tr>
<tr>
<td>Copper</td>
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</tr>
<tr>
<td>Manganese</td>
<td>mg</td>
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</tr>
<tr>
<td>Selenium</td>
<td>μg</td>
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</tr>
<tr>
<td>Vitamins</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vitamin C (total ascorbic acid)</td>
<td>mg</td>
<td>27.7</td>
</tr>
<tr>
<td>Thiamine</td>
<td>mg</td>
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</tr>
<tr>
<td>Riboflavin</td>
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<tr>
<td>Niacin</td>
<td>mg</td>
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</tr>
<tr>
<td>Pantothenic acid</td>
<td>mg</td>
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</tr>
<tr>
<td>Vitamin B₆</td>
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</tr>
<tr>
<td>Folate, total</td>
<td>μg</td>
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<tr>
<td>Folic acid</td>
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</tr>
<tr>
<td>Folate, food</td>
<td>μg</td>
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</tr>
<tr>
<td>Vitamin B₁₂</td>
<td>μg</td>
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</tr>
<tr>
<td>Vitamin A</td>
<td>IU</td>
<td>765</td>
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<tr>
<td>Retinol</td>
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<tr>
<td>Vitamin E (α-tocopherol)</td>
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</tr>
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<td>Vitamin K (phyloquinone)</td>
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<td>Fatty acids, total saturated</td>
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</tr>
<tr>
<td>4:0</td>
<td>g</td>
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</tr>
<tr>
<td>6:0</td>
<td>g</td>
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</tr>
<tr>
<td>8:0</td>
<td>g</td>
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</tr>
<tr>
<td>10:0</td>
<td>g</td>
<td>0.000</td>
</tr>
<tr>
<td>12:0</td>
<td>g</td>
<td>0.001</td>
</tr>
<tr>
<td>14:0</td>
<td>g</td>
<td>0.009</td>
</tr>
<tr>
<td>16:0</td>
<td>g</td>
<td>0.052</td>
</tr>
<tr>
<td>18:0</td>
<td>g</td>
<td>0.003</td>
</tr>
<tr>
<td>Fatty acids, total monounsaturated</td>
<td>g</td>
<td>0.101</td>
</tr>
</tbody>
</table>
Postharvest Physiology

Table 14.1. Continued

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Unit</th>
<th>Value per 100 g edible portion</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:1 undifferentiated</td>
<td>g</td>
<td>0.048</td>
</tr>
<tr>
<td>18:1 undifferentiated</td>
<td>g</td>
<td>0.054</td>
</tr>
<tr>
<td>20:1</td>
<td>g</td>
<td>0.000</td>
</tr>
<tr>
<td>22:1 undifferentiated</td>
<td>g</td>
<td>0.000</td>
</tr>
<tr>
<td>Fatty acids, total polyunsaturated</td>
<td>g</td>
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</tr>
<tr>
<td>18:2 undifferentiated</td>
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<td>0.014</td>
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<tr>
<td>18:3 undifferentiated</td>
<td>g</td>
<td>0.037</td>
</tr>
<tr>
<td>18:4</td>
<td>g</td>
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<tr>
<td>20:4 undifferentiated</td>
<td>g</td>
<td>0.000</td>
</tr>
<tr>
<td>20:5 n-3</td>
<td>g</td>
<td>0.000</td>
</tr>
<tr>
<td>22:5 n-3</td>
<td>g</td>
<td>0.000</td>
</tr>
<tr>
<td>22:6 n-3</td>
<td>g</td>
<td>0.000</td>
</tr>
<tr>
<td>Cholesterol</td>
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</tr>
<tr>
<td>Amino acids</td>
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<td></td>
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<tr>
<td>Tryptophan</td>
<td>g</td>
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<tr>
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<tr>
<td>Isoleucine</td>
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<td>Leucine</td>
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</tr>
<tr>
<td>Lysine</td>
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<td>0.041</td>
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<tr>
<td>Methionine</td>
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<tr>
<td>Phenylalanine</td>
<td>g</td>
<td>0.017</td>
</tr>
<tr>
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<td>g</td>
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</tr>
<tr>
<td>Valine</td>
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<td>0.026</td>
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<tr>
<td>Arginine</td>
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</tr>
<tr>
<td>Histidine</td>
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<tr>
<td>Alanine</td>
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<tr>
<td>Aspartic acid</td>
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<td>Glutamic acid</td>
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<tr>
<td>Glycine</td>
<td>g</td>
<td>0.021</td>
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<tr>
<td>Proline</td>
<td>g</td>
<td>0.018</td>
</tr>
<tr>
<td>Serine</td>
<td>g</td>
<td>0.022</td>
</tr>
<tr>
<td>Other</td>
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<td></td>
</tr>
<tr>
<td>Ethanol</td>
<td>g</td>
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</tr>
<tr>
<td>Caffeine</td>
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</tr>
<tr>
<td>Theobromine</td>
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</tr>
<tr>
<td>β-Carotene</td>
<td>μg</td>
<td>445</td>
</tr>
<tr>
<td>α-Carotene</td>
<td>μg</td>
<td>17</td>
</tr>
<tr>
<td>β-Cryptoxanthin</td>
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<td>11</td>
</tr>
<tr>
<td>Lycopene</td>
<td>μg</td>
<td>0.000</td>
</tr>
<tr>
<td>Lutein + zeaxanthin</td>
<td>μg</td>
<td>0.000</td>
</tr>
</tbody>
</table>

et al., 1969). Vitamin C content was 105.2, 65.7 and 17.3 mg/100 g in ‘Langra’, ‘Ashwini’ and ‘Fazli’ mangoes, respectively (Gofur et al., 1994), and decreased rapidly 5–7 weeks after fruit set, and when ripe fruit were stored at room temperature. Vitamin B<sub>1</sub> (thiamine) in two mango cultivars was 35–60 μg/100 g,
and vitamin B₂ (riboflavin) in three cultivars was 45–55 µg/100 g (Stahl, 1935). Thiamine content of four Philippine cultivars was 57–600 µg/100 g, and riboflavin content of three cultivars was 37–730 µg/100 g (Quinones et al., 1944). Folic acid in green mangoes was 36 mg/100 g (Gosh, 1960).

The mango fruit is a rich source of carotenoids, some of which function as provitamin A: β-carotene (all-trans), β-cryptoxanthin (all-trans and cis), zeaxanthin (all-trans), luteoxanthin isomers, violaxanthin (all-trans and cis) and neoxanthin (all-trans and cis) (Mercadante et al., 1997; Yahia et al., 2006b; Ornelas-Paz et al., 2007, 2008). Total carotenoid content rose from 12.3 to 38.0 µg/g in ‘Keitt’ and from 17.0 to 51.2 µg/g in ‘Tommy Atkins’ from the mature-green to the ripe stage (Mercadante and Rodriguez-Amaya, 1998), and ripening alterations occurred principally in the major carotenoids, violaxanthin and β-carotene. With ‘Keitt’, all-trans-β-carotene, all-trans-violaxanthin and 9-cis-violaxanthin increased from 1.7, 5.4 and 1.7 µg/g, respectively, in the mature-green fruit to 6.7, 18.0 and 7.2 µg/g in the ripe fruit (Mercadante and Rodriguez-Amaya, 1998). In ‘Tommy Atkins’ these carotenoids increased from 2.0, 6.9 and 3.3 µg/g to 5.8, 22.4 and 14.5 µg/g, respectively, during ripening. Geographic effects were reported to be substantial (Mercadante and Rodriguez-Amaya, 1998). Some of the cis and trans isomers of provitamin A reported in ‘Haden’ and ‘Tommy Atkins’ mangoes include 13-cis-β-carotene (trace amounts), trans-β-carotene (12.5–15.5 µg/g) and trans-α-cryptoxanthin (0.3–0.4 µg/g) (Godoy and Rodriguez-Amaya, 1994). In processed mango juice, violaxanthin was not detected, auroxanthin appeared at an appreciable level, and β-carotene was the principal carotenoid (Mercadante and Rodriguez-Amaya, 1998). The major carotenoid in ‘Bourbon’, ‘Haden’, ‘Extreme’, ‘Golden’ and ‘Tommy Atkins’ mangoes is β-carotene (48–84% of the total), while epoxycarotenoids (violaxanthin, luteoxanthin and mutatoxanthin) constitute 13–49% of the total (Godoy and Rodriguez-Amaya, 1989). Mean vitamin A in these mangoes (retinol equivalents/100 g) ranges from 115.3 (‘Haden’) to 430.5 (‘Extreme’).

Children in Senegal with normal cytology had higher serum retinol and β-carotene levels than those with abnormal cytology after massive oral doses of vitamin A and consumption of mangoes (Carlier et al., 1992). Mango retinol is highly bioavailable (82% efficiency) by estimating vitamin A and carotene reserves in the liver and plasma of rats (Yuyama et al., 1991). During mango fruit ripening, vitamin A increases – ripe mangoes are tenfold richer in carotene than partially ripe fruit, while unripe green mangoes contain only trace amounts (Modi and Reddy, 1967). Mevalonic acid, a precursor of carotenoids, increases progressively during mango ripening (Modi and Reddy, 1967). Vitamin A equivalents in 100 g of mango fruit are 1000 to 6000 IU (Singh, 1960). The β-carotene content of the fruit of 30 mango cultivars in Puerto Rico ranged from 400 to 800 IU/100 g fresh fruit (Iguina de George et al., 1969). The development of β-carotene in mangoes held at 16–21°C was lower than that at 20–28°C (Vazquez-Salinas and Lakshminarayana, 1985). Jungalwala and Cama (1963) identified 16 different carotenoids in ‘Alphonso’ mangoes, and β-carotene accounted for 60% of the total. Of the oxycarotenoids, luteoxanthin, violaxanthin and cis-violaxanthin were present in significant amounts.
All the oxytocarotenoids were present as β-carotene derivatives, mostly as epoxides of zeaxanthin. Variation in carotenoid content, as in many other constituents, is due to several factors, including cultivar, geography, climate, storage/processing conditions and analytical procedures employed.

Several carotenoids occur in fruit of different mango cultivars (Cano and de Ancos, 1994; Ben-Amotz and Fishler, 1998; Chen et al., 2004), but only a few of them occur in significant concentrations (Ornelas-Paz et al., 2007). Mercadante et al. (1997) quantified several carotenoids in ‘Keitt’ mangoes; the most predominant ones were all-trans-β-carotene, all-trans-violaxanthin and 9-cis-violaxanthin, accounting for 27, 38 and 18% of the total carotenoid content, respectively. Similar findings have been reported for crude extracts from other mango cultivars (Mercadante and Rodríguez-Amaya, 1998; Pott et al., 2003a, b). Carotenoids are responsible for the yellow-orange colour of mango mesocarp (Vázquez-Caicedo et al., 2004). All-trans-β-carotene and the dibutyrates of all-trans-violaxanthin and 9-cis-violaxanthin are the main carotenoids in ‘Ataulfo’ and ‘Manila’ mangoes (Yahia et al., 2006b; Ornelas-Paz et al., 2008; Fig. 14.1). The content of these carotenoids during fruit ripening increased exponentially in ‘Ataulfo’ and exponentially or in a second order polynomial manner in ‘Manila’, and the highest correlation coefficients were obtained for the relationships between the internal and external a* and h° colour values and the content of the evaluated carotenoids in both mango

![Graph showing carotenoid content in different mango cultivars](image-url)

**Fig. 14.1.** Content of selected carotenoids in pulp of several mango cultivars. Data represent the mean of eight individual observations for each cultivar ± standard error (Source: Ornelas-Paz et al., 2007).
cultivars \((R = 0.81–0.94)\). Equations to predict the content of the most important carotenoids in ‘Manila’ and ‘Ataulfo’ mangoes on the basis of their internal and external colour values were obtained by Ornelas-Paz et al. (2008).

The content of \(\alpha\)-tocopherol is approx. 0.5 mg/100 g in an unidentified cultivar from Costa Rica (Burns et al., 2003), while the United States Department of Agriculture (USDA) Nutrient Database (USDA/ARS, 2007) indicates an \(\alpha\)-tocopherol content of 1.12 mg/100 g. Ornelas-Paz et al. (2007) found that \(\alpha\)-tocopherol is the only detectable tocopherol in seven mango cultivars (Fig. 14.2); ‘Haden’ and ‘Tommy Atkins’ mangoes had the highest amounts (380 and 470 \(\mu\)g/100 g, respectively), with c.200–250 \(\mu\)g/100 g in the other cultivars.

Mango fruit are rich in several types of antioxidant phytochemicals, that is carotenoids and phenolics (Ornelas-Paz et al., 2007; Rocha-Ribeiro et al., 2007). Botting et al. (1999), showed that mango fruit have antimutagens and the heterocyclic amine 2-amino-3-methylimidazo[4,5-\(f\)]quinoline. Percival et al. (2006) observed that whole mango juice inhibited cell proliferation in the leukaemic cell line HL-60 and also inhibited the neoplastic transformation of BALB/3T3 cells. García-Solís et al. (2008) studied the effect of ‘Ataulfo’ mango consumption on chemically induced mammary carcinogenesis and plasma antioxidant capacity in rats treated with \(N\)-methyl-\(N\)-nitrosourea (MNU). Mango was administered in the drinking water (0.02–0.06 g/ml) during both short-term and long-term (LT) periods to rats treated or not with

![Fig. 14.2. The content of \(\alpha\)-tocopherol in the pulp of several mango cultivars. Data represent the mean of eight individual observations for each cultivar ± standard error (Source: Ornelas-Paz et al., 2008).](image-url)
MNU. Rats treated with MNU showed no differences in mammary carcinogenesis or in plasma antioxidant capacity measured by both ferric reducing/antioxidant power (FRAP) and total oxyradical scavenging capacity assays. However, in animals not treated with MNU, but with an LT intake of mango, the plasma antioxidant capacity as measured by the FRAP assay tended to increase in a dose-dependent manner. This suggests that mango consumption by healthy subjects may increase antioxidants in plasma.

14.3 Mango Ripening Physiology

Ripening is part of the natural senescence of mango fruit. It is an irreversible process that contributes to organelle disruption and changes in chemical constituents, flavour and texture. While ripening improves the eating quality of mango fruit, the postharvest life of the fruit is reduced. Natural senescence, and thus ripening, is aggravated and promoted by ethylene, mechanical injury and high temperature. This process can be delayed by lower temperature, elimination of mechanical damage and reducing ethylene production (Yahia et al., 2006a). Ripening of mango is inhibited while fruit are attached to the tree, and respiration and ripening are stimulated upon detachment (Lakshminarayana, 1973). Burg and Burg (1962) reported that ethylene levels in the tissues of mature-green, attached mango fruit were relatively high (1.87 \mu l/l) and suggested that ethylene was ineffective for promoting ripening due to a ripening inhibitor supplied by the tree.

Changes associated with mango fruit ripening include: (i) flesh colour from greenish yellow to yellow to orange in all cultivars (Plate 80a); (ii) skin colour from green to yellow in some cultivars (Plate 80b); (iii) chlorophyll decreases and carotenoid content increases; (iv) flesh firmness decreases and juiciness increases; (v) starch is converted into sugars; (vi) total soluble solids (TSS) content increases; (vii) titratable acidity decreases; (viii) characteristic aroma volatiles increase; (ix) CO₂ production rate decreases from 40–50 to 160–200 mg/kg/h at 20°C; and (x) ethylene production rate increases from 0.1–0.2 to 1–3 \mu l/kg/h at 20°C. Gowda and Huddar (2000) found the changes in eight mango selections during ripening included reductions in fruit weight, volume, length, thickness, firmness, pulp content, pulp:peel ratio, starch and vitamin C, and increases in TSS, pH, total sugars, sugar:acid ratio, pulp carotenoid content and peel colour.

Climacteric behaviour

Mango is a climacteric fruit, exhibiting a climacteric pattern of respiration and an increase in ethylene production during ripening (Cua and Lizada, 1990; Reddy and Srivastava, 1999; Lal et al., 2003; Fig. 14.3). The initiation of ethylene production within the fruit triggers and coordinates the changes that occur during ripening. These changes include colour changes in the peel and flesh, softening of the flesh, and development of sweet flavour and
aroma. Mangoes can be ripened after harvest when picked at physiological maturity (mature-green), when they are fully sized, but before ripening has been initiated. Maturity indices are chosen to predict fruit quality potential and postharvest behaviour (Peacock et al., 1986; Medlicott et al., 1988). After harvest, the fruit is then cooled and isolated from possible sources of ethylene (ripening fruit, engine exhaust, smoke, etc.) during storage or shipping. This is the primary strategy used to control ripening and thus extend shelf life. Respiration patterns and ripening behaviour vary among cultivars, with different climatic conditions and growing locations (Krishnamurthy and Subramanyam, 1970). Respiration is very high after fruit set and then declines and is maintained at a low rate until fruit ripening begins.

The rise in respiration and ethylene production during the climacteric is related to fruit ripening. The respiratory peak in ‘Alphonso’ mangoes harvested mature-green occurs 5 days after harvest, and the fruit ripens within 7 or 8 days (Karmarkar and Joshi, 1941), while in ‘Kent’ and ‘Haden’ mangoes the peak occurs on days 9 and 11, respectively (Burg and Burg, 1962), and in ‘Pairi’ mangoes on day 9 (Krishnamurthy and Subramanyam, 1970). These differences are normal due to differences in location, climatic conditions, orchard and tree conditions, and postharvest temperature. The rise in the climacteric respiration in ‘Dashehari’, ‘Amrapali’ and ‘Rataul’ mangoes coincides with the highest level of sucrose and polygalacturonase (PG; EC 3.2.1.15) activity in ripening fruit (Kalra and Tandon, 1983). Respiration and ethylene production are excellent maturity indices, but require considerable expense to measure.

The expression of alternative oxidase (Aox) and uncoupling proteins (Ucp) has been investigated during mango ripening and compared with the expression of peroxisomal thiolase (EC 2.3.1.16), a ripening marker in mango (Considine et al., 2001). The multigene family for Aox in mango is expressed differentially during mango fruit ripening. Abundance of Aox message and protein peaks at the ripe stage, while expression of the single gene for the Ucp peaks at the turning or half-ripe stage, and the protein abundance peaks at the ripe stage. Proteins of the cytochrome chain peak at the mature-green

Fig. 14.3. The climacteric pattern of respiration and ethylene production during mango fruit ripening (Source: Lalel et al., 2003).
stage, suggesting that increases in cytochrome chain components are important for facilitating the climacteric burst of respiration and that Aox and Ucp are important in postclimacteric senescence processes (Considine et al., 2001). Because both message and protein for the Aox and Ucp increase in a similar pattern, their expression is not controlled in a reciprocal manner but may be active simultaneously.

Fruit slicing affects respiration rate (Allong et al., 2001). Slicing of mature-green ‘Julia’ and ‘Graham’ mangoes increased respiration rate immediately after cutting, but it decreased significantly within the first 12 h of storage at 5 or 10°C, yet still remained at levels above that of the intact fruit throughout the storage period. The effect of slicing on half-ripe and firm-ripe fruit is an initial increase in respiration followed by a decline to levels of the intact fruit.

Ethylene production and responses

Mangoes have a moderate ethylene production peak of 1–3 µl/kg/h during ripening at 20°C. Ethylene, applied directly or as ethrel, induces faster and more uniform fruit softening (Lakshminarayana, 1973; Barmore, 1974; Lakshminarayana et al., 1974; Somsrivichai and Waru-Aswapti, 1989). Ethylene treatment can be prior to shipping (Barmore and Mitchell, 1975). There is disagreement regarding the effect of ethylene treatment on quality (Chaplin, 1988), and this may be related to maturity when treated. Treatment of immature fruit leads to softening, but the fruit have poor flavour.

Mango fruit ripening is accompanied by increased ethylene production, which coordinates the ripening process. Mango expresses an autocatalytic increase in ethylene production during ripening (Mattoo and Modi, 1969b). Ethylene production starts before full ripeness is reached (Burg and Burg, 1962; Cua and Lizada, 1990). Ethylene production in unripe mango fruit is very low (<0.1 µl/kg/h) (Burdon et al., 1996). Ethylene production decreases as the fruit matures, is then undetectable for a time and reappears upon initiation of ripening (Akamine and Goo, 1973). ‘Kent’ and ‘Haden’ mango fruit have internal ethylene concentrations of c.0.01 µl/l during the preclimacteric phase, increasing to c.0.08 µl/l at the initiation of the climacteric, and up to 3.0 µl/l at the climacteric peak. Burg and Burg (1962) reported that ethylene production rises when or before CO₂ production rises in ripening mangoes, while Biale and Young (1981) included mangoes among fruits in which ethylene rises after CO₂ production rises.

Only a small concentration of exogenous ethylene (≥0.005 µl/l) is needed to initiate mango ripening (Wills et al., 2001). The small amount of ethylene in the fruit at harvest is sufficient to initiate ripening (Burg and Burg, 1962). While fruit of ‘Amrapali’ and ‘Deshehari’ mangoes produce a measurable amount of ethylene during ripening (Reddy and Srivastava, 1999), ethylene production does not follow a climacteric pattern and two ethylene peaks (at the mature-green and full-ripe stages) were recorded. This is probably due to the way that ethylene was measured in the different fruit, and the lack of control exerted on maturity stages of fruit. In ‘Carabao’ mangoes, the peak of
ethylene production occurs 110 days after flower initiation, and declines as fruit approached full maturity (Cua and Lizada, 1990). The content of 1-aminocyclopropane-1-carboxylic acid (ACC), the immediate precursor of ethylene, increases in different tissues (peel, outer and inner mesocarp) during ripening in both cultivars, ‘Amrapali’ and ‘Deshehari’, while ACC oxidase (ACO; EC 1.14.17.4), which catalyse the conversion of ACC to ethylene and ethylene production, decline (Reddy and Srivastava, 1999). Fruit peel has the highest levels of ethylene and ACO and less ACC accumulation than the outer and inner mesocarp at the mature-green stage. The inner mesocarp has less ACO activity and high ACC accumulation during the ripening process compared to peel; levels in the outer mesocarp are intermediate between those in the peel and inner mesocarp. Changes in the ability to convert ACC to ethylene in the peel are not related to changes in ripening parameters in the fruit pulp (Lederman et al., 1997). Mango seed also produces ethylene (Reddy and Srivastava, 1999). Fruit slicing has no measurable effect on ethylene production in ‘Julia’ and ‘Graham’ mangoes (Allong et al., 2001).

Treatment of mango fruit with acetaldehyde or ethanol (0.1, 0.5 or 1% ethanol or acetaldehyde vapour) has concentration-dependent inhibitory effects on ethylene production (Burdon et al., 1996). Application of ACC to acetaldehyde- or ethanol-treated fruit discs indicates that acetaldehyde can completely eliminate increased ACO activity, whereas ethanol cannot (Burdon et al., 1996). Accordingly, Burdon et al. (1996) suggested that acetaldehyde can either inhibit ACO activity directly or prevent the increase in the enzyme, thereby providing a possible mechanism for retarding fruit ripening.

14.4 Compositional Changes during Fruit Maturation and Ripening

Several important metabolic changes occur during the maturation and ripening of mangoes, and some of those are useful as maturity indices (Ketsa et al., 1991). The ripening changes are irreversible senescence processes that are related to degradation of organelles or changes in chemical constituents, and thus relate to the quality and postharvest life of the fruit. Natural senescence is aggravated and promoted by ethylene, mechanical injury and high temperature, and can be delayed by low temperature, elimination of mechanical damage and reduction of ethylene production.

**Organic acids**

Organic acids are important for respiratory activity and as flavour constituents. During maturation and ripening, mango fruit experience a substantial loss of organic acids. The predominant acids in mature mango fruit are citric, succinic, malic and tartaric acids; citric acid has the highest concentration and tartaric acid the lowest (Shashirekha and Patwardhan, 1976; Sarker and Muhsi, 1981; Medlicott and Thompson, 1985). Citric acid content increases steadily during fruit development in ‘Irwin’, reaching a maximum at the beginning of the endocarp-hardening period, and then decreases steadily
Postharvest Physiology

(Ito et al., 1997). In ‘Keitt’ the predominant organic acids are citric and malic acids, but tartaric, oxalic, ascorbic, and α-ketoglutaric acids also are present, and the initial loss in acidity is due to a substantial loss in citric acid and a small loss in malic acid (Medlicott and Thompson, 1985). In ‘Badami’ mangoes, citric acid is the major organic acid, but malic and succinic acids are also present (Shashirekha and Patwardhan, 1976). In ‘Fazli’ mangoes, oxalic, citric, malic, pyruvic and succinic acids have been detected and tartaric acid has been detected in ‘Zardalu’ mangoes (Kumar et al., 1993). In general, citric and succinic acids decrease during ripening while malic acid shows different changes with different cultivars (Lizada, 1993).

Mango fruit contain organic acids involved in tricarboxylic acid cycle reactions (i.e. oxalic, succinic, pyruvic, oxaloacetic and α-ketoglutaric acids). In ‘Pairi’ mangoes, maximum concentration of α-oxoglutaric and pyruvic acids occur before the climacteric peak. Aspartic and glutamic acid concentrations increase for about 3 days after harvest and then decrease as the climacteric maximum is reached (Krishnamurthy et al., 1971). Malic enzyme (EC 1.1.1.40), which catalyses the oxidative decarboxylation of L-malic to pyruvic acid, occurs in the three-quarter-ripe and ripe stages and the activity pattern during ripening is similar in ‘Alphonso’, ‘Banganpalli’, ‘Dasheri’, ‘Fazli’, ‘Langra’ and ‘Suvarnarekha’ (Selvaraj and Kumar, 1994). In ‘Alfonso’ (sic), the levels of malic dehydrogenase (EC 1.1.1.37) and succinic dehydrogenase (EC 1.3.5.1) increase with the onset of ripening; whereas, the level of citrate synthase (EC 2.3.3.1) increases several-fold during maturation but decreases markedly during ripening (Baqui et al., 1974). The activity of malic enzyme increases during ripening, reaching a maximum immediately after the climacteric peak, and then declines (Dubery et al., 1984). The activity patterns of phosphoenol pyruvate carboxylase (PEPC; EC 4.1.1.49) and pyruvate decarboxylase (EC 4.1.1.1) during ripening vary among different cultivars, while malic enzyme activity increases during ripening. PEPC activity is relatively high in ‘Alphonso’ and ‘Langara’, but low in ‘Dashehari’ and ‘Totapuri’ during ripening (Selvaraj and Kumar, 1994).

**Soluble sugars**

The increase in soluble sugars is a major change during mango fruit ripening, and sweetness is the most important compositional change related to mango flavour. While starch content increases in chloroplasts during mango fruit development, it is almost completely hydrolysed to simple sugars during ripening (Medlicott et al., 1986; Selvaraj et al., 1989; Kumar et al., 1994; Ito et al., 1997). In ‘Alphonso’, starch content is 14% (by weight) at the immature stage and c.0.3% at the ripe stage. Similarly, starch is almost undetectable in ‘Irwin’ mangoes after ripening, whereas sucrose increases significantly and fructose increases slightly (Ito et al., 1997). Starch content decreases slightly during ripening of ‘Haden’, but is insufficient to account for the observed increase in the level of sucrose (Castillo et al., 1992).

Ripe mango contains up to 10–20% total sugars on a fresh weight (FW) basis, depending on the cultivar and the stage of ripeness. At the beginning
of ripening, reducing sugars make up most of the sugar content, while there are more non-reducing (c.17%) than reducing (3%) sugars in completely ripe fruit. Sucrose contributes 57% of the total sugar in ripe ‘Keitt’ mangoes, with fructose and glucose making up 28% and 15%, respectively (Medlicott and Thompson, 1985). Although Krishnamurthy et al. (1971), Lakshminarayana (1973, 1975) and Shashirekha and Patwardhan (1976) reported a simultaneous increase of glucose, fructose and sucrose during ripening, Vazquez-Salinas and Lakshminarayana (1985) observed a gradual reduction in glucose and fructose and a continuous increase of sucrose during ripening in ‘Haden’, ‘Irwin’, ‘Kent’ and ‘Keitt’. Medlicott and Thompson (1985) and Vazquez-Salinas and Lackshminarayana (1985) identified the main reducing sugar as fructose, while Selvaraj et al. (1989) reported that glucose is predominant. Conflicting reports on the relative concentrations of individual sugars in mango fruit during ripening is cultivar-dependent and due to different storage and handling conditions (Medlicott and Thompson, 1985).

Sucrose content increases during ripening as a result of starch hydrolysis from increased amylase (EC 3.2.1.1) activity (Mattoo and Modi, 1969a; Fuchs et al., 1980; Tandon and Kalra, 1983). The high activities of sucrose synthase (EC 2.4.1.13) and invertase (EC 3.2.1.26) in the mesocarp during ripening indicate active sucrose metabolism (Kumar et al., 1994). Hexoses and hexose phosphates can be formed from pyruvate by gluconeogenesis (Selvaraj and Kumar, 1994). The activity of glucose-6-phosphatase (EC 3.1.3.9) reportedly increases up to the three-quarter-ripe stage; whereas, fructose-1,6-diphosphatase (EC 3.1.3.11) activity increases as the fruit ripens from the three-quarter-ripe to full-ripe stage (Kumar and Selvaraj, 1990). The glycolytic enzyme hexokinase (6-phosphofructokinase; EC 2.7.1.11) has maximum activity at the ripe stage, while pyruvate kinase (EC 2.7.1.40) activity increases until the three-quarter-ripe stage and declines at ripening (Selvaraj and Kumar, 1994). The pattern of activity changes in hexokinase/phosphofructokinase and pyruvate kinase demonstrates that glycolysis is activated during mango fruit ripening.

Reducing sugars, mainly fructose, increase slightly during ripening, and sucrose synthase (EC 2.4.1.13) activity increases approximately ten times during the phase of rapid sucrose accumulation (Castrillo et al., 1992). This activity accounts for the maximum rate of sucrose synthesis. The proportion of sucrose phosphate synthase (EC 2.4.1.14) activity that is sensitive to inhibition by inorganic phosphate changes during ripening (Castrillo et al., 1992). Maximum catalytic activity of sucrose synthase is constant throughout the ripening period and contributes significantly to sucrose metabolism. The activities of neutral and acid invertases (EC 3.2.1.26) are very low in comparison with the other enzymes of sucrose synthesis. Acid invertase activity increases and later decreases during ripening.

**Structural polysaccharides**

Pulp firmness is important for the evaluation of fruit maturity potential for transport and storage, and as a quality characteristic. Fruit softening and cell
wall changes are principal changes associated with fruit ripening. Fruit texture changes are due to changes in cell walls and pectic substances in the middle lamella, and these are cultivar-related (Selvaraj and Kumar, 1989). Softening of mango fruit is characterized by increased solubility of cell wall pectins (Roe and Bruemmer, 1981; Tandon and Kalra, 1984; Lazan et al., 1986; Nasrrial, 1993). In general, water-soluble polysaccharides increase during ripening (Lazan et al., 1986; Brinson et al., 1988), but water- and alkali-soluble pectins decline in ‘Keitt’ mangoes, and ammonium oxalate-soluble pectins increase as the fruit become soft (Roe and Bruemmer, 1981). There is an overall loss of galactosyl and deoxyhexosyl residues during mango fruit ripening, the latter indicating degradation of the pectin component of the wall (Muda et al., 1995). The loss of galactose appears to be restricted to the chelator soluble fraction of the wall pectin, while loss of deoxyhexose seems to be more evenly distributed among the pectin.

Pectinesterase (PE; EC 3.1.1.11), which catalyses the deesterification of methyl groups from acidic pectins, has been detected in ripening mangoes (Tahir and Malik, 1977; Roe and Bruemmer, 1981; Ali et al., 1990, 1995; Abu-Sarra and Abu-Goukh, 1992). Physiological maturity in ripened mangoes is associated with lower PE activity (van Lelyveld and Smith, 1979) and peel has higher PE activity than pulp (Ashraf et al., 1981). Endo-polygalacturonase (PG; EC 3.2.1.15), which is responsible for degrading the 1-4-linked galacturonic acid residues, occurs in ripening fruit (Lazan et al., 1986, 1993; Abu-Sarra and Abu-Goukh, 1992). Enzymatic and/or non-enzymatic processes, in addition to PG activity, are involved in the extensive softening of fruit (Mitcham and McDonald, 1992). Other cell wall hydrolases can be detected in ripening fruit, including cellulases (EC 3.2.1.4; Lazan et al., 1986; Abu-Sarra and Abu-Goukh, 1992), β-galactosidase (EC 3.2.1.23; Ali et al., 1990, 1995; Lazan et al., 1993), galactanase (EC 3.2.1.145; Ali et al., 1990) and xylanase (EC 3.2.1.8; Ali et al., 1990).

Ripening in mangoes, as characterized by decreased tissue firmness, is initiated in inner mesocarp tissue close to the seed, and progresses outwards (Lazan et al., 1993). Pectin solubilization in inner and outer mesocarp tissues is comparable, but pectin solubilization begins earlier in the inner than in the outer mesocarp (Lazan et al., 1993). The outer mesocarp of ‘Keitt’ remains firm longer than ‘Tommy Atkins’, and the inner is softer than the outer mesocarp at each stage of ripening in both cultivars (Mitcham and McDonald, 1992). Cell wall neutral sugars, particularly arabinosyl, rhamnosyl and galactosyl residues, decrease with ripening in both cultivars. ‘Keitt’ has more loosely associated, chelator-soluble pectin, accumulates more soluble polyuronides and retains more total pectin at the ripe stage than ‘Tommy Atkins’. Both cultivars have similar PG activity, which increases with ripening. The amount and molecular weight (MW) of cell wall hemicellulose decreases with ripening in both cultivars. Galactose is the only cell wall neutral sugar to show a significant decrease during ripening of ‘Sensation’ mangoes (Seymour et al., 1990). Losses of neutral sugars can be due to hydrolysis of galactans and arabinogalactans by β-galactosidase having galactanase activity. β-Galactosidase activity shows a parallel increase to tissue softening during
ripening. The close correlations between changes in β-galactosidase during ripening, and between changes in β-galactosidase activity with tissue softening, and increased pectin solubility and degradation suggests that β-galactosidase has an important role in cell-wall pectin modification and mango fruit softening during ripening (Ali et al., 1995).

Postharvest treatments, such as refrigeration, packaging, application of fruit coatings, etc., can retard mango fruit softening and activity of pectinases (Lazan et al., 1990; Nasrijal, 1993). Calcium (Ca) joins free carboxyl groups resulting from PE-catalysed hydrolysis of methyl ester bonds to form Ca-bridges between adjacent pectin molecules. Calcium application to ‘Haden’ mangoes by infiltration or dipping extends their storage life by 1 week (Zambrano and Manzano, 1995). Postharvest vacuum application of Ca to mango has also been tried (Tirmazi and Wills, 1981; Wills et al., 1988; van Eeden, 1992; Yuen et al., 1993). Vacuum (300 mm Hg) infiltration of 1–4% calcium chloride (CaCl₂) into ‘Amrapali’ and ‘Deashehari’ mangoes ripened at 25°C inhibits PG activity, while ethylene treatment (1 μl/l) markedly increases its activity (Reddy and Srivastava, 1999). Pressure (115 kPa for 2 min) or vacuum infiltration (32 kPa) with 1–8% CaCl₂ delays ripening of ‘Kensington Pride’ mangoes by 12 or 8 days, respectively (Yuen et al., 1993). Yuen et al. (1993) reported that vacuum infiltration of CaCl₂ causes some peel injury, which can be reduced by: (i) increasing the temperature of the fruit flesh or the CaCl₂ solution during pressure infiltration; (ii) packaging the fruit in sealed polyethylene during pressure infiltration; and (iii) packaging the fruit in sealed polyethylene bags or cling or shrink wraps after CaCl₂ treatment. Calcium chloride infiltration of ‘Keitt’ mangoes reduces ethylene production, respiration rate and the incidence of storage decay (van Eeden, 1992).

Pigments and colour

Mango skin colour is important for its role in the perception of overall quality (González-Aguilar et al., 2001) and can be important for determining the appropriate maturity for harvesting (Cocozza et al., 2004; Jha et al., 2007), processing (Mahayothee et al., 2004) and consumption (Cocozza et al., 2004; Jha et al., 2007). The loss of green colour is an obvious sign of fruit ripening in many mango cultivars. The development of the optimum skin colour usually defines mango quality. Some mango cultivars retain green colour in ripe fruit. Depending on the cultivar, skin colour can change from dark to olive-green; sometimes reddish, orange-yellow or yellowish hues appear from the base colour. Some cultivars develop a reddish blush, which has been attributed to anthocyanins. Colour changes in mango fruit are due to the disappearance of chlorophyll and the appearance of other pigments (Fig. 14.4). Chloroplasts are transformed to chromoplasts containing yellow or red pigments (John et al., 1970; Lakshminarayana, 1980; Parikh et al., 1990; Lizada, 1993). Well-arranged grana and osmiophilic globules occur in chloroplasts of cells in the peel of unripe mangoes (Parikh et al., 1990), and lose integrity during ripening. Osmiophilic globules appear, indicating the transformation
of the chloroplast to a chromoplast. In yellow cultivars, carotenoids and xanthophylls are the predominant pigments. The anthocyanin paeniodin-3-galactoside occurs in the skin of some cultivars (Proctor and Creasy, 1969). During fruit ripening, chlorophyll concentration decreases substantially in ‘Keitt’, while carotenoid concentration increases and anthocyanin decreases gradually in ‘Tommy Atkins’ (Medlicott et al., 1986). In ‘Keitt’, a substantial loss of chlorophyll in the peel occurs after the fruit begin to soften. Peel colour is not an adequate maturity index, since the fruit is already soft when the colour change occurs. ‘Tommy Atkins’ mangoes develop more red and yellow pigmentation in the peel and mesocarp than ‘Keitt’ (Mitcham and McDonald, 1992).

Mango fruit pulp contains high concentrations of carotenoids (up to 9 mg/100 g), causing the development of an intense yellow to orange colour. Mango is a good source of vitamin A. The pulp carotenoid level is cultivar-dependent. In ‘Alphonso’, 16 fractions of carotenoids have been reported: 50% of those are β-carotene (Jungalwala and Cama, 1963; John et al., 1970). No qualitative changes in carotenoid composition have been reported for ‘Keitt’ and ‘Tommy Atkins’ mangoes from mature-green to the ripe stage, although quantitative changes occur during ripening (Mercadante and Rodriguez-Amaya, 1992).

![Fig. 14.4. Carotenoid, anthocyanin and chlorophyll concentrations in the peel of ‘Tommy Atkins’ mango during ripening at 22°C (Source: Medlicott et al., 1986). LSD, least significant difference.](image-url)
1998). However, John et al. (1970) detected 15, 14 and 17 carotenoids in ‘Badami’ mangoes at mature-green, partially ripe and fully ripe stages of fruit, respectively. Variation with respect to pigment types and quantities is due to cultivar differences, geography and climate, different maturity stages and treatments after harvest; discrepancies in results are probably due to different analytical procedures.

Mango skin colour can be used to estimate the content of all-trans-β-carotene (Vázquez-Caicedo et al., 2004), the most important provitamin A carotenoid (Wolf, 1984). Ornelas-Paz et al. (2007) demonstrated that the values of external and internal colour are similar in ‘Manila’ and ‘Ataulfo’ mangoes (non-blushed) in contrast to blushed cultivars (‘Criollo’, ‘Paraíso’ and ‘Kent’). The carotenoids in fruit skin of some mango cultivars can be correlated with some non-destructive colour measurements (Table 14.2; Figs. 14.5–14.8 (Ornelas-Paz et al., 2008).

The most abundant carotene of mango is all-trans-β-carotene, while the most important xanthophylls are violaxanthin and its isomers (Wilberg and Rodriguez-Amaya 1995; Chen et al., 2004). Mercadante et al. (1997) quantified many carotenoids of ‘Keitt’ mangoes and concluded that the most predominant xanthophylls were all-trans-violaxanthin and 9-cis-violaxanthin, accounting for 38% and 18% of total carotenoid content, respectively, although other xanthophylls are important in other cultivars (Ben-Amotz and Fishler, 1998; Setiawan et al., 2001).

Modi and Reddy (1967) reported an increase during mango ripening of the carotene precursors, mevalonic acid (MVA) and geraniol, with a concomitant increase in carotene content. The geraniol concentration of unripe ‘Alphonso’

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Colour valuea</th>
<th>All-trans-violaxanthin</th>
<th>9-cis-Violaxanthin</th>
<th>All-trans-β-carotene</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Ataulfo’</td>
<td>a*</td>
<td>0.84/0.90</td>
<td>0.83/0.87</td>
<td>0.90/0.90</td>
</tr>
<tr>
<td></td>
<td>b*</td>
<td>–0.05/0.41</td>
<td>0.00/0.41</td>
<td>–0.05/0.45</td>
</tr>
<tr>
<td></td>
<td>L*</td>
<td>–0.75/0.19</td>
<td>–0.75/0.21</td>
<td>–0.80/0.27</td>
</tr>
<tr>
<td></td>
<td>C*</td>
<td>0.31/0.71</td>
<td>0.34/0.70</td>
<td>0.33/0.72</td>
</tr>
<tr>
<td></td>
<td>h°</td>
<td>–0.88/–0.89</td>
<td>–0.86/–0.87</td>
<td>–0.94/–0.90</td>
</tr>
<tr>
<td>‘Manila’</td>
<td>a*</td>
<td>0.92/0.87</td>
<td>0.93/0.89</td>
<td>0.86/0.81</td>
</tr>
<tr>
<td></td>
<td>b*</td>
<td>0.76/0.69</td>
<td>0.75/0.67</td>
<td>0.67/0.54</td>
</tr>
<tr>
<td></td>
<td>L*</td>
<td>–0.86/0.35</td>
<td>–0.86/0.32</td>
<td>–0.74/0.18</td>
</tr>
<tr>
<td></td>
<td>C*</td>
<td>0.81/0.74</td>
<td>0.81/0.73</td>
<td>0.73/0.61</td>
</tr>
<tr>
<td></td>
<td>h°</td>
<td>–0.90/–0.89</td>
<td>–0.92/–0.91</td>
<td>–0.82/–0.82</td>
</tr>
</tbody>
</table>

a Colour was recorded using the Commission Internationale de l’Eclairage (CIE) L*a*b* uniform colour space, where L* indicates lightness on a scale of 0 (black) to 100 (white), a* indicates chromaticity on a green (−) to red (+) axis, and b* indicates chromaticity on a blue (−) to yellow (+) axis. Numerical values of a* and b* were converted into chroma (C) and hue angle (h°), which represent colour purity and the shade of colour, respectively.
Fig. 14.5. Relationships between the content of all-trans-β-carotene (▲), all-trans-violaxanthin (as dibutyrate, ●), 9-cis-violaxanthin (as dibutyrate, ○) in mesocarp and the a*, b* and L* values, measured in mesocarp or peel of ‘Ataulfo’ mango fruit during ripening. Each point represents the mean of two independent measurements ± the standard error (vertical bars). The continuous line represents an exponential regression (Source: Ornelas-Paz et al., 2008).
mangoes varies from 0.5 to 3.0 μmol with 0.0 to 0.5 μmol MVA; in ripe mangoes the corresponding levels are 5–10 and 1–5 μmol, respectively. The increase in free geraniol and MVA indicates that these compounds are dephosphorylated during ripening. Acid phosphatase (EC 3.1.3.2) may regulate carotenogenesis in ripe mangoes (Mattoo et al., 1968). Mangoes stored at low temperatures and then ripened at room temperature fail to synthesize as much carotenoids as fruit held at room temperature (Krishnamurthy and Subramanyam, 1973; Thomas, 1975). Hot water treatments increase the colour intensity of the pulp (Medlicott et al., 1986) and the peel (Esguerra and Lizada, 1990).

‘Tongdum’ mangoes, which ripen without changing colour, have three-fold more chlorophyll and slightly more β-carotene in the peel and have higher rates of ethylene production compared with ‘Nam Dok Mai’ mangoes, which change from green to yellow upon ripening (Ketsa et al., 1999). Activities of chlorophyllase (EC 3.1.1.14) and peroxidase (EC 1.11.1.7) in the peel of ripe ‘Tongdum’ fruit are about half of that in ‘Nam Dok Mai’ fruit. Changes in the peel of ripe green mangoes are due to either or both a lower activity of chlorophyllase or peroxidase activity and are not a result of low ethylene production.

**Phenolic compounds**

The phenolic content of mangoes is high early during development, then decreases and remains fairly steady during ripening (Lakshminarayana et al.,
Fig. 14.7. Relationships between the content of all-trans-β-carotene (▲), all-trans-violaxanthin (as dibutyrate, ●), 9-cis-violaxanthin (as dibutyrate, ○) in mesocarp and the a*, b* and L* values, measured in mesocarp or peel of ‘Manila’ mango fruit during ripening. Each point represents the mean of two independent measurements ± the standard error (vertical bars). The continuous line represents an exponential or second order polynomial regression (Source: Ornelas-Paz et al., 2008).
1970). This is associated with loss of astringency (Selvaraj and Kumar, 1989). The peel of mango fruit has a higher phenolic content than the pulp at all stages of fruit development (Jain, 1961; Lakshminarayana et al., 1970).

Polyphenol oxidase (PPO; EC 1.14.18.1) catalyses the oxidation of mono- and diphenols to $o$-quinones, which polymerize to produce brown pigments. PPO activity increases slightly from harvest maturity to the half-ripe stage and then declines in ‘Bangana palli’, ‘Dashehari’, ‘Fazli’ and ‘Langra’ mangoes, and decreases in ‘Alphonso’, ‘Suvarnarekha’ and ‘Totapuri’ mangoes (Selvaraj and Kumar, 1989). The PPO isolated from ‘Haden’ mango is active towards the $o$-diphenolic compounds, showing higher activity in the presence of catechol, followed by chlorogenic acid, but not with monophenols (Park et al., 1980).

**Flavour (taste, aroma)**

Sugar changes are very important for organoleptic attributes in the mango fruit. Fruit flavour is mostly a balance between the content of sugars and organic acids (Medlicott and Thompson, 1985) as well as aromatic volatiles. Kapse et al. (1989) determined that increasing TSS and decreasing acidity
increases flavour ratings of mango fruit. Sucrose is the predominant sugar in ripe mango fruit (Tandon and Kalra, 1983; Medlicott and Thomson, 1985; Vazquez-Salinas and Lakshminarayana, 1985). The predominant acid in mango fruit is citric (Medlicott and Thompson, 1985; Lizada, 1993). Several factors affect sugar and acid contents in mango, including cultivar (Kapse et al., 1989; Kundu and Ghosh, 1992; Gowda et al., 1994), stage of maturity at harvest (Shashirekha and Patwardhan, 1976; Morga et al., 1979; Tandon and Kalra, 1983), postharvest treatments (Kumar et al., 1993) and storage conditions (Vazquez-Salinas and Lakshminarayana, 1985).

Ripe mangoes contain >300 volatiles (Pino et al., 2005), but not all of them are odour-active and thus do not contribute significantly to aroma. Studies have identified the volatiles of mango, but not their aromatic activity. The predominant volatiles in some cultivars are monoterpenes and sesquiterpenes (MacLeod and De Troconis, 1982; Engel and Tressl, 1983; Pino et al., 2005), as well as lactones and some fatty acids (MacLeod and Peris, 1984; MacLeod and Snyder, 1985; Wilson et al., 1990). However, there is no indication of the presence of a single flavour impact component (Engel and Tressl, 1983). Some mango cultivars have a peach-like flavour that may be related to the presence of lactones, which contribute to the flavour of peaches (*Prunus persica*) (Lakshminarayana, 1980; MacLeod et al., 1988, Wilson et al., 1990). MacLeod et al. (1988) detected four lactones in ‘Kensington Pride’ that are also the major volatiles of peach. Monoterpene hydrocarbons represent about 49% (w/w) of the total volatiles in ‘Kensington Pride’, with α-terpinolene being the most abundant (26%) and 16 esters representing 33% (MacLeod et al., 1988). The esters, together with some of the lactones, contribute to the flavour of ‘Kensington Pride’ mangoes.

Indian mangoes have a unique flavour, which has been attributed to (Z)-ocimine (Engel and Tressl, 1983; Lizada, 1993). Pino et al. (1989) detected 83 volatiles in ‘Corazon’, ‘Bizcochuelo’ and ‘Super Haden’ mangoes, and total volatiles ranged between 39 mg/kg in ‘Bizcochuelo’ to 70 mg/kg in ‘Corazon’. The identified volatiles include α-cubebene, β-maaliene, ethyl(Z)-9-hexadecanoate, ethyl(Z)-9,12-octadecanoate, ethyl(Z)(Z)(Z)-6,9,12-octadecanoate, cucarvone, 2-methylpropane-2-ol, 3-methylepentan-ol, thymol and carvacrol (Pino et al., 1989). MacLeod and Snyder (1985) listed the volatile components of several mango cultivars, including ‘Willard’ and ‘Parrot’ from Sri Lanka; levels of α-terpinolene were similar to ‘Kensington Pride’.

Kostermans and Bompard (1993) considered that lack of fibre was linked to an absence of aroma and flat taste and smell, but some cultivars such as ‘Kensington Pride’ are low in fibre and have a distinctive flavour and aroma profile, and a high level of α-terpinolene (Bartley and Schwede, 1987; MacLeod et al., 1988). Lipid content of the pulp is correlated with the flavour characteristics of some mango cultivars (Bandyopadhyay and Gholap, 1973a; Gholap and Bandyopadhyay, 1975b, 1976). The ripening of ‘Alphonso’ mangoes at ambient temperature is accompanied by a sharp increase in triglyceride content, together with the development of a strong aroma and flavour (Gholap and Bandyopadhyay, 1975a, 1976), but ripening at 10°C results in a bland aroma and flavour (Bandyopadhyay and Gholap, 1973b). ‘Totapuri’ mangoes,
a bland cultivar, showed no change in the development of aroma or in the pulp lipid content (Gholap and Bandyopadhyay, 1975b). During ripening at ambient temperature, palmitoleic acid content is higher than that of palmitic acid in ‘Alphonso’, whereas ripening at low temperature does not affect the proportions of these two fatty acids (Bandyopadhyay and Gholap, 1973b). The relative proportions of palmitoleic and palmitic acids in ‘Totapuri’ mango pulp are constant irrespective of the ripening conditions (Gholap and Bandyopadhyay, 1975b). Gholap and Bandyopadhyay (1976, 1980) suggested that the relative contents of palmitic and palmitoleic acids determine the flavour quality of mango fruit.

The absence of lactones having coconut-like odour notes in ‘Totapuri’ mangoes may be significant for differentiating its aroma characteristics from ‘Alphonso’, together with the presence of certain similar and dissimilar components (Bandyopadhyay, 1983). The aroma of green mangoes has been attributed to cis-octimine in ‘Alphonso’ and β-myrcene in ‘Batali’ mangoes (Gholap and Bandyopadhyay, 1976; Bandyopadhyay, 1983). Table 14.3 lists characteristic aromas of ‘Alphonso’ and ‘Totapuri’ mangoes and their possible chemical identities.

In almost all fruits, aromatic volatiles are produced at later stages of ripening (Yahia, 1994). Tree-ripe ‘Tommy Atkins’ mangoes produce higher levels of all aroma volatiles except hexanal than do mature-green fruit (Bender et al., 2000a). Both mature-green and tree-ripe mangoes stored in 25 kPa CO₂ tend to have lower terpene (especially p-cymene) and hexanal concentrations than those stored in 10 kPa CO₂ and air-stored fruit. Acetaldehyde and ethanol levels tend to be higher in tree-ripe mangoes held in 25 kPa CO₂ than in those from 10 kPa CO₂ or air storage, especially at 8°C. Inhibition of volatile production by 25 kPa CO₂ is greater in mature-green than in tree-ripe

Table 14.3. Characteristic aromas in ‘Alphonso’ and ‘Totapuri’ mangoes and their possible chemical causes (Source: Bandyopadhyay, 1983).

<table>
<thead>
<tr>
<th>Aroma</th>
<th>‘Alphonso’</th>
<th>‘Totapuri’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fruit, estery</td>
<td>Acetaldehyde, methyl acetate, ethyl acetate, n-butyl acetate</td>
<td>Propionaldehyde</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Methyl acetate</td>
</tr>
<tr>
<td>Green-mango-like</td>
<td>cis-Ocimine</td>
<td>β-Myrcene</td>
</tr>
<tr>
<td>Camphoraceous</td>
<td>Not detected</td>
<td>Detected, but not identified</td>
</tr>
<tr>
<td>Earthy</td>
<td>Caryophyllene-pinene</td>
<td>Not detected</td>
</tr>
<tr>
<td>Almond-like</td>
<td>Benzoaldehyde</td>
<td>Not detected</td>
</tr>
<tr>
<td>Burnt-sugar-like</td>
<td>Benzonitrile</td>
<td>Not detected</td>
</tr>
<tr>
<td>Spicy</td>
<td>Not detected</td>
<td>α-Terpinene</td>
</tr>
<tr>
<td>Sweet, sugar-like</td>
<td>Detected, but not identified</td>
<td>Not detected</td>
</tr>
<tr>
<td>Coconut oil-like</td>
<td>α-Caprolactone, α-octalactone, α-undecalactone</td>
<td>Not detected</td>
</tr>
</tbody>
</table>
mangoes, and at 8°C compared to 12°C for tree-ripe fruit. However, aroma volatile levels in tree-ripe mangoes from 25 kPa CO₂ are equal to or greater than those in mature-green fruit treatments. Atmospheres that prolong mango shelf life by slowing ripening processes can allow tree-ripe mangoes to be stored or shipped without sacrificing their aroma quality.

Quality enhancement has been used to determine properties critical to flavour acceptability of mangoes, and focus group interviews have been conducted to determine sensory attributes important to the purchase and consumption of mangoes (Malundo, 1996). Sugars and acids enhance perception of specific flavour notes in mango, including aromatics (Malundo et al., 2001).

14.5 Transpiration and Water Loss

Water loss lowers fruit weight, resulting in shrivelling, and may further reduce quality by causing poor colour development and uneven ripening. Water is lost from mango fruit through stomata, lenticels and other openings. Relative humidity (RH) inside the fruit is 100% and water is lost when RH in the environment surrounding the fruit is <100%. Water loss is also greatly influenced by temperature. With constant RH and air movement, water loss increases significantly with any increase in temperature. Transpiration rate is influenced by cultivar and ripeness stage. It is correlated with skin thickness, morphological structure, epidermal cells and surface wax coating. For example, waxes usually develop on the epidermis of fruit in the later stages of development and thus it is common for fruit harvested early to shrivel faster compared with those harvested at a more advanced stage of development (Yahia et al., 2006a).

14.6 Physical Damage and Physiological Disorders

Mangoes are susceptible to physical damage at every step of the postharvest handling chain (see Johnson and Hofman, Chapter 15, this volume) and reduction/elimination of mechanical injury is essential to reduce losses in quality and postharvest life. Mango fruit are susceptible to various physiological disorders that influence fruit quality (see Galán Saúco, Chapter 9, this volume). These disorders are either induced or inherent, and several of them become apparent during fruit ripening. Disorders, i.e. chilling injury (CI) and heat injury, may be induced after harvest. Inherent physiological disorders include ‘spongy stem end’ in ‘Kensington Pride’ (Brown et al., 1981), ‘soft nose’ in Florida mangoes (Young, 1957) and ‘internal breakdown’, ‘spongy tissue’ or ‘soft nose’ in Indian ‘Alphonso’ mangoes (Subramanyam et al., 1971).

Chilling injury (CI)

Low storage temperatures can injure mature-green mangoes if storage exceeds a day or so at or near 0°C to a few weeks at just below 12°C. This problem limits the use of low storage temperature to manage postharvest ripening
and seriously affects the ability of handlers to store mangoes or transport them over long distances, because temperatures that are low enough to delay ripening, decay and senescence may damage the fruit. The symptoms of CI include greyish, scald-like discoloration on the skin, followed by pitting, uneven ripening, and poor flavour, aroma and colour development (Hatton et al., 1965; Medlicott et al., 1990). The symptoms often are not apparent at the low temperature, but develop later, when the fruit are brought to warmer temperatures for ripening or are displayed for sale. Other symptoms in mango fruit held at room temperature for 1–2 days after low temperature storage were described as discoloured and with pitted areas on the surface (Srivastava, 1967; Kane, 1977) followed by increased susceptibility to microbial spoilage (Sadasivam et al., 1971; Subramanyam et al., 1975).

Chilling susceptibility varies with cultivar (Farooqui et al., 1985); ‘Haden’ and ‘Keitt’ are particularly susceptible. ‘Sensation’ developed more skin symptoms than ‘Sammar Bahisht’ mangoes (Farooqui et al., 1985). While CI has generally been reported to occur in mango fruit at temperatures below c.10–13°C (Mukherjee, 1958; Akamine, 1963; Hatton et al., 1965; Musa, 1974; Couey, 1986), some cultivars (i.e. ‘Dashehari’ and ‘Langara’) were reported to be safely stored at 7–8°C for up to 25 days (Mann and Singh, 1976). While most cultivars show injury at <10°C if fruit have just reached maturity, tolerance of CI increases as fruit ripen (Medlicott et al., 1990; Mohammed and Brecht, 2002). Tolerance of ‘Keitt’ mango fruit of CI was induced by pre-storage heat treatments (McCollum et al., 1993).

Heat injury

Mango is highly tolerant of heat (Yahia et al., 2000; Jacobi et al., 2001b). Mangoes that are not stored in refrigerated conditions after harvest may be exposed to extremely high ambient temperatures in many production areas. This may lead to heat injury, especially if the fruit are exposed to >30°C for >10 days, but injury can also occur more rapidly at higher temperatures. The heat disinfestation treatments of mangoes that are required for insect quarantine security may injure fruit that are not fully mature (Jacobi and Giles, 1997; Jacobi et al., 2001a).

External symptoms of heat injury include lenticel spotting and skin browning (‘scald’) with secondary disease development, while internal symptoms include mesocarp browning, tissue cavitation and ‘starch spots’ (Jacobi and Wong, 1992; Jacobi and Giles, 1997; Mitcham and McDonald, 1997; Jacobi et al., 2001a, b). Ripening of heat-injured mangoes may also be inhibited (Jacobi et al., 2001a, b).

14.7 Modified Atmospheres (MA) and Controlled Atmospheres (CA)

Long-term marine shipping in MA and CA has been used for transit from several countries (Yahia, 1993). Research results are very contradictory due to
the different cultivars and maturity stages of mangoes used, different atmospheres implemented and lack of experimental controls. Optimum condition for prolonged shipping or storage is reported to be 3–5 kPa O2 plus 5–10 kPa CO2, which can delay ripening, but the benefits are not very significant. Use of CA and MA would most likely be beneficial in delaying fruit ripening during marine transport for 2 weeks or more.

Bender et al. (2000b) determined the tolerance of preclimacteric ‘Haden’ and ‘Tommy Atkins’ to reduced O2 levels for storage times in typical marine shipments. They reported that mangoes can tolerate 3 kPa O2 for 2–3 weeks at 12–15°C and that tolerance of low O2 decreases as mangoes ripen. All low O2 treatments reduced mature-green mango respiration; however, elevated ethanol production occurred in 2 and 3 kPa O2 storage, with the levels two to threefold higher in ‘Tommy Atkins’ than in ‘Haden’. ‘Haden’ fruit at the onset of the climacteric accumulated ethanol in 4 kPa O2 and produced 10–20 times more ethanol in 2 and 3 kPa O2 than preclimacteric fruit. There were no visible injury symptoms, but off-flavour developed in mature-green fruit at 2 kPa O2 and in ripening-initiated fruit at 2 and 3 kPa O2. Ethanol production was not affected by storage in 25 kPa CO2. Ethylene production was reduced slightly by low O2; however, ‘Haden’ fruit also showed a residual inhibitory effect on ethylene production at 2 or 3 kPa O2 storage, while ‘Tommy Atkins’ fruit stored in 2 kPa O2 produced a burst of ethylene upon transfer to air at 20°C. Fruit firmness, total sugars and starch levels did not differ among treatments, but 2, 3 or 4 kPa O2 and 25 kPa CO2 maintained significantly higher acidity than 5 kPa O2 or air. The epidermal ground colour responded differently to low O2 and high CO2 in the two cultivars. Only 2 kPa O2 maintained ‘Haden’ colour better than air, while all low O2 levels maintained ‘Tommy Atkins’ colour better than air. High CO2 was more effective than low O2 in maintaining ‘Haden’ colour, but had about the same effect as low O2 on ‘Tommy Atkins’.

Properly selected atmospheres, which prolong mango shelf life by slowing ripening processes, can allow tree-ripe mangoes to be stored or shipped without sacrificing their superior aroma. Mature-green and tree-ripe ‘Tommy Atkins’ mangoes were stored for 21 days in air or in a CA (5 kPa O2 + 10 kPa or 25 kPa CO2) at 12°C (mature-green) and at either 8 or 12°C (tree-ripe) (Bender et al., 2000a). Tree-ripe mangoes produced much higher levels of all aroma volatiles except hexanal than mature-green fruit after ripening for 2 days. Both mature-green and tree-ripe mangoes stored in 25 kPa CO2 had lower terpene (especially p-cymene) and hexanal levels than those stored in 10 kPa CO2 and air-stored fruit. Acetaldehyde and ethanol levels were higher in tree-ripe mangoes from 25 kPa CO2 than in those from 10 kPa CO2 or air storage, especially at 8°C. Inhibition of volatile production by 25 kPa CO2 was greater in mature-green than in tree-ripe mangoes, and at 8°C compared to 12°C for tree-ripe fruit. Aroma volatile levels in tree-ripe mangoes from the 25 kPa CO2 treatment equalled or exceeded those in mature-green fruit treatments.

Mangoes have high tolerance of short-term elevated CO2 atmospheres (Yahia, 1998). Mangoes can tolerate CO2 atmospheres of up to 25 kPa for
2 weeks at 12°C (Bender et al., 2000b). High (25 kPa) CO₂ inhibits ethylene production, but increases ethanol production. Aroma volatiles are reduced following 25 kPa CO₂ treatment, while 10 kPa CO₂, low O₂ atmospheres and storage temperature did not significantly influence production of terpene hydrocarbons, which are characteristic of Florida-type mangoes. Mature-green ‘Tommy Atkins’ mangoes can be stored for 21 days in CA (5 kPa O₂ + 10 kPa or 25 kPa CO₂) at 12°C, while tree-ripe fruit can be stored for 21 days in the same atmospheres at either 8 or 12°C (Bender et al., 2000a).

The quality of ‘Keitt’ mangoes was evaluated during storage for 6 days at 20°C in an extremely low O₂ (LO) CA (approximately 0.3 kPa) before storage in modified atmosphere packaging (MAP) made from three, low-density polyethylene (LDPE) films with different gas permeability characteristics (González-Aguilar et al., 1997). Both LO and MA treatments delayed the losses of colour, weight and firmness. Fruit maintained good appearance with a significant delay of ripening. Mangoes are very tolerant of LO treatment; however, some MAP fruit developed a fermented taste after 10 and 20 days at 20°C. Short duration (6-day) storage of mangoes in LO did not otherwise have any deleterious effect on fruit quality during subsequent storage under MA or normal atmosphere. Properly selected atmospheres, which prolong mango shelf life by slowing ripening, permit fruit to be shipped without sacrificing superior aroma.

Beaulieu and Lea (2003) studied ‘Keitt’ and ‘Palmer’ mangoes without heat treatment to assess volatile and quality changes in stored fresh-cut mangoes prepared from firm-ripe (FR) and soft-ripe (SR) fruit, and to assess what effect MAP may have on cut fruit physiology, overall quality and volatile retention or loss. Subjective appraisals of fresh-cut mangoes based on aroma and cut edge or tissue damage indicated that most SR cubes are unmarketable by day 7 at 4°C. Both cultivars stored in MAP at 4°C had almost identical O₂ consumption, which is independent of ripeness. The CO₂ and O₂ concentrations measured for cubes stored in passive MAP indicated that the system is inadequate to prevent potential anaerobic respiration after 7 days storage.

**Injuries associated with MA and CA**

A 10 kPa CO₂ atmosphere alleviates chilling symptoms in ‘Kensington Pride’ fruit, but higher concentrations are injurious; low O₂ (5 kPa) has no significant effect (O’Hare and Prasad, 1993). Higher concentrations of CO₂ (>10 kPa) are ineffective for alleviating CI at 7°C, and tend to cause tissue injury and high levels of ethanol in the pulp. Injury in ‘Kensington Pride’ caused by higher levels of CO₂ appears to be more severe at lower temperatures (O’Hare and Prasad 1993; Bender et al., 1994, 1995), which could be a result of either compounding injury (chilling + CO₂) or reduced sensitivity of ripe mango to CO₂.

‘Rad’ mangoes develop internal browning and off-flavour in atmospheres containing 6 and 8 kPa CO₂ (Noomhorm and Tiasuwon, 1995). The presence of starchy mesocarp in ‘Carabao’ mangoes, which is characteristic
of internal breakdown, increases during storage in MA (Gautam and Lizada, 1984). Fruit stored for 4–5 days have severe symptoms, including air pockets in the mesocarp resulting in spongy tissue (Nuevo et al., 1984a, b). Parenchyma cells of affected tissues have c.18 starch granules per cell, compared to c.2 starch granules in healthy adjacent cells. However, no difference in starch granule shape was detected between the spongy and healthy tissues. The spongy tissue, which usually occurs in the inner mesocarp near the seed and becomes evident during ripening, has almost ten times the starch content of healthy tissue in the same fruit. External symptoms of internal browning due to MA include failure of the peel to develop colour beyond the half-yellow stage.

‘Carabao’ mangoes stored in polyethylene bags (0.04 mm thickness) for 1 day at 25–31°C had a faint fermented odour that disappeared during subsequent ripening outside the bags (Gautam and Lizada, 1984). The fermented odour increases with time, and persists throughout ripening when the fruit are stored for 2–5 days. The respiratory quotient of this cultivar ranged from 0.59 at 21 kPa O₂ to 6.03 at 2.4 kPa O₂, which indicates a progressively anaerobic metabolism (Sy and Mendoza, 1984). CO₂ production decreases as O₂ decreases from 21 to 3 kPa, but increases at <3 kPa O₂. Fermentative decarboxylation could explain the odour (Lakshminarayana and Subramanyam, 1970).

Pronounced decay appears after storage of ‘Rad’ mangoes for 20 days in atmospheres containing 4–6 kPa O₂ with 4–8 kPa CO₂ at 13°C and 94% RH, and severe incidence of decay appears after 25 days (Noomhorm and Tiasuwon, 1995). Greater incidence of decay (stem-end rot and anthracnose) occurs in ‘Carabao’ mango stored in MA for 2–5 days at 25–31°C (Gautam and Lizada, 1984).

Modified atmosphere packaging (MAP)

Modified atmosphere packaging is used to create a beneficial MA around a packaged product using semipermeable film to restrict the movement of respiratory gases into and out of the package; at equilibrium, the respiration rate of fruit in MAP is equal to the diffusion of the respiratory gases through the film. Fruit wrapped in 0.08 mm thick polyethylene bags, with and without perlite-potassium permanganate (KMnO₄) and stored for 3 weeks at 10°C before treatment with ethylene developed normal colour, texture and flavour (Esguerra et al., 1978). Individually sealed ‘Keitt’ in low-density (LDPE) and high-density (HDPE) polyethylene films for 4 weeks at 20°C exhibited delayed ripening, reduced weight loss and did not develop any off-flavours (Gonzalez et al., 1990). The LDPE had a thickness of 0.010 mm and permeabilities of 700 cm³ O₂/m²/h/atm and 0.257 g H₂O/m²/h/atm. The HDPE film had a thickness of 0.020 mm and permeabilities of 800 cm³ O₂/m²/h/atm and 0.166 g H₂O/m²/h/atm.

In a study to model MAP for mango, ‘Keitt’ fruit were individually vacuum packaged in LDPE film (0.0245 mm thick, 25.0 g/m²) and stored at 7°C/80–90%
RH, 12°C/75–85% RH, 17°C/70–80% RH, 22°C/65–75% RH or 25°C/65–75% RH (Yamashita et al., 1997). After mass transfer had reached steady state, respiration rates, moisture loss, permeability of peel and film to water vapour, and composition of atmosphere around the fruit were determined for 33 days. Daily rates of weight loss increased from 4.1 g/kg of fruit at 7°C to 10.9 g/kg at 25°C. Respiration rates also increased with storage temperature for both packaged and unpackaged mangoes, and were 21, 38 and 43% less in packaged fruit at 12, 17 and 22°C, respectively. Permeability of peel was 600-fold greater than that of the plastic film. The in-package CO2 levels increased and O2 decreased with time; concentration changes were greatest during the first 10–15 days of storage and were more marked at the higher temperatures. Experimental and calculated values for CO2 levels differed by 29%, depending on temperature.

‘Tommy Atkins’ mangoes individually sealed in heat-shrinkable films and stored for 2 weeks at 12.8°C and then ripened at 21°C had less weight loss, but did not show differences in firmness, skin colour development, decay development or time to fruit ripening, and had more off-flavours than unwrapped fruit (Miller et al., 1983). Polyethylene films used were: Clysar EH-60 film of 0.01 mm nominal thickness, Clysar EHC-50 copolymer film of 0.013 mm nominal thickness, and Clysar EHC-100 copolymer film of 0.025 mm nominal thickness. Individual mature fruit of the same cultivar were later sealed in Clysar EHC-50 copolymer film with 0.013 mm thickness, and Cryovac D955 with 0.015 mm thickness, and stored at 21°C and 85–90% RH (Miller et al., 1986). The O2 permeabilities of the films were 620 cm3/24 h/m2/atm and 983 cm3/24 h/m2/atm, respectively. Water permeability was 1.5 g/24 h/m2 and 2.0 g/24 h/m2 at 23°C, respectively. Fruit in MAP had less weight loss, but higher incidence of decay and off-flavour at soft-ripeness than unsealed fruit. The authors concluded that there were no practical benefits from wrapping this fruit in these films and storage at 21°C or even at lower temperatures. ‘Film wrapping mangoes at various stages of ripeness after harvest…will not improve the maintenance of mango quality during storage or ripening.’

‘Keitt’ mangoes were individually sealed in LDPE films and in a heat-shrinkable copolymer (Cryovac D-955) film with non-sealed mangoes as the control and stored for up to 5 weeks at 12°C, 17°C or 22°C (Yamashita et al., 1999). MAP reduced the rate constant of vitamin C degradation at all temperatures and vitamin C content of individually packaged mangoes was less affected by storage temperature than the control. Values for Q10 (the ratio of CO2 production to O2 consumption in respiration) were 1.3 and 1.0 for mangoes wrapped with the heat-shrinkable copolymer and the LDPE films, respectively, and 2.8 for the non-sealed control.

The combined effect of hot benomyl (1000 ppm) at 55°C for 5 min and film packaging in 0.01 mm PVC extended the storage life of mature-green ‘Nam Dok Mai’ mangoes stored at 13°C (Sornsriwichai et al., 1992). Fruit quality was not affected by film packaging after 4 weeks, but fruit showed inferior quality after 6 weeks. The inhibition of carotene pigmentation in the peel of this cultivar may be related to O2 concentration inside the package and not
to CO₂ concentration (Yantarasri et al., 1994). At least 16 kPa O₂ is essential for development of peel colour to the marketable stage (greenish).

‘Kensington Pride’ mangoes treated with heated benomyl (0.5 g/l at 51.5°C for 5 min) and sealed in polyethylene bags (0.04 mm thickness) for various durations at 20°C, had off-flavour and lacked normal skin colour when ripened, but ripened satisfactorily in perforated bags (Chaplin et al., 1982). The postharvest life of these fruit was not consistently longer than the control. The CO₂ concentration in the bags was >20 kPa while the O₂ concentration was <5 kPa. The incidence of off-flavours was reduced by including ethylene-absorbent blocks in the bags. The authors concluded that ‘mangoes cannot be stored satisfactorily at ambient temperature by such technique’; however, Stead and Chithambo (1980) reported that fruit ripening at 20–30°C was delayed 5 days by sealing in polyethylene bags (0.02 mm thickness) with ethylene-absorbent blocks without any abnormal flavour.

‘Tommy Atkins’ and ‘Keitt’ mangoes were individually sealed in shrinkable Cryovac polyolefin films (0.015 or 0.019 mm thickness), either non-perforated (MD film) or perforated with eight holes of 1.7 mm diameter/ inch² (MPY) or eight holes of 0.4 mm diameter/inch² (SM60M) (Rodov et al., 1994). After 2–3 weeks at 14°C and an additional week at 17°C, mangoes packaged in perforated polyolefin films ripened normally. Optimum results were achieved when the film with 0.4 mm perforations was combined with increased free volume inside the package by sealing the fruit within polystyrene trays. After 3 weeks of storage and 1 week of shelf life, sealed ‘Keitt’ mangoes were inferior to the control; they were less ripe, but beyond 4 weeks (up to 6 weeks) sealed fruit had better quality scores because they were less overripe. Sealing did not reduce decay of fruit stored for long periods.

Non-perforated PVC film packaging of ‘Nam Doc Mai’ mangoes was not sufficiently permeable for O₂ exchange to allow proper ripening (Yantarasri et al., 1995). Therefore, a ‘perforated MA’ was used in which fruit were wrapped in polystyrene trays (three fruit/pack) at 20°C with perforation area of ≥0.004 cm². Fruit ripened normally with no off-flavours. Colour development in the peel required a higher concentration of O₂ than the flesh. A film of pore area ≥0.008 cm² allowed fruit colour to develop after 3 weeks while a pore area of ≥0.39 cm² allowed the fruit to colour within 2 weeks.

Semipermeable coatings

Some fruit coatings can create an internal MA within the fruit due to semipermeable restriction of O₂ and CO₂ movement in and out of the fruit. Baldwin et al. (1999) tested two types of fruit coatings – polysaccharide-based and carnauba wax-based – for their effect on external and internal mango fruit atmospheres and quality factors during simulated commercial storage at 10 or 15°C with 90–99% RH, followed by simulated marketing conditions at 20°C and 56% RH. The coatings exhibited markedly different O₂ permeability characteristics under laboratory conditions. Polysaccharide coatings were less permeable to respiratory gases (i.e. O₂ and CO₂) and more permeable to
water vapour compared to carnauba wax. When applied to fruit under simulated commercial conditions, however, the differences between the coatings with regards to their permeability to respiratory gases were much reduced, most likely due to high RH during cold storage. Both coatings created a MA within the fruit, reduced decay and improved appearance by imparting a subtle shine; but only the polysaccharide coating delayed ripening and increased concentrations of flavour volatiles. The carnauba wax coating significantly reduced water loss compared to uncoated and polysaccharide-coating treatments.

‘Julie’ mangoes treated with 0.75% w/v aqueous solution of Pro-long semipermeable fruit coating (a mixture of sucrose esters of fatty acids and sodium salt of carboxy methyl cellulose) and stored at 25°C and 85–95% RH exhibited reduced weight loss, retarded ripening and increased storage life (6 days longer) without evidence of adverse effects on quality (Dhalla and Hanson, 1988). Treatment with 1.0% Pro-long could increase ethanol concentration in the pulp. Treatment with Pro-long (0.8–2.4%) also delayed ripening of ‘Haden’ (Carrillo-López et al., 1996).

Insecticidal CA

Mangoes are very tolerant of insecticidal atmospheres, and thus a potential commercial application is feasible, especially in combination with other treatments (i.e. heat). ‘Keitt’ mango tolerated as low as 0.2 kPa O₂ and as high as 80 kPa CO₂ for up to 5 days without any injury upon ripening, although fermentative odours could be noted while the fruit were under atmosphere stress (Yahia, 1993, 1994, 1995, 1997; Ortega and Yahia, 2000). Other mango cultivars were also evaluated and were very tolerant of extreme atmospheres (Yahia, 1998).

Storage of ‘Keitt’ mangoes in an insecticidal MA (0.03–0.26 kPa O₂, 72–79 kPa CO₂, balance nitrogen (N₂)) and CA (0.2 kPa O₂, balance N₂; or 2 kPa O₂ + 50 kPa CO₂, balance N₂) for up to 5 days at 20°C delayed fruit ripening as indicated by respiration, flesh firmness and colour development (Yahia et al., 1989; Yahia, 1993; Yahia and Tiznado, 1993; Yahia and Vázquez, 1993). The activities of phosphofructokinase, alcohol dehydrogenase (EC 1.1.1.1) and pyruvate decarboxylase were enhanced but activity of pyruvate kinase, succinate dehydrogenase and α-ketoglutarate dehydrogenase (EC 1.2.4.2) was unaffected. Although these atmospheres caused changes in glycolysis and tricarboxylic acid cycle, there was no indication of injury and the fruit ripened normally in air. Sensory evaluation conducted after fruit ripening showed no off-flavours, and there were no differences between fruit maintained in the MA or CA and those maintained continuously in air. ‘Keitt’ mango is therefore very tolerant of insecticidal atmospheres, and 5 days exposure is sufficient to control many insects (Rojas-Villegas et al., 1996).

Storage of ‘Keitt’ and ‘Tommy Atkins’ mangoes for 21 days at 12°C in atmospheres containing 25, 45, 50 or 70 kPa CO₂ plus either 3 kPa O₂ or air, induced ethanol production of 0.18–3.84 ml/kg/h after transfer to air at 20°C
for 5 days (Bender et al., 1994). Atmospheres containing 50 or 70 kPa CO₂ caused fruit injury, and resulted in the highest ethanol production rates. Enclosure of ‘Haden’ and ‘Tommy Atkins’ mangoes in sealed 20 l jars with an initial atmosphere of 90 kPa CO₂ in air or 97 kPa N₂ + 3 kPa O₂ for 24 h prior to storage delayed their ripening, and no injury was reported (Pesis et al., 1994).

14.8 Manipulation of Mango Postharvest Physiology by Molecular Biology

Mango fruit quality is compromised when harvest occurs before the fruit are fully mature since they are unable to achieve the full complement of flavour and aroma during the postharvest handling period compared with fruit harvested at a fully mature or ripening-initiated stage of development. As a climacteric fruit, maturity in mango corresponds to attainment of ripening competence. The presence of ethylene is required for the progression and completion of mango ripening. Thus, strategies for prolonging the postharvest life and maintaining postharvest quality of mango other than disease control are focused on reducing the effects of ethylene. This situation provides an excellent opportunity to utilize genetic transformation to improve mango postharvest quality by manipulating the role of ethylene (see Litz et al., Chapter 18, this volume). Cruz-Hernández et al. (1997) transformed ‘Hindi’ mango with mango ACO and ACC synthase (EC 4.4.1.14) in the antisense orientation. A cDNA that codes for mango ACO was also isolated and characterized by Zainal et al. (1999). Suppression of mango ethylene biosynthesis should allow harvesting of advanced maturity fruit that contain high levels of sugars and possess enhanced capacity to produce ripe aroma volatiles after exposure to exogenous ethylene. Progression of ripening in such fruit can be easily halted at the most desirable and convenient time by simply removing exogenous ethylene.

A cDNA homologue of the ethylene receptor gene ETR-1, referred to as METR1, which codes for a polypeptide of 802 amino acids with a predicted 89 kDa MW has been isolated (Gutierrez-Martínez et al., 2001). Two or more ETR homologues exist in mango. The level of METR1 mRNA in the mesocarp increases transiently during wounding. Repression of genes involved in ethylene action in mango fruit should result in ethylene-insensitive fruit that are minimally affected by exposure to ethylene in the postharvest environment, resulting in better control of ripening and senescence to maintain mango postharvest quality.

Internal breakdown in mango fruit is essentially a problem of premature ripening; the longer harvest of susceptible varieties is delayed, the greater the incidence of internal breakdown. Using molecular approaches to reduce ethylene production and action in mature fruit could reduce internal breakdown or premature ripening and lead to greatly improved quality. Another approach to mitigating internal breakdown would be to target genes involved in the maintenance of cell wall integrity. Vasanthaiah et al. (2006) demonstrated
differential expression of several genes in tissue showing internal breakdown symptoms compared with healthy tissue. They suggested that oxidative stress may be one of the causes of the disorder.

Sane et al. (2005) have isolated and characterized an ethylene-dependent α-expansin gene, *MiExpA1*, which is correlated with softening in mango. Expression of *MiExpA1* increases with the progression of ripening and treatment with 1-methyl cyclopropene inhibits both ripening/softening as well as *MiExpA1* transcript and protein accumulation. Recently, a pectate lyase (EC 4.2.2.2) homologue from ripening mango (*MiPel1*) has been cloned (Chourasia et al., 2006). A progressive increase in transcript accumulation was observed during ripening but expression was delayed significantly in fruit in air without exogenous ethylene. The expression was specific to fruit and was triggered only during ripening. Increased transcript accumulation during ripening was associated with pectin solubilization. Pectate lyase may be closely associated with pectin degradation and have an important role in mango softening.

14.9 Conclusions

Mango fruit have the potential to develop extremely desirable texture, taste and aroma that make this fruit highly appreciated and desirable. Strategies used to extend mango shelf life are based on control of ripening, ethylene action and ethylene production. Therefore, fruit are usually harvested at the mature-green stage, prior to ripening initiation, and stored and transported at low temperatures at or near the threshold for induction of chilling injury. These practices result in poor quality, immature and chill-injured mangoes on the market. Successful handling of ripening-initiated mangoes is problematic due to the fruit’s short shelf life and the increased incidence of internal breakdown that accompanies delayed harvests makes international transport of ripening mangoes almost impossible. Consequently, the export market for fresh mangoes, which expanded rapidly in the 1990s, has not continued its rapid expansion in recent years.

Future expansion of mango consumption will require an understanding of mango postharvest physiology in order to overcome the problems of CI, internal breakdown, and premature and uneven ripening. This may involve increased transport of tree-ripe mangoes in CA-equipped marine containers or in MAP. It may involve development of improved procedures for storage and ripening to offer preconditioned, ripening-initiated, ready-to-eat mangoes to consumers. It may also involve genetic transformation of mango to manipulate the progression and uniformity of ripening and softening.

References


of mangoes to extend shelf life. *Journal of Food Science and Technology* 34, 399–404.


