Postharvest Biology and Technology of Apple

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Introduction

Apple (*Malus domestica*) is commercially grown in the temperate regions of the world (Arseneault and Cline 2016). It is one of the leading fruits produced in the world, with an estimated production of 89,329,179 tons (FAOSTAT 2017). The leading countries for apple production include China, India, Iran, and Japan in Asia; the United States, Mexico, and Canada in North America; France, Italy, and Russia in Europe; Argentina and Brazil in South America; and South Africa, Egypt, and Morocco in Africa. Asia has the highest apple production and the largest cultivated area in the world, followed by Europe, North America, South America, Africa, and Australia (Ferree and Warrington 2003).

There are over 5000 known cultivars of apple grown all over the world. Each country and area has its own local cultivars. However, some cultivars are familiar all over the world. For example, the most widely grown cultivars by far are 'Golden Delicious' and 'Delicious' group (Sansavini et al. 2004). Since the apple is a long-lived tree and vegetatively propagated, cultivars known for hundreds of years ago still exist.

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S. A. Mir et al. (eds.), *Postharvest Biology and Technology of Temperate Fruits*,
https://doi.org/10.1007/978-3-319-76843-4_9

Apple fruit have one of the highest consumption rates in the world. Sensory qualities, such as firmness, flavor, and appearance, are important, but the nutritional characteristics are also crucial in apple consumption. They are good sources of vitamins, fibers, minerals, and antioxidants. Apple quality and the postharvest life can be influenced by several factors, including maturity indices, storage conditions, and postharvest treatments. The storage of apples in a controlled atmosphere (CA) is widely used because of the beneficial effect of CA in maintaining fruit quality and reducing the incidence of physiological disorders, both during and after storage. In addition, a number of technologies has been developed for extending the shelf life of apple fruit, each one having its own advantages.

Fruit Development

The fruit development in apple is characterized by the continuous enlargement of the receptacle and the subsequent fruit growth occurs mainly due to cell expansion. In the developed fruit, fructose, glucose, and sucrose are the principal sugars found in apple flesh and vary with stage of fruit development, cultivar, climate, and cultural practices (Aprea et al. 2017). The type and amount of nutrients, chemicals, herbicides, and pesticides also have a direct influence on the sugar content of the fruit. In apple, starch accumulates at a very early stage of its development and is hydrolyzed into sugars with the advancement of maturity. The starch disappearance is higher at the later stages of fruit development. The hemicellulose and dextrin are at higher levels at early stages of development, which gradually decline with the advancement of maturity. The titratable acidity of fruit steadily decreases as the fruit matures, but the absolute amount of acid present in the fruit increases just before harvest, when it slightly decreases (Warrington et al. 1999; Harker et al. 2002).

Fruit Maturity and Ripening

Fruit maturity at harvest is a critical factor affecting postharvest ripening and flavor development, and is, therefore, a determinant of postharvest handling of fruit. Harvest too early may result in pronounced lack of flavor development, while late-harvested fruit undergoes rapid firmness loss during storage (Mattheis et al. 1991). In contrast, harvest of unripe fruit enhances a number of desirable characteristics, such as increased ripening period and delayed decline in firmness, acidity, and green ground color relative to ripe fruit (Smith 1984). On the other hand, less mature fruit generally do not develop typical full flavor and, as a result, taste is often strongly impaired (Bangerth et al. 2012).

Ripening of apple fruit involves many physiological and biochemical changes. From an applied perspective, the most important of these are softening, the change of background or ground color from green to yellow, loss of acidity, conversion of

starch to sugars, formation of cuticular waxes, and synthesis of aromatic compounds (Knee et al. 1989). Many of these changes are at least partly desirable for human consumption, and the objective of apple industries is to harvest fruit at the appropriate maturity and apply postharvest technologies to control the rates of these changes in order to provide the consumer with an acceptable product.

Harvesting Time

Fruit flavor, one of the most important criteria in the selection of apples, is difficult to analyze since the constituents of flavor are a complex combination of acids, sugars, tannin, and aromatic substances. The basis of taste and flavor in apple is acidity and sweetness; it is the balance between these two components, irrespective of aroma, that primarily determines the acceptability of the fruit. The acidity and sweetness are inherited independently. Apples that are high in acid and low in sugar are quite unpalatable, being too acid; similarly, apples high in sugar and low in acid are too sweet and insipid. The acid in the mature fruit is almost entirely malic acid, and is measured either as a percentage of malic acid or pH of the fruit juice. The main sugars are fructose, sucrose, and glucose, conveniently measured by the refractive index as a percentage of total sugars in the fruit juice (Mahmood et al. 2012).

The harvesting time of apples for the fresh market differs from those planned for long-term storage. The harvest date within the maturation and ripening period has a profound effect on the storage quality of fruit. Generally, apples intended directly for consumption as fresh products are harvested at a later stage when color, sweetness, acidity, juiciness, and other quality attributes meet consumer preferences. As quality factors such as flavor and aroma of the fruit increase, the storage potential of the fruit decreases and, therefore, harvest decisions are a compromise between quality and storability of fruit. Before harvesting, several parameters, such as intended use and storage requirements, should be taken into consideration because these parameters are directly related to quality loss and shelf life of the fruit. However, when apples are harvested at a later stage, or the fully red stage, when acetonitrile and aroma biosynthesis are fully expressed, these fruits are no longer suitable for long-term storage, since postharvest decay and other losses will be high. For example, the optimal time for the harvesting of apple cv. Jonagold for long-term storage should be close to their preclimacteric respiration minimum, which coincides with the early onset of the climacteric ethylene production. However, the optimal harvesting time is largely dependent on the prevailing temperature and genotype–environmental interaction (Mahajan et al. 2014).

Some of the early varieties may be ready for harvest during August or early September in Asian countries like India, while in the United States, most apples are harvested later in September through October. Days after full bloom is widely used as a guideline for the maturity of apples. For example, Gala and Fuji apples have maturities at 110–120 and 170–185 days after full bloom, respectively. The objective

measurements which are used to determine the optimum harvesting dates for apples include pressure tests (for measuring firmness) using a penetrometer or texture analyzer (Harker et al. 2006).

Measuring the apple fruit maturity stage on the tree is not an easy task due to the various metabolic processes affected by the environmental conditions and production systems. However, decisions have to be made on the harvest date, which should be carried out during the optimum harvest window with respect to the desired fruit processing. During shelf life, the fruit quality maintenance is determined by the storage conditions and storage duration (Vielma et al. 2008). During the last few decades, extensive research has been carried out on the development of non-destructive sensors (Arendse et al. 2018). None of the planned approaches seem to provide all the information necessary to characterize fruit maturation and quality. Consequently, different measuring principles concerning fruit firmness, sweetness, but also volatile compounds and pigment contents of fruit have been recently used in parallel to improve the available information concerning the fruit maturity and quality (Zhang et al. 2017).

Half of the yearly yield of 'Jonagold' apples in West Europe is destined for long-term storage (Goffings and Herregods 1993). By selecting the ideal harvest time (between half of September and half of October) in combination with optimal storage conditions, climacteric ripening can be postponed for several months (Wills et al. 2001). Nevertheless, some ripening and quality loss during storage needs to be anticipated. Quality involves the level of color, sweetness, acidity, juiciness, and texture, the latter of which appears to be the main parameter in the evaluation of eating quality by consumers. When apples are harvested immature, they do not develop their full ripeness after storage, which leads to small size, poor fruit color, sour and starchy flavor, and a weak aroma. If harvest takes place when fruit are overmature, problems with fruit drop appear and apples can no longer be used for long-term storage, as this could lead to a soft mealy texture, off–flavors, and greasy skin (Little and Holmes 2000).

Nutritional Composition

Apples are one of the most consumed fruits all over the word. Apple contains biologically active compounds of various classes, such as pectins, dietary fibers, vitamins, oligosaccharides, triterpenic acids, and phenolic compounds (Vasco et al. 2009; Hyson 2011). It also contains a good source of vitamin C. The apple is one of the most important dietary sources of phenolic compounds. Fruits contain five major groups of phenolic compounds, namely, hydroxycinnamic acids, dihydrochalcones, flavanols, flavonols, and anthocyanins (Łata et al. 2009). The distribution of these compounds differs among varieties and tissue types.

Cooling

The rapid cooling of fruits after harvesting and subsequent storage at a low temperature is an effective means to increase the shelf life of fruits by reducing the respiration rate, ethylene production, disease development, and the overall decay process (Ganai et al. 2016). Fruit should be removed from exposure to radiant energy in the orchard to refrigeration, or at least shade, after harvest. However, the rapid cooling varies depending on the cultivar, maturity, and nutritional status of fruit. Early season varieties tend to soften more rapidly than those that mature in the later part of the harvest season. Rapid cooling appears to be more critical for fruit that are more likely to ripen quickly.

The main method of cooling apple fruit involves exposing fruit to air flow in refrigerated rooms. However, this method is slow and inefficient. Forced-air cooling and hydrocooling methods are also used to remove the field heat from fruit. In forced-air cooling, bins or cartons are stacked in patterns so that cooling air is forced through, rather than around, the individual container. In hydrocooling, apple temperatures are reduced by cold water flowing over the fruit surface, by either flooding, spraying, or immersion of the fruit in chilled water. The rate of internal cooling is related to the size and shape of fruit. This method is simple, economical, and effective.

Cold Storage

Apples are living tissues and are subjected to continuous postharvest processes, resulting in senescence and death (Kader 1999). Since complete inhibition of the physiological processes is not possible, decreasing the rate of them is an alternate task. Thus, the objective of storage is to prolong the life of the fruit tissues by slowing down the metabolic processes within the fruit that influence its shelf life. The metabolic processes that occur inside the fruit include, in particular, respiration intensity and internal ethylene production (Paull 1999). Both these processes are correlated with low temperature (Westwood 1993). High storage temperature or low relative humidity, or both, reduce storage potential, decrease apple quality, and enhance disorders (Robinson et al. 1975; Paull 1999).

The recommended conditions for commercial storage of apples are −0.5 to 4 °C, the desired temperature being a function of sensitivity to low-temperature-associated injuries. However, these disorders typically develop over long-term storage, and, sometimes, temperatures closer to 0 °C are used for 1–2 months storage of chilling-sensitive cultivars to maximize firmness retention. Usually, cold storage is used in combination with other technologies for the shelf life enhancement of apple.

Controlled Atmosphere Storage

The apple is the predominant horticultural commodity stored under CA conditions because of the beneficial effect of this technology in maintaining fruit quality and reducing the incidence of physiological disorders, both during and after storage. CA storage has greatly extended the marketing season of apples, which involves holding apples at approximately 0 °C in a facility whose atmosphere contains 1–3% O_2 and 1–3% CO_2 to slow down the respiration of the fruit (Thewes et al. 2017). Under CA conditions, apples can be stored for about 1 year without any appreciable loss of quality. The CA storage requires airtight refrigerated rooms that are sealed after apples are stored inside (Lavilla et al. 1999).

CA storage reduces respiration, ethylene production, and related biochemical and physiological changes. The dynamics of the metabolic changes accompanying initial periods of CA storage of 'Jonagold' apples have been studied by Bekele et al. (2016). The apples were exposed to 1 kPa O_2, 3 kPa CO_2; 3 kPa O_2, 3 kPa CO_2; 1 kPa O_2, 10 kPa CO_2; and air (20.8 kPa O_2, 0.03 kPa CO_2) was used as a control. The effect of air storage preceding CA storage was also investigated. In response to CA, metabolic changes were observed in glycolysis, tricarboxylic acid cycle, amino acids, and other metabolites linked with these pathways. In general, stress response patterns of immediate and delayed CA-stored apples were similar. Aspartate and 1-aminocyclopropane-1-carboxylic acid were positively correlated with O_2 concentration during the first 2 days and after 1 week of storage, respectively, while glucose-6-phosphate and some amino acids such as proline, alanine, and threonine were negatively correlated with O_2 concentration. Glutamate and succinate were correlated with CO_2 concentration.

Aroma compounds, quality parameters, and sensory evaluation of 'Fuji' apples were analyzed after 3, 5, and 7 months of cold storage in normal atmosphere (21% O_2 + 0.03% CO_2) and in three controlled atmosphere treatments, in which oxygen and carbon dioxide were held at proportions 1% + 1%, 1% + 2%, and 3% + 2%. During poststorage ripening, the apples were kept at 20 °C for 1, 5, and 10 days before analytical measurements were made. The highest volatile emission was obtained after 5 months of storage, at which controlled atmosphere conditions gave a lower concentration than normal cold storage. Ultra-low oxygen CA showed the highest ability to maintain the fruit firmness (Echeverría et al. 2004a).

In another study, Echeverría et al. (2004b) harvested 'Fuji' apples on two different dates, over two consecutive years, and stored under different atmosphere conditions: normal cold storage (21 kPa O_2 + 0.03 kPa CO_2), standard controlled atmosphere (3 kPa O_2 + 2 kPa CO_2), or ultra-low oxygen (1 kPa O_2 + 2 kPa CO_2). After 3, 5, or 7 months of storage plus 1 or 10 days of ripening at 20 °C, aroma volatile emission and quality parameters were measured. Generally, the highest total aroma emission was obtained after 5 months' storage and 1 day of ripening at 20 °C, regardless of atmosphere conditions, for early-harvested fruit. After 7 months' storage, the ultra-low oxygen atmosphere depressed total aroma volatile emission. The compounds contributing mostly to the characteristic aroma of 'Fuji' apples were ethyl 2-methylbutanoate, 2-methylbutyl acetate, and hexyl acetate, and their con-

centrations were higher the first day after removal from storage at 5, 3, and 7 months, respectively.

Both et al. (2014) assessed the profile of volatile compounds in 'Royal Gala' apples stored under CA, with O_2 levels ranging from 1.0 kPa to as low as 0.5 kPa during a period of 8 months (0.5 °C), followed by 7 days of shelf life at 20 °C. Straight and branched-chain esters exhibited a distinct pattern. The emission of straight-chain esters decreased under extremely low O_2 (0.5 kPa), while branched-chain esters were not significantly affected in such conditions. 2-Methyl-butyl acetate, a significant contributor to the 'Royal Gala' aroma, was higher in intermediate O_2 concentration, suggesting that lowering the O_2 levels to 0.7 kPa does not negatively affect the volatile composition of 'Royal Gala' apples as compared to the standard CA (1.0 kPa O_2). The remaining volatile compounds were not strongly affected by storing fruits under extremely low O_2.

To control internal browning injury and to reduce quality loss in 'Fuji' apples during storage, a stepwise CA method was applied. Both non-bagged and bagged apples during maturation were stored at 0 °C under 1% O_2 + 1% CO_2, 1% O_2 + 3% CO_2, or air for 10 months, and 1% O_2 + 1% CO_2 for 2 months, followed by 1% O_2 + 3% CO_2 for 8 months (stepwise CA). The concentrations of internal ethylene and carbon dioxide in apples kept for 24 h at 20 °C after storage under CA conditions were maintained at a low level, but there was no effect of stepwise CO_2 increase on internal gas concentrations. The non-bagged and bagged apples stored under stepwise CA were not significantly different from those stored under 1% O_2 + 3% CO_2 continuously for 10 months in terms of flesh firmness, titratable acidity, and yellowing index. However, the apples stored under stepwise CA were firmer, more acidic and greener than those stored under 1% O_2 + 1% CO_2 continuously for 10 months. Internal browning injury occurred in apples stored under 1% O_2 + 3% CO_2 continuously for 10 months, but it was suppressed completely by stepwise CA storage. The stepwise CA, increasing of the CO_2 level after holding at 1% CO_2 for the first 2 months of storage, was effective in maintaining the quality and controlling the internal browning injury in non-bagged and bagged 'Fuji' apples (Chung et al. 2005).

Modified Atmosphere Packaging

Modified atmosphere packaging (MAP) is a technique used for prolonging the shelf life of apples (Sandhya 2010). It has become a widely used food preservation technique, as it minimally affects fresh product characteristics and it is perceived as a natural and additive-free technique by consumers (Day 1996). This preservation technique consists of substituting the air surrounding the food in the package with an atmosphere with a different composition. The atmosphere composition in the package depends mainly on the type of product, and also on the packaging materials and storage temperature. As fruit are respiring products, the interaction between the product and the packaging material is particularly important. Mainly the three gases used in MAP are CO_2, O_2, and N_2. They can be used singly or in combination, with

the aim to extend the shelf life as well as preserving the optimal sensory characteristics of the apples. Some researchers have used different packaging approaches in MAP and then evaluated the effect of packaging materials on the shelf life and quality of apples. It was found that, at 45 days of modified atmosphere, CO_2 was not detected, and ethylene production was observed only in fruits stored in low-density polyethylene film. However, there was an increase in CO_2 levels in the polypropylene treatment during the last days of evaluation. This may have been due to the low permeability of the film to CO_2 and/or the maintenance of the fruit respiration rate during that period (Krugera et al. 2010). Similarly, in another study, it was found that, after 130 days of storage at 2 °C, CO_2 concentrations inside the package doubled in 'Bravo Esmolfe' apples that were packed in polypropylene (Rocha et al. 2004).

With regard to the ethylene production, when comparing the modified atmosphere treatments, it was verified that the high-density polyethylene film showed the lowest ethylene production at 135 days of storage, possibly because of the higher concentrations of CO_2inside the package than those of the other treatments. High CO_2 concentrations are able to reduce the biosynthesis of ethylene, through both the reduction of ATP availability (De Wild et al. 1999) and the inhibitions of 1-aminoc yclopropane-1-carboxylic acid synthase and 1-aminocyclopropane-1-carboxylic acid oxidase (Mathooko 2001). Thus, the high-density polyethylene film used was able to effectively delay the onset of climacteric peak. However, fruits in the control, low-density polyethylene, and polypropylene treatment groups showed an increase in ethylene production at 135 days, followed by a decrease at 225 days, according to the climacteric behavior.

MAP showed a significant effect on the firmness of apples during storage. The MAP-treated samples showed higher firmness values as compared to the controls. Apples stored under modified atmosphere lost less weight than those stored under normal atmosphere (Rocha et al. 2004). Thus, mass loss can be one of the causes of deterioration and decrease in visual quality of fresh products over time, which can lead to dehydration, wilting, loss of firmness, loss of crispness, and nutritional quality reduction, as well as senescence promotion, which reduces the enzymatic and regulatory processes of the fruit (Ben-Yehoshua and Rodov 2003). Viškelis et al. (2011) measured fruit texture and color parameters before and after 8 months of modified atmosphere conditions. Fruit firmness changed slightly when the carbon dioxide concentration in the modified atmosphere was increased. The amounts of soluble solids and sugars in fruits were stable. Fante et al. (2014) observed that storage of the Brazilian 'Eva' apple cultivar under modified atmosphere allowed the preservation of quality for up to 7 months.

Use of 1-Methylcyclopropene

It is widely recognized that 1-methylcyclopropene (1-MCP) is able to influence fruit ripening and improve poststorage quality in most climacteric fruits (Fan et al. 1999; Jung and Watkins 2014). 1-MCP blocks ethylene receptors and prevents

ethylene effects in plant tissues for extended periods (Sisler and Serek 1997). The beneficial effects of 1-MCP on respiration and ethylene production inhibition, delay of fruit ripening, and alleviation of certain ethylene-induced postharvest physiological disorders have been well recognized.

Controlling ethylene production and action is a primary goal in the postharvest management of apples. 1-MCP, an ethylene inhibitor, can delay fruit softening, yellowing, respiration, loss of titratable acidity, and, sometimes, the reduction in soluble solids, as well as the development of some physiological disorders, although volatile aroma compounds can also be inhibited (Watkins et al. 2000). The response of fruit to 1-MCP may be affected by cultivar and fruit maturity. Volatile production by apples is also inhibited by 1-MCP (Rupasinghe et al. 2000). These results are consistent with the view that volatile production is regulated by ethylene, and consumer studies on the acceptability of 1-MCP-treated fruit will be required to ensure that flavor is not unacceptably compromised.

DeEll et al. (2002) studied the efficacy of 1-MCP treatments at various temperatures and durations, to evaluate the effects of 1-MCP on 'Cortland' and 'Empire' apple quality after storage. 'Cortland' apples treated with 1-MCP at 3 °C showed improved firmness retention (>63.0 N) with at least 9 h of treatment, whereas those treated at either 13 or 23 °C showed improved firmness retention with at least 6 h of treatment. 'Empire' apples treated with 1-MCP showed improved firmness retention (>67.5 N) with only 3 h of treatment, regardless of temperature, but those treated at 3 °C for 3 h no longer had the full firmness advantage after an additional 7 days at 20 °C. Treatment with 1-MCP for 3 h at any of the temperatures significantly reduced the incidence of superficial scald in cv. 'Cortland'.

'Fuji' apple harvested 10 days before normal harvest (H_1) and at normal harvest (H_2) were untreated or treated with 1 μL L^{-1} 1-MCP and stored at 0 °C for up to 30 weeks by Lu et al. (2012). Fruits from H_1 were firmer and had higher titratable acidity but lower soluble solids concentrations than those from H_2. 1-MCP treatment delayed loss of firmness and titratable acidity in fruit from both harvests during storage. Superficial scald incidence was decreased by 1-MCP treatment, but flesh browning was unaffected. H_2 fruit had higher total phenolics, flavonoid, and glutathione content, as well as total antioxidant activity, than H_1 fruit at harvest and throughout storage. 1-MCP-treated fruit tended to have higher levels of these constituents than untreated fruit in peel, but not in flesh tissues. These results suggest that fruit harvested at the mature stage have better integral quality with 1-MCP treatment.

The efficacy of 1-MCP treatment on apple cultivars and maturity was investigated by Jung and Watkins (2014). Apple cultivars 'McIntosh', 'Cortland', and 'Empire' were categorized by internal ethylene concentrations at harvest, treated with 1 μL L^{-1}1-MCP, and the internal ethylene concentrations of individual fruit followed at 30-day intervals during air storage at 0.5 °C for 90 days. Internal ethylene concentrations at harvest ranged from <0.5 μL L^{-1} to ≥100 μL L^{-1}, 51 < 100 μL L^{-1}, and 10 < 50 μL $L^{-1}$for 'McIntosh', 'Cortland', and 'Empire', respectively. 1-MCP treatment resulted in a decrease of internal ethylene concentrations in the fruit of all cultivars by day 30 after harvest. During subsequent storage,

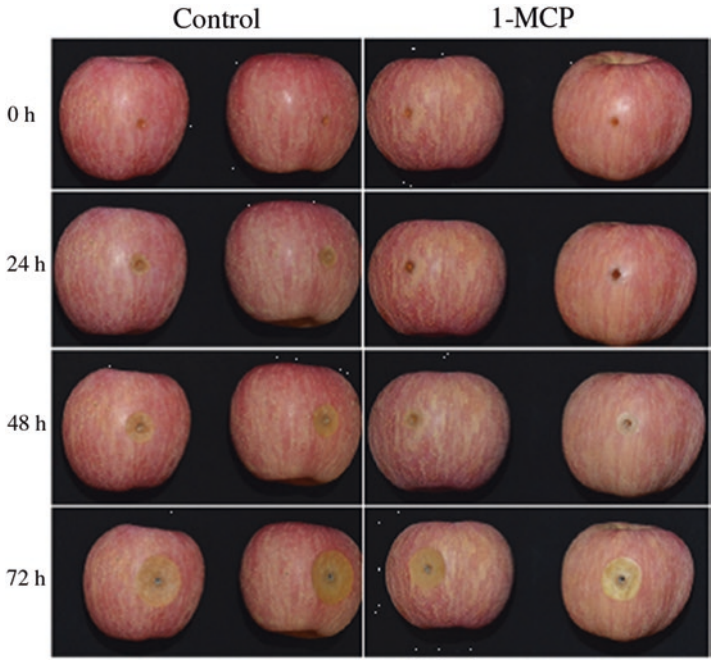

Fig. 1 Effect of 5 μL L^{-1} 1-MCP on blue mold rot caused by *P. expansum* in apple fruit. (Source: Li et al. 2017)

internal ethylene concentrations remained low in fruit, with <1 μL L^{-1} at harvest, but in 'McIntosh' and 'Cortland' increased in proportion to internal ethylene concentrations at harvest, but not in 'Empire'. The importance of initial internal ethylene concentrations in fruit on the persistence of 1-MCP inhibition of ethylene production was confirmed in a further experiment, in which internal ethylene concentrations in untreated and 1-MCP-treated 'McIntosh' and 'Empire' apples were measured for up to 194 days. 1-MCP also decreased 1-aminocyclopropene-1-carboxylic acid concentrations in the fruit.

The effect of 1-MCP on inhibiting postharvest blue mold of apple fruit caused by *Penicillium expansum* and suppressing the growth of *P. expansum* in vitro was investigated by Li et al. (2017). The treatment of 5 μL L^{-1}1-MCP significantly decreased disease severity of apple fruit caused by *P. expansum* and suppressed the mycelial growth and spore germination of *P. expansum*(Fig. 1). After treatment with 1-MCP, lower integrity of plasma membrane in the spores of *P. expansum* was detected, higher levels of reactive oxygen species in the spores and malondialdehyde in the mycelium was observed, indicating that 1-MCP treatment enhanced oxidative damage to *P. expansum* and destroyed the integrity of plasma membrane of spores.

The effects of calcium (Ca) in combination with 0.6 and 1.0 μL L^{-1}1-MCP on flesh firmness and aroma volatiles has been investigated on 'Fuji' apples stored at

room temperature by Lu et al. (2018). The results from electronic nose detection and texture evaluation showed that 1-MCP (0.6 L^{-1}) presented an interactive effect with Ca application on promoting volatile emission and reducing softening. The amount of branched and straight esters and total aroma volatiles, as well as related enzymes, including aromatase-related acyltransferase, alcohol dehydrogenase, and pyruvate decarboxylase, were significantly higher in fruit treated with 1-MCP 0.6 + Ca than 1-MCP 1.0 after 50 and 100 days' storage. There was no significant difference between the two treatments 1-MCP 0.6 + Ca and 1-MCP 1.0 in maintaining fruit firmness. Fruit treated with 1-MCP 0.6 + Ca had higher aroma quality than 1-MCP 1.0 according to sensory evaluation, but showed no significant difference in terms of texture quality. The 1-MCP of reduced concentration combined with calcium treatment had a synergetic effect on the aroma formation and softening inhibition of apple fruit, resulting in advanced sensory quality.

In another study, Gago et al. (2016) investigated the effect of calcium chloride and 1-MCP alone or combined on the incidence and development of physiological disorders and the delay of ripening of apples during storage (at 0.5 °C in air) and subsequent shelf life at room temperature ≈22 °C. 'Golden Delicious' apples were harvested in ten orchards and treated with calcium chloride (1.5%, w/v), 1-MCP (625 nL L^{-1}), calcium chloride plus 1-MCP, and without any treatment (control). The 1-MCP treatment was effective in preventing superficial scald, slowing softening, increasing soluble solids content, and reducing electrolyte leakage and color changes associated with ripening, during storage, and shelf life. However, this treatment also enhanced the development of bitter pit, especially the moderate and severe symptoms in some orchards, which may be attributable to orchard cultivation techniques. Calcium chloride alone and calcium chloride plus 1-MCP reduced bitter pit intensity by reducing moderate and severe incidence, maintained higher lightness, and had firmer fruit than the control. Postharvest dips of 'Golden Delicious' apples in $CaCl_2$ before 1-MCP application (CA + MCP) may be a good solution to prevent scald and reducing the bitter pit, which is enhanced by 1-MCP alone.

Tomic et al. (2016) compared the effects of 1-MCP and diphenylamine postharvest prestorage treatments on changes in the sensory properties of 'Granny Smith' apples during cold storage, along with subsequent keeping of fruit at room temperature. 1-MCP samples showed relatively low rates of juiciness, cohesiveness, hardness, crunchiness, greenness, and sourness reduction during the observed period of storage as compared to control and diphenylamine samples. The highest level of freshness loss during the storage period was observed in control samples, which undergo changes in quality after 9 months of storage at such a level that the fruit were decayed and not suitable for consumption. The most resistant to scald forming were 1-MCP-treated apples. No scald was found after 9 months of cold storage. The treatment of 'Granny Smith' apples with 1-MCP extended the storage time in standard normal atmosphere storage for at least 3 months without significantly losing freshness, even 2 weeks after removal from cold storage, and is more effective in preserving sensory attributes related to apple freshness when compared with the diphenylamine treatment.

The use of 1-MCP in combination with CA can further improve the storability of fruits. It must be kept in mind that only good quality apples with long storage potential should be cold stored in controlled atmospheres. Immature or overripe apples should not be held in this manner (Bai et al. 2005). DeEll et al. (2016) investigated the effects of multiple 1-MCP treatments on fruit quality and disorder development in apples, with a second 1-MCP treatment applied after several months of CA storage. 'McIntosh', 'Empire', and 'Northern Spy' apples were harvested from commercial orchards and cooled overnight to 3 °C. 1-MCP (1 μL L^{-1}) was applied 2 days after harvest and then again to half of the fruit after 4 months of CA storage. 'Northern Spy' apples also received a single 1-MCP treatment after 4 months of CA storage. Similarly, fruit from all cultivars were also not treated with 1-MCP. 'McIntosh' and 'Empire' were held at 3 °C and 'Northern Spy' at 0 °C for 9 months in CA storage (2.5 kPa O_2 + 2 kPa CO_2 for 'Empire', 2.5 kPa CO_2 for 'Northern Spy', and 2.5 up to 4.5 kPa CO_2 for 'McIntosh'). Overall, 1-MCP reduced internal ethylene production and improved firmness and acidity retention in all apple cultivars. The addition of a second 1-MCP treatment after 4 months of CA storage further improved firmness retention in 'McIntosh' and late-harvested 'Empire' apples after 7 days at room temperature. 'Northern Spy' apples treated with 1-MCP had lower incidence of external CO_2 injury, regardless of 1-MCP treatment timing. Multiple 1-MCP treatments had varying effects on the incidence of core browning; late-harvested 'McIntosh' treated twice with 1-MCP exhibited the highest incidence of core browning, while late-harvested 'Empire' treated twice had less core browning than those that were not treated. 'Northern Spy' treated only at harvest time had more core browning compared to those treated only or also after 4 months of CA storage and non-treated fruit. 1-MCP treatment had no significant effect on the incidence of internal browning in 'McIntosh' or 'Empire' apples.

The quality of 'McIntosh' and 'Empire' apples after treatment with 1-MCP and delayed CA storage has been investigated by Watkins and Nock (2012). 1-MCP suppressed the internal ethylene concentrations of the fruit during the14-day period before CA conditions were applied, but the extent of suppression was lower in fruit with high ethylene concentrations at harvest. Untreated fruit of both 'McIntosh' and 'Empire' exposed to CA storage after 2 days maintained firmness similar to 1-MCP-treated fruit, but only for 1 day of shelf life. 1-MCP treatment resulted in firm fruit after delayed CA up to 14 days, but the most consistent effects were found in 'Empire', which has lower internal ethylene concentrations than 'McIntosh'. Orchard block differences in internal ethylene concentration affected the persistence of 1-MCP effects on firmness. The effects of 1-MCP treatment on storage disorders were inconsistent, although slight increases in the risk of external carbon dioxide injury were detected. Rapid treatment of fruit with 1-MCP after harvest can afford storage operators more freedom to delay CA storage application, but attention to cultivar, fruit maturity, and susceptibility of fruit to storage disorders must be considered.

The effect of 1-MCP on ripening and concentrations of total phenolics, flavonoids, anthocyanins, and total antioxidant activity of 'Empire' apples was studied by Fawbush et al. (2009). Fruit were stored in air for up to 5 months, and in CA of 2 and 3 kPa O_2 (2 kPa CO_2) at 0.5 and 2.2 °C for 4.5 and 9 months. Ripening was delayed by 1-MCP treatment in both air and CA storage, as indicated by lower

internal ethylene concentrations and slower softening than in untreated fruit. Total phenolic, flavonoid, and anthocyanin concentrations, as well as antioxidant activity, were relatively stable during air and CA storage. In air-stored fruit, the total phenolic concentrations were higher in the peel of 1-MCP-treated fruit than in the control fruit, but slightly lower in the flesh of 1-MCP-treated fruit. In CA-stored fruit, interactions between O_2 partial pressures, temperature, and storage duration were detected, but, overall, few consistent trends were observed. However, flavonoid concentrations were higher in the flesh of 1-MCP-treated than untreated fruit kept in 2 kPa O_2 while anthocyanin concentrations, only measured in the peel, were not affected by 1-MCP treatment. Ascorbic acid concentrations declined in both peel and flesh tissues of untreated and 1-MCP-treated fruit stored in air, while changes of ascorbic acid concentrations in CA-stored fruit were inconsistent.

It is recognized that 1-MCP is able to influence fruit ripening, reduce superficial scald, and improve poststorage quality in apples. However, 1-MCP may also increase disorders such as bitter pit and diffuse skin browning. Gago et al. (2015) investigated the effect of 1-MCP (625 nL L^{-1}) and three different maturity stages (early, middle, and late harvest date) on the incidence and development of physiological disorders and ripening delay during storage at 0.5 °C and subsequent shelf life at room temperature ~22 °C, in 'Golden Delicious' apples. 1-MCP treatment of 'Golden Delicious' was effective for slowing softening and reducing electrolyte leakage and color changes associated with ripening (lightness and hue parameters). 1-MCP inhibited superficial scald and significantly reduced rot; however, this treatment enhanced the development of bitter pit in some orchards. The harvest date did not influence scald, bitter pit, and firmness, but decreased weight loss, total phenols, soluble solid content, and antioxidant activity from the second to third harvest. The application of 1-MCP, 3 days after cold storage, to 'Golden Delicious' apples, reduced ripening and superficial scald, did not induce diffuse skin browning, but increased bitter pit incidence.

Coatings

The postharvest quality of perishable horticultural produce likes apples changes rapidly due to accelerated rates of transpiration, respiration, and ripening. In order to overcome these changes, there is a need to develop alternative strategies, such as the use of bioactive edible films and coatings. The concept of using edible films or coatings to extend the shelf life of fresh fruits has been receiving considerable attention in recent years. The use of coatings and films formulated with bioactive compounds in order to convey new functionalities or extending the shelf life of apples offer a multitude of benefits to both consumers and the food industry.

Dávila-Aviña et al. (2014) incorporated olive leaf extracts in chitosan for the development of bioactive edible films and coatings for various apple cultivars and reported that weight loss and decay area significantly increased in uncoated films, and the reverse was the case for coated samples. The addition of olive leaf extract to

chitosan coating films meaningfully reduced the gradual decline in total phenolics, flavonoids, and antioxidants.

Apples cv. 'Bravo de Esmolfe' was coated with a polysaccharide-based or a protein-based coating. Alginate and gelatine coatings at different concentrations plasticized with glycerol and carboxymethyl cellulose plus sucroesters coatings plasticized with mono/diglycerides were tested. The 2% alginate and 5% gelatine coatings significantly reduced weight loss, thus maintaining fruit firmness and, thereby, preserving fruit freshness. The effects of those coatings also include the improvement of appearance and imparted an attractive natural looking gloss to the fruit (Moldao-Martins et al. 2003).

The effect of nanochitosan-based coating on the quality and storage life of apple cv. 'Golab Kohanz' was studied by Gardesh et al. (2016). The results showed that coating significantly reduced weight loss, respiration rate, ethylene production, and peroxidase activity of the samples compared with the control. Coating had a significant effect on polyphenol oxidase activity, slowed down the softening process, and improved the flesh color after the climacteric peak. Nanochitosan coating with 0.5% chitosan concentration significantly extended the quality and prevented the weight loss of the fruits, over the entire storage period. Edible coating formulated with candelilla wax and fermented extract of tarbush was applied for immersion to evaluate its effects on the shelf life and quality of 'Golden Delicious' apples in marketing conditions stored at room temperature. Edible coatings were able to reduce significantly the change in appearance, weight loss, water activity, and firmness of the apples. The results of the sensory evaluation demonstrated that edible coating with fermented extract of tarbush did not alter the appearance and taste of apples (De León-Zapata et al. 2015).

Apple fruits were sprayed with six different coating formulas, including chitosan–water wax coating, in addition to the uncoated fruits. The bioactive substances drastically changed in uncoated rather than coated fruits. Conversely, weight loss and decay area significantly increased in uncoated fruits. Amazingly, the addition of olive leaf extract to chitosan coating films meaningfully reduced the gradual decline in total phenolics, flavonoids, and antioxidants. Olive pomace extract recorded the lowest influence on anthocyanins during storage at 4 ± 1 °C for 35 days. Also, both olive leaf and pomace extracts enhanced the coating distribution, due to no pores being observed in the fruits' surfaces. Decidedly, the incorporation of olive leaf extracts with a proportion of 2% into chitosan coating solution was the best formula compared with the others. Thus, olive waste extracts, incorporated into chitosan fruit coatings, relatively improve the nutritional quality of apple fruits during postharvest (Khalifa et al. 2017).

The shellac and several coating formulations, including candelilla wax and shellac carnauba, were applied on different cultivars of apples, viz., 'Delicious', 'Fuji', 'Braeburn', and 'Granny Smith'. The shellac coating resulted in maximum fruit gloss, lowest internal O_2, highest CO_2, and least loss of flesh firmness for all of the varieties. The 'Granny Smith' cultivar with shellac had low internal O_2 (<2 kPa) with both freshly harvested and 5-month-stored apples, and the freshly harvested 'Braeburn' had high internal CO_2 (25 kPa). This excessive modification of internal gas induced an abrupt rise of the respiratory quotient, prodigious accumulation of

ethanol in both ‘Braeburn’ and ‘Granny Smith’, and flesh browning at the blossom end of ‘Braeburn’. In addition, the shellac coating gave an unusual accumulation of ethanol in freshly harvested and 5-month-stored ‘Fuji’. Candelilla and carnauba–shellac coatings maintained more optimal internal O_2 and CO_2 and better quality for ‘Fuji’, ‘Braeburn’, and ‘Granny Smith’ apples, although even these coatings may present too much of a gas barrier for ‘Granny Smith’. In general, the gas permeabilities of the coatings were useful as an indicator of differences in coating barrier properties, but did not account for differences in pore blockage (Bai et al. 2003).

Physiological Disorders

Bitter Pit

Bitter pit occurs mainly during the period of cold storage and is characterized by brown corky spots just under the skin, which dehydrate with time and form depressions in the skin of fruit (de Freitas et al. 2015). The susceptibility of fruit to bitter pit has three components: genetic, climatic, and orchard management. Even within susceptible cultivars such as ‘Golden Delicious’, seasonal differences are common, i.e., hot dry summers are associated with higher disorder incidence than cooler summers. Bitter pit is a physiological disorder of apples that has been related to calcium deficiency in the fruit (Saure 1996). Preharvest calcium sprays are commonly applied to reduce bitter pit development (Ferguson and Watkins 1989). Rapid cooling and CA storage may also reduce its development during storage.

Senescent Breakdown

Senescent breakdown incidence is related to the harvesting of overmature fruit or fruit with low calcium concentration (Prange et al. 2011). It can be exacerbated by storing fruit at higher than optimal temperatures. Its incidence has also been aggravated by low calcium levels in the fruit or prolonged storage (Saks et al. 1990). This disorder affects the skin and manifests as diffuse browning and roughening of the skin. The incidence of senescent breakdown can be reduced by the application of calcium chloride, harvesting fruit at a less mature stage, rapid cooling, and reducing the duration of storage.

Superficial Scald

Superficial scald is one of the most common physiological disorders causing brown or black patches on fruit skin that appear during or after storage on certain cultivars of apples (Lurie and Watkins 2012). Scald reduces significantly the market quality

of fruit and causes economic losses for the tree fruit industry. Various factors, including cultivar, climate, and harvest date, affect susceptibility of fruit to the disorder (Emongor et al. 1994). Du et al. (2017) reported that the antioxidant and redox system, phenyl propanoid metabolism, ethylene biosynthesis, allergens, sulfur amino acids containing proteins, and programmed cell death have a direct link to the scald development. Diphenylamine is usually applied with a fungicide to reduce decay incidence, and calcium salts may also be included at the same time to reduce bitter pit or senescent breakdown. The low oxygen and low ethylene CA storage also reduce the scald incidence.

Chilling Injury

Chilling injury is among the most common disorders recognized by the apple industry. It is physiological damage to fruit cell membranes that may occur due to adverse environmental conditions during the growing season, transportation, distribution, or storage. The membrane damage leads to secondary effects, such as ethylene production, increase in respiration, and an alteration of the cellular structure, causing the fruits to be more susceptible to diseases. This injury first appears as a slight browning discoloration of the flesh, sometimes accompanied by core browning. The chilling injury disorder of apples can progress quickly to make the fruit unmarketable (Watkins and Jackie Nock 2004). It is difficult to detect and diagnose chilling injuries at an early stage, as the injured produce often looks sound, as long as it remains at low temperatures. Chilling injury symptoms only become apparent as the temperature rises (ElMasrya et al. 2009). Damage in fruit cell membranes due to chilling injury affect normal firmness and lead the fruit to gain a spongy texture.

Pathological Disorders

The main postharvest diseases of apples which develop during storage are blue mold caused by *Penicillium* species and gray mold caused by *Botrytis cinerea*. These species enter fruit primarily through cuts, stem punctures, or bruises. Blue mold and gray mold are usually controlled during long-term storage by the postharvest application of benzimidazole fungicide, thiabendazole, or diphenylamine.

Conclusion

The shelf life of apples is affected by a number of factors, such as harvesting operations, storage conditions, etc. They have a relatively long storage life compared with other fruits crops. However, the main problem of apple storage is the fruit firmness,

which is one of the most important determinants of fruit quality and consumer acceptability. As apple crops are harvested in a short period of time, storage techniques are developed to maintain fruit quality and increase the period of supply to the consumer market. In addition other techniques, such as modified atmosphere packaging, use of 1-MCP, coatings, etc., have been exploited to increase the shelf life and postharvest quality of apple.

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