Postharvest Biology and Technology of Strawberry

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Introduction

Strawberry belongs to the family Rosaceae and the genus *Fragaria*. It is cultivated in plains as well as in the hills up to an elevation of 3000 m in humid or dry regions. They are native to the temperate regions of the northern hemisphere, and developed varieties are widely grown throughout the world. In India, strawberry cultivation extends from temperate to subtropical regions, and it behaves as an annual in subtropical regions and perennial in temperate regions. Strawberry is produced in 71 countries worldwide and is among the highest-yielding fruit crops (Husaini and Abdin 2007). The annual production of strawberry fruit is 8.11 million tons with the highest production in the United States, Mexico, Turkey, Spain, and Egypt (FAOSTAT 2017). Botanically, it is described as an aggregate fruit, wherein many one-seeded achenes are embedded in a swollen, fleshy, red receptacle. The sizably voluminous, fleshy receptacles are the succulent edible portions of the fruit. Strawberry for commercial purposes has a red color outside and inside shading ranging from white to dark red. Fruit shape and size varies depending upon factors like variety, environmental conditions under which it was grown, planting area, fertilizer dose, etc. (Smith et al. 2003).

Strawberries are sought all over the world due to their high nutraceutical profile and commercial value (Bhat and Stamminger 2015). Strawberry is not only famous for its cute appearance, but also for its spectacular nutritive figures, which include essential nutrients and beneficial phytochemicals. Strawberries are considered a potentially good source of vitamin C and are rich in a wide array of bioactive compounds, such as polyphenols, flavonoids, anthocyanins, and tannins (Battino et al. 2009; Tulipani et al. 2009; Giampieri et al. 2012, 2013). However, the composition of strawberries varies depending on the individual genotypes, cultivar, environment

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factors of the growing regions, maturity stage during harvest, as well as pre- and postharvest agricultural practices (Aaby et al. 2012).

Strawberries must be picked at or near the fully ripe stage to obtain the best eating quality. Their respiration rate is high and increases two- to three-fold when the temperature is between 10 and 20 °C. The exceptionally high respiration rate can be attributed to fast postharvest deterioration. Harvest season, maturity stage, temperature, duration of storage, and packaging influence the quality and shelf life of strawberries (Mingchi and Kojimo 2005; Panda et al. 2016). Strawberry fruit has a very short shelf life and senescent period, due to its susceptibility to mechanical injury, excessive texture softening, physiological disorders, and infection caused by several pathogens that can rapidly reduce the quality of fruit, and which make marketing a challenge (Vu et al. 2011). Several preservation techniques such as refrigeration, modified atmosphere packaging, and heat treatments have been studied to extend the shelf life of fresh strawberries.

Maturity and Ripening

Fruit maturity is the main index for the sorting and harvesting of strawberry crop. In the traditional method, the fruit changing to red indicates ripeness of strawberries. Liming and Tiezhong (2007) developed a new method to confirm the mature stage, which is the red degree from light red to black red on the strawberry surface. The quality components of strawberry include appearance (color, shape, size, freedom from defects, and decay), firmness, flavor, and nutritional value. Color, firmness, flavor, nutritive value, and safety of strawberries are related to their composition at harvest and compositional changes during postharvest handling. These factors have been identified as important contributors to the overall quality of strawberry fruit (Shamaila et al. 1992). Montero et al. (1996) evaluated various quality parameters to indicate the optimum harvest date for the cultivar 'Chandler'. The results showed that the best quality characters were within the period of 28–35 days from fruit set. From the data, it is possible to predict that the strawberry fruits are at the best stage of development and ripening on day 28 from fruit set.

Generally, flavor is one of the most important properties that give commercial value to fruits. Strawberry flavor is balanced by sugars and acids expressed in ripe fruits. The attractive colors are due to sugar derivatives of anthocyanidins. Pigments are important esthetic components, being natural indicators of ripeness. Due to the large genotypic variations in strawberry composition, it is possible to develop new cultivars having good eating quality and can withstand postharvest handling (Kader 1991). The texture of fruits is governed by structural polysaccharides (pectic substances). The loss of firmness during ripening is a major factor determining strawberry fruit quality and postharvest shelf stability. The complex relationship between carbohydrate composition, cell structure, and the physical property of the whole tissue is further complicated by increase in cell volume, which continues throughout ripening (Manning 1993). As strawberry fruit ripens, an increase in anthocyanin content is accompanied by decreases in firmness and chlorophyll content. The increase in anthocyanin content coincides with the induction of the activities of phenylalanine ammonia-lyase and uridine diphosphate glucose (Given et al. 1988). Acids can affect flavor directly and are also important in processing. They affect the formation of off-flavors, gelling properties of pectin, and also regulate cellular pH. The predominant acids in strawberry are citric and malic acids. Glycolic and shikimic acids are also present, but in lower quantities.

Strawberry has been classified as a non-climacteric fruit, showing no increase in the respiration rate or ethylene production during ripening. It is also because of the inability to accelerate strawberry fruit ripening by the external application of ethylene or ethylene-releasing compounds. Despite low levels of this hormone in the fruit, ethylene presents a characteristic pattern of production during different developmental stages. It is moderately high in green fruits, decreases in white fruits, and, eventually, increases at the red stage of ripening (Perkins-Veazie et al. 1996; Leshem and Pinchasov 2000; Iannetta et al. 2006). Strikingly, this last increase is accompanied by an enhanced respiration rate which resembles that of climacteric fruits at the onset of ripening (Iannetta et al. 2006). Moreover, postharvest color changes in three-quarters, colored and full-red strawberries have driven a few researchers to propose that strawberry might be a climacteric rather than an absolute non-climacteric fruit. The compositional changes with ripening include increase in soluble solids, total sugars, total ascorbic acid, pH, and water-soluble pectins; and decrease in acidity, total phenols, total pectin, cellulose, and activities of polyphenol oxidase and peroxidase (Spayd and Morris 1981).

Many pre- and postharvest factors influence the composition and quality of strawberries. These include genetic, environmental factors and cultural practices. Sunny days and cool nights produce better flavored strawberries than cloudy, humid, and warm nights (Sistrunk and Morris 1985). Inadequate light intensity reduces ascorbic acid, pH, color, and soluble solids. Excess levels of nitrogen applied to plants decrease firmness, total soluble solids, and flavor (Sistrunk and Morris 1985).

Composition of Strawberry

Strawberries are a nutritious fruit with putative health benefits, because of their rich content of nutrients, with unique color, flavor, and taste. Strawberry fruit is good source of vitamin C and folate. Moreover, it is also a source of several other vitamins, such as thiamin, riboflavin, niacin, vitamin B_6, vitamin K, vitamin A, and vitamin E, though to a lesser extent (Giampieri et al. 2012).

Strawberry is rich in polyphenols and, as it is consumed in high quantities, it can be a valuable source of phenolic compounds in the diet. The main phenolic compounds in strawberries are anthocyanins, flavonols, flavanols, derivatives of hydroxycinnamic acid, and ellagic acid (Aaby et al. 2007, 2012). Many studies have reported the total anthocyanin content to be from 150 to 600 mg/kg of fresh weight (Lopes-da-Silva et al. 2002; Castro et al. 2002). Some investigators have found values of up to 800 mg/kg of fresh weight (Garcia-Viguera et al. 1998).

Flavanols are the only class of flavonoids that do not occur naturally as glycosides. They are present in strawberries in monomeric (catechins) and polymeric forms, called condensed tannins or procyanidins (Aaby et al. 2007). Strawberries also contain a selection of phenolic acids that emerge as derivatives of hydroxycinnamic acid (i.e., caffeic acid) and hydroxyl benzoic acid (i.e., gallic acid) (Mattila et al. 2006; Aaby et al. 2007).

Phytosterols are plant-derived sterols that have structural and functional similarities to cholesterol. Jimenez-Escrig et al. (2006) mentioned that strawberry was recognized as a fruit source of phytosterols in the Spanish diet, providing approximately 0.7 mg of the total phytosterols obtained from a daily intake of 6 g of strawberries.

Cold Storage

Strawberries are extremely perishable fruit with a storage life of 1–2 days at room temperature (Garcia et al. 2011). Temperature management is one of the most important factors in minimizing the deterioration of the strawberry fruit. Higher storage temperatures result in higher respiration rates and shorter storage periods, which are, in turn, associated with the loss of fruit quality (Ayala-Zavala et al. 2004; Cordenunsi et al. 2005). The most pervasive technique for keeping up quality and controlling decay is rapid cooling after harvest and storage at low temperatures (Han et al. 2004).The shelf life of fresh strawberries at cold temperature (0–4 °C) is usually around 5 days (Vargas et al. 2006). It is, therefore, important to apply an appropriate postharvest treatment to delay respiration, prevent physical damage and dryness, and to restrict fungal decay in order to extend shelf life.

Low temperature can extend the marketable life of fruits by delaying the natural aging process considerably (Bohling 1986). Also, at low temperature, the development of postharvest pathogens is slow, while rapid growth occurs when the fruit is stored at ambient temperature (Sommer et al. 1973). Among other postharvest techniques, a rapid postharvest cooling process is the most important factor to maintain the quality and enhance the shelf life of fresh strawberries (Kader 2002). Many researchers (Nielsen and Leufvén 2008; Choi et al. 2016; Giuggioli et al. 2015; Caner et al. 2008) have reported that strawberries should be kept at low temperatures near 0 °C and at high humidity after harvest, as they have a fast metabolism which leads to rapid senescence. Harvey et al. (1980) reported that strawberry temperatures during commercial transport actually ranged from 2 to 9 °C.

Controlled Atmosphere Storage

Controlled atmosphere (CA) storage involves maintaining an atmospheric composition that is different from air composition. Atmosphere modification should be considered as a supplement to the maintenance of optimum ranges of temperature and relative humidity for each commodity in preserving the quality and safety of fresh fruits. Almenar et al. (2006) examined the effect of controlled atmosphere storage to extend the shelf life of 'Reina de los Valles', a wild strawberry fruit variety, and concluded that the shelf life of berries can be extended by exposing the fruit to cold environment and an adequate atmosphere composition. After storing fruits in different atmosphere compositions, the results showed that a 10% CO_2 and 11% O_2 combination can efficiently prolong the shelf life of wild strawberries by maintaining the quality parameters within acceptable values, through inhibiting the development of *Botrytis cinerea*, without significantly modifying consumer acceptance. Li and Kader (1989) found that, during the storage of strawberry fruit cv. 'Selva' at 2 °C, O_2 level of 0.5% and CO_2 in the range of 15–20% was more effective in decreasing the rate of respiration. Reduction in the rate of respiration can help in minimizing the compositional changes during storage, which could better maintain the taste and nutritional value of fruit. The main benefit from CA for strawberries is the control of gray mold caused by *Botrytis cinerea*, which is the most serious postharvest disease of strawberry fruit (Maas 1984). Couey et al. (1966) found that decay caused by *Botrytis cinerea* was decreased by reducing the ambient O_2 concentration to 0.5% or less. Also, Couey and Wells (1970) found that decay control in CA storage is due to elevated CO_2levels ($\geq$10%). CA storage has also been tested for insect control (Aharoni et al. 1979). Concentration ranges of 5–10% O_2 and 15–20% CO_2 have been recommended as optimal for CA storage of strawberries at a storage temperature of 0 °C (Kader 1992). Moreover, in CA storage, CO_2 and O_2 may be adjusted to maximize their beneficial effect on individual quality parameters, depending on the anticipated temperature during postharvest handling (Nunes et al. 1995).

Modified Atmosphere Packaging

An inexpensive tool that is an alternative to CA storage is the use of modified atmosphere packaging (MAP). MAP may be used to maintain the favorable environment within a sealed package until the product is sold, and it can be a supplement to proper temperature maintenance in the effort to delay ripening (Giuggioli et al. 2015). MAP can be carried out by sealing fresh strawberries in polymeric film packages that modify the O_2 and CO_2 levels within the package atmosphere (Zheng et al. 2008). Several authors (Fishman et al. 1996; Hirata et al. 1996) concluded that combinations of polymeric and perforated films could potentially provide adequate fluxes of O_2 and CO_2 for commodities such as strawberries having high respiration rates. Emond and Chau (1990) presented the concept of perforation-mediated MAP and Emond et al. (1991) simulated the use of this packaging system in strawberries. Sanz et al. (2002) assessed the capacity of the microperforated packaging system for strawberry and found that fruit quality was kept for 10 days at 2 °C. Choi et al. (2016) reported that the shelf life of 'Maehyang' strawberry could be extended by CO_2 treatment alone or a combination of CO_2 and MA. The optimal gas composition of the MAP test for strawberries was found to be 2.5% O_2 and 16% CO_2 (Sandhya 2010; Giuggioli et al. 2015).

Modeling of transport and biological phenomena occurring inside modified atmosphere packages has turned into a useful tool in MAP design. It allows the prediction of package performance through the analysis of the interaction that happens between produce respiration, O_2 and CO_2 permeation through packaging film, and storage temperature fluctuations (Rennie and Tavoularis 2009). Rennie and Tavoularis (2009) tested two distinctive respiration rate models in a simulation of perforation-mediated MAP of strawberries (cv. Oso Grande) and found significant differences in the resulting gas composition inside the package, reinforcing the importance of obtaining accurate respiration rate data for the given variety and conditions of the stored commodity. Hertog and Banks (2003) focused on the relevance of a systematic characterization of different products respiration rate, as a function of at least O_2, CO_2, and temperature, to enable a fundamental approach to MAP design. Respiration rate models encountered in the literature take into account gaseous composition and temperature effects (Torrieri et al. 2010). Barrios et al. (2014) developed a model for strawberry (cv. San Andreas) and respiration rate was determined as a function of O_2 and CO_2 concentrations and temperature. Temperature and atmosphere gaseous composition (O_2 and CO_2 concentrations) influenced the respiration rate of strawberry. Temperature had a higher impact on respiration rate than gaseous concentration. A 72–82% decrease in respiration rate was achieved when temperature was reduced from 23 to 10 °C for all gaseous mixtures studied. Higher O_2 concentrations increased the respiration rate at all temperatures, regardless of CO_2 concentrations.

The impact of equilibrium atmosphere packaging technology on improving quality attributes including pH, acidity, Brix, color, and texture profile analyses of fresh strawberries depends on the characteristics of the packaging material and the choice of appropriate quality parameters. In equilibrium modified packaging, atmosphere modifications depend on adjustment of the atmosphere inside the package, accomplished by the natural interaction between two processes, the respiration of the strawberries and the transfer of gases through the packaging, that prompts to an atmosphere richer in CO_2 and lower in O_2. Equilibrium-modified atmosphere packaging using various lid films was shown to maintain the initial quality of fresh strawberries for at least 10 days storage. Compared with the linear low-density polyethylene, cast polypropylene and polyethylene terephthalate/ethylene vinyl alcohol/polyethylene low acetyl fractions were much more successful in maintaining strawberry quality during storage. Reduction in packaging film permeability was accompanied by retention in the quality of strawberries (Caner et al. 2008).

Edible Coatings

The application of edible coatings has been extensively studied in strawberry shelf life enhancement (Tapia et al. 2008; Aday and Caner 2010). An edible coating consists of a thin layer which is formed directly on the surface of product as a protective cover. These materials act as barriers that produce modified atmospheres, minimizing respiration rates, reducing moisture exchange, delaying deterioration, controlling microbial growth, and carrying functional ingredients like antioxidants, antimicrobials, and other preservatives (Geraldine et al. 2008; Aday and Caner 2010). Considering economical issues and functional advantages, fruits with high economic value and short postharvest life like strawberries are the main products benefitting from coating application.

Guerreiro et al. (2015) studied the effect of edible coatings based on sodium alginate and pectin enriched with essential oils on the shelf life extension of strawberries, and reported that coatings were effective in reducing microbial spoilage of fresh fruits and could be stored with good sensory properties for a period of 7 days. Edible active coatings based on pectin, pullulan, and chitosan incorporated with sodium benzoate and potassium sorbate were employed to improve the quality and shelf life of strawberries (Trevino-Garza et al. 2015). Edible active coatings based on polysaccharides improved the physicochemical, microbiological, and sensory characteristics, increasing the shelf life of strawberries from 6 (control) to 15 days (coated fruits) (Fig. 1).

Fan et al. (2009) developed a novel edible biofilm in which the fruit surface was covered with the microorganism *Cryptococcus laurentii* in combination with alginate, glycerol, palmitic acid, glycerol monostearate, and cyclodextrin. Edible alginate-based biofilms containing *C. laurentii* as an active compound acted as an antagonist and reduced microbiological decay, decreased weight loss, maintained the firmness of strawberries, and preserved the commercial quality of the fruit throughout the storage period of 20 days. Sogvar et al. (2016) studied the effects of an edible coating based on natural *Aloe vera* gel in combination with ascorbic acid at different concentrations on strawberry fruit and found that treatment may be a useful biochemical method to delay weight loss, had higher soluble solids content, vitamin C concentrations, and titratable acidity. The coatings reduced the population of total aerobic mesophilic organisms, yeasts, and molds during storage. To increase the shelf life of strawberries, the effect of edible films made of polymers like candelilla wax and beeswax were studied by researchers (Velickova et al. 2013; Oregel-Zamudio et al. 2017). Candelilla wax in combination with a biocontrol microorganism *Bacillus subtilis* HFC103 strain is a promising alternative to reduce postharvest deterioration of strawberry (Oregel-Zamudio et al. 2017). Chitosan and addition of beeswax as separate or composite coatings showed remarkable results. Chitosan-based coatings prolonged the storage period of strawberries for 7 days at a temperature of 20 °C and relative humidity of 53%. The coatings modified the respiration rates of the strawberries and slowed down their metabolism, as shown by the retention of the color and texture of the tissue (Velickova et al. 2013). Eshghi et al. (2014) developed a novel technique of using nanochitosan suspension (50–110 nm) at 4 ± 1 °C with 70 ± 5% relative humidity for 20 days. The nanochitosan-based edible coating improved the shelf life more than 2.5-fold compared with the uncoated samples. Sensory analysis of strawberries based on visual damage showed that nanochitosan coatings delayed fruit senescence associated with color changes, off-flavor development, and dehydration.

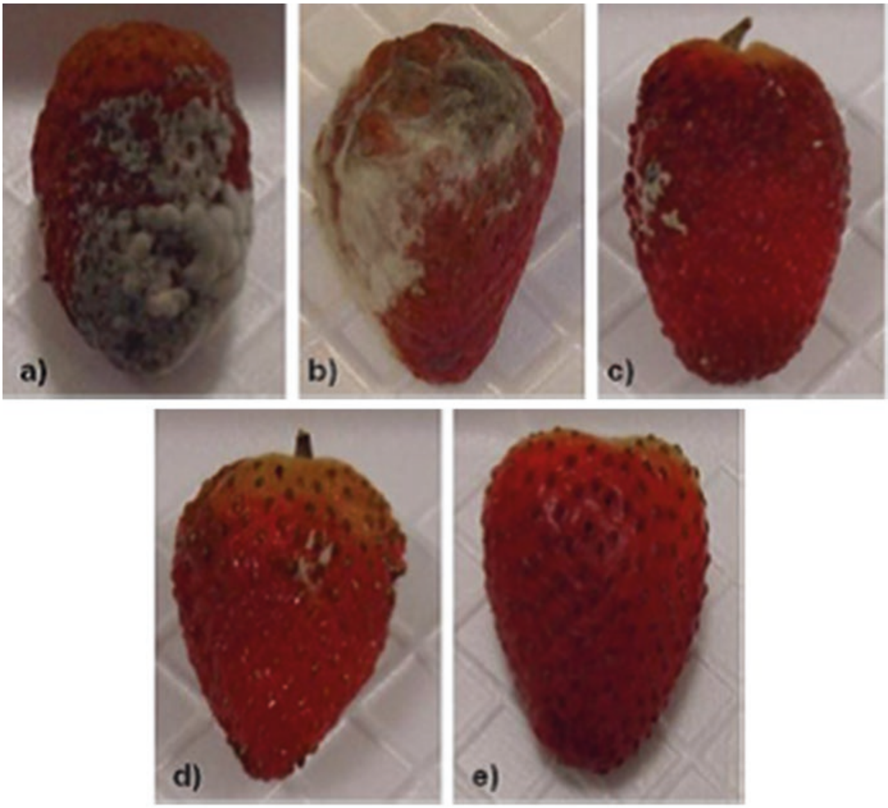

Fig. 1 Effect of edible coatings on the decay rate of strawberries stored at 4 °C for 15 days: (**a**) control, (**b**) antimicrobial treated, (**c**) pectin edible active coatings, (**d**) pullulan edible active coatings, (**e**) chitosan edible active coatings (Trevino-Garza et al. 2015)

Strawberries are highly prone to in-transit vibration damage causing skin abrasion and bruising. From these abrasions and bruises on the tissues of berries, microbes are able to enter, which, in turn, causes the degradation of berries and reduce the shelf life. Dhital et al. (2017) studied the impact of edible coatings for extending the shelf life of 'Chandler' variety subjected to simulated vibrations of local transportation. Curcumin and limonene were used as natural antimicrobials and coatings were set up from their liposomes and overcoated with methyl cellulose. Among different coating types, liposomes were found to be the most effective for the preservation of strawberry quality and the limonene liposome was observed to be effective in controlling fungal decay on strawberries for a prolonged period of storage. Pagliarulo et al. (2016) reported that peony extracts (*Paeonia rockii*) in chitosan coating was able to effectively slow the growth of the native fungal microflora on strawberries. The microbiological tests showed a high antifungal activity of the edible active coating at relatively low concentrations of peony extract.

Considering the remarkable effectiveness and security, edible coatings serve as a very promising tool for the shelf life enhancement of strawberries.

Gamma Irradiation

Processing by ionizing radiations such as gamma accelerated electron beams and X-ray has become an effective means of preserving fresh fruits (Fan et al. 2003). Food preservation by ionizing radiation, especially from cobalt-60 gamma sources and electron accelerators, has received much attention over the past few decades and detailed investigations have been undertaken into the possible use of this process for solving the problems encountered with fruits. Many investigations on this subject have been carried out and they established that the shelf life of fresh strawberries can be extended by postharvest irradiation treatments (Quaranta and Piccini 1984; Hussain et al. 2007).

Gamma irradiation treatments proved to be effective in reducing microorganisms in fresh strawberries, and an upper dose of 2.0 kGy was found to reduce fungal infections without affecting the quality of fruit (O'Connor and Mitchell 1991). Hussain et al. (2007) also confirmed that a gamma irradiation dose of 2.0 kGy was effective in delaying the mold growth and extending the storage life of strawberry by 8 days under refrigerated conditions. Also, a combination of carboxymethyl cellulose coating and irradiation at a dose of 2.0 kGy was found to be significantly effective in maintaining the quality, and delaying the decay and appearance of the mold growth for up to 18 days during refrigerated storage (Hussain et al. 2012). Hence, it can further facilitate the marketing of the strawberry fruit to distant markets. The efficacy of gamma irradiation on minimizing the decay of fruits may be associated to its ability of penetration deep into tissues and destroying spoilage microorganism harbored in wounds or inside host tissues, thus preventing or minimizing the decay process by inhibiting the growth of these microbes (Barkai-Golan 2001).

Vachon et al. (2003) studied the effect of gamma irradiation and various edible coatings on fresh strawberries. Their investigation showed that the gamma irradiation treatment and coating process were effective for reducing mold infections and, thus, extending the shelf life of fresh strawberries when stored at 4 ± 1 °C. Gamma irradiation of the strawberries at a mean dose of 1.5 kGy produced better results in terms of mold growth than coating the strawberries with a formulation based on calcium caseinate. The irradiation of the protein coating solution prior to the coating process of non-irradiated strawberries reduced the level of fruit contamination during the storage period compared to non-irradiated coating solution. However, no synergistic effect was observed when strawberries were irradiated at 1.5 kGy and coated with an irradiated caseinate-based formulation. The effect of low-dose gamma irradiation (1 kGy) and active equilibrium-modified atmosphere packaging on the quality of strawberries stored at 4 °C for 21 days was investigated by Jouki and Khazaei (2014). The results showed that the gamma irradiation protected strawberries from spoilage for up to 2 weeks in active equilibrium-modified atmosphere packaging at 4 °C without any attack of fungus or any change in their external appearance. It was concluded that low-dose gamma irradiation in combination with active equilibrium-modified atmosphere packaging will enable food processors to deliver larger amounts of high quality strawberry with extended shelf life. Studies have shown that strawberries treated with gamma irradiation exhibited higher antioxidant activity and less decay than controls (Maraei and Elsawy 2017). This behavior of phenolic compounds may be due to the destructive processes of oxidation and gamma radiation, which are able to break the chemical bonds of polyphenols, releasing soluble phenols with low molecular weight and increasing these compounds with antioxidant action (Adamo et al. 2004).

Methyl Jasmonate

Jasmonic acid and its methyl ester (methyl jasmonate) are cyclopentanone compounds and are regarded as naturally occurring plant growth regulators. Strawberries treated with methyl jasmonate in conjunction with ethanol showed higher antioxidant activity, total phenolics, and anthocyanins than those treated with ethanol or the controls (non-treated). The strawberry maintained an acceptable overall quality for the longest storage duration. Postharvest life was longer for those berries treated with methyl jasmonate–ethanol and methyl jasmonate than those treated with ethanol or control fruit (Ayala-Zavala et al. 2005). Mukkun and Singh (2009) studied the role of methyl jasmonate in strawberry cv. Pajaro fruit ripening by monitoring its endogenous concentration in fruit at various stages of development and the effects of exogenously applied methyl jasmonate at these stages on ethylene biosynthesis. Endogenous methyl jasmonate detected in fully ripe, half-ripe, and white ‘Pajaro’ strawberry fruit was trans-methyl jasmonate. The concentration of trans-methyl jasmonate in strawberry was significantly higher at the white stage (162 ng g^{-1}) and declined to 1.3 ng g^{-1} as the fruit developed to the fully ripe stage. Higher concentrations of endogenous methyl jasmonate in the white stage of strawberry fruit and its decline as the fruit ripens indicates that methyl jasmonate may play an important role in modulating fruit ripening. The ethylene production was highest when applied at 50 μM. It also increased the activities of 1-aminocyclopropane-1-carboxylic acid synthase and 1-aminocyclopropane-1-carboxylic acid oxidase, depending on the concentration of methyl jasmonate applied, as well as on the fruit developmental stage.

1-Methylcyclopropene

1-Methylcyclopropene (1-MCP) is a competitive inhibitor of ethylene action which binds to the ethylene receptor to regulate tissue responses to ethylene.1-MCP inhibits ethylene action in plants at very low concentrations and extends the life of fruits

(Jiang et al. 1999; Ku and Wills 1999). Jiang et al. (2001) treated strawberry (cv. Everest) with 1-MCP at various concentrations from 0 to 1000 nL/L at 20 °C for 2 h. 1-MCP treatment maintained strawberry firmness, color, and also reduced ethylene production. It delays fruit color and firmness that can be attributed to the decrease in ethylene production. However, disease resistance was decreased in fruits treated at high 1-MCP concentrations (500 and 1000 nL/L). Treatment with 1-MCP also inhibited phenylalanine ammonia-lyase activity, which is a key enzyme in the biosynthesis of phenolics (Cheng and Breen 1991), and decreased anthocyanins and phenolic compounds. The low levels of phenolics in the fruit treated at the highest concentration (i.e., 1000 nL/L) of 1-MCP could account for the reduced resistance to natural infection. Aguayo et al. (2006) reported that 1-MCP alone had no effect on firmness and appearance quality of fresh-cut strawberry fruit. However, 1-MCP had a synergistic effect in slowing down softening and deterioration rates when combined with a calcium chloride dip and controlled atmosphere storage at 3 kPa O_2 and 10 kPa CO_2.

Active Packaging

Active packaging can be outlined as a mode of packaging within which the package, the product, and the environment interact to extend shelf life or enhance safety or sensory properties, at the same time retaining the quality of the product (Suppakul et al. 2003). Active packaging involves setting absorbers inside the package (Guynot et al. 2003), and includes concepts such as oxygen and carbon dioxide scavenging and generation, and moisture regulation systems (Suppakul et al. 2003). Strawberries are known to be sensitive to humidity. Strawberry fruit can lose water during storage, which can be trapped within the headspace of the package and supports microbial growth and undesirable textural changes (Mahajan et al. 2008). Moisture-absorbing sachets containing silica gel can be utilized to control this problem. Aday and Caner (2011) assessed the potential effects of liquid chlorine dioxide, zeolite, and silica gel sachet systems combined with active packaging treatments in preserving the quality of fresh strawberries during storage at 4 °C. Chlorine dioxide treatments had a beneficial effect on firmness, total soluble solids, and color values. The minimum weight loss was obtained in strawberries with sachet treatments. Treatments delayed the senescence process, with resulting minimum CO_2 levels at the end of the storage. In another study, Aday et al. (2011) reported the effectiveness of carbon dioxide and oxygen scavengers to maintain the quality characteristics of fresh strawberries. The fruit was treated with oxygen and carbon dioxide scavengers throughout storage at 4 °C for 4 weeks. The use of active packaging resulted in slow accumulation of carbon dioxide and consumption of oxygen. The package headspace with CO_2 absorbers had the lowest CO_2 accumulation and O_2 absorbers resulted in constant O_2 levels throughout storage. The results showed that oxygen and carbon dioxide scavengers could be a feasible way for maintaining quality, controlling decay, and, therefore, extending the shelf life of strawberry.

Furthermore, active packaging could be used satisfactorily during the distribution and storage chain.

A novel nanopackaging material with lower relative humidity, oxygen transmission rate, and high longitudinal strength was synthesized by blending polyethylene with nanopowder. When used as a package for strawberries at 4 °C, it was able to maintain sensory, physicochemical, and physiological quality of strawberry fruits at a higher level compared with polyethylene bags (Yang et al. 2010). The result indicated that nanopacking displayed distinguished quality benefits appropriate to the preservation of fresh strawberry and will likely assist commercial producers and retailers in extending the shelf life of products over a broader range.

Postharvest Diseases and Disorders

Strawberries have a very limited shelf life due to their susceptibility to fungal decay, loss of firmness, loss of brightness and color darkening, mechanical injury, texture softening, physiological deterioration, and microbiological decay (Velde et al. 2013; Vu et al. 2011). A number of fungal species are known to cause postharvest diseases of strawberries, like gray mold rot, *Rhizopus* rot, and anthracnose. The latter two diseases are major problems at warmer temperatures, whereas the former usually develops under refrigerated conditions.

Gray mold rot caused by *Botrytis cinerea* is the most serious disease of strawberry fruits. The development of this disease during postharvest handling results from preharvest infections, while postharvest infections occur occasionally when healthy fruits are oppressed against the lesion of a diseased fruit. Control of *B. cinerea* is normally carried out by the regular application of fungicides (Wedge et al. 2007). Application of the biocontrol yeast *Rhodotorula glutinis* with salicylic acid provides a more effective control of postharvest gray spoilage and natural spoilage of strawberries (Zhang et al. 2010). Chitosan beads loaded with lavender essential oil can extend the mold-free storage life of strawberry stored at 7 °C from 2 days (control) to 8 days (Sangsuwan et al. 2016). Jin et al. (2017) found that UV-C treatment directly activated disease resistance against gray mold caused by *B. cinerea* in strawberry fruit.

Rhizopus rot caused by *Rhizopus stolonifer* is another severe postharvest disease of strawberries (Romanazzi et al. 2001). Protective fungicidal sprays are helpful for the control of rot. The combination of antagonistic yeast *Cryptococcus laurentii* and short hot water dips (at 55 °C for 30 s) could be an alternative to chemicals for the control of postharvest *Rhizopus* rot on strawberries (Zhang et al. 2007).

Anthracnose caused by either *Colletotrichum gloeosporioides*, *C. acutatum,* or *C. fragariae* is responsible for serious damage on foliar and fruiting plant parts, as well as for root necrosis (Freeman et al. 1998). Wedge et al. (2007) reported that cyprodinil + fludioxonil and azoxystrobin fungicide treatments were effective in reducing anthracnose in strawberries.

Conclusion

Strawberry is a highly perishable fruit with huge nutraceutical and commercial value. Thus, quality maintenance and shelf life enhancement of strawberry is very important. Harvesting at the proper stage of maturity is essential for optimum quality and, often, for the maintenance of this quality after harvest. There are many challenges concerning the safety and quality of strawberries which are faced during pre- and postharvest stages. The application of new technologies can help to maintain fruit quality, thereby extending their shelf life and decreasing the postharvest losses.

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