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Chapter

Postharvest Quality Management of Strawberries

Muhammad Azam, Shaghef Ejaz, Rana Naveed Ur Rehman, Mumtaz Khan and Rashad Qadri

Abstract

Strawberry fruit (*Fragaria* × *ananassa*), a genus of the Rosaceae family, is the most commonly consumed berry fruit crop worldwide and is valued for its unique flavor and nutritional quality. Strawberries are expensive and filled with vitamins, fiber, and antioxidants. The susceptibility of strawberry fruit to postharvest diseases and decline of quality attributes increases after harvest and through extended storage, and as a consequence changes in physiological and biochemical parameters. Exogenous spraying, coating, or dipping was widely used to prolong the shelf life of strawberries. The temperature, atmospheric gas, and exogenous postharvest treatment (spraying, coating, or dipping) contribute to the maintenance of the fruit's postharvest quality. Previous studies examined the effects of exogenous treatments on strawberry quality. In this review, we will thus discuss the influence of postharvest treatment on strawberry postharvest shelf life and quality management during storage conditions.

Keywords: strawberry fruit, edible and essential oil coatings, exogenous chemicals, control atmosphere, physiological and biochemical changes, quality and shelf life

1. Introduction

Strawberry (*Fragaria* × *ananassa* Duch.) is perennial herb plant that belongs to family *Rosaceae* and genus *Fragaria*. Most of the members in genus *Fragaria* are characterized by polyploidy and their cultivation in temperate zones of the world. In addition to this, other members of *Rosaceae* family (such as apple, plum, pear, and others) are climacteric in nature; however, strawberry is nonclimacteric since fruit maturation and ripening is almost independent from ethylene biosynthesis. The modern cultivated strawberry fruit is octoploid hybrid (8n) in genetic makeup, containing 56 chromosomes. This hybrid was developed by successful cross between Chilean strawberry (*Fragaria chiloensis*) and meadow strawberry (*Fragaria virginiana*) in 1780 in USA.

Botanically, fruit is not berry but it is aggregate accessory since fleshy part is derived from central receptacle that holds floral ovary. The outermost fruit surface contains imbedded achene (average 200 on each strawberry) that encompasses seeds inside. Strawberry is one of the most adorable fruit crop often characterized by its unique organoleptic properties and nutraceutical importance. Fresh slices of strawberry fruit are rich source of flavonoids, fibers, vitamins, potassium, and diverse array of phenolic acids such as hydroxycinnamic and hydroxybenzoic acids [1].

Strawberry, although nonclimacteric, is one of the most perishable fruit. During ripening, various physiological, morphological, and compositional changes transform inedible strawberry fruit into a highly cherished fruit. Loss of chlorophyll, gain of anthocyanin, increase in sugars, ascorbic acid and pectin, and reduction in acidity, phenolic and cellulose occur during the ripening stage. Also, fruit softening due to disassembly of cell wall mainly due to dissolution of middle lamellae occurs during this phase. Finally, fruits are harvested at fully ripened stage for its markedly favorable organoleptic features. However, these desirable fruit characters are accompanied by high respiration and tissue softening rate, water loss and susceptibility to physical damage and, hence, fungus infestations, particularly *Botrytis rot* and *Rhizopus rot*. Therefore, it is of utmost importance to develop and strictly adhere to strawberry-specific postharvest management procedures to ensure fruit quality and quantity for longer period.

The postharvest practices are aimed at slowing the respiration rate and water loss, maintaining fruit firmness and minimizing the growth of pathogens. Strawberry fruits have a narrow marketable window of 7–10 days if special care is taken. The objective of this chapter is to compile and comprehensively describe the general code of practices which should be adopted during harvest and postharvest operations of strawberry to reduce the losses and consequently resolving the quality management issues.

1.1 Uses, nutritional value, and health benefits

Fresh fruit of strawberry is rich source of magnesium and potassium which help smooth circulation of blood pressure and relaxation of nerves. Several reports have shown that vitamin C is more abundant in strawberry than in other fruits including citrus. Strawberry also contains niacin that is well renowned for its positive effects against cardiovascular diseases.

Strawberry contains high content of anthocyanins, flavonols (myricetin and quercetin derivatives), flavanols (catechin, epicatechin, proanthocyanidin B1 and B2), dihydrochalcones (phloridzin) [1, 2]. Fisetin (7,3′,4′-flavon-3-ol) is another novel flavonol biosynthesized in the strawberry fruit through branchy and intricate phenyl-propanoid pathway. Fisetin plays major role for improving antioxidant activity and anticancer ability by blocking PI3K/AKT/mTOR pathway [3]. The fleshy fruit of strawberry contains significant quantity of hydrolysable tannins (ellagitannins and gallotannins). The estimated content of ellagitannin ranges 8–23 mg per 100 g fresh weight of strawberry fruit. After ingestion of ellagitannins, they reach in stomach, followed by small intestine and finally in colon where they are catalyzed into urolithins by gut bacteria [4].

Deep red coloration of strawberry fruit is bestowed by pelargonidin-3-glucoside and cyanidin-3-glucoside (anthocyanin). Besides this, four minor pigments with purple shade anthocyanin have also been reported such as (1) epicatechin (4α → 8) pelargonidin 3-O-β-glucopyranoside, (2) catechin (4α → 8) pelargonidin 3-O-β-glucopyranoside, (3) epiafzelechin (4α → 8) pelargonidin 3-O-β-glucopyranoside, and (4) afzelechin (4α → 8) pelargonidin 3-O-β-glucopyranoside [5, 6]. Anthocyanin contributes nearly 75% of total polyphenols in the strawberry fruits. The total anthocyanin content ranges 20–60 mg 100^{-1} g fresh weight of strawberry fruit that is rapidly absorbed in the body after catalytic activity of phase II enzymes in small intestine or liver.

1.2 World production

Poland has the largest area under strawberry cultivation; however, due to utilization of technological advances and advantage of climatic conditions, USA is the

largest producer of strawberry fruit by producing more than 1,420,570 tons from 21,242 hectares during 2016 (**Figure 1**). California produces 88% of total strawberry fruit produced in USA with cultivation area 35,915 acre, generating $316,394,000 worth revenue by exporting to Japan, Canada, and other European countries [7].

In USA, it is mainly grown along the coastal belt of California followed by Florida, Oregon, North Carolina, Michigan, and Washington. However, temperate climate of California allows the year-round growing of strawberry thus producing more strawberry per hectare than any other state [8]. Whereas the climatic condition of other states limits the cultivation of strawberry for only 5 months.

Followed by USA, Mexico, Egypt, Turkey, Spain, Russia, and Poland are the major producers in the world. Major producing areas in Mexico include Guanajuato, Michoacán, Jalisco (Central Mexico), and Baja California. During last decade (2004–2014), exported volume of strawberries in Mexico augmented nearly four times to that of 2003 [9].

1.3 Cultivation

Strawberry can be cultivated on wide range of soil types from sandy to clay loam. Well-drained sandy-loam soil of pH (5.5–6.5), enriched with organic matter and sufficient water-holding capacity is excellent for plant growth. Alkaline (pH > 8.5) or heavy clayey soils with poor drainage are not suitable for planting strawberry and affect plant growth by encouraging disease development. Strawberry plants are very sensitive to saline soil. The root system of strawberry plant is shallow; that is, 20–30 primary active roots are present in the upper 30–40 cm layer of well-drained soil. Depending on soil condition, fertilizer with an NPK ratio at 1–2–1 or 1–3–1 should be applied at the time of soil preparation. Planting strawberry along with application of perlite, peat-moss, or other organic media enhances the plant growth.

Commercially, there are three different methods used for cultivation of strawberry plants. The most common planting method is matted-row-system. Strawberry plants are cultivated at 45–60 cm plant-to-plant distance on raised beds and runners have sufficient space to grow from the mother plants. This method is cheap and requires least labor for agronomic practices. Spaced-row system is the second type of strawberry planting system. Plants are cultivated on narrow ridges (20 cm high) at the same distance (45–60 cm); however, runners are less likely to

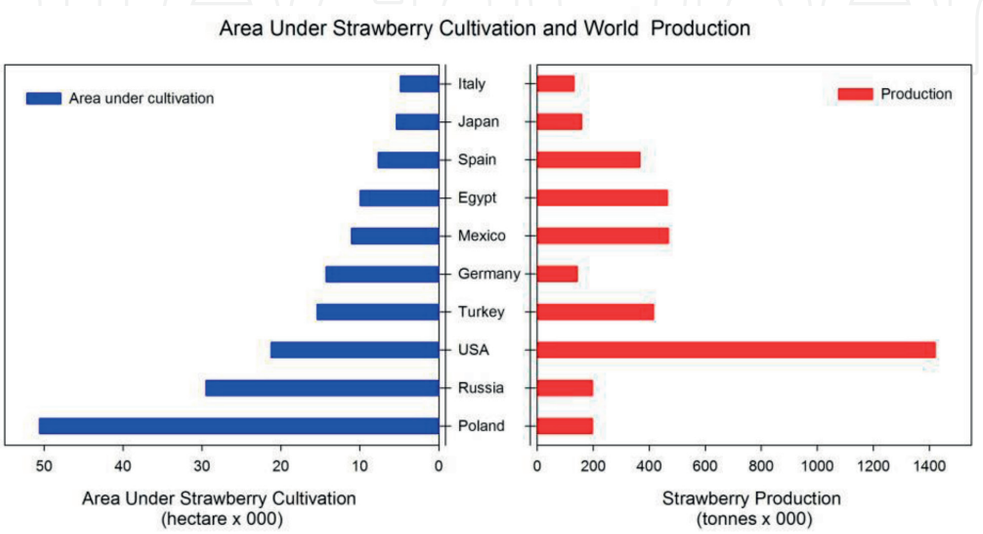


Figure 1.
Strawberry area and production in the world.

grow further. Runners are pruned after growth length reaches up to 12 cm. Though it is labor intensive method, it produces high-quality fruit with large berry size and less disease incidence. Third planting system is often suitable for the hilly areas. The runners are completely removed from the mother plant to yield high and better quality. This method is also labor intensive. After removal of runners, mother plants flourish quickly and produce high yield.

After soil preparation, organic mulch (dry straw) or plastic sheet is spread over the ridges leaving plant cultivation holes in aisles. It helps to maintain the soil temperature, moisture content, and suppress the germination of weeds or other unwanted plants. Soon after transplantation of the suckers, water is applied through drip irrigation or other available source. Water logging due to frequent irrigation or too late watering affects plant growth, consequently berry yield. Sprinkler irrigation system has also gained popularity due to water saving and being cheap installation. Low doses of fertilizer can also be applied by drip or sprinkler (foliar application) irrigation system (fertigation).

1.4 Fruit growth, development, and maturation

Strawberry cultivars can be classified on the basis of their bearing habit as June-bearing, ever bearing and day-neutral cultivars. "June-bearing" strawberry cultivars produce flower when day-length is short (<12 h). And "ever-bearing" cultivars bloom only when day light is available for relatively long durations (>12 h). Similarly, day-neutral cultivars are independent from day-length but flower only when the temperature range is 18–24°C. Hence, choice of cultivars depends on geographical location, yield potential, marketability, and disease susceptibility [10].

Generally, strawberry flower is hermaphrodite having white petals with 22–25 yellow-colored anthers and central disk of stigma placed over receptacle. Although flowers are self-fertile, viability of stigma surpasses the duration of pollen liberation from anthers that increases the chances of cross-pollination. The basal end of the stamen contains nectar that helps to recruit the pollinator. Usually, stigma receptivity lasts from 7 to 10 days, while pollens are available during 1–3 days. Flowers are produced in clusters and the earliest flower sets first fruit with largest size due to having more number of ovules (**Figure 2**).

Poor pollination results in reduced number of fruit set. Sometimes, small and misshaped fruits are produced due to poor pollination. Hence, honey bee cages (approximately, one large bee hive for 1 acre) are recommended for commercial cultivation of strawberry that can increase fruit set (up to 10%) and significantly reduced share of deformed berries.

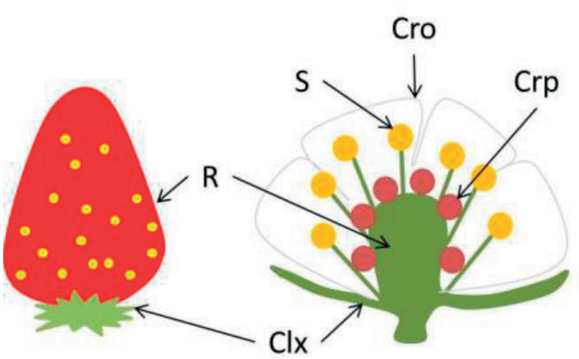


Figure 2.
Morphological representation of flower and fruit parts. S, stamen; Cro, corolla; Crp, carpel; R, receptacle; and Clx, calyx.

After fruit set, fertilizer should be applied as per schedule and special care should be given for disease prevalence. *Verticillium wilt* is a soil-borne disease for strawberry plants and precultivation fumigation with methyl bromide has been suggested to be the best remedy. However, methyl bromide has been banned due to its destructive effects in the ozone layer [11]. Foliar applications of micronutrients (trace elements) boost the plant growth, improve berry quality, and enhance crop yield. Boron application improves flower size, increases pollen quantity, and enhances root elongation. Magnesium deficiency is characterized by leaf marginal scorch and reduction in calcium causes immature and undersize fruit. These deficiency symptoms can be recovered by preflowering foliar application of magnesium nitrate and calcium nitrate. Depending on varietal characteristics and genetic makeup, the fruit with different morphological features is produced (**Figure 3**).

1.5 Biochemical changes during fruit ripening

As fruit matures, sucrose is continually provided by photosynthetic reactions. As a result, sucrose invertase activity increases during developmental stages. Accumulated sucrose in immature fruit tissues is hydrolyzed into monosaccharide (such as fructose and glucose). These three carbohydrates are major constituent of soluble sugars of fully ripened strawberries. It is estimated that nearly 150% of these accumulates have been observed as fruit fully ripens [12]. These massive transformations of primary metabolites initiate carbon fluxes into intricate and branchy biosynthetic pathways of secondary metabolites. This metabolic activity of fruit ripening can be observed by late accumulation of red pigmentation (pelargonidin 3-glucoside).

The fluctuation in the profile of bioactive compounds also depends on environmental cues. Temperature is positively correlated with soluble solid contents (SSC) and vitamin C; however, harvesting of late-season fruits showed inverse relationship between SSC and temperature. Similarly, ascorbic acid decreased gradually during postripening era. However, further studies have suggested that fluctuations in SSC content are independent from photosynthetically active radiation (PAR) [13, 14]. This phenomenon advocates that these events are driven genetically. Microarray analysis has demonstrated that gene expression plays key role in ripening of red (60% upregulation) and green (40% downregulation) fruits. *Polygalacturonase 1* (*FaPG1*) is a fruit-softening gene that induces softening by disassembling cell wall, middle lamella, and consequently reducing the firmness [15].

Besides this, other dramatic changes in the content of fatty acids, organic acids, ketones, aldehydes, esters, alkanes, and sugars took place as fruit ripens. Biosynthesis of diverse volatile compounds and their precursors begins after full maturation of the fruit. As fruit color begins to change during ripening (green-to-red), emission of volatile compounds also initiated. Major volatiles reported in several studies include methyl ester, hexanoic acid, ethyl ester, butanoic acid, 1,6-octadien-3-ol,

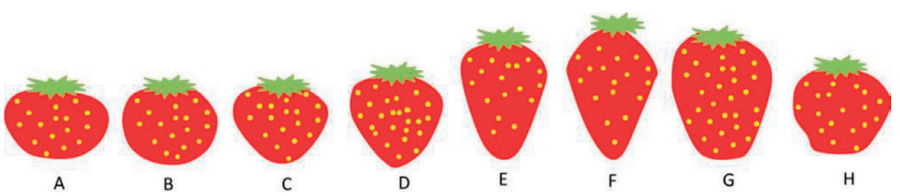


Figure 3.
Depending on morphological characteristics of strawberry fruits, it can be divided into eight shapes. A, oblate; B, globose; C, globose conic; D, conic; E, long conic; F, necked; G, long wedge; and H, short wedge.

4-methoxy-2,5-dimethyl-, 3,7-dimethyl-(-linalool), and 1,6-octadien-3-ol. It is estimated that more than 350 volatile compounds are produced for generating aroma and other organoleptic attributes in strawberry fruit [16–18].

1.6 Harvesting and handling management

The delicate heart-shaped strawberry is a nonclimacteric fruit and it ripens while it is attached to parent plant. Harvesting and handling operations are the key determinant of fruit quality. Loss of quality is due to high rate of metabolic activities and fruit sensitivity to fungal decay mainly gray mold (*Botrytis cinerea*) and/or rhizopus rot (*Rhizopus stolonifer*). Fruit is also very fragile to water loss, mechanical injuries, and skin bruising due to soft-textured berry without any protective rind (exocarp).

Strawberry should be harvested when fruit reaches appropriate shape and size according to varietal characters. Other biochemical parameters such as total soluble solid, vitamin C, and titratable acidity can also be assessed by taking field samples. The fruit can be harvested when skin colors fluctuate with 50–75% pink or red pigmentation, depending on local or distant markets.

After drying of dew drops, morning is the best time for harvesting strawberry fruit; and harvesting in afternoon should be avoided. Strawberry fruit intended for export consignments should not be harvested when temperature of berry exceeds 25°C. Since warm fruit might sustain significant pressure during handling, it needs more energy for precooling to remove the field-heat. After immediate rainfall, wet fruit should not harvest as it enhances the greater incidence of fungal diseases (*Botrytis gray mold*). Moisture and temperature are the major determinant of deciding harvesting time. Hence, many innovative growers cultivate strawberry crop under protected structures (tunnels or green houses) to hamper the fruit quality issues. Soft-textured fruits should be harvested on daily basis to avoid the deterioration.

The strawberry fruit should be picked with sharp knife while calyx (green leaves) is attached. However, for processing industry fruit can be harvested without calyx. The fruit can be picked by holding the stem (0.5–1.0 cm above the calyx) between index finger and thumb of right hand, followed by slight pinching of the stem. The fingers should not touch the fruit berry (fleshy part). The farmer or harvester should not wear any metal ring or any ornament to avoid the bruising. The slight squeezing of fruit cause release of sweet solution (sucrose) that acts as substrate for botrytis; hence damaged fruit should be separated immediately.

Generally, fruit packaging is done in the field in transparent box (250 or 500 g) right after harvesting. Picker should be trained enough to assess the fruit maturity stage, size, color immediately. Fruits with uniform size and color should be packed in same box. Diseased, unripen, mechanically injured, overripened, and skin-bruised fruit should be separated for different grades. Small packaging of strawberry fruits can be placed into big plastic crates. The crates can be loaded on picking carts. The picking carts hold the strawberry container in a horizontal position without rolling the fruit packaging. The packages are transported to field collection area or pack house.

2. Fruit harvesting and postharvest handling practices affecting strawberry fruit quality

2.1 Harvesting methods

Being a nonclimacteric fruit, strawberry fruits attain its highest quality features like normal size, regular shape, full red color, sweet taste, glossiness, firmness, and

aroma when fruits fully ripe while still attached to plant. This stage, for cultivar Chandler, one of the widely grown cultivar in subtropical climate, arrives between 28 and 35 days after the fruit set [19]. The onset of ripening stage is characterized by fruit changing color to red. A marketable strawberry fruit has healthy green calyx and stem. However, at this stage, the pericarp of the fruit is thin and delicate that needs a very careful and skillful harvesting method and, therefore, the fruits are harvested in the early morning when fruit temperature is low, and fruit is relatively firm [20].

For distant or export markets, relatively firmer fruits with ≥75% red color development are preferably picked to withstand rigors of transport. Although such fruits do not improve in taste, still they soften up and develop full red color. Strawberries are harvested in cooler part of the day when fruits are not wet and pulp temperature does not exceed 25°C; otherwise, chances of bruising injury, shriveling, decay incidence, and high precooling cost will increase. Strawberry fruit along with its calyx is cautiously harvested by pinching the stem (0.5–1.0 cm above calyx) manually without squeezing the fleshy part of fruit. Grading and packing are normally carried out in the field. Overripe and too large fruits are not desirable as these fruits fetch low market value due to low cosmetic value.

Although, hand harvesting is the most widely used method of harvesting in strawberry, there have been several studies on mechanical and intelligent robotic harvesting methods. One of the first such systems was developed to harvest strawberries grown under hydroponics system [21]. Similarly, a computer vision-assisted robot system has been developed by [22] to detect and approach ripened strawberries grown under bench-type cultivation system. The programming was based on using real-time position tracking algorithms for fruit detection under natural light conditions. Further functions in this robotic system include gripping and cutting the fruit stem without damaging the strawberry fruit itself. Another such system for harvesting bench-type strawberries is based on machine vision, navigation system, and sonar technology to distinguish fruits according to hue and saturation histogram and the cutting area of stem was selected on the basis of binocular-vision system [23]. Improvement in fruit detachment and fruit classification method has been studied for robotic systems [24].

2.2 Losses due to physical and mechanical injury

During and after harvest, soft fruits like strawberry are naturally prone to physical injury because these fruits have fragile epidermis. Mechanical damages are accompanied by morphological and physiological changes leading to adverse fruit sensory quality that may have economic repercussions. After harvest at ripening stage, strawberry fruits rapidly soften up owing to degradation of middle lamella due to pectin solubilization and hydrolysis of hemicellulose and cellulose [25]. During postharvest handling, strawberry fruits may get compressed, collide, punctured, or bruised leading to shorter shelf life and decay. This happens due to careless harvesting by untrained persons, piling harvested fruits, packing forcefully in rough container, handling fruit directly again and again, transporting in improper vehicle or on uneven road.

Bruising is the most undesirable damage caused that seriously limits not only the cosmetic value of fruits but also provides gateway to pathogens especially fungus [26]. Comparison between a sudden impact and slow compression on strawberries has shown that the fruit tissues are easily bruised by slow compression as sudden impact is absorbed by the fruit [27].

Therefore, proper standard procedures are followed in strawberry harvest to achieve economically profitable quality; otherwise, market value of the fruits drops sharply. To reduce such physical damage, strawberries are harvested by

trained persons and handled only once during the whole supply chain that is during harvesting, packed immediately after harvest in special containers and transported carefully in designed vehicle to reduce compression and jerks.

2.3 Temperature management

Strawberry fruit is very sensitive to high temperature and at room temperature may survive up to 24–48 h with marketable quality [28]. Improper or no field heat removal and poor temperature management during the supply chain incur rapid quality deterioration and thus irreversible losses. After harvest, low temperature is the most appropriate strategy to maintain fruit quality [29] as rate of respiration increases exponentially from 28 ml CO_2 kg^{-1} h^{-1} at 5°C to 127 ml CO_2 kg^{-1} h^{-1} at 20°C [30]. As a first step, harvested fruits should be precooled immediately with forced air cooling or placing in refrigerated room as a delay of every 1 h between picking and precooling reduces 1 day of shelf or storage life at ~0°C [31, 32]. Therefore, to maintain strawberry fruit quality after harvest, the most common method is instant cooling of the fruits after harvesting and then storing continuously at low temperature range from 0 to 4°C [33]. Also, storing the fruit at temperature range between 0 and 1°C (32 and 34°F) and relative humidity from 90 to 95% increases its shelf life, minimizes physiological deterioration, and suppresses pathogenic decay incidence [32, 34].

Enzymatic and nonenzymatic antioxidant systems in strawberry fruit respond to low or high temperature in different ways. At higher temperature (≥5°C), the enzymes in strawberries that are involved in antioxidant mechanism viz. glutathione reductase, glutathione peroxidase, ascorbate peroxidase, guaiacol peroxidase, catalase, superoxide dismutase, monodehydroascorbate reductase, and dehydroascorbate reductase show greater activities compared to the enzymes in fruits stored at low temperature (0°C) [35]. Other important enzymes like RuBisCO are also significantly abundant in fruits stored in low temperature [36]. Antioxidant compound also behaves similarly, whereby glutathione, ascorbic acid, total anthocyanins, and total phenolic contents are higher in fruits stored either at higher temperature or for longer period. This also leads to higher antioxidant and radical scavenging activities in such fruits [35]. Low-temperature storage also effects higher fruit firmness, titratable acidity, total soluble solids, ascorbic acid content, and total terpenes in strawberry fruits; moreover, dehydration stress is more severe in strawberry fruits stored under room temperature [36].

2.4 Modified atmosphere packaging

Strawberry fruits are seal-packed while modifying the air inside sealed packaging such that the air has high CO_2 concentration is called modified atmosphere packaging (MAP). This is relatively inexpensive technique used for maintaining fruit quality than CA storage. Generally, perforated (types include micro- and macroperforated) and nonperforated polymeric films are used in MAP as these films have specific and selective permeability for CO_2 and O_2. Micro- and macroperforated packaging has shown promising results in sustaining the keeping quality and extending the storability of strawberry fruits [37].

Generally, recommended composition of MAP is 5–10% O_2, 15–20% CO_2, and 70–80% N_2 for strawberries [38]. Standard packing of fresh strawberry fruits is recommended by modifying internal atmosphere to 10% O_2 and 15–20% CO_2 and storage at 0–5°C, whereas for sliced strawberry fruit, few reports suggested to keep the concentration of O_2 at 1–2% and CO_2 at 5–10% and storage at 0–5°C [39]. Maintaining at least moderately low temperature is prerequisite for MAP storage as

respiration rate is greatly influenced by temperature than by gaseous concentration, with a 72–82% reduction in respiration rate if temperature was decreased from 23 to 10°C for various O_2 and CO_2 mixtures [40].

A computational model was developed for predicting the concentrations of O_2, CO_2, N_2, and H_2O in perforation-mediated polymeric packages during cold storage of strawberries [41]. The model incorporates respiration, transpiration, and diffusive transport of O_2, CO_2, N_2, and H_2O in microperforated package. The mathematical model depicted that the recommended concentrations of gases were marginally achieved at 5°C with 30-μm-thick polymeric packaging with six microperforations each of 50 μm diameter.

Polypropylene packaging with different perforation sizes has been used to naturally create mixture of gases in a concentration that resembles the concentrations used for modified atmospheric storage [42]. Polypropylene packages with different perforations stored strawberries at 2°C [43]. After 3 days, inside the packages, CO_2 concentration was between 1.5 and 2.6%, whereas O_2 levels were between 17.8 and 18.9% and this atmosphere composition remains stable for 1 week which caused maintenance of acceptable fruit quality for the first 10 storage days. Therefore, these perforated packaging was recommended due to less loss of marketable fruits, no signs of *Botrytis*-related decay and just a slight reduction in sucrose content.

However, modified atmosphere packaging alone is not fully capable to stopover infection of fresh strawberries by fungi such as *Botrytis mycosis* and *Rhizopus*. Therefore, prior treatment of strawberry fruits with different gases and coating before packing them in modified atmosphere packaging has been evaluated and found to be increasing the overall impact of MAP. MAP (2.5% O_2 and 15% CO_2) combined with ozone pretreatment and an edible film coating extended shelf life up to 8–10 days compared to only MAP that increased shelf life by 4–6 days. All MAP treatments increased soluble sugar, ascorbic acid, acidity, and anthocyanin and decreased browning index and cell membrane permeability. Similarly, strawberries are pretreated with 30% CO_2 concentration for 3 h at 3°C before packaging the fruits in modified atmosphere packaging film, storing for 1 day at 1°C, transporting for 10 days at 1°C, and finally, distributing for 3 days at 4°C [44]. Treatment with CO_2 when combined with MAP maintained strawberry fruit quality by reducing weight loss, tissue softening index, and decay rate.

2.5 Controlled atmosphere storage

Generally, controlled atmosphere (CA) storage is characterized by increasing the concentration of CO_2 and decreasing that of O_2 in the ambient atmosphere of storage chamber [45]. However, change in composition of atmosphere is always accompanied by low temperature and high humidity during long-term storage. CA storage slows down rate of respiration, microbial infestation, and fruit-softening process, whereas suboptimum gaseous levels during CA storage may cause production of off-flavors and skin discoloration [25]. Most of the studies have suggested that CO_2 concentration between 15 and 20%, and O_2 concentration between 5 and 10% constitute the most suitable atmosphere composition for successful strawberry storage [46]. Lower or higher concentrations of oxygen such as 17, ≥2, and 1.5% have also been recommended.

Strawberry fruits stored in CA retain better quality traits even at higher temperature (10°C) than fruits stored in air storage [47]. However, fruits stored at lower temperature (4°C) in CA storage show better quality than those stored at high temperature. Other than lowering respiration rate, one of the most important features of increased CO_2 level in CA storage is the excellent control of decay caused by *Botrytis* and *Penicillium* species [48]. Generally, strawberry fruit may be stored

for 10–14 day at 1°C with CA composition of 3–5% O_2 and 15–20% CO_2. Too much concentration of CO_2 or too low concentration of O_2 produces off-flavors in strawberries. Other fruit quality features are also affected by CA storage. Strawberry fruits stored in CA storage retain firmness longer than just cold-stored fruits and rotting-related loss of fruits is also less in CO_2-enriched storage. Strawberries stored in controlled atmosphere comprised of 2% O_2 and 12% CO_2 led to higher fruit firmness, titratable acidity, total soluble solids, and ascorbic acid content in strawberry fruits than fruits stored in air [36]. This study also found that controlled atmosphere storage maintained higher volatile concentrations than simple air storage. The esters and furanones, two of the most common volatiles produced during storage, were higher in CA-stored strawberries. Similarly, total terpenes, total acids, total alcohols, and tolerance to cold stress were also higher in strawberries stored in CA storage compared to air-stored strawberries. Glyceraldehyde 3-phosphate dehydrogenase (GAPDH) is a multifunctional enzyme that is stored during cold stress. CA storage led to significantly higher abundance of GAPDH and the expression of chloroplastic fructose-bisphosphate aldolase 3 (a protein of the Calvin cycle) was significantly higher in CA storage. Similarly, malic enzyme that is involved in carbon metabolism pathways had significantly greater abundance indicating potential capacity of CA-stored fruits for carbon fixation during senescence or photosynthesis.

2.6 Edible coatings

Edible films or coatings are nontoxic, environment friendly, and food grade formulations used to maintain postharvest quality and increase shelf- and storage life of fruits and vegetables. These formulations are also used as active packaging to reduce dehydration, microbial attack, skin browning, and tissue softening. Edible coatings are applied in solution form, whereas edible films are first molded into sheets and then wrapped around food products. Edible films or coatings are based on carbohydrates, protein, lipids, or their different combinations. For example, chitosan, pullulan, alginates, starches, and pectin have been widely studied edible coatings or films [49, 50]. Recent researchers have shown that beneficial effects and easy handling of edible coatings and films make their use a preferable choice for preserving fruits and vegetables, especially for soft fruits such as strawberries. The bioactive and functional benefits of edible coatings include slow rate of respiration and tissue softening, extended postharvest life, biodegradability, and lower microbial infestation [50–52].

Pullulan and alginate are other polysaccharides that have been extensively used as edible coating [53, 54]. Chitosan, alginate, and pullulan were applied on strawberry fruits stored at 4°C to evaluate the effect of these coatings on fruit quality and its antioxidant system. They found that these polysaccharides-based coatings delayed tissue softening and decay, loss of total soluble solid, titratable acidity, ascorbic acid, and total phenolic contents. Additionally, polysaccharide coatings also enhanced the activities of superoxide dismutase, peroxidase, catalase, and ascorbate peroxidase that prevented lipid peroxidation and reduced membrane damage. Combinations of coatings such as carboxymethyl cellulose and hydroxypropylmethyl cellulose exhibit better retention of fruit quality [55, 56]. *Aloe vera* gel and gum Arabic also play significant role for improvement of shelf life [33, 57].

The essential oils are bioactive compounds used as additives to edible coatings for enhancing the ability of edible coatings to preserve fruit quality and reduce microbial spoilage. Essential oils of oregano, red thyme, peppermint, and lemongrass incorporated in chitosan coatings on strawberry fruits have shown antifungal properties and reduced the number of decayed fruits during storage, thus extending storage life of fruits at 4°C [58]. Similarly, strawberry fruits coated with alginate and pectin-based coatings loaded with citral and eugenol showed higher values for

firmness, total soluble solids, and antioxidant activity, and lower value for weight loss and microbial spoilage [59]. Strawberry fruits coated with the combination of oleic acid [60], sodium benzoate and potassium sorbate [53], and calcium salts [61] with chitosan have shown improvement in postharvest quality and life.

Studies conducted to compare the effectiveness of chitosan (practical grade) in combination with different acids (like formic, glutamic acetic, and hydrochloric acid), and commercially applied water dissolving chitosan formulation to control various types of postharvest diseases of strawberry fruit such as blue mold, gray mold, and Rhizopus rot mold during 4 days' storage at 20 ± 1°C. However, commercial grade chitosan showed good control of strawberry diseases kept 7 days (0 ± 1°C) and 3 days' shelf life. Furthermore, it was noticed that the treatment (0 ± 1°C) which is experimentally resistant induces effectively in controlling blue mold, gray mold, and Rhizopus rot stored for the 7 days of storage of strawberry fruit which thereafter exposed to 3 days shelf-life [62, 63].

The effect of a novel edible biofilm containing *Cryptococcus laurentii* (109 cfu ml^{-1}) in combination with glycerol, palmitic acid, alginate, glycerol, glycerol monostearate, and β-cyclodextrin to reduce the incidence of diseases and to extend the postharvest life of strawberries by applying sodium alginate film containing the *C. laurentii*, effectively controlled microbial decay, maintained the quality and firmness, reduced weight loss thus enhancing the shelf life and storage properties of strawberry fruit [51]. The candelilla wax alone and in combination with a (*Bacillus subtilis*) HFC103 strain on postharvest life of strawberry fruit kept for 6 days at 25°C by [64]. Reduction in weight loss and decay percentage in comparison to control since 3 days was observed in the treatments having bacteria and film alone and combination of both. However, reduced decay percentage was recorded around 100% in film + bacteria treatment, as compared with control on day 6 significantly reduced the severity index in film followed by bacteria and film + bacteria treatments.

2.7 Chemicals treatments

Strawberry is perishable fruit which is highly susceptible to different postharvest losses (50%) due to sudden attack of fungal diseases. For a decade, various kinds of synthetic chemicals have been utilized to increase postharvest life; however, their uses are highly restricted due to food safety issues. Alternative strategies such as heat treatments can be used to enhance the postharvest storage life by increasing natural resistance and antioxidative systems in postharvest technology. 1-Methylcyclopropene (1-MCP) was applied on strawberry cv. Everest tended to maintain firmness and color, and higher level of disease was observed in fruit treated at higher application rates of 1-MCP. 1-MCP showed reduction in advancement of anthocyanin and phenolic contents and inhibited phenylalanine ammonia-lyase (PAL) activity. Higher level of 1-MCP application to strawberry fruits might lower disease resistance in strawberry fruits [65].

Two varieties of strawberry fruit including Camarosa and Red Dream and two raspberry cultivars Nova and Killarney fruits were harvested and dipped in (2.5 min) into ascorbic acid solution (0, 1 or 2%), frozen at−40°C using plastic containers for storage at −20°C for 6 months. Total soluble solids, pH, and total phenolic contents decreased less in treated fruits than control in the same rate in strawberry and raspberry cultivars after 3 months of storage periods. Polyphenol contents increased in ascorbic acid treatments, while increasing trend in different in cultivars [66].

Frozen strawberries show changes in color and texture degradation which affects the overall quality attributes. Fresh strawberry was dipped alone or in combination of calcium lactate and citric acid during freezing process. Citric acid clearly lowers browning index and improves the ascorbic acid and total anthocyanins content

(TAC), while calcium lactate in texture maintenance and firmness after thawing. The combination of both citric acid and Ca lactate (0.4% + 1%) showed better quality characteristics, like maintaining vitamin C content, firmness, anthocyanin content while reduction in drip loss improving in color attributes in comparison with other treatments [67].

Application of melatonin to strawberry fruits significantly reduced decay, weight loss, and senescence of strawberry fruit during storage [68]. It was further observed that melatonin also affected the various fruit quality attributes like fruit color, firmness of fruit, total soluble solids content (SSC), and titratable acidity (TA) of the fruit. Treated fruits showed higher antioxidant capacity, and reduced the hydrogen peroxide and malondialdehyde. Moreover, melatonin improves the quality attributes, extends postharvest life and expression of melatonin biosynthetic genes, and increased amount of internal melatonin.

2.8 Heat treatments

In the previous studies, the effect of heat treatments has also been checked for improvement of quality attributes and postharvest life of strawberry fruits. Heat-treated strawberry fruit treated with heat at 45°C for 3 h showed high firmness, reduced activities of enzyme like β-Xyl 9 β-xylosidase), EGase (endo-1,4-β-d-glucanase) which delayed hemicellulose deprivation in both zones (external and internal fruit zones). In addition, inhibited polygalacturonase (PG), β-galactosidase (β-gal) activity, and elevated the PME activity with higher EDTA soluble pectins in heat-treated fruits than the control. Moreover, these activities varied in exterior and inner surface of fruits which could affect solubilization of hemicelluloses and pectins [69].

Reduced decay in heat-treated strawberries (45°C, 3 h) was noticed during storage period in comparison to control [70]. It was also seen that heat-treated fruits also have lower levels of H_2O_2 than control fruit during storage. In addition, higher antioxidant capacity and enzymes activities (APX, SOD) were recorded in heat-treated fruit during the course of storage which representing changes in the oxidative metabolism of the fruit. Moreover, heat-treated fruits showed differential responses during storage which could save the fruit against reactive oxygen species (ROS) produced during senescence or invasion of pathogen. Three different strawberry cultivars including Dover, Campineiro, and Oso Grande harvested and kept for 6 days at 6, 16, and 25°C by [31]. Strawberry varieties presented variation in chemical composition at different storage temperatures and these differences might be concerning regarding their adaptation to low temperatures.

However, some quality attributes are negatively (anthocyanin and vitamin C) affected to low temperature, some are positively (soluble sugars) affected, while some bioactive compounds remain same or decreased like ellagic acid, flavonols, and total phenolic contents (TPC) during storage conditions. Few reports suggested that heat-treated strawberry fruits (*Fragaria ananassa* Duch., cv Camarosa) showed higher firmness of fruit and lower appearance of expansin genes (FaEXP1, FaEXP2, and FaEXP6) during the following 24 h after which might contribute to delay softening in strawberries [71].

2.9 Essential oils

Essential oils have strong antimicrobial activities and have been incorporated in edible coatings and films not only to improve texture of coatings but also as antimicrobial agents. Essential oils of clove, cinnamon, and oregano were used in

paraffin coatings of paper packaging materials that totally inhibited the growth of *Candida albicans*, *Aspergillus flavus*, and *Eurotium repens* on strawberry fruits for 7 days at 4°C [72].

In the recent years, numerous researches have been initiated for new alternative technologies to preserve foods which are prime interest to the fast-growing food industry. Essential oils of clove and/or mustard in vapor phase were evaluated in vitro and in vivo on strawberries against *Botrytis cinerea*. Essential oils showed good results in combination rather than individual application. Essential oils exhibited inhibitory activity which is due to major compounds presented in the mustard and clove oils and reduction in the development of *Botrytis cinerea*. It has synergistic antifungal effect which is more effective in combination compared to individual essential oil application [73]. Studies have shown that there is an ecofriendly and consumer-acceptable approach for pathogen control on various fruits like strawberries during postharvest storage. Application of *cassia* oil in 400–800 ppm concentration effectively repressed the growth of *E. coli* in vitro and *Botrytis cinerea* on treated strawberries [74]. It also strongly inhibited the enlargement of germ tube and spore germination at an application rate of 100 ppm. Cassia oil application reduced decay percentage, weight loss in strawberries during postharvest storage.

Tea tree oil (TTO) was applied before harvest on strawberries to investigate the physicochemical properties and quality parameters. TTO reduced the decay, and delay firmness, decreases number of microorganisms during storage. It also reduces the accumulation of H_2O_2 with increasing antioxidative activities of various enzymes including catalase and ascorbate peroxidase as well as β-1,3-glucanase. TTO-treated fruit showed 188 differentially expressed proteins as compared with control. Of these, 29 were abundant, 159 are less abundant, and 3 proteins related to cell metabolism were downregulated, and 4 proteins related to stress were upregulated in fruit treated with tea tree oil. TTO application before harvest significantly reduced decay, microorganisms, delays fruit senescence, and improves the defense proteins [75]. Chitosan (CH) and carboxymethyl cellulose (CMC) coatings enriched with *Mentha spicata* essential oil (MSO) can be utilized in food industry as suitable active packaging materials for the preservation of fresh strawberries. The effects of edible coatings of CMC and CH in combination with essential oils of MSO (0.1 and 0.2%) on microbial growth, sensory and physicochemical attributes of fresh strawberries fruit during refrigerated storage conditions [56]. It has been found that 0.2% CMC-MSO proved best in organoleptic and physicochemical attributes as well as microbial inhibition during storage period [56].

2.10 UV irradiation

UV-C irradiation plays an important role in reducing fruit decay and delaying ripening of fruits. It has been used extensively before storage at relatively higher doses due to their higher impact and use. Strawberry fruits were subjected to different repeated doses of UV-C irradiation for quality maintenance during storage. UV-C irradiation reduced decay, weight loss, and softening in strawberries. Two-step or multistep UV treatments showed higher quality retention and reduced calyx browning more efficiently. UV-C treatments could be more effective to enhance the postharvest life of strawberry during storage conditions [76]. Also, studies showed that UV-C radiation increased in total phenolic, volatile contents, proanthocyanidins, anthocyanins, and esters in external tissues. However, aroma character compounds decreased with the application of UV-C treatments [77].

Strawberry fruits were subjected to blue light to improve quality, antioxidant capacity, and enzyme activities stored at 5°C. Blue light illumination

increased ascorbic acid, total sugar, titratable acidity, total phenolic, and DPPH (1,1-diphenyl-2-picrylhydrazy) radical-scavenging activity in strawberries during the course of storage. In addition, higher activities of reactive oxygen species like APX, SOD, and CAT maintained lower amounts of superoxide anion (SO_2), hydrogen peroxide (H_2O_2), and malondialdehyde (MDA). Thus, for maintenance of quality attributes and improvement in nutritional quality of strawberry fruit, exposure to blue light illumination might be affective due to the enhancement of their antioxidant systems and free radical-scavenging abilities [78]. Strawberry fruits were exposed to the lower dose gamma irradiation at 1 kGy and different amounts of EMAP (active equilibrium-modified atmosphere packaging) at the rate of EMAP1: CO_2 10%: O_2 5%; N_2 85% and EMAP2: CO_2 5%: O_2 10%; N_2 85%, and stored at 4°C. EMAP1 packages showed good texture, appearance, and firmness than EMAP2 during storage time. It has been noted that the exposure to lower irradiation dose in combination with EMAP1 maintained external appearance, less fungus attack, and enables high-quality strawberry with improved shelf life [79].

3. Conclusions

Strawberry is a highly perishable fruit and subjected to several postharvest losses after harvest. There are several stages which are responsible for quick losses such as improper harvesting methods, developmental stage, improper picking time, sorting and packaging, transportation postharvest treatments, and storage conditions and as well as untrained labor. However, numerous pre- and postharvest studies were conducted to develop strategies for extension of strawberry shelf life such as harvesting methods, heat treatments, UV-C irradiations, coating, and essential oil applications. Furthermore, there is need a to study these technologies on commercial scale to increase the net income. There is a need to develop ecofriendly alternative technologies to enhance the shelf life of strawberries.

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Author details

Muhammad Azam[1*], Shaghef Ejaz[2], Rana Naveed Ur Rehman[1], Mumtaz Khan[3] and Rashad Qadri[1]

1 Pomology Laboratory, Institute of Horticultural Sciences, University of Agriculture, Faisalabad, Pakistan

2 Department of Horticulture, Bahauddin Zakariya University, Multan, Pakistan

3 Department of Environmental Sciences, Gomal University, Dera Ismail Khan, Pakistan

*Address all correspondence to: muhammad.azam@uaf.edu.pk

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