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The Effect of Preharvest Factors on Fruit and Nutritional Quality in Strawberry

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Abstract

Strawberries play an essential role in human nutrition and health, especially as a source of vitamins, minerals, and dietary fiber. They also have health-promoting compounds that lower the risk of cancer and cardiovascular disease. The nutritional value of strawberries varies greatly among cultivars. Traditional and molecular breeding techniques can be used to develop varieties with enhanced nutritional quality and improved flavor to meet consumer preferences. Climatic conditions, such as temperature and light intensity, and other preharvest factors, e.g., soil type, fertilization, irrigation, mulching, and other cultural practices, have a significant effect on strawberry fruit quality. Additionally, the extent of postharvest physical and physiological injury and potential fruit loss is affected by preharvest parameters. In this chapter, the effect of preharvest factors on fruit and nutritional quality of strawberry is discussed.

Keywords: strawberries, cultivar, genetics, environment, light, nutrition, temperature, soluble solids, acidity, firmness, fruit quality

1. Introduction

Several reports confirm significant (35–50%) loss in horticultural produce after harvest. These losses are mainly due to dehydration, decay, and physiological disorders during postharvest handling. Fresh products also undergo rapid changes in nutritional and sensory quality after harvest, some of which contribute to loss of market value [1]. Losses can be mitigated through better management of pre- and postharvest factors. Differences in postharvest loss of fresh produce between developed (5–35%) and developing countries (30–50%) as reported by Kader [2], Salami [3], Kitinoja [4], and Ray and Ravi [5] are due to the higher capacity and better infrastructure in developed economies for managing these factors [1].

In strawberry, preharvest management is a prerequisite for producing good quality fruit. Quality deterioration starts as soon as the produce is harvested, and postharvest factors can only maintain but not improve the quality. The growers' decisions and management directly affect the final market value of strawberry and its acceptance by the consumers [1]. Many preharvest factors affect fruit quality at harvest. In this review, we will discuss genetic variability, climatic conditions, and cultural practices that affect quality of strawberries.

Some review papers exist on the effect of preharvest factors on strawberry fruit quality [6–9], but the most recent one [9] addresses major temperate berry crops and does not focus solely on strawberry. Also, since then many new research papers have been published. Therefore, this chapter will review recent publications and elaborate on the effect of preharvest factors on strawberry fruit and nutritional quality.

2. Strawberry fruit quality

Strawberry fruit quality is a composite of sensory characteristics (color, appearance, texture, mechanical properties, diseases, and defects) that give value and enjoyment to consumers [10]. Currently, strawberry producers and handlers are lengthening shelf life through early harvesting of firm fruit with less developed color. This process pays little attention to flavor, taste, and nutritional quality of harvested fruit and yet repeat purchases by consumers have been shown to depend on taste and eating quality of fruits. Therefore, the challenge is to encourage consumers to be willing to pay more for local fruit and varieties with higher quality (because they often require more careful handling and have lower yield), and producers and handlers to pay more attention to maturity, sugar content, taste and flavor of harvested strawberries [2].

Like other fresh produce, strawberry fruit quality is a product of the interaction between variety and preharvest factors. Preharvest factors such as climatic conditions and cultural practices determine the inherent quality of strawberries and the interaction of genetic characteristics, and preharvest factors determine the ultimate quality of the fruit [11]. Because strawberry fruit quality cannot be improved after harvest, the role of preharvest factors must be understood in order to improve consumer acceptance and shelf life [12]. This is because the ripening process in strawberries stops at harvest, and fruit should be picked when fully ripe to ensure good flavor and quality [13].

Maturity indices are important for deciding when to harvest strawberries. Color, soluble solids content (SSC), and titratable acidity (TA) are used as harvest indices in strawberries with >2/3 of fruit surface showing pink or red color, minimum SSC of 7% and maximum TA of 0.8% accepted as a minimum standard for timing of harvest [14]. Once strawberries ripen, they require quick marketing and careful handling to minimize injury and spoilage [13], and the indices provide some marketing flexibility to ensure that eating quality is attained by the time the fruit reaches the consumer while at the same time limiting postharvest losses. The necessity to ship strawberries to distant markets often results in harvesting at less than ideal maturity meaning less optimum quality for the consumer [13].

Berry fruits are extremely perishable and have a short market life. Several studies have shown that strawberry fruits harvested slightly under-ripe are firmer, have less decay and a longer shelf-life, and would ship better than fully ripe strawberries [15]. Because they are nonclimacteric fruit, strawberries produce very small amounts of ethylene and do not respond to ethylene treatment [13]. Therefore, ripened fruit should be kept at 0°C until time for display at retailers [14].

Sugars and organic acids have an important impact on the sensory quality of strawberry fruit. For example, a strawberry with very low sugar and acid content tastes flat [16]. Strawberry fruit contains reducing sugars such as fructose, glucose, and sucrose, comprising >65% of total fruit SSC [16]. Glucose and fructose are found in almost equal concentrations [17], while sucrose levels are generally much lower [18, 19]. The proportions of fructose, glucose, and sucrose are important in the perception of fruit quality since fructose is 1.8 times sweeter than sucrose, [20] and sucrose is about 1.7 times sweeter than glucose [16, 21].

Citric acid forms the major organic acid found in strawberry fruit [22], representing 88% of the total organic acids in ripe fruit [23]. Malic acid is the second most prominent organic acid in the fruit [23], and the organic acid level (malic + citric) was found to be positively correlated with TA [16].

The major phenolic compounds in strawberries include anthocyanins and proanthocyanidins, ellagitannins and ellagic acid conjugates, cinnamic acid conjugates and hydroxycinnamic acid derivatives, catechin, flavan-3-ols, flavonols, and flavones [24]. These compounds have numerous health benefits [25] such as antioxidation and anti-inflammatory activities [26, 27]. Also present in the strawberry fruit are polyphenols or tannins, which are responsible for astringency [19, 28].

Nutritive composition of sugar, organic acid, and phenolic compounds in strawberries is very diversely distributed. To obtain the best nutritive values, the interaction between genotype and environment not only needs to be optimized, ideal harvest and post-harvest storage conditions must also be maintained.

3. Genetic variation

Results indicate that the effect of genotype on strawberry fruit and nutritional quality is stronger than that of growing conditions [29]. Strawberry cultivars vary greatly in their rate of softening and overall texture [30]. It has been found that genetic factors have a direct influence on strawberry texture with environmental factors acting only to modify the expression of textural traits [30].

Studies have shown that that genotype affects total organic acid content [31], while vitamin C content in strawberry varies among cultivars and between tissues. For example, Nelson et al. [32] found a range from 19.3 to 71.5 mg/100 g ascorbic acid in six strawberry cultivars from four locations [33], while Ezell et al. [34] found a higher rate of 38.9–88.9 mg/100 g in 28 named varieties and 16 numbered selections. Nelson et al. [32] and Ezell et al. [34] reported an average of 45 and 60 mg/100 g, respectively with Ezell et al. [34] concluding that the ascorbic acid average of 60 can be increased to 80 or more through breeding. However, malic acid concentration appears to be independent of genotype [31].

The main anthocyanin found in strawberries is pelargonidin 3-glucoside, with cyanidin 3-glucoside and pelargonidin 3-rutinoside present as minor components [35]. Differences have also been reported for other quality attributes. For instance, Anagnostou [36] reported that fruit from the cultivar “Fern” had better color and more anthocyanins than from “Selva.” When evaluated for firmness, “Carlsbad” was the firmest and “Rosalinda” the softest [37], confirming that firmness is mainly cultivar dependent [36]. In the same study, Anagnostou [36] also found that TA was not significantly affected by cultivar. Differences in the incidence of albino fruit production as reported by Sharma [38] can be attributed to genetic variability among cultivars.

It has also been shown that relative distribution of phenolic compounds varies with genotype. Up to a 4-fold difference in flavonol content was observed between cultivars but with only slight variations associated with growing environment [39].

These results suggest that different cultivars can be used for different purposes. Some such as “Toyonoka” are firmer and more suitable for distant markets but may have lower vitamin C, anthocyanins, phenolics and flavonols, others like “Oso Grande” with good nutritional values are suitable for fresh consumption, while some like “Mazi” with high anthocyanin and flavonol content but lower levels of vitamin C, citric acid, and total soluble solids (TSS) may be valued for their functional properties [35].

Nutritional quality can be considered an inheritable trait that can be improved through breeding [29], and breeding and biotechnology programs are working to produce new varieties with improved fruit and nutritional qualities combined with

high plant production efficiency [29]. Wild species like *F. virginiana* spp. glauca and *F. vesca* are good sources of bioactive compounds. *F. virginiana* spp. glauca is also an important genetic source of nutritional quality and other unique traits such as day neutrality, and plant and disease resistance [29]. Breeding for improved nutritional and fruit quality parameters offers the possibility of new commercial varieties that can yield high-quality fruit at reasonable cost [29].

4. Climatic conditions

Environmental conditions seem to have a major influence on flavor compound formation in strawberry. Watson [19] reported that SSC in strawberry was more dependent on environmental conditions during production than on the genetic makeup of the plant. Furthermore, relating growth conditions to flavor data may allow modeling of plant and fruit responses to the environment and provide a powerful tool to growers and retailers to manipulate fruit quality [19].

Below are environmental factors that affect fruit quality in strawberry.

4.1 Light intensity

Preharvest conditions such as light intensity can affect strawberry fruit quality and phytonutrient content. Light is required for proper leaf and fruit development and can improve the fruit quality, but light above photosynthetic saturation levels, especially intense exposure, can increase the fruit temperature and may result in fruit damage and a loss of quality [30, 40]. On the other hand, insufficient light typically results in smaller strawberry fruits [41]. In strawberry, low light decreases the surface glossiness of the fruit [41] and reduces color development [11, 38].

Ezell et al. [34] concluded that bright sunny weather favored high ascorbic acid content, while cool, wet weather resulted in low values. This confirms an observation by Wang [12] that strawberries grown at higher light intensity had increased levels of ascorbic acid. Even fruits shaded by foliage or ripened on cloudy days had 10% less ascorbic acid than berries exposed to sun [42], while berries shaded by leaves showed little change between cloudy and sunny days. Ezell et al. [34] also reported that everbearing varieties grown during the long, warm days, and intense light of early June averaged 34% more ascorbic acid than did the same varieties in late September. By shading either or both berries and plants, Hansen and Waldo [43] found that unshaded berries contained 13% more ascorbic acid than did the shaded ones and 68% more than when plants and berries were shaded. Unshaded plants produced higher dry matter in fruits at the expense of leaf growth but not fresh weight implying fruits with lower moisture content [44].

Light intensity, affected firmness, TSS, acidity, and anthocyanins [36]. The effect of shading was not significant for phenolics, but the opposite was observed for anthocyanins. Shading of strawberry plants has also been shown to cause significant reduction in the concentration of flavor compounds (hexenal, hexanal, ethyl methyl butyrate, and methyl butyrate) in fruit [19].

Light also influences anthocyanin synthesis and therefore color formation in fruit [45]. It appears that lower light intensity favors the development of albinism in strawberry with Sharma et al. [38] reporting that strawberry plants grown under low light intensities (shade) tend to produce a higher proportion of albino fruit.

Production methods will affect the amount of light to which a crop is exposed. Solar radiation experienced by crops grown in a polythene tunnel with new plastic may be 10% less than an outdoor crop, and a glasshouse could reduce light levels by 30% or more compared to that of an outdoor crop [46].

4.2 Light quality

The color of plastic mulches frequently used in raised-bed culture affects fruit quality. The most commonly used plastic mulch color is black [47]. Berries that ripened over red plastic mulch were about 20% larger, had higher sugar to organic acid ratios, and emitted higher concentrations of favorable aroma compounds. It has been said that the ratio of far red (FR) to red (R) light reflected from the red mulch modified gene expression through plant phytochrome and increased fruit size, phytonutrient concentrations, flavor, and aroma compounds [47].

Strawberry (cv. Toyonoka) fruit color was greatly affected by light quality under different colored filters (green, neutral, yellow, blue, to red light). Fruit color (chroma), ascorbic acid, yield per plant, and fruit size improved with increasing exposure to reddish orange color. All fruit quality parameters measured (e.g., color, sugar, acid) were negatively affected by green color [48].

In another study using five different mulch colors (red, blue, yellow, green, black, and silver), red mulch gave results similar or better than black mulch. Silver mulch reduced fresh fruit weight, fruit length and leaf area, while red mulch increased it. Silver mulch also reduced pH, ratio of TSS/TA and fruit dry weight, while black mulch increased the ratio. It is thought that increased light from the red and far-red spectrum reflected from red mulch is absorbed by phytochromes resulting in improved plant growth and fruit quality [49].

4.3 Temperature

Plant growth and development is largely affected by temperature. Temperature also affects cellular compounds and their structure, which ultimately affects firmness. Lower temperatures during the growing season increased fruit firmness [36], and growing strawberry under different temperatures (day/night) could also affect antioxidant activity and total flavonoid content. High temperature growing conditions (25/30°C) significantly enhanced antioxidant activity, as well as anthocyanin and total phenolic content [12]. Wang et al. [51] also reported that “Kent” strawberries exposed to warmer nights (18–22°C) and warmer days (25°C) had higher antioxidant activity than berries grown under cool day and night temperatures (18/12°C). In a separate study, Moretti et al. [50] found that high temperature conditions significantly increased flavonoid levels and consequently antioxidant capacity. Ascorbic acid content in strawberries is also highly affected by climate conditions and growing area [12]. Moretti et al. [50] showed that higher day and night temperatures have a direct influence on strawberry fruit color with berries ripened under these conditions being redder and darker.

However, Wang et al. [51] showed that in strawberry, fruit temperatures can exceed air temperatures by as much as 8°C on sunny days. High fruit temperatures could inhibit enzymes, such as sucrose synthetase, which acts on sucrose production. Increased fruit temperatures may also induce a higher transpirational flux within the fruit [51].

Freezing temperatures on the other hand can be detrimental to strawberries. A radiative freeze typically occurs under clear skies with calm or light wind, and a relatively high subfreezing temperature or dew point (similar to the conditions that often cause frost). Radiative freeze damage of strawberry often results in smaller fruit, and depending upon the developmental stage when damage occurs, misshapen fruit are produced [11].

4.4 Climate change and elevated levels of carbon dioxide and ozone

Although the climate change subject is controversial, its potential impact on agriculture continues to be discussed. However, few studies have considered the

potential impact of climate change on fruit and vegetable quality after harvest [52]. Temperature increase and the effects of greenhouse gases are among the most important issues associated with climate change. Beside rising temperatures, climate changes are also a consequence of changes in the composition of gaseous constituents in the atmosphere. Carbon dioxide accumulation in the atmosphere has direct effects on postharvest quality [50].

The highest temperature that strawberry fruit mature normally is 35°C. At high temperatures and elevated CO₂ levels, carbohydrates, such as starch and soluble sugars are degraded in the respiration process and the proteins and most minerals decrease. The nutritional quality also decreased due to more phenols and ascorbic acid. However, the effect of temperature is more pronounced than the elevated CO₂ levels [52].

Elevated CO₂ levels in storage slightly increased dehydroascorbic acid and firmness, prevented ascorbic acid reduction, and reduced anthocyanin, flavonoids, antioxidant activity and total phenolic compounds [53]. In contrast, increased CO₂ concentrations in the growing atmosphere (300 and 600 µmolmol⁻¹ above ambient) resulted in increased anthocyanin and phenolic and ascorbic acid content [54]. Siriphanich [55] also reported increased firmness in strawberry treated with CO₂. Cell wall analysis showed lower water-soluble pectin and higher chelating soluble pectin in CO₂-treated strawberries. The mechanism of firmness enhancement by CO₂ was possibly due to changes in intercellular pH and its solute composition.

The influence of ozone on strawberry depends significantly on cultivar and susceptibility to oxidative stress. The effect of ozone on vitamin C content is variable in the reviewed articles and mostly cultivar dependent. In “Korona” and “Elsanta” tested by Keutgen and Pawelzik [56], ozone caused a decrease in ascorbic acid content, and lowered fruit sweetness. The ozone stress did not influence yield, size, antioxidative capacity, anthocyanins, or phenolic compounds of fruit. In the more sensitive cv. “Elsanta,” ozone induced sepal injuries and fruit impairment, and a decrease in glutathione content. In contrast, fruit quality of the less sensitive cv. “Korona” remained almost constant [56].

In cv. “Camarosa,” ozone enriched storage (0.35 µL/L) for 3 days, increased vitamin C by three times, and reduced volatile esters 40% compared to control [57]. On the other hand, Moretti et al. [50] reported that strawberries stored in atmospheres with ozone ranging from 0.3 to 0.7 µL/L showed no effect on ascorbic acid levels after 7 days of storage under refrigerated conditions.

5. Cultural practices

5.1 Soil and soil amendments

Soil types, fertilization, composts, and mulching influence the water and nutrient supply to the plant and can affect the nutritional composition, ascorbic acid content, and antioxidant activity of harvested fruit [16]. Plants grown in low-organic-matter and low-cation-exchange-capacity sandy soil amended with Ca, magnesium (Mg), and N produced more ascorbic acid in fruit than plants without supplemental fertilizer [12]. Also, Wang and Lin [16] reported that strawberry organic acids, malic acid and citric acid, were increased by the addition of fertilizer [16].

Composts have been utilized in agriculture as a significant source of organic matter. As a soil supplement, compost significantly enhances plant growth, fruit quality, and ascorbic acid and flavonoid content in strawberries. Compost causes changes in soil chemical and physical characteristics that increase beneficial microorganisms, and nutrient availability and uptake thus favoring plant growth.

Strawberry plants grown with compost yielded fruits with high levels of phenolics, flavonol, and anthocyanin content. The free radical absorbance capacities for peroxy, superoxide, hydrogen peroxide, hydroxyl, and singlet oxygen in strawberries increased significantly with increasing compost use [12, 16]. Also, compost significantly increased levels of organic acids (malic and citric acid), sugars (fructose, glucose, and total sugars), soluble solids content, and TA content in “Allstar” and “Honeoye” strawberry cultivars [16].

Strawberries grown organically showed higher levels of total phenolics compared to those produced by conventional agricultural practices, mostly because they received all required nutrients from organic matter. Also, flavonol content was higher in organically grown than in conventionally grown strawberry fruits. These data provide evidence that an improvement in the antioxidant defense system of the plant occurred as a consequence of the organic cultivation practice [12]. It has been shown that N can become a growth-limiting nutrient in organic production [39].

Strawberries need nearly neutral (6–6.5) soil pH and variation from this range affect mineral uptake and plant growth, development, yield, and fruit quality [58]. Increasing soil pH significantly reduces uptake of minerals such as iron and manganese [58, 59]. Iron deficiency has been observed in many crops when grown in high pH calcareous soils. In these soils, iron deficiency is the most important abiotic stress limiting strawberry production [60]. In fact, iron deficiency results in extensive fruit abortion with a consequent reduction of yield and fruit weight [61].

However, although most studies show a positive correlation between organic production and crop performance in strawberry, Hargreaves [59] found that organic amendments did not increase fruit quality compared to inorganic amendments, and no differences in total phenolic content were observed between conventionally and organically grown strawberries.

5.2 Substrates

Strawberry is commonly produced in open fields, glasshouses or plastic tunnels. Pests and diseases gradually build up in soils and limit strawberry culture. Therefore, the use of alternative substrates (soilless culture) is a common cultural method in strawberries, especially in protected environments, and has been shown to improve fruit yield and quality [62].

Physical and chemical properties of substrates exhibit direct and indirect effects on plant yield and fruit quality. Different substrates such as peat moss, coconut coir, perlite, rockwool, and pine bark have been used. However, peat has been the best substrate for hydroponic culture [63].

Cheaper alternatives to peat are being explored. For example, Zeolites (alumina silicate crystals) that have a negative charge, high cation exchange capacity, and high water holding capacity have been tested. Djedidi et al. [64] reported improved yield and quality in tomato grown in a mixture of zeolite and perlite, while Fotouhi Ghazvini [65] reported improved yield but decreased fruit quality in strawberries in similar substrate.

5.3 Mineral nutrition and salinity

An important determinant of fruit quality is the availability of essential nutrients during growth and development. Among them, calcium (Ca) slows down the ripening and senescence processes in many fruits including strawberry [66]. Nestby et al. [67] and Prange and De Ell [9] report that research conducted over the past 25 years on the effect of Ca on postharvest quality of strawberry has provided contradictory conclusions. In some studies, foliar applications and soil amendments

of Ca did not affect fruit quality, regardless of cultivar, yet other studies have shown increased shelf life due to Ca application [66].

Furthermore, Singh et al. [66] reported that preharvest Ca sprays greatly influenced fruit color during storage. In storage, fruit harvested from control plants turned darker whereas from the Ca spray treatment were comparatively brighter. Similarly, higher values of hue (a) and chroma (b) in such fruit indicate that fruit receiving Ca were redder and more vivid. Strawberries soften considerably during storage as a result of degradation of middle lamella, cell wall, and cortical parenchyma cells. By extension, cell wall strength, cell to cell contact and cellular turgor, which are greatly influenced by Ca may affect fruit firmness. Thus, fruits which received Ca were firmer even after 5 days of storage [66].

Calcium deficiency represents one of the most common issues for strawberry growers. Calcium plays a role in cell division and the maintenance of cell permeability and cell integrity, all of which directly influence factors such as firmness and shelf life [66]. Strawberry fruits from Ca-deficient plants are small, hard textured, acidic, seedy, or with patches covered densely with achenes, with increased deformity [17]. Calcium sprays increase fruit firmness, vitamin C and shelf life during storage [68].

However, there are reports that increasing Ca application did not affect sensory quality and decreased TA and TSS of strawberries. Calcium increased firmness and storage life up to 900 ppm. Higher concentration seems to create toxicity and imbalances of other minerals in leaf tissue.

The form of Ca applied also changes the result. Application of gypsum at planting time did not influence fruit Ca content. Therefore, cultivar, form of Ca applied, and environmental factors must be considered during Ca fertilization of strawberries [68].

Nitrogen is another important nutrient for fruit quality with both positive and negative effects of N on yield and fruit quality reported. The effect of N on fruit chemical components is inconsistent and varies from year to year, depending on time and rate of application and other environmental factors [67]. Recommended optimum concentrations of leaf N for high-yielding strawberry fields in California, North Carolina, northeastern United States, and Ontario, Canada ranges from 2.0 to 4.0%, with samples collected mostly from the leaf blade [69–73]. Form of N also affects fruit quality. Ammonium up to a ratio of 1 to 6 nitrate increased fruit firmness, but reduced red color compared to nitrate alone. Fruit vitamin C, pH, and TSS decreased with addition of ammonium up to a ratio of 1:6 (ammonium: nitrate) and then returned to the original level at the ratio of 1.5:6. Ammonium reduced TA at all concentrations [74].

Tabatabaei [40] demonstrated that both high concentrations of NO_3 (100%) and NH_4 (75%) has an inhibitory effect on growth of strawberry, and it becomes more pronounced in the shaded conditions.

While low concentration of ammonium improved plant growth, higher concentrations, reduced growth due to the high demand for carbohydrates for ammonium detoxification and low nitrate concentrations.

Another possible explanation is that a high concentration of NH_4 reduces the uptake of cations such as Ca^+ and K^+ and increases the concentration of NH_4^+ , which is toxic for the plant [40].

Higher concentration of NH_4 significantly reduced postharvest life probably due to Ca deficiency in fruit. Calcium deficiency associated with NH_4 nutrition can induce loss of membrane integrity which in turn may lower the concentration of potassium (K) and Mg and influence the function of chloroplasts and mitochondria. In addition, higher rates of organic acid synthesis because of NH_4 nutrition may immobilize Ca and Mg within the roots. Ammonium also reduces the uptake of Ca and K by the roots, and is used only sparingly or not at all during the early growth of crops under poor light conditions [40].

The general conclusion is that proper N fertilizer application could be effective in improving fruit quality. Plants with low or moderate vegetative growth tend to have firmer fruits. Higher N doses decreased fruit size and increased pest and disease occurrence and fruit rot and malformation. Petiole sap nitrate testing is a standard method that determines the N requirement at different developmental stages of growth and would help to reduce uncertainty of time and amount of N application [67].

Imbalances in certain macronutrients can also have a pronounced effect on shape, and size [11]. Magnesium and phosphorous deficiency tend to decrease flower and fruit size and increase the incidence of albinism. Potassium-deficient plants may produce shriveled fruits with brown calyxes, fruits fail to develop full color, and have pulpy texture, and insipid taste [67].

Among microelements, boron (B) has a direct effect on fruit quality. For example, B deficiency causes distorted flowers and fruits, reduces fruit size and number, and increases malformation [11, 67]. The influence of B on phenol metabolism has also been well studied [39]. Fewer malformed fruit in plants receiving B can be correlated with a higher concentration of B both in leaves and fruit [66], which may be due to the significant role of B on pollen germination and pollen tube growth.

Studies conducted by Sing [66] indicate that B application does not influence fruit quality in strawberry; however, B deficiency usually results in poor accumulation of TSS, and ascorbic acid. Other microelements also have roles in plant growth and development and are needed at lower concentrations compared to macronutrients. Iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and molybdenum (Mo) are needed at 40, 25, 20, 3, 0.4 ppm per dry matter of leaves, respectively [67]. No major effects of Fe, Cu, and Mn have been reported on fruit quality [67]. In general, balanced fertilization has an important effect on both fruit yield and quality.

Fruit quality has been observed to increase with saline solute concentration. A solution strength of 1.3 mS cm^{-1} EC is preferred during the spring season whereas 2.2 mS cm^{-1} EC proved to be best in the winter in terms of fruit quality. Fruit ripening was accelerated in salt-stressed plants [75], and salinity had no effect on fruit number, but decreased fresh and dry weight [44]. In three different studies on the effect of salinity on two strawberry cultivars differing in their sensitivity to NaCl stress: cv. Elsanta (sensitive) and cv. Korona (less sensitive) [76–78], salinity decreased total soluble solids and sugar (especially sucrose) content. Fruit quality, characterized as taste, aroma, and texture by a panel decreased significantly in “Elsanta,” but not in “Korona” [76, 78]. The more tolerant cv. Korona was characterized by an increase in reduced glutathione and better fruit taste [78].

Salt stress increased the antioxidant capacity, antioxidants pools (ascorbic acid, anthocyanins, superoxide dismutase) and selected minerals such as Na^+ , Cl^- , K^+ , N, P, and Zn^{2+} , as well as lipid peroxidation in both cultivars [78], and also free and essential amino acid content, especially in cv. Elsanta. The ability of “Korona” to retain Cl^- in the root system more effectively than “Elsanta” resulted in 41% less leaf Cl^- at the highest salinity level and better growth under NaCl stress leading to relatively higher fruit yield and quality [76].

5.4 Irrigation

Strawberry plants need frequent irrigation due to a shallow root system, large leaf area, and fruits with high water content [79]. In a field study, it was found that irrigating at 200 hPa resulted in higher yield and better fruit quality when compared with irrigating at 300 hPa. Decreased fruit firmness and increased fruit size was also observed in irrigated plots [80, 81]. Particularly in light soils, irrigation significantly increases fruit yield and quality, and creates an opportunity for intensive

strawberry production. Both sprinkler and drip irrigation systems produced the same result, but water use was considerably lower with drip irrigation [82].

When strawberries are exposed to long-term water stress, leaf, crown, and runner growth are decreased. Fruit number and weight (yield) also decreases even as fruit maturity is accelerated [83]. Therefore, strawberries are generally considered unfit for deficit irrigation. However, mild deficit irrigation has been tested as a method to limit water use, and depending on the cultivar, to increase the concentration of some taste- and health-related compounds. For example, [84] report that deficit irrigation reduced berry size but increased dry matter content, sugars and acids in cvs. Elsanta, Sonata, and Symphony but not in cvs. Florence and Christine.

5.5 Cultural systems

Strawberries are commonly grown on raised-beds using different polyethylene mulches. This system keeps the fruits clean, eases harvesting, saves water, and lowers herbicide use. Moreover, in Europe, strawberries grown on plastic mulches ripen a week earlier than those without mulch because of higher soil and canopy temperature, and reflection caused by the mulch may improve light conditions [39].

Significantly higher phenolic content has been reported in fruit from strawberry plants grown on plasticulture than in those grown in matted row culture. Additionally, higher anthocyanin content has been observed in strawberry fruits grown on plastic mulch compared to those grown on straw mulch. The elevated temperature inside the plastic may explain the higher phenolic content. White mulch increased the contents of the total phenolics and ellagic acid and the antioxidant activity in strawberry fruits more than brown mulch, whereas the total anthocyanin content was highest in fruits grown on brown mulch. Strawberries grown on red plastic mulch have been found to contain significantly higher amounts of aroma compounds than those grown on black mulch, which may be due to different light conditions caused by the mulch color [39].

Cultural systems affect plant metabolites such as total phenolic compounds, anthocyanin, and antioxidants. Hill plasticulture systems significantly increase total phenolic compounds, anthocyanin, antioxidants, and flavonoids compared to matted row systems. Cultural systems affect the quantity and quality of light reaching the plant and therefore, plant and soil temperatures, and soil moisture content. These conditions will affect plant growth and development and subsequently plant metabolites such as those mentioned previously [12, 51].

5.6 Planting date

Planting date in glasshouse production affected phenolic content, and a statistically significant interaction was found between planting date and fruit order [39]. The crop from the latest planting date seems to have the highest total phenolic content and antioxidant activity, whereas anthocyanin content was lowest. In a related study, it was found that harvest date affected the ellagic acid content, with prevailing temperature and rainfall during harvest assumed to cause the differences [39].

Fruit quality did not change with the cultural cycle (summer-spring versus fall-spring), but the berries harvested in the spring had higher vitamin C and sucrose content and lower nitrate content compared with berries harvested in the winter [79]. Several works have demonstrated flavor differences between crops grown during different seasons [19]. Planting date affects plant mineral content due to changes in nutrient solution strength and light intensity. At lower light intensity during winter, growers increase nutrient solution strength, which can lead to higher fruit nitrate content compared to the spring. This can be considered undesirable, since nitrates may pose a potential threat to human health [19].

5.7 Maturity

Chemical composition in strawberry fruit varies by genotype and maturity. Following the pink stage, many phytonutrients are synthesized in parallel with the overall development and maturation of the fruit.

Harvesting at optimal maturity is essential for ensuring good fruit quality since important changes in individual sugar and acid content occurs in the final stages of ripening.

Antioxidant capacity also varies considerably with maturity. Many phytonutrients are synthesized in parallel with the overall development and maturation and strawberry fruit harvested at ripe stage consistently yielded higher antioxidant values than those harvested at the pink stage [12, 16]. Strawberries have the highest oxygen radical absorbance capacity (ORAC) values during the green stages [15, 16], while fruit harvested at pink stage (50% maturity) had the lowest ORAC and 2,2-diphenyl-1-picrylhydrazyl radical scavenging activity.

The concentration of total phenolic compounds is highest at the green stage and reduces during prolonged storage and processing. Ellagic acid concentration is highest in the early stages of fruit maturation (green strawberries) and gradually declines with ripening [85].

Ascorbic acid content increased from green to the pink stage by about 95% and then did not change until berries were overripe, when it then decreased. Ascorbic acid is lower in the inner than in the outer part of the fruit.

Overall quality and firmness of fruit harvested at the red ripe stage declined more rapidly than the white tip stage. Also, fruits were lighter and less red, reflecting less anthocyanin accumulation. Therefore, fruits harvested at three quarters red ripening stage can be stored for longer periods with better color and firmness than the fruit harvested when fully red. Strawberries harvested at early stages of color development (white stage) can become red during storage similar to commercially ripe fruit [15, 86]. This indicates that strawberries harvested at certain stages of maturity can synthesize pigment during storage under favorable conditions that are temperature dependent [45, 86] and can occur in darkness, but light can slightly increase the rate of pigment formation [45].

5.8 Harvest time and method

There are large variations in flavor quality between fruits per harvest and also from harvest to harvest. In strawberry, primary fruits are larger and ripen first and have less competition for resources. Therefore, there is a variation between primary, secondary, tertiary, and quaternary fruit in flavor and nutrient content. At each harvest, fruits from different stage of maturity and ripeness will increase the variability.

Different harvests during the season may even have more variability than fruit ripening stage, because, environmental conditions such as light may alter flavor compounds as well. Previous data from tomatoes Anagnostou [36] suggested a strong correlation between juice sugar and solar radiation across one season. The results show the difficulty in interpreting data where there is a variable light integral as well as differences [36].

Soluble solids and sugars decreased as the harvest season progressed, while TA, ascorbic acid content and anthocyanins increased [36]. A steady decrease in SSC and sugars as the harvest season progressed was noticed, most probably because plants were exhausted. Low levels coincided with peak production, while the highest values were noticed during low and early production (January) periods characterized by very low light intensity and short days. Titratable acidity increased from January to June, in parallel with increases in day length and light intensity [36].

Seasonal factor and environmental conditions affect fruit content and quality very strongly.

Organic acids that affect flavor (citrate and malate) and ascorbic acid were significantly higher in the spring than winter. This could be due to the higher carbohydrates as the precursors for ascorbic synthesis. Carotenoids are also available in strawberries, although less abundant than ascorbic acid. Unlike ascorbic acid, the amount of carotenoids is higher during winter than spring. This suggests that carotenoid synthesis is dependent on the interaction between temperature and light intensity [79].

The method of harvest and handling operations can determine the extent of physical injury and maturity variation, which both affect the nutritional quality of strawberries. Physical injury during harvest such as abrasions, cuts, and bruising can reduce the amount of ascorbic acid and increase fruit decay. Best harvest and handling practices should be implemented to reduce physical injury and maintain fruit quality [33].

5.9 Pollination, fruit order, and crop load

Inadequate pollination creates distorted strawberry fruit at maturity due to inadequate fertilized ovules, which secrete hormones necessary for fruit cell division and enlargement [11]. Insect pollination results in uniform strawberry fruit and bee (*Apis mellifera*) colonies are introduced into protected cultivations to pollinate flowers. Honey bees are not efficient in colder temperatures and other insects such as bumble bees are commonly used [87]. In Utah, field-grown strawberries pollinated by caged honey bees produced fewer malformed fruits than controls. Honey bees and large Diptera (*Eristalis* spp.) were the most common visitors to the strawberry flowers while sweet bees (*Halictus ligatus*) were the most efficient pollinators [88]. In Brazil, stingless bees (*Scaptotrigona* aff. *depilis* and *Nannotrigona testaceicornis*) work efficiently as strawberry pollinators in greenhouses [89].

Temperatures above 25°C can significantly affect pollen viability and germination and consequently yield and quality. However, certain strawberry cultivars produce heat-tolerant pollen, which in turn could result in higher fruit set [90, 91].

Fruit order significantly affected the phenolic content in fruits. In two separate experiments, the levels of the total phenolics, ellagic acid, and antioxidant activity were found to increase from primary to tertiary fruits. Fruit order caused at highest a 1.5–2.0-fold difference in phenolic acid content [39]. However, the highest anthocyanin content was found in secondary fruits.

Primary fruits are the largest and have more resources available for growth and protein synthesis and less available for the phenylalanine ammonium lyase enzyme to convert it to phenolic compounds. Another explanation is the dilution effect of larger cells with higher biomass in primary fruits [39].

In strawberry, the effect of crop load on fruit quality depends on the genotype. Low crop load is associated with higher total soluble solids in “Ventana” and “Candongá,” but not in “Camarosa” [92]. Crop load also increases over time meaning that even at similar light levels, the amount of assimilates available to individual fruits will change throughout the harvest period. The greatest demand for assimilates will occur during the development of secondary and tertiary fruits [19]. Crop load also affects firmness, TSS, acidity, and anthocyanin [36].

5.10 Chemical sprays and residues

Evaporation of surface water from overhead irrigation or chemical, fertilizer, and pesticide sprays create an unpleasant strawberry fruit appearance [11].

However, strawberries cannot be exposed to free water after harvest meaning residual chemicals on fruit surfaces cannot be washed away. Furthermore, pest control products may indirectly change fruit flavor and composition. For example, mite control improved sweetness and flavor intensity of “Sweet Charlie” strawberries but had no effect on fruit color or firmness [93]. There are many commercial products that affect plant growth and development, which may or may not be plant growth regulators. These products seem to enhance fruit set and growth, resulting in bigger fruit size and higher yields, or protect the plants and fruits from biotic and abiotic stresses [94].

Plant growth stimulators (seaweed extract, mixture of an auxin plus gibberellic acid, and nitrophenolates) increased fruit yield, size, and total anthocyanin concentration of strawberry cv. Camarosa, but did not change other characteristics (i.e., fruit juice pH, TA and TSS concentration, organic acid and carbohydrate concentration and fruit color). In a taste panel, the mixture of auxin and gibberellic acid received the best score [94].

In another experiment, strawberry plants were sprayed during fruit ripening and after 10 days with 2, 4 and 6 g l⁻¹ chitosan with no phytotoxic effect [95]. Chitosan increased firmness and reduced fruit decay, ripening rate, TA, and anthocyanin content during 4 weeks of storage. Formation of a chitosan film on fruit acts as a barrier for oxygen uptake thereby slowing the ripening process and modifying the atmosphere and ethylene levels without causing anaerobic respiration. In addition, chitosan coating can reduce desiccation by providing a moisture barrier as was reported earlier [95]. The reduced decay by chitosan is mostly related to delayed fruit senescence.

Plants receiving salicylic acid (SA) during vegetative stage through their nutrient solution produced firmer fruits with less weight loss, decay, and better quality [96]. Weight loss is due to metabolic activity, respiration and transpiration, and it is possible that SA decreased respiration rate and fruit weight loss by closing stomata. Salicylic acid as an electron donor produces free radicals, which prevents normal respiration. Pre- and postharvest application of salicylic acid significantly increased strawberry ascorbic acid content, TSS, TA and total antioxidant potential, and prevented fungal growth [97]. Increased ascorbic acid is mostly due to the increased activity of ascorbate peroxidase, [12]. Also, increased antioxidant ability and antistress power of plants and fruits induced by SA prevents vitamin C destruction. Salicylic acid decreased fungal development, although not fungicidal. However, activity of defensive enzymes (peroxidase, chitinase, and phenylalanine ammonia-lyase) increased in pear after SA spray. Conversely, rapid decrease in endogenous SA of fruits during ripening is simultaneous with rapid softening of fruits. It has been shown that SA affects cell swelling, which leads to higher firmness of fruits and prevents fruit softening (Wang [12]).

5.11 Silicon, and other natural compounds

Recent studies show that silicon (Si) is a beneficial element for plant growth that plays an important role in plant resistance to biotic and abiotic stresses. Silicon improved strawberry plant fresh and dry weight, leaf area and relative water content, and yield under salinity stress. Both Si and salinity treatments increased acidity of fruit, but did not affect other fruit quality characteristics [98]. Silicon fertilization also reduced powdery mildew severity under high tunnel on all strawberry cultivars tested, and significantly increased yield of marketable fruits reaching as much as 300% with cv. Monterey [99]. A silicon-based wetter (Omex SW7) significantly increased the number and length of leaf hairs on both the upper

and lower surfaces of strawberry leaves and reduced the number of germinating powdery mildew (*Podosphaera aphanis*) ascospores and colonies. Moreover, potassium carbonate alone or mixed with Omex SW7 significantly reduced the number of germinating ascospores and colonies [100].

6. Conclusion

Several reports confirm significant (35–50%) loss of horticultural produce after harvest. In strawberry, preharvest management is a prerequisite for producing good quality fruit. Fruit quality and nutrient content of strawberries varies widely depending on the variety and environmental factors. Berry fruits are extremely perishable and have a short market life. Because strawberry quality cannot be improved after harvest, the role of preharvest factors must be understood in order to improve the shelf life.

Results indicate that the effect of genotype on strawberry fruit and nutritional quality is stronger than that of growing conditions and cultivars could be selected for maximum adaptability to the environmental conditions and market demand.

Environmental conditions seem to have a major influence on nutritional and flavor compounds in strawberries. Preharvest conditions such as light intensity can affect strawberry fruit quality and phytonutrient content. The color of plastic mulches frequently used on raised beds also affects fruit quality. Plant growth and development is largely affected by temperature, which affects cellular compounds and their structure and fruit firmness. Changes in the composition of atmospheric CO₂ and ozone constituents due to climate change may also affect fruit quality. Soil types, fertilization, composts, and mulching influence the water and nutrient supply to the plant and can affect the nutritional composition, ascorbic acid content, and antioxidant activity of harvested fruit. The use of alternative substrates (soilless culture) is a common cultural method in strawberries, especially in protected environments that has been shown to improve fruit yield and quality. Nitrogen and Ca are among the most critical elements for improving strawberry yield and quality. Strawberry plants need frequent irrigation due to a shallow root system, large leaf area, and fruits with high water content.

Cultural practices affect strawberry metabolites significantly. Higher phenolic content has been reported in fruit from strawberry plants grown on plasticulture than in those grown in matted row culture. Also, there is a large variation in flavor quality between fruits per harvest and from harvest to harvest.

Some of these environmental factors can be optimized in open fields according to the light and temperature conditions, such as planting date, mulch color and fertilization, although, their interactions may be hard to control. Other environmental factors can only be manipulated under protected cultivation. In general, to obtain reliable data on fruit and nutritional quality, when there is such a larger variation in growing conditions, other factors should be closely monitored.

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