

Review Article

The effects of pre-harvest and post-harvest factors on the nutritional quality of strawberry fruits: A review

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Abstract. In the last years, the nutritional quality of fruits has been widely evaluated and requested by consumers, mainly because of the health effects they provide. As known, these benefits can be due to micronutrients, as vitamins and minerals, but also to phenolic compounds, as flavonoids and ellagitannins. In this context, strawberries represent a very good choice for a diet low in saturated fats and sodium and, at the same time they are rich in fiber, potassium and other minerals, vitamins, and antioxidant phytochemicals: all elements that are currently considered as the essential constituents of a well-balanced diet. However, the nutritional quality of strawberry fruits can be considerably affected by several pre-harvest and post-harvest conditions, which, in most cases, may decrease the nutrient and the phytochemical contents of this fruit.

This paper reviews and updates the current knowledge on the nutritional and phytochemical composition of strawberry, paying particular attention on the role played by the genotype, the maturity, the environment, the storage and the processing on the nutritional quality of this fruit.

Keywords: Strawberry, nutritional quality, phenolic compounds, antioxidant capacity, maturity, genotype, environment, storage, processing

1. Introduction

The nutritional quality (NQ) of fruit is a very complex parameter, since it is still very hard to identify the attributes which could give a comprehensive idea of the “healthy power” of a fruit. Certainly, the fruit content of specific micronutrients (minerals, vitamins) is a clear NQ indicator, whereas the situation is much more complicated when evaluating the content of non essential compounds, like polyphenols.

Strawberry (*Fragaria × ananassa*) has a relevant NQ, due to its high levels of micronutrients as vitamin C, folate and minerals as well as of phenolic constituents [1–4], that have shown huge biological potentialities in humans [5–8].

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This fruit is of economic and commercial relevant importance and largely consumed both in fresh or in processed form, such as jams, juices, and jellies, making it the most studied berry from an agronomic, genomic and nutritional point of view.

Micronutrients and phenolic compound concentrations in strawberry are known to be affected by many pre-harvest conditions, as genotype and maturity at harvest, and postharvest factors, as storage period and temperature, and processing [9, 10]. For example, several significant changes in nutrient and phytochemical composition are related with the genotype, that determines the quantity and the quality of fruits, but also with the ripening, because many chemical and compositional modifications occur when the fruit is still attached to the mother plant. On the other side, the delay between harvest and storage at the appropriate temperature is known to be critical for the success of the treatment, while the use of low temperature and of modified atmospheres is essential to avoid least partially mould growth and fruit senescence, and thus extending strawberry shelf-life.

The aim of this work is to discuss the nutrient and photochemical composition of strawberry, with specific focus on the most significant compounds and the effects that several pre- and post-harvest factors may exert on the NQ of this fruit.

2. Composition

2.1. Nutrients

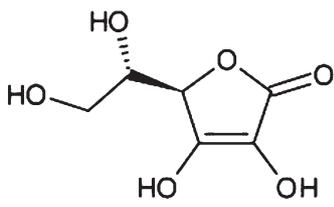
According to their nutrient composition, strawberries are a very healthy fruit. Firstly, they are low in total calories, with a 100 g serving providing only 32 kcal; then, their sweet flavor make them a delicious wholesome snack alternative to processed foods, as their dietary fiber (2.4 g/100 g) and fructose (>50% total sugars) contents both regulate blood sugar levels by slowing digestion, and contribute to a satiating effect [4]. The extremely high content of vitamin C (Fig. 1) in strawberry (even higher than citrus fruit) is one of the aspects of major nutritional relevance. The vitamin C content of strawberry fruits results to vary between 0.1 and 1 mg g⁻¹ FW (fresh fruit) for several strawberry genotypes, while its content in flesh is about 58.8 mg/100 g FW [4, 10, 11]. Thus, the vitamin C content in strawberry is a crucial factor affecting NQ of the fruit, and its variation is an important parameter when comparing both commercial varieties and new selections.

Folate (Fig. 1) is a micronutrient that strengthens the NQ of strawberry being in the range of 20–25 µg/100 g (FW), much higher than in other fruits [4]. However, there are still few studies focused on the evaluation of the folate content of fresh strawberries [11, 12], of its stability during storage, as well as of its retention after fruit processing.

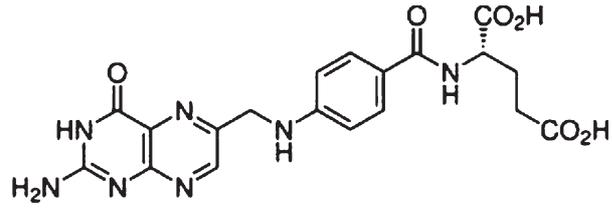
Because of the lower content of other vitamins in strawberry, the main interest is currently focused on the determination of vitamin C and folate in the fruits, for their potential impact on human health. However, strawberry, even if in a lower extent, is a sufficiently good source of several other vitamins, such as thiamin (B1), riboflavin (B2), niacin (B3), vitamin B6, vitamin K, vitamin A and vitamin E [4]. Strawberry contains also many minerals, as manganese, potassium, iodine, magnesium, copper, iron and phosphorus [4].

2.2. Phytochemical compounds

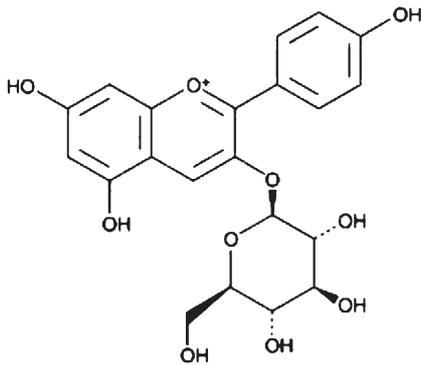
In addition to traditional nutrients, strawberries are among the richest dietary sources of phytochemicals. In the strictest sense, phytochemicals can be defined as secondary metabolites produced by plants; however, the term is generally used to describe chemicals from plants that may affect health, but are not designated as traditional nutrients. In the last decades, with the advent of highly sensitive analytical methods, knowledge on the composition of strawberry fruits has rapidly expanded, allowing to obtain the phytochemical profiles or “chemical fingerprint” of these fruits. They serve many diverse biological functions including roles in plant growth, development, and defense: for example, they provide pigmentation, antimicrobial and antifungal functions, insect-feeding deterrence, UV radiation protection, chelation of toxic heavy metals, antioxidant quenching of free radicals generated during photosynthesis, and much more. There are four main classes of strawberry phenolic compounds: flavonoids (mainly anthocyanins, with flavonols, and flavanols giving a minor contribution), hydrolyzable tannins (ellagitannins and gallotannins), phenolic acids (hydroxybenzoic acids and hydroxycinnamic acids) and condensed tannins (proanthocyanidins). Structural diversity



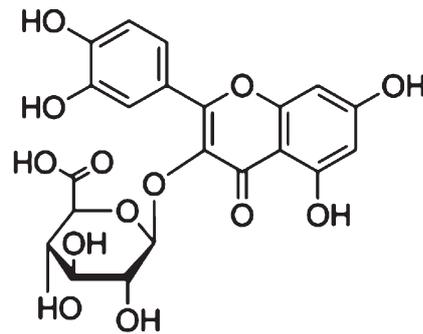
Vitamin C



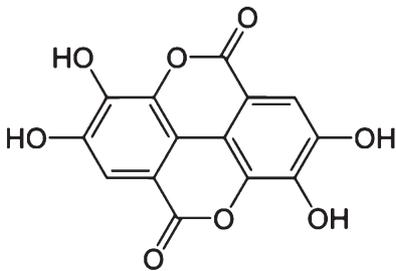
Folate



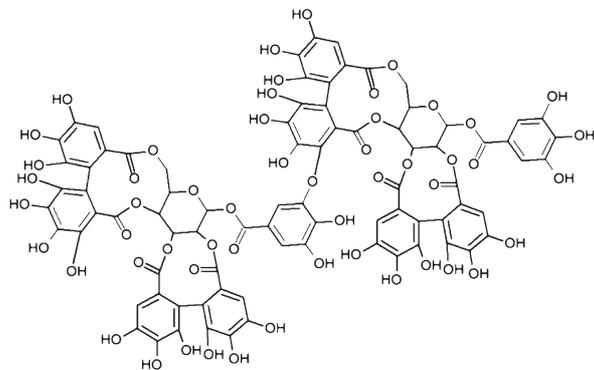
Pelargonidin-3-glucoside



Quercetin-3-glucuronide



Ellagic acid



Sanguin H-6

Fig. 1. Chemical structures of the most common compounds present in strawberry.

within these phenolics is dependent on types and oxidation levels of their heterocyclic ring(s), their substitution patterns of hydroxylation, their glycosylation by various sugars and/or acylation by organic and phenolic acids, and by conjugation to form polymers.

2.2.1. Anthocyanins

Anthocyanins are the glycosylated form of anthocyanidins, which are polyhydroxyl and polymethoxy derivatives of 2-phenylbenzopyrylium or flavylum salt. They contain two benzoyl rings (A and B) separated by a heterocyclic (C) ring. The deglycosylated or aglycone forms of anthocyanins are known as anthocyanidins. The six most common forms of anthocyanidins are cyaniding (Cy), delphinidin, pelargonidin (Pg), malvidin, petunidin, and peonidin, with a distribution in nature of 50, 12, 12, 12, 7, and 7%, respectively [13]. They represent the most relevant water-soluble pigments in plant, and flavonoid subclass which probably deserves the most attention, since the daily uptake of anthocyanins in human diet is remarkable and much higher than the total intake estimated for other flavonoids.

Pg 3-glucoside is the major anthocyanin in strawberry (Fig. 1) [14–16], but, even if in smaller amount, also Cy 3-glucoside seems also to be constant in all varieties [17–19], as well as Pg 3-rutinoside, which are commonly found in strawberry fruits [4, 20]. Moreover, other anthocyanins have been found in some strawberry cultivars as Pg 3-arabinoside [21] and Cy 3-rutinoside [17]. These findings are in agree with those obtained in a recent study that confirmed similar anthocyanin compositions in nine Italian cultivars [22].

Various acylated anthocyanins with a range of aliphatic acids have been reported in several strawberry cultivars, too. In particular Pg 3-(6-malonylglucoside) has been indicated as one of the main pigments in several Japanese cultivars, comprising 5–30% of total anthocyanin content [23, 24]. Other acylated anthocyanins also found in strawberry are Pg 3-acetylglucoside and Pg succinylglucoside [14, 15].

2.2.2. Ellagitannins

Ellagitannins (ETs) are together with anthocyanins the most abundant phenolic compounds in strawberry [25, 26]. They are hydrolyzable tannins, with a wide range of structures such as monomers (ie, ellagic acid glycosides) (Fig. 1), oligomers (ie, dimers sanguin H-6) (Fig. 1), and complex polymers. Even if ETs have been identified as the active principles in medicinal plants [27], they are quite unusual in foodstuffs. Recently, Koponen et al. [28] studied 33 commonly consumed foods in Finland and screened them for ellagitannin content. Ellagic acid compounds were detected only in five foods, all berries from the family Rosaceae (cloudberry, raspberry, rose hip, and strawberry), that contained high levels of ellagic acid equivalents. In this study the ellagitannin contents, expressed as ellagic acid equivalents, ranged between from 21.7 to 83.2 mg/100 g (FW), while free ellagic acid derivatives ranged between 0.7 and 4.3 mg/100 g (FW). The authors reported that ellagic acid was mostly presented as ellagitannins, and the relative amount of free ellagic acid and its glycosides (non-tannin ellagic acid) was <6%, and in most cases only 1–2%. Other previous study reported the ellagitannin contents of strawberry were between 25–59 mg/100 g in fresh samples [29–31].

Despite of the above considerations, a few studies have identified and quantified the ellagitannin compounds themselves. Recently, Aaby et al. [31] and Seeram et al. [32] reported an important group of oligomeric ellagitannins in strawberry (*Fragaria × ananassa*): galloylbis-hexahydroxydiphenoyl (HHDP)-glucose, previously reported in Rubus berry [4]. This molecule is a basic unit of many ETs, for example, sanguin H-6 and lambertianin C contain 2 and 3 units, respectively [4]. However, in this field more studies are desirable, especially because of their important impact on human health.

2.2.3. Other phenolics

Strawberry is also a moderate source of other polyphenolic compounds. Many studies focused on strawberry flavonol content and composition [4, 33]. Similarly to anthocyanins, flavonols occur naturally in glycosylated forms, where the associated sugar moiety is very often glucose or rhamnose, although other substituents such as glucuronic acid, galactose, arabinose and xylose may also be involved. The flavonols identified in strawberries are derivatives of quercetin and kaempferol, being quercetin-3-glucuronide (Fig. 1) the most abundant. Also acylated flavonols such as quercetin- and kaempferol-3-malonylglucoside, and kaempferol-coumaroylglucoside have been found in some strawberry cultivars [31]. The interest on the flavonol composition in strawberry is recently arisen since convincing evidence suggests that these molecules appear in human plasma and urine in far higher concentrations than anthocyanins [4]. Additionally, mechanisms of passive and active transport of quercetin aglycones and glucosides through the epithelia of the gastrointestinal tract have been extensively studied in human [34] and animal models [35, 36], and the potential bioefficacies of the bioavailable metabolites are under investigation.

Flavanols are the only subclass of phenols that do not occur naturally as glycosylated forms. In strawberry they have been found in both monomeric (catechins) and polymeric forms called condensed tannins or procyanidins (PCs), especially in strawberry flesh and achenes [26]. They have shown to possess directly and indirectly antioxidant, antimicrobial, anti-allergy, anti-hypertensive, and inhibition of the activities of some physiological enzymes and receptors properties [37].

Finally, a variety of phenolic acids are present in strawberry as derivatives of hydroxycinnamic acid (HCA, i.e. caffeic acid) and hydroxybenzoic acid (HBA, i.e. gallic acid) [4]. Soluble HCA derivatives are more common than the HBA ones, consist chiefly of *p*-coumaric, caffeic and ferulic acids [29, 31] and are generally found as glycoside and as esters with sugars or quinic acids (such as *p*-coumaroylhexose, *p*-coumaroylhexose-4-O-hexoside, or ferulic acid hexose derivatives). Unlike HCA, HBA derivatives are mostly found in the form of glucosides, even if glucose esters are occasionally observed.

3. Antioxidant capacity

In past decades, strong attention has been given to the antioxidant power of fruit as an eligible parameter for quality and as indicator of the presence of beneficial bioactive compounds in foodstuffs and, therefore, of their healthfulness. This parameter is strictly associated to the concentration of efficient radical scavengers, such as vitamin C and phenolic compounds. In this context, strawberries possess greater antioxidant capacity (2- to 11-fold) than apples, peaches, pears, grapes, tomatoes, oranges, or kiwifruit [2], with vitamin C responsible, per se, for more than 30% of the TAC followed by the anthocyanins contributing between 25–40% (depending on the cultivar) and the rest attributed to the contribution of mainly comprised ellagic acid derivatives and flavonols [22]. These findings may support previous studies, confirming that associations between the antioxidant properties and the proportion of phenolics present as anthocyanins or ETs are generally not very evident in strawberry [25, 38–43].

4. Factors affecting the NQ of strawberry

4.1. Maturity

The polyphenol composition of strawberry changes through growth and stage of ripening: generally unripe fruit pulp have higher levels of phenolic compounds than ripe fruit pulp. While the strawberry are green, the total content of phenolics and flavonoids are high, and they decrease over the ripening period. In a recent study [44] four cultivars from three different ripening stages (full size green fruits, pink fruits and ripe red fruits) were compared and was found that green strawberries of all genotype had a higher content of phenolic compounds than pink and red one. These results are in keeping with other studies, which reported that green strawberry fruits of different varieties had the highest level of phenolics compound and flavonoids than pink or red fruits and that these contents decreased during maturity [45–47]. In contrast, the levels of vitamin C can increase in the dark red berries, but this increase is not always statistically significant, depending on genotype, storage effects or environmental factors [48, 49].

Also anthocyanin profile varies during maturity, but with an opposite trend: in all cultivars anthocyanins are stored in red stage, coinciding with a red-color fruits, whereas small amounts are present in pink fruits and they are absent in green fruits [9, 46, 47].

Finally, the antioxidant capacity varies during ripening period with the same trend of the phenolic compounds; according to many studies, the TAC of the fruits gradually decrease during maturity and this reduction is strictly associated with a strong decrease of tannins, while polar non-phenolic antioxidants, such as vitamin C, only slightly increase upon ripening, without affecting the decreasing trend [9, 47, 49].

4.2. Genetic and environmental factors

Phenol concentrations and TAC in foods vary according to many genetic, environmental, and technological factors, some of which may be controlled to optimize the NQ of fruits and vegetable [35]. In particular, the genetic background

plays an important role on the NQ of strawberry fruits, since the content of micronutrients and phytochemicals may greatly vary from cultivar to cultivar. However, few genotypes have been well characterised for these important features, and still limited knowledge is available on the possibility of improving strawberry nutritional traits by breeding. On the other hand, growing conditions, such as type of soil, exposure to sunlight and humidity level, can also influence the micronutrient and phytochemical content of strawberry fruits, thus affecting their nutritional value. Regarding the total phenolic content, there are large differences among cultivars and among cultural systems. In a study Tulipani et al. [23] compared four different genotypes of strawberry and found a 1,8-fold difference between the highest and lowest value of total phenolic content. In particular, cultivar Adria had the lowest value (2.11 mg GAE/g FW), while Sveva had the highest (2.83 mg GAE/g FW). Other values were found by Wang et al. [47], who reported that the individual concentration of total phenolic in the extract of eight strawberry cultivars ranged between 95 and 152 mg/100 g (FW), while Capocasa et al. [50] and Skupien et al. [30] reported a concentration that ranged from 1.80 to 3.20 mg GAE/g (FW) and from 3.17 to 4.43 mg GAE/1 g, respectively. Finally, Scalzo et al. [3] analyzed six cultivated varieties and one wild strawberry, observing important differences among cultivars, with a range of concentration between 1093 mg GAE/L (cv Idea) and 2128 mg GAE/L (cv Patty).

The anthocyanin profile and levels can vary by several factors, too. Lopes da Silva et al. [15] reported a notable variability among several samples of different variety and year: the individual concentrations of the three major anthocyanins (i.e. Cy 3-glucoside, Pg 3-glucoside, Pg 3-rutinoside) in the extracts of five strawberry varieties ranged between 200 to 600 mg/kg (FW). Other values of total anthocyanins were reported by Clifford [13], between 150–350 mg/kg, while Meyers et al. [51], in a study carried out with eight different strawberry varieties, reported average concentrations of 414 mg/kg, with strong differences among cultivars. Moreover, Garcia-Viguera et al. [52] reported concentrations from 185 to 840 mg/kg in samples of Oso Grande and Camarosa, respectively. It is interesting to note that anthocyanin content in Camarosa strawberries determined by Castro et al. [53] (482 mg/kg, FW) was closer to those reported by Lopes da Silva et al. [15] (468 mg/kg, FW). On the other hand, Tulipani et al. [54] indicated concentrations between 99–296 mg/kg (FW) in nine Italian strawberry cultivars.

As evidenced, phenolic compounds and anthocyanin concentrations may strongly differ, even within the same variety, depending of the degree of ripeness, the climatic factors and post-harvest storage, and these characteristics are necessary when assessing these parameters as possible indicators of the NQ of fruit. It should also be taken into account that differences in concentration found for a same variety by different authors might also be due to the use of different extraction techniques.

Since the TAC parameter is closely related to the presence of vitamin C and phenolic compounds, there is a considerable variability in TAC values among strawberry cultivars. Scalzo et al. [3] have exposed a positive proof that the interaction of these different factors can determine the antioxidant capacity of a specific fruit and should be taken into account to better characterize agronomic production and information to the consumer. In this study, the authors showed that the TAC is strongly influenced by species or cultivar: the wild species *F. vesca* had the highest TEAC values, which were 2.5-fold higher than the average of the most common cultivated Italian strawberry varieties. These results are in agreement with other studies, that found remarkable differences in antioxidant capacities between different cultivars of strawberry fruits [23, 47, 49].

All these studies suggest that, when a comparison is made among data in the literature, the varieties should be known and considered and, because genetic modifications produce differently enriched fruits, the possibility of different manipulations (by means of traditional breeding or advanced biotechnology or genetic manipulation) [55, 56] could be a powerful tool for modifying antioxidant fruit patterns and contents [2, 3, 22, 47].

Finally, also the environmental conditions in which plants grow and climate changes that take place each year during the strawberry ripening period may partly explain the large difference in the content of micronutrients and phytochemicals. When assessing the content of polyphenols and TAC of strawberry fruits, different cultural practices need to be taken into account. Wang and Millner [42] reported that fruits from plants grown in compost socks had significantly higher phenolic content, flavonoid, anthocyanin and oxygen radical absorbance capacity rather than those grown in a matted row system. Moreover, these authors found also that vinegar treatment in culture practice showed significant effect, generally increasing total phenolic, total anthocyanin and TAC values. These results are in agreement with other studies, showing a lowest content of micronutrient and antioxidant capacity in fruits of plants grown in the matted row system than that grown in the hill plasticulture system [57].

Furthermore, Jin et al. [58] compared two different varieties cultivated both in organic and inorganic cultivation, finding that strawberries grown from organic culture exhibited generally higher activities in antioxidant enzymes and contained significantly higher level of phytonutrients than those produced from conventional culture. On the contrary, a study carried out by Hakkinen et al. [33] showed that organic cultivation had no consistent effects on the level of phenolic compounds in strawberry. These authors analyzed three different varieties and found similar levels of flavonols and phenolic acids when these different cultivation techniques were used, except for the cultivar Jonsok, which had a 12% higher concentration of total phenolics if cultivated with organic system. However, this difference was due to the higher contents of ellagic acid and kaempferol in strawberry cultivated by the organic technique than in those cultivated by the conventionally system. Unfortunately, there are still few studies on the effect of cultural system on nutritional value of strawberry, so that further analysis should be performed.

4.3. Storage and processing effects

Short-term storage strongly influences NQ and micronutrient and phytochemical profiles of strawberry, and storage temperature seems to be one of the key factors particularly affecting the stability of phenolic antioxidants in fruits, during postharvest storage. Many authors have studied how phenolic composition, anthocyanin, and TAC in berry may change during storage treatments [49, 54, 59–61]. Our group [54] also found that the most evident effect of storage (storage for two days at 4°C one day at room temperature, in the dark) in the cultivars investigated was in folate content, since the levels of folate increased in all the genotype studied. Unfortunately, this investigation remains one of the very few studies currently available on the effect of the storage on folate, whereas further evidence are needed.

With regard to the NQ, the total phenolic and anthocyanin content are not affected by storage, as well as vitamin C; on the contrary, the flavonoid concentration is significantly higher in fruits after short-term storage [49, 54, 59–61]. These results could be due to the fact that during storage an increase in the content of early-eluting polar phenolic antioxidants occur. The total phenolic compounds and anthocyanin of strawberry fruits may increase if temperature and storage time are extended. Kalt et al. [41] stored strawberry at 0°, 10°, 20°, and 30° C for up to 8 days. The most considerable increase in phytochemical composition was recorded for anthocyanin: in fact, its content increased an average of 4,3-fold after 8 days, and the magnitude of increase was related to temperature. When strawberry were stored at 0°C for 8 days, anthocyanins increased 1,7-fold, while for the same period at 30°C, the apparent increase was 6,8-fold. Other authors obtained similar results: they stored strawberry at 0°, 5°, 10°C for up to 7 days and found that berries stored at 10°C had higher level of total phenolics and total anthocyanins content than those stored at 0° or 5°C [58, 62]. This result could be ascribed to the postharvest phenolic metabolism of fruits and anthocyanin would have been formed from a pool of precursors with a small overall effect on antioxidant capacity.

Short-term storage positively affects also the antioxidant capacity of strawberry fruits, since the complex reactions taking place within the fruits during postharvest period may facilitate formation of compounds with enhanced antioxidant capacity, even when fruit attributes, such as taste and smell, have already significantly deteriorated [61]. Generally, during storage TAC can increase [54] or remain stable [60, 61], and the higher is the exposure time and temperature of storage the greater is the increase in antioxidant capacity [58, 62].

In conclusion, storage temperature >0°C, especially during prolonged periods, seems to positively affect phenolic metabolism in strawberry, thus enhancing, in most cases, phenolic content and TAC, but more studies are necessary to better define these features.

Strawberries are generally consumed as fresh fruits, even if many products such as juice, nectar, puree, jam and jellies are available on the market. The fruit juice redilution or concentration, the storage in tank farm, the production of strawberry jam by heating under vacuum, bottling, closing under vacuum and cooling are the main processes for strawberry derived products [63]. Several studies showed that strawberry products possess a decreased NQ compared to fresh fruits, and that the degree of reduction is strictly related to production time and processing steps, such as heat treatment. For example, Hartmann et al. [64] studied the influence of different processing steps on quality parameters of strawberry and found that thawing, mashing and especially pasteurization showed a negative effect on vitamin C, total phenolic content, and anthocyanins, while TAC was only slightly affected. This is probably due to the formation of new antioxidant compounds, such as the products of the Maillard reaction that occur during heating. The authors reported that to reach the maximal yield of polyphenols, anthocyanins, and TAC, a short enzymatic treatment is

favorable. Klopoteck et al. [63] processed strawberry fruits to juice, nectar, wine and puree, finding a decrease in all investigated parameters (total phenolic content, anthocyanin, vitamin C and TAC) within processing berry to the different products. Only puree, produced with a few processing steps without pasteurization, showed the best quality of the measured compounds. Finally, Bursac Kovacevic et al. [65] reported that during processing fruit into jams, phenolic compounds decreased in all jam samples by 45–63%, flavonoid by 10–36% and nonflavonoid by 7–40%, while in a study by Hakkinen et al. [66] the loss was about 15–20% for flavonoid and 20% for total ellagic content. In conclusion, processed strawberry may be an excellent source of food ingredient especially only if compositional changes associated with processing are minimised, so that each processing step should be executed efficiently, and long holding times should be avoided to restrict oxidation processes.

5. Conclusions

Strawberries contain a variety of beneficial compounds, including minerals, vitamins, fatty acids, and dietary fiber, as well as a wide range of polyphenolic phytochemicals (flavonoids, phenolic acids, hydrolysable and condensed tannins). As evidenced, strawberry nutrient and phenolic concentrations may vary according to many pre- and postharvest factors, depending of the genotype, the degree of ripeness, the climatic factors and post-harvest storage: these characteristics are necessary when considering these parameters as possible indicators of the NQ of fruit. These considerations are also essential for both agronomic production and for fruit industry, on one side to improve strawberry genotypes in term of nutrient and phytochemical compounds and, and on the other side, to avoid processing steps and product treatments that lead to a high reduction of the NQ.

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