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Review

The Influence of Physical Treatments on Phytochemical Changes in Fresh Produce after Storage and Marketing

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Abstract: More food with high nutritional content will be needed to feed the growing global human population, which is expected to reach 10 billion by 2050. Fruits and vegetables contain most of the minerals, micronutrients, and phytonutrients essential for human nutrition and health. The quantity of these phytochemicals depends on crop genetics, weather and environmental factors, growth conditions, and pre-harvest and post-harvest treatments. These phytochemicals are known to have anti-cancer properties and to regulate immunity, in addition to hypolipidemic, antioxidant, anti-aging, hypotensive, hypoglycemic, and other pharmacological properties. Physical treatments have been reported to be effective for managing several post-harvest diseases and physiological disorders. These treatments may affect the external, internal, and nutritional qualities of fruits and vegetables. Therefore, the aim of this review is to summarize the information recently reported regarding the use of physical treatments applied either directly or in combination with other means to maximize and maintain the phytochemical content of fresh and fresh-cut or processed fruits and vegetables.

Keywords: fruits; heat treatments; pre-harvest; post-harvest; shelf-life; vegetables

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1. Introduction

The growing human population presents agriculture with unprecedented challenges. More food of higher nutritional content, especially fruits and vegetables, will be needed to feed the world population, which is expected to near 10 billion by 2050 [1]. Fresh fruits and vegetables are important dietary sources of nutrients and health-promoting phytochemicals. According to dietary guidelines, a balanced and healthy diet should include daily consumption of fruit and vegetables. Phytochemicals such as vitamins, polyphenols, carotenoids, phytoestrogens, glucosinolates, and anthocyanins are abundant in fresh produce [2] and help prevent diseases such as cancer and control chronic diseases such as obesity; type 2 diabetes; cardiovascular disease, including hypertension and stroke; osteoporosis, and hypoglycemia [1–8]. Insufficient quantities of essential micronutrients and minerals in the diet can have long-term negative effects on human health and lead to classic micronutrient-deficiency diseases [9,10]. The phytochemical contents of different types of produce are greatly influenced by genotype, weather and environmental conditions, production systems, and harvest, pre-storage and post-harvest treatments, cold storage, and marketing conditions [11–14].

This article aims to review the latest information from the most current research on the phytochemical changes in fresh produce, as well as fresh-cut fruits and vegetables that are caused by pre-storage physical treatments.

2. Pre-Harvest Factors That Affect Changes in Phytochemicals during Storage

The importance of cultivar and pre-harvest factors must be taken into account, as fresh produce quality cannot be improved after harvest and prolonged storage, only maintained. Growers usually select cultivars based on their marketability (visual qualities specific to the market of choice) and yield, as these factors directly affect their bottom line. However, the genetic background of the cultivars, growth conditions, and sanitization treatments, as well as light, temperature, humidity, biotic and abiotic stresses affect the overall quality. In addition, the stage of maturity, harvest time, storage period and temperatures, and atmosphere modification during storage period all affect the external and internal qualities of fresh produce [15,16].

Heat stress is a common abiotic stress in hot countries such as those in the Mediterranean region and is an important issue for crops grown in greenhouses or plastic tunnels during the summer. High temperatures directly affect plant metabolism and enzyme activities, and therefore, the nutritional content in the fruit or vegetable. Many physiological processes are slowed down or impaired by high temperatures. In particular, high temperatures can induce the accumulation of antioxidants, which protect the cell membrane from breakdown and peroxidation. Heat stress usually induces the accumulation of ROS and the activation of detoxification systems [17]. Tomato (*Solanum lycopersicum* L.) plants exposed to a temperature of 35 °C showed increased levels of ascorbic acid (vitamin C) and improved activity of their ascorbate/glutathione-related enzymes [18]. Recently, Rocchetti et al. [19] investigated the combined effect of storage at 4 °C for 10 days and in vitro gastrointestinal digestion on the phytochemical profile of red beet (*Beta vulgaris*) and amaranth (*Amaranthus* sp.) microgreens. An impact on the total phenolic content was observed, with maximal increases in total phenolic content observed after a 10-day storage period for both red beet microgreens (+1.3-fold) and amaranth microgreens (+1.1-fold). On the other hand, in vitro digestion of both red beet and amaranth microgreens, produced a significant increase in total phenolic content (36–88%), antioxidants (6–43%), and total betalains (41–57%), with maximum levels observed when the material was stored for 10 days prior to digestion. Using different cultivation systems, Pignata et al. [20] reported that after 9 days of storage at 4 °C, baby green and red leaf lettuce (*Lactuca sativa* L.) that were harvested from soilless cultivation systems retained its phytochemical content better than lettuce grown in traditional soil-based cultivation systems. The effects of genotype and harvesting day on phytochemical quantities were evaluated in two cultivars of loquat (*Eriobotrya japonica*) fruit [21]. The study showed that, phenolic content and antioxidant capacity were influenced by the cultivar and storage conditions, but not by the harvest date. Similar results were reported for mango (*Mangifera indica* L.) fruit, in a study in which the physicochemical, nutritional, antioxidant, and phytochemical characteristics of 10 mango cultivars were evaluated, exposing significant variations between the cultivars [22].

The quality of raw material at harvest and its suitability for processing are of fundamental importance for the shelf life of fresh-cut produce [23]. In addition, increased public concerns on the pesticides used in crop production have driven many consumers to prefer organic fresh produce. A meta-analysis of many publications found that, on average, organic crops contain significantly higher concentrations of phytochemicals, as compared to conventional fresh produce [24].

3. Physical Treatments

Post-harvest technologies allow horticultural industries to meet the global demands of local and large-scale production and intercontinental distribution of fresh and fresh-cut produce with high nutritional and sensory quality. Several physical treatments have been reported to be effective for managing many post-harvest diseases and physiological disorders [25,26]. These treatments include hot-water treatments, short periods of rinsing in hot water accompanied by brushing, hot air, and steam treatments, alone or in combination with other treatments. These methods are safe, do not leave any chemical residues, and allow the fruit to retain its quality during prolonged cold storage and on the shelf [25,26]. Temperature is also the main abiotic factor that regulates plant growth and development and influences levels of metabolites and phytochemicals. Heat treatments can be used to activate or deactivate and reduce the effects of enzymes activity that can affect the phytonutrients content in the fresh produce [27]. Various types of heat pretreatments have been reported to influence fruit quality, including steam, immersion in hot water and brushing, high-humidity hot air vapor, hot air drying, and microwave heating [26]. Another type of physical treatment involves radio frequency (RF). RF is a dielectric heating method with a frequency range of 3–300 MHz and is widely applied in the industry, scientific research, and medical contexts. RF generates heat through the reciprocal rotation and collision of polar molecules induced by an alternating electromagnetic field. In food processing, RF is mainly used for pest control, drying agricultural produce, and for blanching fruits and vegetables [28].

4. Physical Treatments and Phytochemicals

Physical treatments have been proven to modify quality traits. An adequate combination of temperature and time could affect ripening processes, external, and internal post-harvest quality [26]. Physical treatments have also been reported to influence the phytochemical profiles and antioxidant capacities of freshly harvested fruits and vegetables after short or prolonged storage and their shelf lives (see Table 1).

The antioxidant (AOX) capacity in bell peppers (*Capsicum annuum* L.) was increased after treatment in hot water rinsing and brief brushing (55 °C) before storage, in combination with low temperature (2 °C) during 3 weeks of storage, compared to non-heated fruit [29]. Another hot-water treatment (55 °C for 60 s) helped maintain the quality of cherry peppers after 14 days of storage. This treatment preserved the quality of the peppers, inhibited phenylalanine ammonia lyase (PAL) activity, and did not markedly affect the peppers' antioxidant content during storage [30]. Immersing breaker-turning tomatoes into water at 52 °C for 5 min significantly increased (by 17%) their lycopene content after 2 weeks of storage at 5 °C. This treatment also increased the tomatoes' ascorbic acid content by 11%, their lipophilic phenolic content by 18%, and their total phenolic content by 6.5% [31]. In another study, mature-green tomatoes were immersed in hot water (52 °C) for 5 min [32]. That treatment promoted the accumulation of carotenoids and lipophilic phenolics, and also led to a slightly higher antioxidant potential, but did not otherwise affect the composition of the ripe fruit. The tomatoes ripened normally after the immersion. The treated fruit were darker red and less yellow-orange in color. The higher AOX and phenolics were associated with the heat treatment that boosted the enzymes related to these phytochemicals [32].

Post-harvest heat treatments were applied to broccoli (*Brassica oleracea* var. *italic*) to delay senescence and to preserve its quality. The most effective thermal treatments were found to be temperatures between 41 and 52 °C [33]. The post-harvest hot-water treatment (50 °C for 1 min) is not recommended for stored carrots, with reference to water loss and root shriveling, but is an option for preserving their β-carotene and vitamin C contents [34]. Kale (*Brassica oleracea*) sprouts were immersed in hot water at 40, 50, and 60 °C for 10, 30 or 60 s and then kept for 2 more days at ambient temperature. Treatment at 50 °C for at least 20 s significantly induced the accumulation of phenolic compounds and glucosinolates, as well as antioxidant capacity, as compared to the untreated control [35].

A study of the effects of treating cucumbers (*Cucumis sativus* L.) with short hot-water immersion at 45 and 55 °C for 5 min compared with fruit that was dipped in 25 °C water. The fruit treated at 55 °C had the lowest peroxidase activity, but also had the best appearance, color, taste, and the highest catalase activity during cold storage and on the shelf, as compared with the control (25 °C) and 45 °C-treated fruit [36].

The effects of intermittent heat treatment on the root quality and antioxidant capacity of sweet potato were investigated during cold storage at 5 ± 0.5 °C and 80–85% RH. Roots were heat-treated in an air oven (45 °C) for 3 h continuously or intermittently. Intermittent treatment was achieved by letting the temperature revert to room temperature after every 1 h of continuous treatment. This intermittent heat treatment was found to be a safe, physical method for preserving the root quality at a low temperature, by increasing antioxidant metabolism to alleviate oxidative damage [37].

The phytochemicals of fruits can also be affected by physical treatments. Phenolic compounds and flavonoids in muskmelon fruit (*Cucumis melo*) were significantly enhanced by a hot-water treatment at 53 °C for 3 min [38]. 'Red Fuji' apples (*Malus domestica* Borkh) subjected to forced-air heat at 45 °C for 3 h maintained the highest total phenolic content and antioxidant capacity compared to 60 °C for 3 h or untreated fruit. 'Golden Delicious' apples were more sensitive to heat treatment based on their loss of titratable acidity (TA) [39]. Maghoumi et al. [27] reported that hot-water treatment at 55 °C for 30 s optimized the blanching of pomegranate (*Punica granatum*) arils and reduced their enzymatic activity. Although, dipping in hot water effectively suppressed polyphenol oxidase activity in the fresh-cut arils, the peroxidase activity was increased after 14 days of storage at 5 °C.

The effects of hot-water treatment on antioxidant content and fruit quality were also investigated in banana fruits (*Musa* sp.). Bananas treated with 53 °C water for 9 min or 55 °C water for 7 min had higher total sugar contents, greater acidity, and more β-carotene than the untreated fruit. However, the vitamin C content of the treated bananas was reduced [40]. Mango (*Mangifera indica* L.) is a commercial fruit crop produced in tropical and subtropical regions. It is widely consumed and valued for its delicious flavor, pleasant aroma, and the fact that it is a rich source of nutrients and phytochemicals (i.e., vitamin C, vitamin E, β-carotene, lutein, quercetin, angiferin, omega 3 and 6 polyunsaturated fatty acids. Mango fruits were immersed in water at 46.1 °C for 70 to 110 min and the fruit quality was evaluated after 4 days of subsequent storage at 25 °C, in terms of changes in polyphenolic content, antioxidant capacity, and fruit quality. During 4 days of storage, only minor changes were observed in the levels of polyphenolic compounds, whereas the total soluble phenolic levels and antioxidant capacity decreased in all of the hot water-treated fruits [41]. Hot water can be also used as a quarantine treatment. Hot water treatment (48 °C for 60 min) imposed as an obligatory quarantine protocol for mango exported from Pakistan to China had no negative effects on the fruits' visual or biochemical quality, and the treated mangoes had a higher marketability index. The treated mangoes had a better flavor, slightly increased soluble solid contents, a higher sugar-acid ratio and ascorbic acid than the control fruits [42]. The vapor heat treatment technology is used for quarantine purposes in various tropical fruits for export. Mature green guava fruits (*Psidium guajava* L.) were subjected to the vapor-heat treatment at a commercial certified facility, maintaining a core pulp temperature of 47.5 °C for 0, 12, and 25 min, followed by keeping fruit at ambient conditions (28 ± 2 °C) for 6 days. The fruits treated with 47.5 °C vapor for 25 min had higher sugar-acid ratios, ascorbic acid levels, and total phenolic contents and were of better eating quality, as compared with fruits that received a 12-min vapor-heat treatment and the untreated control fruits. However, the total antioxidant content and TA acidity of the fruits were not affected by the duration of the vapor-heat treatment [43].

Mume (*Prunus mume* Sieb. et Zucc.) fruits are harvested and consumed at the mature green stage and have a short storage life at ambient temperature. A pre-storage hot-water treatment in which 'Nankou' fruit were immersed in 45 °C water for 5 min extended the storage life 3-fold at 6 °C. The hot-water treatment delayed the decrease in ascorbate contents and total antioxidant capacity that are usually detected during storage. During cold storage, the activities of antioxidant-related enzymes, including ascorbate peroxidase and monodehydroascorbate reductase, were higher in the hot water-treated fruits than in control fruits [44].

The quality of fresh-cut fruits and vegetables can be maintained by physical treatment without affecting their external and internal quality parameters. The effect of precutting hot-water treatment on the quality of minimally processed kiwifruits (*Actinidia deliciosa*) was studied. Whole fruits were immersed in hot water (45 °C) for 25 or 75 min, minimally processed, packed, and stored at 0 °C for 8 days. The total phenolic content of the untreated control fruits was significantly higher than that observed for kiwifruit that were dipped into hot water for 25 or 75 min. The vitamin C content decreased during storage, and that decrease was not significantly affected by the different treatments or storage times [45].

5. Heat Treatments Applied in Combination with Other Treatments Affect Changes in Phytochemicals during Storage

In contrast to a single heat treatment, combined treatments may be more effective for maintaining the external and internal qualities of fresh and fresh-cut fruits and vegetables, and limiting disorders. A hot-water rinse (55 °C for 15 s) over brushes combined with individual shrink-wrap packaging of bell pepper fruits maintained the fruit quality during storage at a low temperature. The wrapped fruit ripened normally during the shelf-life period, when the peppers were shifted to 20 °C after unwrapping. This study showed that antioxidant levels of pepper fruit might be preserved during storage [46]. The hot-water treatment has also been proven to alleviate chilling injury in bell pepper (*Capsicum annuum* L.) and other *Solanaceae* species. This phenomenon has been associated with the presence of metabolites such as sugars and polyamines, which protect the plasmic membrane [47]. Immersing pepper fruit for 1 min into hot water at 53 °C reduced vitamin C loss and induced chilling tolerance, which was associated with a higher phenolic content during 21 days of storage at 5 °C plus 7 days at 21 °C [47]. The hot-water treatment (52 °C for 5 min) of mature, green harvested tomatoes applied in combination with ethylene at 30 °C for 24, 48 or 72 h or 35 °C for 24, 48 or 72 h followed by the completion of ripening at 20 °C provided a synergistic effect, promoting color development and increasing the antioxidant content of the ripe fruit [32]. In work done in plum (*Prunus salicina* Lindl. cv. Sanhua), the combination of heat treatment (hot air at 37 °C for 6 h) and the use of chitosan as an edible coating has been reported to enhance total phenolic and flavonoid contents and antioxidant activity during post-harvest storage [48]. The enhancement in total phenols and antioxidant activity was also due to the chitosan, itself, as it is known to activate the defense mechanism and antioxidants in the fruit tissues [48].

Microwave heating and cooking has become a common practice in kitchens. A study was conducted to estimate the phytochemical constituents and antioxidant activities of tomato slices heated with microwaves (1000 W) for 30 and 300 s. The levels of polyphenols, flavonoids, and lycopene were significantly higher among the tomatoes that were treated for 300 s, as compared to the untreated tomatoes and tomatoes that were microwaved for 30 s [49].

Yao et al. [50] investigated the effects of radio-frequency (RF) energy and conventional hot-water blanching (95 °C for 2 min) on the physiochemical properties of stem lettuce (*Lactuca sativa* L.). The residual vitamin C content was significantly increased with the increasing RF heating temperature (65-85 °C). In addition, stem lettuce treated with RF at 75 °C showed better nutrient retention than lettuce that was blanched in hot water.

Onion (*Allium cepa* L.) is a rich source of bioactive compounds, including flavonoids and organosulfur compounds. Onions are commonly consumed either fresh or after being subjected to a wide variety of cooking methods that induce significant changes in the onion's composition and bioactive compounds [51,52]. A novel, commercially available produce derived from onion, known as "black onion", was developed by processing (aging) raw onion in a temperature- and humidity-controlled room. The fresh onion was kept at 65 or 70 °C and 90% RH for 28 days, after which the bulbs are dried at 15% RH and 50 °C for 24 h. The total flavonoid content was decreased up to 12-fold in black onions, as compared with fresh onions, while the quantity of isoalliin, the main organosulfur compound in black onions, is dramatically higher than that found in fresh onions. The higher level of organosulfur compound was probably due to the formation of intermediate compounds such as thiosulfinates and the subsequent transformation to organosulfur volatiles due to the heat treatment [53]. Levels of fructose and glucose also increased significantly during the treatment process, which contributed to the sweetness of black onions. The heating decreases the antioxidant activity of the onion [53].

Peaches (*Prunus persica*) contain high levels of vitamins, phenols, and procyanidin B3, and are a good source of minerals such as phosphorus, iron, and potassium [54].

Peach fruits were immersed in water at 0, 40 and 60 °C for 60 s and then exposed to 0.5 or 1.0 kGy of gamma radiation. They were then stored at 25 ± 2 °C and 70% RH for 2 weeks. The ascorbic acid content of the peaches decreased with the increase in temperature and radiation dose [54]. The application of heat treatment in combination with 1-methylcyclopropene (1-MCP), can have a synergistic effect that enhances the antioxidant potential and maintains the quality of peach fruits. The pre-storage heat treatment was more effective for suppressing oxidative stress and improving fruit quality when the fruit was kept at room temperature, as opposed to low temperatures [55].

Fresh-cut 'Braeburn' apple slices were dipped into cold water (4 °C for 2 min) or hot water (48 or 55 °C for 2 min) followed by dips into 0 or 6% w/v aqueous calcium ascorbate (CaAsc, 2 min, 0 °C) and stored in air up to 28 days at 4 °C. The combination of the 48 °C treatment and the CaAsc dip led to a 7-fold increase in the level of ascorbic acid inside the apple tissue (0.25-1.85 g kg^{-1}) and consequently increased the antioxidant activity. The hot-water treatment did not increase the ascorbic acid content when it was applied alone, without the CaAsc treatment [56].

Another study evaluated the effect of a quarantine hot-water treatment (46.1 °C, 75–90 min), calcium lactate (CaLac, 0.05%), and their combination on the activity of antioxidant enzymes in 'Keitt' mango stored for 20 days (at 5 °C) and during ripening (at 21 °C). The combined hot water-CaLac treatment increased the activity of the antioxidant enzymes in the fruit [57]. A similar study examined the effects of hot water (48 °C/20 min), calcium chloride (1%/20 min), and their combination on the levels of bioactive compounds and antioxidant activity in papaya (*Carica papaya* L.). The papayas that were treated with both hot water and $CaCl_2$ showed higher ascorbic acid contents, phenolic contents, and antioxidant activity than the untreated fruits and the fruits that received either the hot-water or $CaCl_2$ treatments alone. This correlated with their ascorbic acid, phenolic and β-cryptoxanthin contents [58]. Thai guava (*Psidium guajava* L.) fruits were immersed in water at 40 °C for 30 min (H), 0.1 mM MeJA for 10 min (0.1 mM MeJA) or H followed by 0.1 mM MeJA (H + 0.1 mM MeJA) in a study in which untreated fruits were used as a control. The H + 0.1 mM MeJA treatment enhanced both the antioxidant activity and free radical-scavenging activity. These changes were accompanied by changes in the levels of bioactive compounds such as ascorbic acid, total phenols and flavonoids, and changes in peroxidase activity. There was also a partial suppression of the expected decrease in the catalase activity [59].

Hami melons (*Cucumis melo* var. *saccharinus*) were submerged in water at 55 °C for 3 min and dried, after which they were coated by dipping in 1% (*w*/*v*) O-carboxymethyl chitosan (CMC) solution for 15 s and air-dried using fans. The total antioxidant capacity and total phenolic content of those melons were generally higher than those observed in the untreated fruit [60].

In a study with strawberry (*Fragaria x ananassa*), fruits were initially dipped into hot water containing 1 mM salicylic acid, 2% $CaCl_2$, and a combination of salicylic acid and $CaCl_2$ at two different water temperatures (20 and 45 °C) for 5 min and then stored at 4 °C for 14 days. Combining the salicylic acid and $CaCl_2$ dip treatments with the hot-water treatment (45 °C) maintained the strawberry's fruit quality during storage more effectively than when the salicylic acid + $CaCl_2$ treatment was applied without the hot-water treatment. Specifically, the salicylic acid + $CaCl_2$ + hot water treatment was associated with improved antioxidant capacity and higher levels of total phenolic compounds, vitamin C and total protein, but also decreased the polyphenol oxidase (PPO) activity [61].

Table 1. Different heat treatments that alone and in combination with other treatments affect phytochemicals in fresh and fresh-cut produce during storage.

Crop	Treatment	Phytochemical Changes	Reference
Tomato	HA [a], 30 days at 25 °C And 35 °C	Increased ascorbic acid (vitamin C), activity of the ascorbate/glutathione-related enzymes	[18]
Pomegranate (fresh-cut)	HW, 55 °C for 30 s	Suppressed polyphenol oxidase activity	[27]
Potato	Radio frequency (RF) heating	Changed the potato cells and starch	[28]
Pepper	HWRB [b], 55 °C for 15 s	Increased lypophilic antioxidant activity; hydrophilic AA [c] unchanged	[29]
Pepper (cherry)	HW, 55 °C for 60 s	Inhibited PAL [d] activity, antioxidant levels were not markedly affected	[30]
Carrot	HW, 50 °C for 1 min	Preserved β-carotene and vitamin C levels	[34]
Kale	HW, 50 °C for 20 s	Better accumulation of phenolic compounds, glucosinolates and antioxidants	[35]
Apple 'Red Fuji'	Forced-air heat, 45 °C for 3 h	Preserved high total phenolic content and antioxidant capacity	[39]
Banana	HW, 53 °C for 9 min or 55 °C for 7 min	Higher TSS, total sugars, acidity and β-carotene	[40]
Mango	HW, 48 °C for 60 min	Maintained fruits' visual and biochemical quality	[42]
Kiwifruit (fresh-cut)	HW, 45 °C for 25 or 75 min	Increased level of total phenolic compounds	[45]
Pepper (red bell)	HW, 55 °C for 12 s + shrink-wrapped fruit	Antioxidant activity was fairly constant throughout the storage period	[46]
Plum	HA, 37 °C for 6 h + chitosan	Increased total phenolic, flavonoid and antioxidant	[48]
Mango	HW, 46 °C for 70 to 110 min	Diminished total soluble phenolic, gallic acid and gallotannin levels	[52]
Onion	HA, 65-70 °C, 90% RH for 28 days, 50 °C for 24 h, 15% RH	Increased levels of fructose and glucose	[53]
Apple (fresh-cut)	HW, 55 °C and 65 °C for 30 s + AA/CA	Positive effects on TSS, TA and vitamin C content	[55]
Papaya *Carica papaya*	HW, 48 °C for 20 min + 1% $CaCl_2$	Increased ascorbic acid, phenolic and antioxidant contents	[58]
Hami melons (*C. melo* var. *saccharinus*)	HW, 55 °C for 3 min chitosan	Higher total antioxidant capacity and higher total phenolic content	[60]
Tomato, mature green	HW [e], 52 °C for 5 min + ethylene at 30°C for 24-72 h	Increased antioxidant content of the ripe fruit	[62]
Ponkan (*Citrus reticulata*)	HA, 40 °C for 2 days	Increased fructose and glucose content and decreased citric acid content (better flavor)	[63]
Mandarin	HW, 50 °C for 3 min	Prevented the loss of TSS, TS, TA [f] and vitamin C contents	[64]
Apple (fresh-cut)	HW, 48 °C, 2 min + Calcium ascorbate	Increased levels of ascorbic acid inside the apple tissue	[65]

[a] HA: Hot air; [b] HWRB: Hot water rinsing and brushing; [c] AA: Ascorbic acid; [d] PAL: Phenylalanine ammonia lyase; [e] HW: Hot water; [f] TSS, TS, TA: Total soluble solids, total solids, titratable acidity, respectively.

6. Conclusions

Daily consumption of fruits and vegetables has been shown to promote human wellness. Increased consumption of fresh and fresh-cut or processed fruits or vegetables and other foods rich in phytochemicals and fibers is beneficial for human health. However, in many countries, the daily consumption of fruits and vegetables is very limited, due to the physiological and pathological deterioration of produce during storage, lack of horticultural diversity, poor growth conditions, and inadequate post-harvest practices and knowledge to maintain the produce quality after prolonged storage or processing.

One strategy for sustainable agriculture is to design cropping systems that have minimal or reduced impacts on the environment and to use genetic approaches to enhance the crop nutritional content. This strategy is appealing since crop genetics are the primary driver of plant nutrient content. However, managing crop production fields with a focus on crop nutrient content is extremely challenging, if not impossible [19]. There is also an urgent need to test newly generated crop cultivars in different cropping systems, as well as the impact of newly developed cropping systems on the nutritional quality of the foods produced from different crop cultivars. Robust crop cultivars are needed that consistently express traits across different agroecosystems and environments [19]. The selection of cultivars with high antioxidant potential or landraces and traditional cultivars of local interest is expected to increase the consumption of horticultural commodities. Marketing strategies should also provide an added boost to growers by directing health-conscious consumers to produce that contains high levels of antioxidants [2].

Low temperature storage is generally one of the most effective post-harvest technologies and is widely used to maintain fresh produce quality. However, several physical treatments have been reported to be effective for managing several post-harvest diseases and physiological disorders. These methods are safe, do not leave any chemical residues, and allow the fruit to retain its quality during prolonged cold storage and on the shelf [25,26]. Nevertheless, these pre-storage treatments can influence the external and internal qualities of the fresh produce [26]. The enhancement and accumulation of phytochemicals in heated fruits and vegetables can be explained by the induction of key enzyme transcripts that are directly related to the synthesis of those phytonutrients. It is also possible that the higher phytochemicals in the heat-treated fruit was due to the heat treatments that helped release them from the cell matrix into the fruit flesh. Heat treatments are feasible to retard ripening and delaying the reduction of phytochemical compounds in flesh commodities during storage, thus increasing their bioactive compounds contents in the fresh produce. Heat treatments were also reported to produce signals that induce the synthesis of specific proteins, some of which are enzymes metabolism of some phytochemicals. The increased activity of these enzymes leads to the accumulation of bioactive compounds in the fruit or vegetable after harvest [29,32,43,49,59,66].

Future studies should include quantitative analyses and the isolation of substances from fruits and vegetables, favoring the understanding of the anti-proliferative, antimicrobial, anti-inflammatory, neuroprotective, and photosensitizing effects associated with these substances. Knowledge regarding the mechanisms of action of these substances that are beneficial for human health will allow researchers to understand the relationships between concentration, effectiveness, and desirable and undesirable effects imparted by these environmental-friendly physical treatments. This knowledge is fundamental for therapeutic planning, in combination with physical treatments, as well as interventions in the case of intoxication.

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