Chapter

Alternative Green and Novel Postharvest Treatments for Minimally Processed Fruits and Vegetables

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Abstract

Minimally processed fresh produce is ready to eat and subjected to minimal technology before consumption. Fresh fruits and vegetables (FFVs) are minimally processed commodities that are metabolically active and undergo physiological processes such as ripening and senescence, reducing their quality and shelf life. Postharvest technologies maintain the quality and prolong the shelf life of harvested produce, without which the quality deteriorates such that significant economic loss ensues due to water and nutrients loss, physiological deterioration, biochemical changes, and microbial degeneration. Conventional postharvest treatments such as temperature management, and chemical and gaseous treatments are widely known for controlling postharvest issues in FFVs. However, there are novel and green alternative safe methods that are employed to maintain the postharvest quality and prolong the shelf life of FFVs. This chapter focuses on seven common alternative novel and green postharvest treatments: nitric oxide, ozone, methyl jasmonate, salicylic acid, oxalic acid, calcium, and heat treatments. These treatments are explained and some of their current application on FFVs are discussed and tabularized indicating the optimum treatment conditions reported in the latest scientific publications.

Keywords: calcium, heat, methyl jasmonate, nitric oxide, oxalic acid, salicylic acid, ozone

1. Introduction

Fresh fruits and vegetables (FFVs) are considered minimally processed because they are ready to eat and subjected to minimal technology before consumption. FFVs are a source of micro- and macronutrients, and secondary metabolites that possess antioxidant and reactive oxygen species (ROS) scavenging abilities for good health [1–4]. FFVs are living tissues and are metabolically active experiencing senescence, and ripening processes that necessitate quality preservation and the reduction of storage losses [4–8]. Postharvest technologies control and prolong the shelf life of harvested produce, without which the quality (i.e., nutritional, appearance, and pathogenic safety) deteriorates such that significant economic losses ensue [5, 6] due to water and nutrient loss, physiological deterioration, biochemical changes, and microbial degeneration [6, 9]. Hence, optimum postharvest treatments must be employed to impede physiological processes (e.g., senescence and maturation) and minimize the occurrence of microbial contamination to preserve quality loss [5, 6, 10]. Temperature management, physical (e.g., heat, irradiation, and edible coatings) chemical (antimicrobials, antioxidants, and antibrowning), and gaseous treatments (e.g., chlorine dioxide) are some conventional postharvest treatments for FFVs [5, 9]. Nevertheless, there are currently novel and green postharvest treatments that are used to maintain and enhance the quality, and prolong the postharvest shelf life of fresh produce.

Novel postharvest treatments are new postharvest treatments that, among other functions enhance bioactive molecule contents or compounds, retard senescence and ripening, prevent postharvest diseases, prolong shelf life, and ensure the overall safety of fresh produce for consumption [6]. On the other hand, green postharvest treatments are those that are environmentally friendly, such that their application is important and socially acceptable to the industry and consumers at large in maintaining and enhancing the postharvest quality, and prolonging the storage life of fresh produce. Green postharvest treatments include non-chemical applications like biological control agents, natural compounds, biomaterials, irradiation (ultraviolet), and heat treatments [6, 11–13]. Therefore, some novel postharvest treatments are green, but not all novel treatments are green. The quality attributes (i.e., nutritional value, appearance, texture, flavour, and chemical, toxicological, and microbial safety) and shelf life of FFVs are maintained via various novel and green postharvest treatments [5]. This chapter presents seven postharvest treatments (i.e., nitric oxide, ozone, methyl jasmonate, salicylic acid, oxalic acid, calcium, and heat treatment) for FFVs. All seven are novel, but four are green (i.e., salicylic acid, oxalic acid, ozone, and heat treatments) [6, 8, 13].

2. Green and novel postharvest treatments and traditional postharvest techniques

Novel postharvest treatments are postharvest treatments other than conventional or already known postharvest treatments whereas green postharvest treatments are those that are environmentally friendly and socially acceptable [6, 12].

Some of the latest novel postharvest treatments include the application of nitric oxide, ozone, salicylic acid, oxalic acid, methyl jasmonates, calcium, and heat [6]. Notwithstanding, various compounds, including AVG (Aminoethoxyvinylglycine), 1MCP (1-Methylcyclopropene), and PAs (Polyamines) and other postharvest treatments have been previously used to regulate postharvest quality in some FFVs at different degrees of effectiveness. The aforementioned chemicals had limitations, such as uneven ripening, post-ripening disorders, and non-viability for commercial use. Conventional postharvest harvest techniques that are used to prolong the shelf life of fruits and vegetables include cold storage, modified and controlled atmosphere storage, suppression of ethylene biosynthesis or ethylene inaction by PAs, AVG, and 1-MCP application [6].

Green and novel postharvest treatments extend the shelf life of freshly harvested produce by maintaining their quality [6]. We focused on the latest applications of nitric oxide, ozone, methyl jasmonate, salicylic acid, oxalic acid, calcium, and heat treatments on FFVs, with emphasis on quality and shelf life under storage. The seven were chosen because of their extensive use on FFVs [6, 8].

2.1 Nitric oxide (NO)

Nitric oxide (NO) is an important signalling molecule mediating several pre- and postharvest developmental and physiological activities in horticultural crops [6, 14].

NO is a bioactive, mobile gaseous molecule that also mediates various abiotic and biotic stress responses [15]. NO can protect against various stressful impacts, scavenge free oxygen radicals, counteract oxidative damage, inhibit, or suppress ethylene biosynthesis, delay ripening and senescence, and enhance the resistance to diseases [6, 14–17]. NO has a more profound effect on non-climacteric horticultural crops (especially fruits) than climacteric crops. Consequently, the climacteric phase (i.e., the surge in ethylene production and an increased respiration rate) of many horticultural crops can be impeded by endogenous NO production. Also, endogenous NO reduces yellowing, chlorophyll degradation and extends the shelf life of fruits and vegetables [6]. Notwithstanding, NO is volatile and exhibits reactive oxygen species toxicity. Hence, super-optimal concentrations can be harmful. Thus, it is necessary that the correct threshold levels are employed to obtain the desirable ripening modulation and extension of shelf life in FFVs [6]. It is worth noting that NO is more effective in its gaseous or donor form in suppressing ethylene production and respiration rate, reducing softness, retarding colour development and metabolism, reducing chlorophyll degradation, and delaying senescence [6].

2.1.1 NO treatments of fresh fruits and vegetables

NO is a good alternative for extending the shelf life of fresh horticultural produce. The application of optimum levels of NO has been shown to impede senescence and ripening processes in many horticultural crops, including FFVs. Donor compounds (e.g., sodium nitroprusside (SNP)) can also be incorporated into biological systems to release NO gas under controlled environmental conditions [6]. Due to the highly diffusible nature of NO, NO was earlier considered an environmental pollutant as it caused, among other things the reduction of ozone in the stratosphere [6, 14]. Also, the emission of NO is related to the greenhouse effect [6, 14, 18]. Moreover, NO gas has a short lifetime, such that in the presence of oxygen (O_2), it can be converted to the noxious gas nitrogen dioxide (NO_2), which can degrade the quality of FFVs. Consequently, NO gas should be placed in airtight containers to minimize contact with oxygen. Further, NO must be diluted by flushing with nitrogen (N_2) after fumigation to avoid damage to FFVs [17].

Postharvest immersion of FFVs such as plum, longan, apple, and broccoli in NO or SNP impeded internal browning. Also, exogenous application of NO via fumigation (In an O_2-free environment or NO-releasing agents such as "N-tert-butyl-α-phenylnitrone" and "3-morpholino sydnonimine") remarkedly delayed maturation and ripening, controlled postharvest pest and prolonged the shelf life of FFVs such as apples, bananas, peaches, strawberries, and some other vegetables [6, 16]. Additionally, NO maintained the levels of polyphenols, soluble solids ascorbic acid in sliced apples, longan, fresh-cut apples, litchi, peach, lettuce, and broccoli and generally improved the quality and postharvest shelf life of some stored fruits and vegetables [6, 17, 19].

A significant reduction of chlorophyll degradation, delayed postharvest yellowing, accumulation of malondialdehyde, and reduced lipid peroxidation were observed in broccoli florets [6]. Treatment of cucumber with 25 microlitres per litre NO also reduced deterioration and exhibited radical scavenging activities compared to the control during storage. Furthermore, NO significantly increased the antioxidative process in cucumber fruits. Browning on the cut surfaces of leafy vegetables was effectively inhibited by NO treatments [6]. **Tables 1** and **2** present treatments of some fruits and vegetables with NO or NO donors, respectively.

2.2 Ozone treatments

Ozone is a highly reactive form of oxygen that decomposes easily into diatomic oxygen. Ozone can function as a potential oxidant and disinfectant when it reacts with targeted organic matter and microorganisms. Historically, it has been used as a water disinfectant. Ozone attained "GRAS" (generally regarded as safe) status and was approved as an antimicrobial additive by the United States Food and Drug Administration (FDA) in 2001 [1, 6, 21].

The influence of ozone on postharvest disease control and storage has been investigated in some fruits and vegetables for shelf life extension and preservation [1, 6, 13, 21–26]. Ozonated water/aqueous ozone has been used for disinfecting vegetables, while gaseous ozone is used for the sanitization and preservation of vegetables during storage. Gaseous ozone is a less effective antimicrobial agent than aqueous ozone [1, 21]. Moreover, ozone can be potentially used for the decontamination of surfaces of freshly harvested produce, degradation of ethylene, odour elimination in mixed storage, spore elimination in storage rooms, and reduction of pesticide levels over the fresh produce [1, 6, 13, 21, 25, 26]. Nevertheless, ozone should be properly used to avoid negative effects such as loss of sensory quality although ozone application is an eco-friendly technology [1, 21]. Consequently, ozone treatments are mostly specific for various fresh produce due to the intrinsic characteristics of fresh produce and the extrinsic factors that affect ozone efficiency [1, 21]. **Table 3** provides information on the ozone treatment of some fresh fruits and vegetables.

2.3 Salicylic acid treatments

Salicylic acid (SA) is a plant hormone that acts as a signalling molecule against environmental and pathogenic stress. SA influences various physiological events in plants [6, 34–36]. SA plays a key role in the retardation of fruit ripening, and the inhibition of ethylene biosynthesis, promoting pathogen resistance, activating antioxidant systems, consequently, maintaining postharvest quality and prolonging the shelf life of fruits and vegetables. Moreover, SA is an effective enhancer of biocontrol agents like antagonist yeast in controlling rot and decay [6, 34]. SA and its derivatives (particularly Methyl salicylate; MeSA) have been generally recognized as safe (GRAS) for fruits and vegetables and are environmentally friendly [34, 35, 37].

Several studies have demonstrated the effect of postharvest SA application (exogenous) in fruits and vegetables [3, 6, 34, 38]. The dose of SA for exogenous postharvest application is varied for various fruits and vegetables, however a general non-toxic range for fruits and vegetables is 0.5–2.0 mM. Higher concentrations can damage fruit skin and cause fungal attacks [37]. **Table 4** presents information on some current applications of SA on some fruits and vegetables.

FVs	Cultivar	NO/NO donor concentrations	Storage condition	Number of days(d)/ hours (h)/weeks of storage	Inferences	References
Apple (*Malus sylvestris* var. domestica Borkh.)	"Fuji"	10 uL L^{-1}	20 ± 0.5°C	50 d	Reduced fruit firmness	[6]
Banana (*Musa spp*.)	"Brazil"	5 mM SNP (slices)	24°C	5 d	Delayed or retarded pulp softening, decreased the activities of PG, PE, and EGase and β-Gal	[6]
Kiwifruit (*Actinidia chinensis* Planch)	"Xuxiang"	1.2 μmol L^{-1} NO dip	20°C	13 d	Delayed fruit softening	[6]
Mango (*Mangifera indica* L.)	"Kensington Pride"	20 μL L^{-1} NO	13°C	21 d	Retarded fruit softening with decreased activities of exo-PG, endo-PG, and Egase	[6]
Plum (*Prunus salicina* Lindell)	"Amber Jewel"	10 and 20 μL L^{-1}	21 ± 1°C or 0°C followed by ripening at 21 ± 1°C	10 or 5, 6, & 7 weeks	Retarded fruit softening	[6]
	"Damili"	1 mM SNP	2°C, 85%–90% RH	90 d &120 d	Delayed fruit softening	[6]
Peach (*Prunus persica* L.)	"Feicheng"	5 and 10 μL L^{-1} NO	5°C & 25°C	35 d & 7 d	Suppressed ethylene production and ACO activity, higher MACC and ACC content, but did not affect ACS activity	[6]
Longan (*Dimocarpus longan* Lour.)	"Shixia"	1 mM SNP	28°C	6 d	Increased SSC and AA; delayed pericarp browning during storage	[6, 15]

Ascorbic acid (AA), 1-aminocyclopropane-1-carboxylicacid synthase (ACS), fresh fruits (FFs), sodium nitroprusside (SNP), polygalacturonase (PG), pectin esterase (PE), endo-1,4-β-D-glucanase (Egase), β-galactosidase (β-Gal), soluble solids content (SSC).

Table 1.
Nitric oxide (NO) treatments on some fresh fruits.

FVs	Cultivar	NO/NO donor concentrations	Storage condition	Number of days(d)/hours (h) of storage	Inferences	References
Tomato (*Solanum lycopersicum* L.)	"Myrock"	200 μL L^{-1} NO	20°C	18 d (mature green) or 10 d (breaker red)	Decreased and delayed ethylene production as well as the expression of LeACO1, LeACOH2, and LeACO4 gene during the ripening stage	[6]
Lettuce Butterhead (*Lactuca sativa* L.)	"Cosmopolia"	100 & 200 ppm NO gas (fumigation)	4°C & 12°C respectively	1 to 2 h respectively	Delayed senescence and significantly prolonged the shelf life of fresh-cut lettuce	[15]
Pointed gourd (*Trichosanthes dioica* Roxb.)	"Rajendra Parwal-1"	2 mM	12°C & simulated ambient storage	14 d plus simulated ambient storage for 3 d	Significant improvement in postharvest shelf life via the maintenance of chlorophyll, phenolics, antioxidant activity. and membrane integrity	[20]

Table 2.
Nitric oxide (NO) treatments on some fresh vegetables (FVs).

FFVs	Cultivar/ variety	Ozone concentration (optimum treatment condition)	Storage condition	Number of days (d) of storage	Inferences	References
Guava (*Psidium guajava* L.), pineapple (*Ananas comosus* L.), and banana (Musa spp.)	—	8 ± 0.2 ml/s for 10 minutes (guava) and 20 minutes (pineapple and banana) (ozonated water)	Room temperature	—	Enhanced the antioxidant capacity but reduced the vitamin C content	[1, 2]
Apple (*Malus domestica*)	“Fuji”	1.4 mg L–1 for 5 minutes (ozonated water)	4 ± 1°C and 90% RH	12 d	Reduced microbial load and quality deterioration, enhanced the antioxidant capacity and shelf life	[1, 27]
Kiwi (Actinidia deliciosa)	“Hayward”	1 mg/L) for 10 minutes (gaseous ozone)	4°C, 80%–85% RH	12 d	Enhanced the antioxidant capacity and improved the shelf life	[28]
Grapes (*Vitis vinifera*) and apples (*Malus domestica*)	—	450 ppb (gaseous ozone)	97% RH and 20°C	12 d	Significant reduction in lesion size, height of aerial mycelium growth, and decay incidence	[21, 25]
Lettuce (*Lactuca sativa*)	“Green leaf”	2 ppm (ozonated water) and 2 minutes exposure time	4°C	12 d	Maintained sensory quality and reduced microbial load	[29]
Cabbage (*Brassica oleracea* L.)	—	1.4 mg/L (aqueous) for 5 minutes and 10 minutes	4°C	12 d	Removed pesticide residues, enhanced the storability of fresh-cut cabbage (10 minutes application), and inhibited microbial growth (10 minutes application)	[1, 30]
Spinach (*Spinacia oleracea* L.)	—	0.8 mg/L for 30 seconds	12°C and > 95% RH.	13 d	Reduced yellowing and microbial population, maintained compositional characteristics, and extended shelf life	[1, 31]
Green bell pepper (*Capsicum annuum* L.)	—	>2.4 mg/L to 3 mg/L for 5 minutes	(5 ± 0.5°C, 85% ± 5% RH	14 d	Reduced microbial load, retained quality characteristics, and prolonged shelf life	[1, 32]
Tomato (*Lycopersicon esculentum* L.)	“Thomas”	0.4 mg L^{-1} for 3 minutes	5°C	10 d	Retained firmness, reduced microbial load, and reduced the consumption of fructose and glucose	[1, 33]

FFVs	Cultivar/ variety	Ozone concentration (optimum treatment condition)	Storage condition	Number of days (d) of storage	Inferences	References
Carrots (*Daucus carota* L.)	"Vitabrite"	15 µl·L^{-1} in a total flow of 0.5 litres per minute (gaseous ozone)	2°C	28 d	Reduction in daily microbial (*Botrytis cinerea* and *Sclerotinia sclerotiorum*) growth rate and physiological damage	[21, 24]
Carrots (*Daucus carota* L.)	—	450 ppb (gaseous ozone)	97% RH and 20°C	2 d	Reduced lesion size, aerial mycelium height, and microbial (*B. cinerea* and *S. sclerotiorum*) growth rate	[21, 25]

Relative humidity (RH).

Table 3.
Ozone treatment on some fresh fruits and vegetables.

FFVs	Cultivar/variety	Salicylic acid concentration (optimum treatment condition)	Storage condition	Number of days (d) of storage	Inferences	References
Pummelo (*Citrus maxima* Merr.)	"Jinshayou"	0.3%	20 ± 2°C	90 d	Maintained higher postharvest storability, enhanced antioxidant capacity, and gave best overall quality	[38]
Pear (*Pyrus pyrifolia* × *Pyrus communis*)	"Punjab Beauty"	2.0 mM (SA)+enriched beeswax (2.0%)	Cold storage	67 d cold storage and 20 d supermarket	Delayed respiration, reduced weight loss, and maintained fruit firmness	[39]
Apricot (*Prunus armeniaca* L.)	"Saimaiti"		4°C and 90%–95% relative humidity.	35 d	Inhibited ethylene biosynthesis and decreased cell degrading enzyme activities	[40]
Satsuma mandarin (*Citrus unshiu*)	—	2 mM (dipped for 2 minutes)	2–16°C; relative humidity: 90%–95%	50 & 120 d	Reduced rot rate, maintained fruit firmness, and increased defence-related metabolites	[41]
Goji (*Lycium barbarum* L.)	—	2 mM/L	0°C	—	Decreased respiration and weight loss, ethylene production, promoted the accumulation of bioactive compounds, and enhanced the antioxidant capacity	[3]
Tomato (*Solanum lycopersicum* L.)	"BSS-488" and "Hisar Arun"	(0.75 mM)	25 ± 1°C C and 75% ± 5%)	15 d	Delayed ripening and cell wall degradation	[37]

Table 4.
Salicylic acid (SA) treatment on some fresh fruits and vegetables (FFVs).

2.4 Oxalic acid treatments

Oxalic acid (OA) is a common organic acid found in plants. OA can enhance the postharvest life and quality of fruits and vegetables. OA retards ripening and senescence, controls post-harvest diseases, inhibits enzymatic browning, reduces decay, and alleviates chilling injury in fruits and vegetables [6, 42]. Exogenous OA induces systemic resistance against fungal, bacterial, and viral diseases in plants. Further, endogenous OA induces intrinsic heat tolerance and increases antioxidant capacity in plants [6]. The recent application of OA for the improvement of postharvest life and quality control during storage has been successful for some fruits and vegetables [6]. OA is abundant in some plant species, such as beets and beet greens (*Beta vulgaris* L.), bell peppers (*Capsicum annuum* L.), spinach (*Spinacia oleracea* L.), swiss chard (*Beta vulgaris* L. cv. Cicla), poppy seeds (*Papaver somniferum*), purslane (*Portulaca oleracea* L.), sorrel (*Oxalis corniculata* L.), and rhubarb (*Rheum officinale* Baill) [6].

Aqueous OA solutions have been applied to fruits and vegetables, including apples, banana, kiwi, mango, peach, tomatoes, lettuce, endives, and other vegetables at millimolar concentrations to delay ripening, quality deterioration, control of postharvest diseases, and alleviate chilling injuries [6, 43, 44]. In such cases the storage life of the various OA treatments were extended [6, 45]. **Table 5** shows the effect of OA treatments on the storage life of some fruits and vegetables.

2.5 Calcium Ca^{2+} treatments

Calcium (Ca^{2+}) delays ripening and senescence-related processes by regulating signalling responses and inhibiting ethylene biosynthesis and respiration in fruits and vegetables [6, 36]. Ca^2+ is also believed to be the most important mineral element determining fruit quality [52]. Postharvest Ca^{2+} treatments prevent loss of flavour and nutritional value, enhance antioxidant capacity, reduce physiological disorders and decay incidence, and increase cell wall strength, thus prolonging the shelf life of FFVs [6, 52, 53]. Fruits and vegetables may be dipped, washed, vacuumed or pressure infiltrated, mixed with wax coatings, or electrostatic powder coatings [6, 52].

Optimum Ca^{2+} application rates either alone or in combination with other techniques may be different for specific fruits and vegetables [6]. Other properties of Ca^{2+}, such as the form and source of the application are also based on the interaction with the type of fruit or vegetable [6]. For example, pressure infiltration with calcium chloride solution is more effective in increasing the calcium concentration of apple fruits than vacuum infiltration and dipping. However, excessive Ca^{2+}uptake may cause injury [52]. **Table 6** provides information on some of the latest applications of calcium treatments on fresh fruits and vegetables.

2.6 Heat treatments

Heat or thermal treatment of fresh fruits and vegetables is an efficient, easy, safe, and cost-effective method for controlling postharvest decay and maintaining quality [7]. Postharvest heat treatment has been used to maintain firmness, preserve colour, prevent overripening, alleviate chilling injury, control insect infestation, and improve the shelf life of fruits and vegetables [7, 59]. Heat treatments include hot water treatment or dips, short hot water rinsing and brushing, hot air or steam treatments [6, 7, 11]. These methods retain the quality of fresh produce during prolonged cold storage, reduce rot development, and provide security [6, 7, 11, 60, 61]. Heat treatments can

FFVs	Cultivar	OA concentrations	Storage condition	Number of days(d)/hours (h) of	Inferences	References
Banana (*Musa* spp.)	"Brazil"	20 mM for 10 minutes	23 ± 2°C and 75–90% RH	24	Reduced fruit deterioration, respiration rate and ethylene production, oxidative injury and delayed the decreases in firmness, and hue angle during storage; thus, generally inhibited postharvest ripening of banana	[6, 46]
Mango (*Mangifera indica* L.)	"Samar Bahisht Chaunsa"	5 mM/L	32 ± 3°C for 7 days ;12 ± 1°C	For 28 days	Reduced ethylene production, respiration rate, and activity of exo-polygalacturonase (exoPG) enzyme; maintained higher fruit firmness and pectin esterase (PE) activity in mango fruit during ripening and cold storage period	[6, 42]
Peach (*Prunus persica* L.)	"Bayuecui"	1 and 5 mM	25°C	4	Higher flesh firmness, lower respiration, maintained membrane integrity, and delayed fruit ripening process	[6, 47]
Pear (*Pyrus* spp.)	"Le Conte"	5 mM	0 ± 1°C with 90%–95% R.H	90	Decreased ethylene production, hue angle and delayed ripening and fruit decay; decreased decay and total loss percentage after cold storage and 5 days during marketing	[6, 48]
Plum (*Prunus salicina* Lindl.)	"Damili"	5 mM/L for 3 minutes and packed into polyethylene bags	25°C for 12 days, or at 2°C for 20 days and 25°C for 12 days.	12 (25°C), 20 (2°C), and 12 (25°C)	Decreased ethylene production, ripening, senescence, and stress injury	[6, 49]

FFVs	Cultivar	OA concentrations	Storage condition	Number of days(d)/hours (h) of	Inferences	References
Sweet cherry (*Prunus avium* L.)	"Cristalina" and "Prime Giant"	1 mM/10 L	Cold storage at 2°C and RH of 85% in darkness	20	Extended the storability, increased the content of bioactive compounds and antioxidant activity	[6, 50]
Tomato (*Solanum lycopersicum* L.)	"Pusa Gaurav", "Pusa Rohini", and 18 others	3 mM	20°C	15 minutes	Prolonged the shelf life and reduced weight loss	[6, 51]
Asparagus (*Asparagus officinalis* L.)	"Grande Vegalim" and "Purple Passion"	1 mM and 3 mM	5°C	12	Reduced respiration, preserved the visual quality, and improved the appearance of spears	[6, 43]

Table 5.
Oxalic acid (OA) treatment on some fresh fruits and vegetables (FFVs).

FFVs	Cultivar	Calcium concentration (optimum treatment condition)	Storage condition	Number of days (d) of storage	Inferences	References
Jujube (*Ziziphus jujuba* Mill.)	—	1% calcium nitrate and 1% calcium chloride (immersion for 5 minutes)	4°C	50 d	Preserved fruit quality (biochemical and organoleptic) after storage	[54]
Banana (*Musa* spp.)	"Grand Nain"	2% $CaCl_2$	20 ± 2°C and 60%–70% RH	8 d	Retarded ripening and retained quality	[55]
Papaya (*Carica papaya* L.)	"Huanong 1"	Calcium chloride (5% $CaCl_2$ solution immersion for 15 minutes)	25 ± 1°C	12 d	Delayed ripening and softening of fruit	[53]
Peach (*Prunus persica*)	"Texas A 69"	4% $CaCl_2$ solution for 10 minutes	±8–10°C and 80–85% RH	30 d	Retained quality attributes, reduced weight loss, disease incidence, and increased fruit firmness	[56]
Apple (*Malus domestica*)	Local	3% $CaCl_2$ for 60 minutes	25°C and 85%–90%	15 d	Enhanced the quality and shelf life	[57]
Broccoli (*Brassica oleracea* var. *italica*)	"Imperial"	2% $CaCl_2$ + 2 mM SA	5°C and 95% RH	21 d	Reduced weight loss and maintained quality (bioactive components and antioxidants).	[36]
Tomato (*Solanum lycopersicum* L.)	"Izmir"	6% $CaCl_2$ for 10 minutes. postharvest coating treatments with either 10% Arabic gum or 50% cactus mucilage for 3 minutes	(10 ± 1°C) and RH 85% ± 3	35 d	Increased fruit firmness, titratable acidity, reduced the percentage of weight loss and percent of decayed fruits	[58]

Table 6.
Calcium (Ca^{2+}) treatments on some fresh fruits and vegetables (FFVs).

also be combined with other methods such as safe GRAS chemicals (e.g., bicarbonate salts and ethanol), Modified Atmosphere Packaging (MAP), Controlled Atmosphere (CA), microbial biocontrol agents, plant extracts (e.g., leaf extracts of essential oils, and edible coatings to provide an effective control system against postharvest decay development, chilling injury, and quality loss [6, 7, 61–63].

Hot Water Treatment (HWT) is the simplest among heat treatments, and it has three categories: batch, continuous, and drainage systems: Hot water treatment may be applied either solely or in combination with other treatments in controlling postharvest disease infestation and rot development of FFVs [6, 60]. Several studies on hot water treatment have been reported on fruits such as banana, mango, papaya, nectarine, peach, papaya, lime, and melon. In these studies, hot water treatments were between 42°C and 60°C for a maximum and minimum duration of 30 and six (6) minutes, respectively, depending on the type of fruit. These treatments mostly controlled disease and rot causing pathogens. Nonetheless, longer exposure times caused injuries to some fruits [6]. Generally, fruits and vegetables tolerate water temperatures of 50–60°C for a duration of 10 minutes. The duration of dipping and immersion can last longer (>1 hour), and temperatures can be less than 50°C for insects disinfestation of FFVs. However, for antifungal treatments, temperatures are greater than 50°C, and the dipping time is shorter (minutes) [7].

Hot water rinsing and brushing is another heat method that cleans and disinfects freshly harvested produce at a relatively high temperature of 45–62°C. The produce is passed over revolving brushes for a short time (15–25 seconds). This is a commercial method that reduces decay development, maintains fruit quality, and prolongs the shelf life of treated fruits and vegetables. Cold storage after hot water rinsing and brushing was found to intensify the effect of the treatment [6].

Vapour or moist hot air, is a heat treatment whereby a fine mist and air are forced under circulation, which forms heated, vapour-saturated air that raises the temperature of the commodity to a required level for a specified duration. By means of condensation of vapour on the produce, latent heat is released, resulting in a quick but even increase in temperature, thus preventing damage [6]. Temperatures normally range from 40 to 50°C [7]. The fresh produce is cooled immediately after the treatment to prevent heat injury to the product [6, 7]. This treatment normally reduces decay susceptibility by killing insects' eggs and larvae [6, 7], enabling some fresh produce (e.g., basil) to be stored at temperatures that usually result in considerable injuries [6].

Steam heating involves a moist hot air treatment that uses water at about 100°C for 2–3 seconds. Steam-based systems such as steam jets coupled with electrical steam-drying elements and reflectors produce high-temperature heating above the rotating produce for 3 seconds. After the treatment, the produce is hydro-cooled. Cooled produce (e.g., carrots) showed a significant reduction in sensitivity to post-storage soft rots caused by *Sclerotinia sclerotiorum* [6]. Information on the effect of some heat treatments for FFVs are provided in **Table** 7.

2.7 Methyl Jasmonates treatments

Methyl Jasmonate (MeJa) is an endogenous phytohormone, a signalling molecule, and a volatile compound vital for regulating and mediating various processes and defence responses against biotic and abiotic stresses. It is a derivative of jasmonic acid. MeJa has been used to prevent postharvest diseases, increase bioactive compounds, maintain fruit quality, and prolong the shelf life of fresh produce [6, 59, 69–72].

FFVs	Cultivar/Variety	Heat treatment (optimum treatment condition)	Storage condition	Number of days(d) of storage	Inferences	References
Peach (*Prunus persica* L.)	-	Hot water (HW) 45°C in distilled water for 10 minutes	0 ± 1°C and 90–95% RH	35 d	Reduced chilling injury index, decreased reactive oxygen species (ROS) accumulation, and increased the activity of ROS-scavenging enzyme	[64]
Mango (*Mangifera indica*)	"Chenab Gold"	HW 48°C for 60 minutes Vapour (47°C for 25 minutes)	25°C ± 1; 60%–65% RH	21 d	Slowed weight loss, better skin colour, and maintained biochemical attributes	[65]
Murcott Mandarins (*Citrus reticulata blanco*)	"Blanco"	50°C heat for 2.5 minutes	25°C	13 d	Delayed mold growth, retained quality, overall acceptability	[66]
Newhall navel Orange (*Citrus sinensis* L. Osbeck)	"Newhall"	Hot air flow (37°C for 48 h) at 85%–95% RH	6 ± 0.5°C and 85–90% RH	120 d	Improved total soluble solid, titrable acids, total sugar, and vitamin C contents; reduced respiration rate, delayed fruit deterioration, reduced oxidative damage, and lipid peroxidation	[11]
Sweet pepper (*Capsicum annuum* L.)	"Winner"	45°C for 15 minutes + 0.05 mmol L^{-1} + methyl salicylate (MS)	Cold storage	—	Reduced chilling injury, mass loss, and maintained a better quality	[61]

FFVs	Cultivar/Variety	Heat treatment (optimum treatment condition)	Storage condition	Number of days(d) of storage	Inferences	References
Cucumber (*Cucumis sativus*)	—	Hot water temperature of 44°C, and immersion time of 10 minutes + LAE (N-alpha-Lauroyl-L-arginine ethyl ester hydrochloride) concentration of 1.00 g L^{-1},	4 +/– 1°C	—	Reduced chilling injury in cucumber fruit via enhancing antioxidant enzymes activities, PA, proline, and GABA contents to maintain ROS homeostasis during cold storage	[67]
Eggplant (*Solanum melongena* L.)	"Senryo"	45°C for 10 minutes	1°C	15 d	Alleviated chilling injury and enhanced antioxidant activity	[68]

Polyamines (PA), gama amino butyric acid (GABA), reactive oxygen species (ROS).

Table 7.
Heat treatments of some fresh fruits and vegetables (FFVs).

FFVs	Cultivar/variety	Methyl Jasmonates concentration (optimum treatment condition)	Storage condition	Number of days(d) of storage	Inferences	References
Persimmon (*Diospyros kaki*)	"Karaj"	16 and 24 μL L^{-1}	0–1°C	120 d	Decreased chilling injuries, preserved physio-chemical properties, increased antioxidant capacity, and maintained phenolic compounds	[73]
Kiwi (*Actinidia deliciosa*)	"Hayward"	1.0 mM	0 ± 0.5°C and 90 ± 5% RH	180 d	Maintained flesh firmness, reduced weight loss, reduced respiration, and enhanced antioxidant capacity	[74]
Mandarin (*Citrus nobilis* L. X *C. deliciosa* L)	"Kinnow"	0.001 μmol L^{-1}	—	75 d	Decreased weight loss, spoilage, firmness, maintained quality, and prolonged shelf life	[72]
Mandarin (*Citrus nobilis* L. X *C. deliciosa* L)	"Kinnow"	1 mM	6 ± 1°C and 90 ± 5% RH	60 d	Maintained the highest level of bioactive compounds	[75]

Table 8.
Methyl jasmonates treatments on some fresh fruits (FFs).

Several studies have demonstrated the application of exogenous MeJa on fruits and vegetables with regard to postharvest quality, senescence and ripening, chilling stress and pathogen infection. These investigations showed that MeJa treatments altered the characteristics of harvested fresh produce, largely by enhancing the antioxidant capacity, volatiles production, phenolics and flavonoids content, and reduced chilling injury, particularly in fruits [59, 69, 71]. **Table 8** provides information on the application of MeJa on some fresh fruits and vegetables.

3. Conclusion

This chapter provided information on four alternative green (ozone, salicylic acid oxalic acid, and heat) and seven novel (nitric oxide, ozone, salicylic acid, oxalic acid, methyl jasmonates, calcium, and heat) postharvest treatments. The optimum concentrations applied, storage conditions, storage duration, and inferences established by some researchers were also provided accordingly. The overall effects of these postharvest treatments were basically to maintain quality, enhance the antioxidant capacity by maintaining high levels of bioactive compounds, control postharvest infestations and, consequently, prolong the postharvest shelf life of fresh fruits and vegetables. Based on the insights obtained from these seven latest novel and green postharvest methods, we recommend that the appropriate method of application, concentrations, and other critical considerations (e.g., storage duration and conditions) must be adhered to when these treatments are applied to specific fresh fruits and vegetables. Further, the compiled optimum conditions of these postharvest treatments are a good starting point for future studies as well as for commercial applications.

Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

The authors are grateful to our corresponding person or author service manager, Ms. Maja Bozicevic, for the continuous support and patience during the preparation of this chapter.

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