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Postharvest treatments of fresh produce

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Postharvest technologies have allowed horticultural industries to meet the global demands of local and large-scale production and intercontinental distribution of fresh produce that have high nutritional and sensory quality. Harvested products are metabolically active, undergoing ripening and senescence processes that must be controlled to prolong postharvest quality. Inadequate management of these processes can result in major losses in nutritional and quality attributes, outbreaks of foodborne pathogens and financial loss for all players along the supply chain, from growers to consumers. Optimal postharvest treatments for fresh produce seek to slow down physiological processes of senescence and maturation, reduce/inhibit development of physiological disorders and minimize the risk of microbial growth and contamination. In addition to basic postharvest technologies of temperature management, an array of others have been developed including various physical (heat, irradiation and edible coatings), chemical (antimicrobials, antioxidants and anti-browning) and gaseous treatments. This article examines the current status on postharvest treatments of fresh produce and emerging

technologies, such as plasma and ozone, that can be used to maintain quality, reduce losses and waste of fresh produce. It also highlights further research needed to increase our understanding of the dynamic response of fresh produce to various postharvest treatments.

1. Introduction

Fresh fruit and vegetables (FFV) are a major source of essential vitamins and minerals, such as vitamin A, vitamin C and potassium, needed for human wellbeing. They are, however, perishable living products that require coordinated activity by growers, storage operators, processors and retailers to maintain quality and reduce food loss and waste. The extent of coordination can vary greatly from loose in the case of local food supplies to complex for global supply chains. The Food and Agriculture Organization estimated that 32% (weight basis) of all food produced in the world was lost or wasted in 2009 [1]. When converted into calories, global losses represent approximately 24% of all food produced. Reducing the loss and waste of FFVs is important because these foods provide essential nutrients and represent sources of domestic and international revenue.

Fresh produce attributes (appearance, texture, flavour and nutritional value) have been traditional quality criteria, but increasingly safety (chemical, toxicological and microbial) and traceability are important for all the role players along the supply chain, from the farm to consumers. Fresh produce is often eaten raw or after minimal processing and food pathogen contamination can present risk of outbreaks of foodborne illnesses [2]. *Listeria monocytogenes*, *Salmonella enteritidis* phage, and *Escherichia coli* O157:H7 and O104:H4 are major pathogens contributing to outbreaks of foodborne illness with fresh produce as vectors for these pathogens [3]. Owing to multiple uncertainties along the supply chain, microbial contamination leading to spoilage and postharvest losses can occur at any of the stages in the continuum from farm to consumer. Therefore, postharvest treatments are essential to minimize microbial spoilage and reduce the risk of pathogen contamination for FFV [4].

Various postharvest physical, chemical and gaseous treatments may be applied to maintain fresh-like quality with high nutritional value and meet safety standards of fresh produce. These postharvest treatments are typically combined with appropriate management of storage temperatures. This article reviews the current status of postharvest treatments and emerging technologies that can be used to maintain quality and reduce wastage of fresh produce. An Overview of such technologies is presented in table 1.

2. Physical treatments

(a) Heat treatment

Heat treatment has been studied as an alternative to chemical treatments for harvested FFV. Treatments include hot water dip (HWD), saturated water vapour heat, hot dry air and hot water rinse (HWR) with brushing [5]. Beneficial effects of these heat treatments are linked (i) through changes in physiological processes such as a reduction in chilling injury and delay of ripening processes by heat inactivation of degradative enzymes [6], (ii) by killing of critical insect contaminations, and (iii) by controlling the onset of fungal decay [5]. Heat treatments can be of short- (up to 1 h) or long-term duration (up to 4 days). Heat treatments have been applied to firm potatoes, tomatoes, carrots and strawberries; to preserve the colour of asparagus, broccoli, green beans, kiwi fruits, celery and lettuce; to prevent development of overripe flavours in cantaloupe and other melons; and to generally add to the longevity of grapes, plums, bean sprouts and peaches, among others [5–7].

Table 1. Overview of postharvest treatments of fresh produce.

treatment	benefits	limitations	commercial example application
heat treatment	reduction of chilling injury, delay of ripening, killing of critical insect contaminants and controls decay	high-energy costs and added labour	potato, tomato, carrot, strawberry, asparagus, broccoli, beans, kiwi, celery, lettuce, melon, grape, plum, peach, spinach and rocket leaves [5–11]
edible coating	provides a partial barrier, minimizes moisture loss; establishes modified atmosphere; preserves colour and texture; retains natural aroma	cost of scaling up, lack of edible materials with desired properties, regulatory challenges	apples, pears, carrots, celery, strawberry and mushrooms [12–15]
irradiation	inhibits sprouting of tubers, bulbs and roots, meets quarantine requirements for export trade and recognized as a safe process	capital intensive, lack of harmonization of regulations, slow consumer acceptance owing to perceived association with radioactivity	potato, onion, strawberry and mango [16–19]
antimicrobial and anti-browning agents	retards browning, deterioration of texture and microbial growth	inaccessible sites for treatments within fresh produce such as calyx and wax area	apple, strawberry, lettuce, melon, orange, prune, tomato, grapes and fresh-cut produce [20–29]
NO	inhibits ethylene biosynthesis, reduces respiration rate, water loss, browning, and lower incidence of postharvest diseases	commercial application depends upon the development of a smart carrier/controlled release system for NO	apple, banana, kiwifruit, mango, peach, pear, plum, strawberry, tomato, papaya, loquat, jujube fruit and bayberry [30–35]
sulfur dioxide	prevents postharvest decay	higher concentration may induce injuries and sulfite residues pose a health risk	grapes, litchi, fig, banana, lemon, apple and blueberries [36–39]

(Continued.)

Table 1. (Continued.)

treatment	benefits	limitations	commercial example application
ozone	easily incorporated into existing cold storage, washing system, better efficacy than chlorine	does not penetrate natural openings, further research is needed to improve application	apples, cherries, carrots, garlic, kiwi, onions, peaches, plums, potatoes and table grapes [40–44]
ethylene	triggers ripening process thereby improves fruit colour and quality	need of optimum ethylene concentration, storage conditions for faster and more uniform ripening	banana, avocado, persimmon, tomato, kiwifruit, mango and citrus fruits [45–58]
1-MCP	maintains fruit cell wall integrity and peel colour, and develop aroma and flavour	it can increase susceptibility to CO ₂ injury and chilling disorders. Additional exposure time is required for fruit to recover its ability to ripen normally	apple, avocado, banana, broccoli, cucumber, date, kiwifruit, mango, melon, nectarine, papaya, peach, pear, pepper, persimmon, pineapple, plantain, plum, squash and tomato [59–72]
CA storage	retards senescence, associated biochemical and physiological changes, reduction in decay severity	capital intensive, fruit volumes must be high and extended storage periods are needed to make investment economical	apple, pear, avocado, strawberry, cherry, cabbages, kiwifruit, avocados, persimmon, pomegranate, asparagus, banana, broccoli, cranberry, mango, melon, nectarine, peaches and plums [73–83]
MAP	delay in respiration, senescence, and slows down rate of deterioration	condensation inside the package resulting in microbial growth and decay of produce	strawberry, banana, cherries, carrots, fresh-cut fruits, salad mix and leafy green vegetables [84–89]

It has been demonstrated that heat shock by using hot water washing at temperatures ranging from 37 to 55°C for a duration of 30 s to 3 min can improve the postharvest quality of spinach, rocket leaves, apples and mandarin fruit [7–10]. A clear mode of action of any water treatment is to wash-off the spores from the fruit surface [5]. Hot water is a better vector of energy than air and has provided comparable reductions in fungal decay. Blue mould on grapefruit caused by *Penicillium* sp. has been controlled by dipping fruit in hot water for 2 min at 50°C [5]. Improvements in the quality of bell pepper, apples, melons, sweet corn, kumquat and grapefruit have been reported with cold water cleaning in combination with brushing and a short HWR [7]. Hot water treatments also influence the structure and composition of epicuticular waxes. Covering of cracks and wounds and the formation of anti-fungal substances in the wax after heating are thought to be possible modes of action [9].

Hong *et al.* [10] suggested that the combination of *Bacillus amyloliquefaciens* HF-01, sodium bicarbonate and hot water could be a promising method for the control of postharvest decay on citrus while maintaining fruit quality after harvest. To date, commercial applications of heat treatments are limited. Heat treatment provides an alternative to fungicide applications, and in Germany HWD has been used in the storage of organic apples. Treatment of fruit after a few days of cold storage or immediately after the opening of a long-term controlled atmosphere (CA) storage room provides new options for prolonging their subsequent storage life [11], although acceptance of this technology by fruit growers has been hampered by high-energy costs and also the need for added labour at the peak work period during harvest time.

(b) Edible coating

Edible coatings are thin layers of external coatings applied to the surface of fresh produce to enhance the waxy cuticle or as replacements for natural barriers where the produce cuticle has been removed [12,13]. The application of edible coatings on fresh produce provides a partial barrier to the movement of moisture on the surface of fresh produce, thereby minimizing moisture loss during postharvest storage; a gas barrier, thereby establishing a modified atmosphere around the product, which slows down respiration, senescence and enzymatic oxidation and preserves colour and texture; helps to retain volatile compounds contributing to produce a natural aroma and restrict foreign odours; maintains fresh produce structural integrity, and protects against mechanical damages; and serves as carriers of functional or active compounds, such as nutraceuticals, flavouring and colouring agents, antioxidants and antimicrobials, that will maintain/improve product quality and safety [13–15]. Edible coatings are composed of hydrophobic groups, such as lipid-based waxes; hydrocolloid/hydrophilic groups, such as polysaccharide or protein-based materials; or an integration of both groups in order to improve the functionality of the coating [12]. Within the last decade, there has been a considerable amount of research and innovations focused on the development of edible coatings from natural or synthetic sources in order to control physiological and pathological challenges of fresh produce (table 2).

Several edible coatings including chitosan, *Aloe vera*, polyvinyl acetate, mineral oils, cellulose and protein based have shown desirable attributes on fresh produce with good barrier properties, without residual odour or taste and efficient antimicrobial activity [13]. However, more research is required to enhance moisture barrier properties of hydrophilic edible coatings, improve coating adhesion and durability during storage. To maximize the benefits of edible coatings for fresh produce, it is important to understand the effect of storage conditions on the desired functions and the adverse effect on fresh produce quality. The main limitation for the application of edible coating at the industrial level is the cost of scaling up research concepts or investment for new installation of film production and coating equipment, the lack of edible materials with desired physical and functional properties as well as the challenges of regulatory status for the different coating materials. Furthermore, process parameters, such as the method of coating and the amount of additives, can affect the film barrier properties and overall quality of the food

Table 2. Summary of edible coating(s) used on fresh/fresh-cut fruit and vegetables [12–15].

coating material	purpose of coating
guar gum; pea/potato starch \pm potassium sorbate	antimicrobial
candelilla wax-based	antimicrobial; antioxidant; quality
soya bean gum; jojoba wax; glycerol and arabic gum	overall quality
Shellac \pm Aloe vera gel	keeping quality
soy protein; carboxymethyl cellulose	antioxidant; H ₂ O barrier
chitosan; zein	antioxidant; H ₂ O barrier
beeswax; coconut and sunflower oil	antimicrobial; antioxidant; quality
pectin base; alginate; carboxymethyl cellulose	antioxidant; H ₂ O barrier
chitosan; methyl cellulose	antimicrobial; antioxidant; O ₂ /CO ₂ /H ₂ O barrier
soy protein; carboxymethyl cellulose	antioxidant; H ₂ O barrier
pectin base	overall quality
Aloe vera gel	overall quality
agar; chitosan; acetic acid (combined)	antimicrobial; O ₂ /CO ₂ barrier
whey protein; rice bran oil	H ₂ O barrier; overall quality
chitosan	overall quality
sucrose-polyester based	H ₂ O barrier; antioxidant activity
alginate and gellan based	O ₂ /CO ₂ /H ₂ O barrier

product. One of the commercial coating products is Natureseal, which maintains colour, texture and shelf life of a number of fresh-cut fruits e.g. apples, pears, carrots, celery, etc., has recorded a good success. However, further research development is required to investigate the influence of edible coatings on individual cultivars of fresh-cuts in order to understand the variation in shelf life.

(c) Irradiation

Irradiation exposes food to radiant energy from γ rays and e-beam (high-energy electrons) that penetrate objects and break molecular bonds, including the DNA of living organisms. Ionizing radiation from cobalt-60 or caesium-137, or machine generated electron beams are used as a source of irradiation for extending shelf life of fresh produce [16]. By inhibiting cellular reproduction, irradiation can neutralize pest and food safety problems. The effect depends on the doses, measured in kilograys (kGy). Low doses of irradiation (less than 1 kGy) only disrupt cellular activity enough to inhibit sprouting of tubers, bulbs and roots and delay senescence. Medium doses (1–10 kGy) reduce microbial loads while high doses (more than 10 kGy) kill a broad spectrum of fungi and bacteria spp. and pests [17]. Most medium- and high-level doses are not appropriate for fresh produce because they can cause sensory defects (visual, texture and flavour) and/or accelerated senescence due to the irreparable damage to DNA and proteins. Irradiation presents an effective postharvest treatment for destroying bacteria, moulds and yeasts, which cause food spoilage, and also control insect and parasite infestation resulting in reduced storage losses, extended shelf life and improved parasitological and microbiological safety of foods [16]. Irradiation has been commercialized for control of potato and onion sprouting, and strawberry decay [17]. Low-dose γ -irradiation on mango (0.3–0.7 kGy) resulted in delay in ripening and extension of shelf life by a minimum of 3–4 days [18]. Recently, Pandey *et al.* [19] reported an

irradiation dose of 1 kGy to be the only effective dose in which enhanced shelf life was achieved without any deterioration of various quality attributes of litchi fruit.

While much of the focus of irradiation use on FFV has been for extending shelf life and reducing decay, it has been known for many decades that irradiation is effective at killing, sterilizing or preventing further development of a wide variety of insect pests of quarantine importance on perishable FFV. Despite some misconceptions, exposing food to irradiation does not make the food itself radioactive. The irradiation process produces very little chemical change in food and does not change the nutritional value of food. Extensive research and testing has demonstrated that irradiated food is safe and wholesome [17].

3. Chemical treatments

(a) Antimicrobial and anti-browning agents

Over the past decade, the increasing number of reported outbreaks of foodborne illnesses has heightened the concern of regulatory agencies, producers and the consumers about the microbial safety of FFV. Outbreaks have been associated with vegetables such as cabbage, celery, cucumber, leeks, watercress, lettuce and sprouts [2,3]. Antimicrobial and anti-browning agents offer the possibility to maintain safety and can be grouped into chemical- and natural/bio-based agents [20]. Chemical-based agents include chlorine-based solutions, peroxyacetic acid (PAA), organic acids, hydrogen peroxide (H_2O_2) and electrolysed water [20]. A chlorine-based solution such as NaClO has been one of the commonly used disinfectants for fresh produce, owing to its very potent oxidizing properties and cost effectiveness [20]. However, its efficacy as an antimicrobial agent is dependent on the levels of chlorine and at high levels may cause taste and odour defects on treated products. Additionally, chlorine-based compounds have been reported to have limited effectiveness in the reductions of microbial load on fresh produce [21]. Surfactants, detergents and solvents, alone or coupled with physical manipulation such as brushing, may be used to reduce hydrophobic nature of the waxy cuticle or remove part of the wax to increase exposure of microorganisms to chlorine. However, chlorine has been associated with the possible formation of carcinogenic chlorinated compounds and this may lead to new regulatory restrictions in the EU [20].

PAA is a very strong oxidizing agent, with no harmful by-products [22]. PAA has been reported to be effective in controlling *E. coli* O157:H7 and *L. monocytogenes* on apples, strawberries, lettuce and cantaloupe [23]. A 5 log reduction in *Enterobacter sakazakii* was reported for lettuce when treated with PAA [24]. Landfeld *et al.* [25] reported that decontamination treatment of fresh-cut carrot with PAA reduced the initial load of aerobic mesophilic bacteria by about 4 log units and yeasts and moulds by 3.5 log units and no further microbial growth was observed during storage.

H_2O_2 possesses a bactericidal, sporicidal and inhibitory ability, owing to its property as an oxidant and being able to generate other cytotoxic oxidizing species, such as hydroxyl radicals [20]. Treatment with H_2O_2 can extend the shelf life and reduce natural and pathogenic microbial populations in melons, oranges, apples, prunes, tomatoes, whole grapes and fresh-cut produce [26]. However, H_2O_2 treatment requires a long duration of application and can cause injury on some produce. Also, it is accepted as a generally recognized as safe for some food applications but not yet approved as an antimicrobial agent [23,26]. However, a recent study by Lopez-Galvez *et al.* [27] found that the newly developed H_2O_2 -based sanitizers provoked a significant increase in the respiration rate and the electrolyte leakage of fresh-cut iceberg lettuce compared with tap water washing.

Organic acid, ascorbic acid and calcium-based solutions have been applied largely to slow down enzymatic and non-enzymatic browning, deterioration of texture and microbial growth on fresh produce. Treatment of fresh-cut melon dipped in 0.52 mM citric acid for 30 s prior to modified atmosphere packaging (MAP) maintained microbial safety and prevented

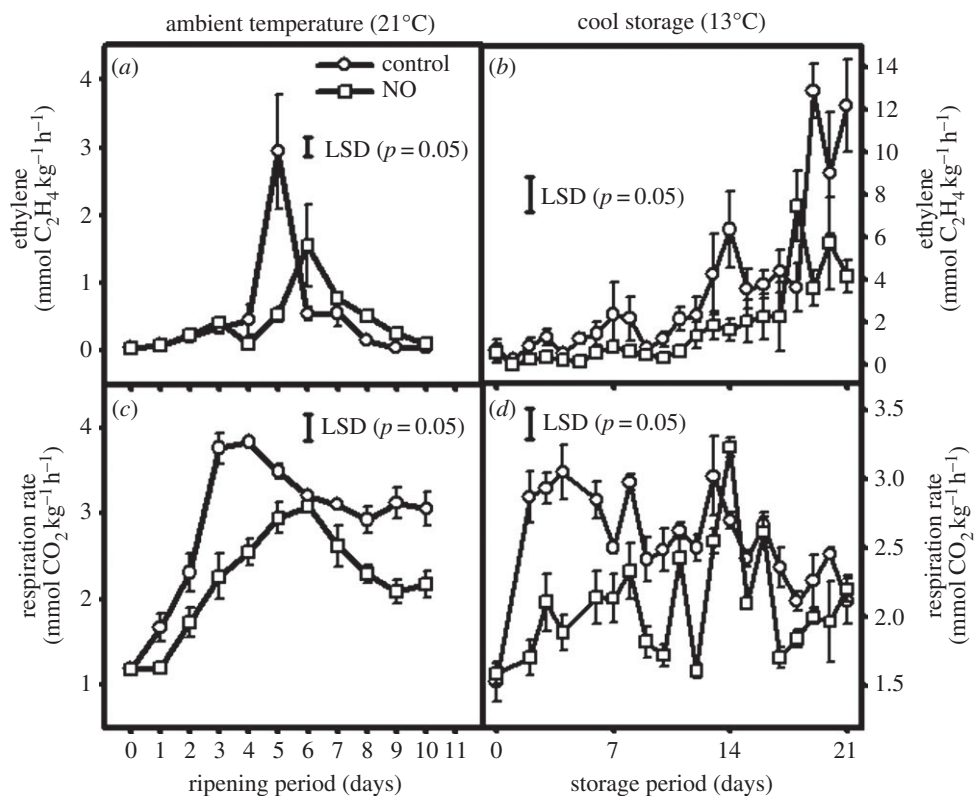


Figure 1. Ethylene production (*a,b*) and respiration rate (*c,d*) of mango as influenced by NO fumigation, ripening period and storage temperature. Reprinted from Zaharah & Singh [32] with permission from Elsevier.

translucency and discoloration [28]. Inhibitory effects of organic acids (acetic, lactic and malic acids) combined with MAP on foodborne pathogens, including *E. coli* O157:H7, *S. Typhimurium* and *L. monocytogenes*, on cabbage was reported by Bae *et al.* [29]. However, there are factors limiting the efficacy of antimicrobial and anti-browning agents such as internalization of bacteria and inaccessible sites within fresh produce such as the calyx. These limitations highlight the need for novel means of applying of antimicrobial and anti-browning agents.

(b) Nitric oxide

Nitric oxide (NO) is a highly reactive free radical gas and acts as a multifunctional signalling molecule in various plant physiological processes, such as fruit ripening and senescence of FFV [30]. Endogenous NO concentrations decrease with maturation and senescence in FFV, thereby offering an opportunity for modulation of their levels with exogenous application to exert the opposite effects [31]. Optimum NO levels delay the climacteric phase of many tropical fruits, prolong the postharvest storage life by impeding ripening and senescence, suppress biosynthesis of ethylene, reduce ethylene production and, consequently, delay in fruit ripening [31]. NO gas is applied as a fumigant or released from compounds such as sodium nitroprusside, S-nitrosothiols and also diazeniumdiolates used as a dipping treatment. Reduced ethylene production during ripening in NO-fumigated fruit has been claimed owing to binding of NO with 1-aminocyclopropane-1-carboxylic acid (ACC) and ACC oxidase to form a stable ternary complex, thus limiting ethylene production (figure 1*a,b*) [32]. Other mechanism of NO action include the inhibition of ethylene biosynthesis, cross-communication with other phytohormones, regulation of gene expression [33] and amelioration of oxidative postharvest stress [34].

Successful application of NO has been reported for apple, banana, kiwifruit, mango, peach, pear, plum, strawberry, tomato, papaya, loquat, Chinese winter jujube fruit and Chinese bayberry [33]. NO treatments reduce the rate of respiration (figure 1*c,d*), water loss and inhibit browning, as well as reducing the incidence of postharvest diseases. NO fumigation in combination with cold storage has a synergistic effect in extending storage life of fruit such as plum and mango [32,34]. Similarly, NO combined with modified atmosphere conditions extended the postharvest life of green beans, broccoli and bok choy [35]. Commercial application of NO in FFV depends upon the development of a smart carrier/controlled release system for NO.

(c) Sulfur dioxide

Sulfur dioxide (SO₂) is widely used on table grapes to prevent decay during storage, by either initial fumigation of fruit from the field followed by weekly fumigation of storage rooms or slow release from in-package pads containing sodium metabisulfite [36]. SO₂ technology has also been tested for control of postharvest decay on other fruits such as litchi, fig, banana, lemon or apple [37]. Cantín *et al.* [38] reported that SO₂ fumigation followed by CA storage (3%O₂ + 6 or 12%CO₂) is a promising postharvest strategy for fresh blueberries to reduce decay, extend market life and maintain high nutritional value. Rivera *et al.* [39] demonstrated that SO₂ is an effective and practical technology for reducing the risk of blueberry grey mould decay during storage and it could be used for the export market. There are disadvantages to SO₂ use; the SO₂ concentration necessary to inhibit fungal growth may induce injuries in grape fruits and stems, and sulfite residues pose a health risk for some individuals [36–38], as well as firming of the texture of some fruit species (pomaces), incomplete de-sulphiting and incomplete re-colouring of red fruits. Nevertheless, SO₂ treatment is a widespread process because of its advantages of universal antiseptic action and economic application.

4. Gaseous treatments

(a) Ozone

Recent research and commercial applications have verified that ozone can replace traditional sanitizing agents [40,41]. Ozone is a very pungent, naturally occurring gas with strong highly reactive oxidizing properties. Ozone is reported to have 1.5 times the oxidizing potential of chlorine and 3000 times the potential of hypochlorous acid. Contact times for antimicrobial action are typically four to five times less than that for chlorine. Ozone rapidly attacks bacterial cell walls and is more effective than chlorine against the thick-walled spores of plant pathogens and animal parasites, at practical and safe concentrations [42]. Ali [41] reported that the fruit exposed to 2.5 ppm ozone had higher levels of total soluble solids, ascorbic acid content, β -carotene content, lycopene content, and antioxidant activity and also reduced weight loss at day 10 compared with untreated fruit. The sensory attributes of papaya of ozone-treated fruit was also superior in sweetness and overall acceptability endorsing ozone as a non-thermal and safe food preservation technique for FFV. Ozone can be employed in cold storage, washing system or process water sterilization. Huyskens-Keil *et al.* [42] reported that irradiation and washing with ozonated water slightly reduced respiration in white asparagus spears, but increased spear tissue toughness. However, neither washing the asparagus spears with ozonated water (3 or 4.5 ppm) nor treating them with radiation (1 kJ m⁻²) systematically and significantly affected their microbial loads during storage [43]. Some commercial use has occurred with commodities such as apples, cherries, carrots, garlic, kiwi, onions, peaches, plums, potatoes and table grapes [44]. However, ozone does not penetrate natural openings or wounds efficiently. Additional research is needed to define the potential and limits of the effective use of ozone for postharvest treatments for the quality and safety of FFV.

(b) Ethylene

Endogenous ethylene production and its exogenous application exhibit both beneficial and deleterious effects on horticultural fresh produce. Beneficial effects of exogenously applied ethylene includes triggering ripening, improving fruit colour and quality in some crops, such as bananas and avocados, kiwifruit, persimmon, tomato, mangoes, de-greening of citrus fruit [45,46]. The deleterious effects of ethylene in postharvest phase horticultural commodities has also been documented, such as shorter storage life, promotion of senescence, fruit softening, discoloration (browning) and russet spotting in lettuce, yellowing of leafy vegetables and cucumbers and increased susceptibility of FFV to decay [47,48]. Therefore, ethylene management plays a pivotal role in maintaining postharvest life and quality of climacteric and non-climacteric horticultural produce. Most commercial strategies for maintaining horticultural commodities involve storing at low temperatures, blocking ethylene biosynthesis and its action, minimizing exposure produce to ethylene during ripening, harvest, storage and transport by controlling temperature and atmospheric gas composition [49]. Newly developed ethylene measurement devices will enable to detect critical concentrations during storage and transportation [50].

Beneficial effects of ethylene biosynthesis inhibitors such as aminoethoxyvinylglycine alone on postharvest quality have been demonstrated in apples and stone fruits [51,52] and in combination with controlled atmosphere (CA) storage [53,54]. Treating FFV with inhibitors of ethylene action, such as 1-methylcyclopropene (1-MCP) or NO alone or in combination with MAP or CA storage, also impedes ethylene production and action consequently extends storage life and maintains quality of FFV (§§3*b* and 4*c*).

Commercialization and limitations of different ethylene inhibitors are discussed in detail by Martínez-Romero *et al.* [55]. A recent development has been palladium-promoted zeolite materials, which can be effective ethylene scavengers to prolong the shelf life of climacteric fresh produce, such as bananas and avocados [56,57]. The material has the potential to be used commercially, as an alternative and/or supplemental treatment to 1-MCP. Martínez-Romero *et al.* [58] developed a carbon-heat hybrid ethylene scrubber for fresh horticultural produce storage purposes. The device comprised a cartridge heater tightly joined to the activated carbon–1% palladium. Application of heat pulses leads to an increase in ethylene oxidation and to auto-regeneration of the activated carbon.

(c) 1-Methylcyclopropene

The discovery and patenting of cyclopropenes as inhibitors of ethylene perception represents a major breakthrough in controlling ethylene responses of horticultural products [59]. The process of discovery of the effects of cyclopropenes, and their proposed method of action, has been described [60,61]. Of the cyclopropenes, 1-MCP proved to be extremely active, but unstable in the liquid phase. However, 1-MCP can be complexed with α -cyclodextrin to maintain its stability; this development represented a major step towards its commercialization as it was then possible to release 1-MCP from the complex to expose to the horticultural products. Regulatory approval for use of 1-MCP has been obtained in more than 50 countries, and approval for use of the technology continues to occur around the world. 1-MCP is registered for use on a wide variety of FFV including apple, avocado, banana, broccoli, cucumber, date, kiwifruit, mango, melon, nectarine, papaya, peach, pear, pepper, persimmon, pineapple, plantain, plum, squash and tomato. 1-MCP affects many ripening and senescence processes [62,63], including pigment changes, softening and cell wall metabolism, flavour and aroma, and nutritional properties, but to varying degrees in both non-climacteric and climacteric products. While aqueous 1-MCP shows similar responses as those treated with gaseous 1-MCP, ripening actors such as activity of cell wall-associated enzymes, e.g. lycopene, antioxidant and volatiles of avocado, are delayed but recover to reach levels similar to those of untreated fruit [64]. The range of responses reflects the enormous diversity of these crops in terms of both inherent diversity and

morphological derivation [65]. Several generalizations can be made about responses of crops to 1-MCP [65,66]:

- genotype, cultivar and maturity effects can be highly variable;
- climacteric fruit are affected by 1-MCP treatment, but the capacity to interrupt ripening once initiated varies by fruit and attributes studied;
- non-climacteric fruit also respond to 1-MCP, providing insights into ethylene-dependent and -independent events during ripening;
- treated fruits are firmer, slower to soften, slower to change peel colour, and develop aroma and flavour. If 1-MCP concentrations and exposure periods for each fruit must be appropriate to allow ripening to occur, so the final quality of the treated fruit is similar to that of the untreated product; and
- the effect of 1-MCP on physiological disorders is dependent on the role of ethylene. 1-MCP decreases senescent-related and ethylene-induced disorders (senescent breakdown of apples and water soaking of watermelons). 1-MCP can increase susceptibility of apple fruit to CA storage-related disorders (CO₂ injury). Some chilling-related disorders (woolliness and internal breakdown of peaches and nectarines, chilling injury of citrus and bananas) can be increased by inhibition of ethylene production. Other chilling-related disorders (superficial scald of apples and pears and internal flesh browning of avocados and pineapples) are decreased by inhibition of ethylene production.

Registration of 1-MCP for FFV has focused on major or specialty products important to specific countries. The apple has been an excellent crop for use of 1-MCP, and the technology is used extensively around the world to maintain quality through the whole marketing chain from storage to consumer [66]. Success of 1-MCP technology for apples is largely associated with a fruit where maintenance of 'at harvest' quality and only moderate softening to a crisp fracturable texture is desirable. Watkins *et al.* [67] found that rapid treatment of fruit with 1-MCP after harvest can afford storage operators more freedom to delay CA storage application, but attention to cultivar, fruit maturity and susceptibility of fruit to storage disorders must be considered. Challenges exist for the effective use of 1-MCP for fruit that ripen uniformly to a melting texture and/or have major colour, flavour and aroma changes that are expected by the consumer. Failure to ripen normally has been shown in avocado, banana, pear and tomato, where fruits were treated at an early ripening stage or where applied 1-MCP concentrations were too high [68–71]. Despite the challenges, successful commercialization of SmartFresh for treatment of avocados, bananas, melons, persimmons and tomatoes has resulted from careful attenuation of 1-MCP concentrations and/or ripening stage at harvest.

Recently, 1-MCP formulations have been approved by the Environmental Protection Agency and other regulatory authorities for preharvest applications, and these are marketed as Harvista for FFV. Semi-commercial trials have been carried out in several US locations, Argentina, Brazil, Canada, Chile, New Zealand and South Africa. Harvista has useful effects on delaying fruit drop, slowing fruit maturation and ripening, and in maintaining postharvest quality, including improving the effects of SmartFresh [71,72].

(d) Controlled atmosphere storage

CA storage refers to the monitoring and adjustment of the CO₂ and O₂ levels within gas tight stores at optimum storage temperature. Thus, the atmosphere is controlled rather than established passively as in the case of MAP outlined in §4e, though the effects of altered atmospheres on metabolism of FFV are essentially the same. In most cases, the concentrations of CO₂ are higher and those of O₂ are lower, optimum concentrations depending on the specific product and the purpose of the CA storage conditions. Reduced O₂ and elevated CO₂ levels affect both primary (glycolysis, fermentation and aerobic respiration) and secondary (e.g. processes involved in ethylene production and action, pigments, phenolics and volatiles) metabolism [73].

Each FFV has an optimal range of O₂ and CO₂ for maintaining quality and extending shelf life [74], and these can differ for whole and fresh-cut products of the same fruit or vegetable. Benefits of CA as well as detrimental effects resulting from exposure of FFV to atmospheres outside of the safe range were summarized by Kader [75]. The beneficial effects of CA include:

- retardation of senescence and associated biochemical and physiological changes, e.g. slowing down rates of respiration, ethylene production and softening;
- reduction in sensitivity to ethylene action at O₂ levels less than 8% and/or CO₂ levels more than 1%;
- alleviation of certain physiological disorders, e.g. chilling injury of avocado and superficial scald of apples and pears;
- direct or indirect effect on postharvest pathogens (bacteria and fungi) and consequently decay incidence and severity e.g. CO₂ at 10–15% inhibits development of *Botrytis* rot on strawberries and cherries; and
- low O₂ (less than 1%) and/or elevated CO₂ (40–60%) can be a useful tool for insect control in some fresh and dried fruits, flowers and vegetables; and dried nuts and grains.

The detrimental effects of CA include:

- initiation and/or aggravation of certain physiological disorders, such as internal browning in apples and pears, brown stain of lettuce and chilling injury of some commodities;
- irregular ripening of fruits, such as banana, mango, pear and tomato, can result from exposure to O₂ levels below 2% and/or CO₂ levels above 5% for more than one month;
- development of off-flavours and off-odours at very low O₂ concentrations (as a result of anaerobic respiration) and very high CO₂ levels (as a result of fermentative metabolism); and
- increased susceptibility to decay when the fruit is physiologically injured by insufficient O₂ or too-high CO₂ concentrations.

Use of CA technology is limited to relatively few FFV, the major crop being apples. Other FFV include cabbages, sweet onions, kiwifruits, avocados, persimmons, pomegranates, nuts and dried fruits, and vegetables [74]. Atmospheric modification during long-distance transport is used on apples, asparagus, avocados, bananas, broccoli, cranberries, cherries, figs, kiwifruits, mangos, melons, nectarines, peaches, pears, plums and strawberries. Limited use of CA for many FFV is related to the high levels of capital investment required for high-quality storage rooms and the maintenance and monitoring of atmospheres; therefore, fruit volumes must be high enough to fill rooms, and extended storage periods are needed to make investments economical. For shipping containers, limitations include maintaining container identity for those with equipment. Specific CA storage technologies that are used are a function of the FFV, growing region and size of the industry. Where used, static systems are still used for the majority of FFV CA storage, ranging from simple controlled ventilation systems to conventional CA (more than 2 kPa O₂). The use of low O₂ (LO) and ultra low O₂ (ULO) CA storage, where O₂ levels are as low as 1.5–2.0 and 0.8–1.2 kPa, respectively [76], is increasingly becoming common. Chong *et al.* [77] proposed a hollow fibre membrane module for generating nitrogen-enriched air stream that controls the concentration of both O₂ and CO₂ in the CA storage.

Other developments include dynamic CA (DCA), initial low O₂ stress (ILOS) and hypobaric storage. The principle of DCA is that responses of fruit to decreasing O₂ in the storage atmosphere are monitored. As O₂ levels reach the anaerobic compensation point, stress responses by the fruit can be detected and the O₂ increased to slightly higher levels. The most common commercial DCA system is based on chlorophyll fluorescence (DCA-DF; [78]), but others include measurement of ethanol in the fruit (dynamic controlled systems, DCS; [79]) and the respiration quotient (DCS-RQ; [80]). Most research has been carried out with apples and pears, a major impetus for research

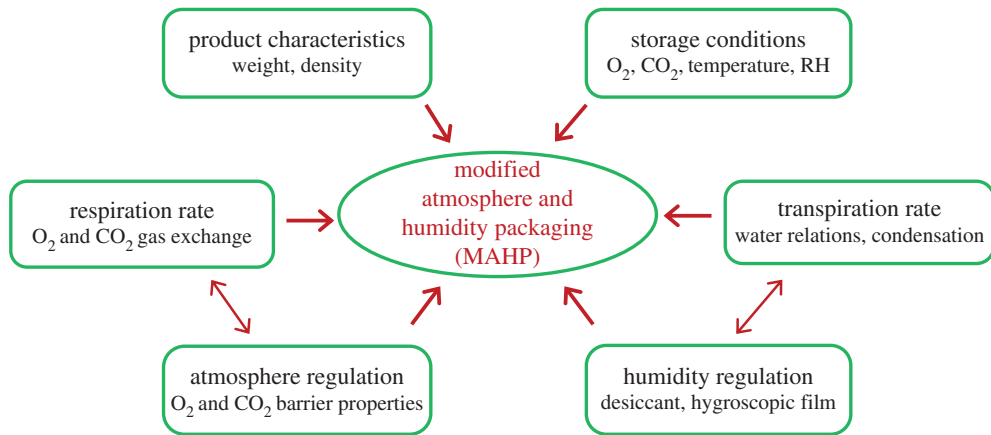


Figure 2. Factors involved in designing MAHP for FFV. (Online version in colour.)

being the loss of diphenylamine, the antioxidant used widely for control of the physiological disorder superficial scald in Europe. However, DCA has been tested with avocado [81] and should work with any chlorophyll-containing product [82]. ILOS involves the use of low partial pressures of O_2 , e.g. 0.4 kPa, that result in ethanol accumulation for short periods of time that result in delay of fruit ripening [83]. Hypobaric or low-pressure storage results in very low O_2 around the product and delay ripening and senescence [76] but has yet to find commercial acceptance because of factors such as cost and safety. These issues may be addressed in the future.

(e) Modified atmosphere packaging

MAP generally involves the packaging of a whole or fresh-cut product in plastic film bags, and can be either passive or active. In passive MAP, the equilibrium concentrations of O_2 and CO_2 are a function of the product weight and its respiration rate, which is affected by temperature and the surface area, perforations, thickness and permeability to gases of films used in packaging. In active MAP, the desired atmosphere is introduced in the package headspace before heat sealing, but the final atmosphere will eventually be a function of the same factors that affect passive MAP. Correct equilibrium atmosphere can delay respiration, senescence, and slow down the rate of deterioration, thereby extending product storage life [3]. More recently, active MAP also includes technologies to adsorb substances, such as O_2 , ethylene, moisture, CO_2 , flavours/odours, and release substances such as CO_2 , antimicrobial agents, antioxidants and flavours [84].

An extensive number of models have been developed to predict respiration rates of FFV under MAP conditions [3]. An example of prediction models is that of Mahajan *et al.* [85], where the Pack-in-MAP software for optimum packaging solutions for FFV was developed. Behind the software is an extensive database on product respiration rate, optimum temperature, optimum ranges of O_2 and CO_2 and gas permeability of packaging materials commonly used in MAP (figure 2). The software is based on a series of mathematical algorithms to simulate the evolution of internal gas composition in the packaging as a result of food respiration and mass transfer through the packaging material and, when used in a reverse manner, to identify the window of gas permeability that satisfy food requirements, size and number of micro-perforations, if needed [86].

Current MAP design considers the respiration rate of product as the only important parameter for deciding target gas barrier properties required to achieve an equilibrium-modified atmosphere. However, besides in-package gas composition it is also important to take into consideration the in-package level of humidity, in order to avoid condensation and/or mould and bacterial development in MAP systems [87]. It is well known that the in-package humidity

is influenced by respiration and transpiration of the fresh produce as well as the water vapour permeability of the packaging material (figure 2). However, most polymeric materials (polyethylene, polypropylene or polyvinyl chloride) used in MAP have lower water vapour permeability relative to transpiration rates of fresh produce; therefore, most water molecules evaporated from the produce do not escape through the film and remain within the package, enhancing the water vapour pressure in the package microenvironment. Under these near-saturation conditions, even minor temperature fluctuation may result in condensation inside the package resulting in produce sliminess and enhancement of microbial growth and decay of produce [88]. Therefore, the major challenge of modified atmosphere and humidity packaging (MAHP) is finding a solution for creating optimal atmosphere and reducing the risk of water condensation in the package while still maintaining produce weight loss as low as possible. Recent developments on high water vapour permeable films such as Xtend, NatureFlex or biodegradable films or use of hygroscopic additives located within the package headspace or directly integrated into the packaging material. However, the hygroscopic additives should not be used for fresh produce, which have high water activity, in order to avoid excessive weight loss of the packed food. Recently, Singh *et al.* [89] reported that the humidity absorption of the trays with NaCl improved the quality and shelf life of fresh mushrooms. In this study, different percentage of NaCl was incorporated in the polymer matrix of a film from which trays were produced. The results indicate that the amount of water vapour absorbed by the tray is directly proportional to the percentage of salt incorporated in the trays, which enhanced the total appearance of the package. The maximal capacity and the rate of moisture absorption by the humidity regulating trays need to be studied further in order to confirm whether the trays have enough moisture absorption capacity to prevent condensation for the selected horticultural crops. Additionally, questions about sustainability and consumer expectations of such humidity regulating trays have to be taken into consideration.

5. Emerging technologies

Plasma is an emerging technique for decontaminating FFV. Plasma is composed of ionized gas molecules, which have been dissociated via an energy input. Depending on the mode of particles activation and the excitation energy, they can generate high or low temperatures, referred to as thermal or cold plasma, respectively [90]. Cold plasma at atmospheric pressure can be generated by transforming argon gas into plasma at radio frequency of 27 MHz [91] or by electric discharge between two electrodes separated by dielectric barriers [92]. Three basic mechanisms have been suggested for the inactivation microbial spores in plasma environments, including the erosion of microbial spore surface atom by atom through adsorption of reactive free radicals 'etching'; direct destruction of DNA via UV irradiation and volatilization of compounds from the spore surface by UV photons through intrinsic photo-desorption. Fernández *et al.* [93] revealed that at the optimal operating conditions of cold gas plasma treatment about 15 min treatment time was required to achieve 2.72, 1.76 and 0.94 log-reductions in viable cells of *S. enteric* sv. *Typhimurium* on lettuce, strawberry surfaces and potato tissue, respectively. Recent study by Baier *et al.* [91] on fresh corn salad leaves showed that the plasma treatment at 20 W for 1 min successfully inactivated *E. coli* by 4 log-cycles. However, more research is required for a complete understanding of the role of microbial cell structure, physiology and stress resistance mechanisms involved in plasma resistance. Also, the effect of plasma treatment on food enzymes and postharvest quality attributes of FFV requires more detailed study. Safety of gases, consumer perception and the translation of laboratory scale to large commercial scale, also requires further investigation.

6. Conclusion and future prospects

A wide range of physical and chemical treatments exist to maintain and extend shelf life FFV. Specific treatments may only be applicable to certain types of product and spoilage conditions

and the effectiveness of existing treatments on emerging quality issues need to be assessed. Postharvest treatments, such as CA and MAP, in combination with appropriate temperature control are the basis for maintaining physical, nutritional and sensory attributes, and by reducing decay incidence. These can be supplemented by chlorine, SO₂, irradiation, hot water, hot air, antimicrobial agents and edible coatings as appropriate for the specific product. Newer technologies include ULO and postharvest technologies based on ethylene oxidation, inhibitors of ethylene action and modulators of ripening, such as NO. Research on these technologies is continuing on a range of FFV, including climacteric and non-climacteric types. Research with DCA represents a new era where the technology is applied in a dynamic fashion, recognizing that the metabolism of the product changes in response to the applied storage conditions. To date, use of this technology is limited but the introduction of nanotechnology to the postharvest arena may open new opportunities. For example, the development of nanocomposite packaging materials with tuneable architecture can act as a smart carrier/controlled release system for 1-MCP, NO or antimicrobial agents. Future research in development of delivery systems will not only improve efficacy of postharvest systems but may also address the safety issues.

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