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POSTHARVEST TECHNOLOGIES FOR FRUITS AND VEGETABLES: CURRENT STATUS AND PROSPECTS

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ABSTRACT

Fruits and vegetables are susceptible to water loss and other physiological and pathological disorders, leading to substantial postharvest losses. These problems have led to the creation of new treatments and preservation technologies that can keep products fresh for longer. In recent years, there has been a growing interest in sustainable technologies that are safe for consumers and leave no toxic residues. These systems include chemical methods, such as ozone, electrolyzed water, hydrogen-rich water, essential oils, and vegetable extracts, as well as physical methods like controlled and modified atmosphere storage, irradiation, and the use of edible films and coatings. Additionally, cold plasma treatment is an emerging technology under active investigation for its potential applications in food preservation. The objective of this review is to present and examine emerging and advanced technologies designed to enhance the preservation and extend the shelf life of fruits and vegetables during the postharvest period.

Keywords: food safety, microbial control, physicochemical preservation, sensory quality, shelf-life extension.

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INTRODUCTION

Fruits and vegetables, rich in vitamins, antioxidants, minerals, and fiber that contribute to a balanced diet and optimal health, are increasingly in demand due to the growing consumer preference for foods with high nutritional value. More than 675 megagrams (Mg) of fruits are produced worldwide each year (Pereira *et al*., 2022). Approximately one-third of the world's production for human consumption, or around 1.3 billion Mg of food, is lost and wasted annually (Moračanin *et al*., 2023). Food losses occur throughout the stages of agricultural production, postharvest handling, and storage, as well as during processing and packaging. In contrast, food waste primarily takes place during the distribution and consumption phases (Gustavsson *et al*., 2011; Elik *et al*., 2019).

A major obstacle to global food security is the postharvest loss of fruits and vegetables, estimated to account for approximately 50 % of total worldwide production. In developing countries, approximately 25–50 % of fruit and vegetable production is lost, primarily due to inadequate handling, poor storage and transportation infrastructure, and the use of insufficient or inappropriate packaging (Elik *et al*., 2019; Tapsoba *et al*., 2022). In contrast, postharvest losses of fruits and vegetables in Europe are estimated to be around 27 %. In developed countries, most losses occur beyond the farm gate, largely resulting from microbiological and physiological deterioration associated with natural senescence, as well as technological, planning, and logistical shortcomings. However, the most significant losses take place during the distribution and consumption stages (food waste), accounting for approximately 46 % (Bennett *et al*., 2011; Elik *et al*., 2019).

Refrigeration has been used for centuries as one of the simplest and most practical methods for preserving fruits and vegetables. However, temperature control alone is often insufficient, particularly given the long distances that food products are transported today. To address this limitation, additional preservation strategies have been developed, including chemical treatments, ultraviolet irradiation, controlled and modified atmosphere storage, edible films and coatings, and, more recently, cold plasma technology (Sandarani *et al*., 2018; Palumbo *et al*., 2022).

Chemical treatments, such as hydrogen peroxide, ozone, and electrolyzed water, are primarily effective in maintaining the microbial quality of fresh produce. Controlled atmosphere storage and modified atmosphere packaging help reduce metabolic activity, thereby extending the shelf life of fruits and vegetables. Irradiation and cold plasma have also proven effective against a wide range of pathogenic microorganisms. Additionally, edible films and coatings can minimize weight loss and metabolic activity in fruits and vegetables, thus preserving their overall quality (Palumbo *et al*., 2022; Wu *et al*., 2024). This review aims to provide an overview of emerging and advanced postharvest treatments and technologies for fruits and vegetables, highlighting their effectiveness, applications, and potential to extend shelf life.

CHEMICAL AND NATURAL TREATMENTS

Synthetic chemical products

The most widely used industrial control system to prevent microbial spoilage and maintain postharvest shelf life is the application of synthetic chemical products. Fungicides such as imazalil and thiabendazole, as well as sanitization with sodium hypochlorite, are particularly notable. However, legislative restrictions in many countries are increasingly limiting their use due to concerns over the emergence of resistant pathogen strains and environmental and food safety issues (Lado *et al*., 2013; Murray *et al*., 2019). Sanitization is considered effective and safe when the agent achieves a 5-log (99.999 % reduction) in bacterial concentration and a 4-log (99.99 % reduction) in mold concentration (Frisón *et al*., 2013).

Ozone

Ozone is a highly effective disinfectant with extremely rapid antimicrobial action. It is an unstable molecule composed of three oxygen atoms and readily decomposes into oxygen (O_2) and nascent oxygen. Ozone does not produce toxic byproducts and is safe, efficient, and environmentally friendly, leaving only oxygen as a residue, which makes it a suitable alternative to chlorine (Frisón *et al*., 2013). To inactivate microorganisms on fruit, high doses of ozone are required, as the organic components of the fruit react easily with ozone, reducing its sanitizing effectiveness. However, excessive ozone must be avoided, as it can damage the tissues of the product and compromise its quality.

Due to the above, it is advisable to carry out prior studies of the optimum ozone doses for each product (Bataller-Venta *et al*., 2010). In cantaloupe melon (*Cucumis melo* L.), gaseous ozone (0.15 ppm during the day and 0.3 ppm at night) maintained firmness and decreased the concentration of ethylene and mesophilic aerobic bacteria, in addition to reducing the enzymatic activity of α-arabinopyranosidase, β-galactopyranosidase, and polygalacturonase from the third day of treatment (Toti *et al*., 2018). In coriander (*Coriandrum sativum* L.), ozone (0.68 mg L^{-1}) maintained physical appearance and suppressed respiration rate and polyphenol oxidase activity and inhibited the activity of chlorophyll-degrading enzymes (Xu *et al*., 2019).

Electrolyzed water

Electrolyzed water is generated by the electrolysis of an aqueous sodium chloride solution (0.5–1 % NaCl). This process produces two types of electrolyzed water: acid electrolyzed water (AEW), also known as oxidizing electrolyzed water, and neutral electrolyzed water (NEW). AEW is produced at the anode, while NEW is generated at the cathode. NEW has a low pH (2.1–4.5), a high oxidation-reduction potential (above 1000 mV), and the presence of hypochlorous acid, which confers a strong bactericidal effect against pathogenic microorganisms and fungi responsible for postharvest diseases (Rico *et al*., 2007; Selma *et al*., 2008). Meanwhile, the oxidation-reduction potential in AEW ranges from 500 to 700 mV, and the pH ranges from 5 to 8.5, resulting in a strong bactericidal effect (Rico *et al*., 2007; Ramos *et al*., 2013).

Both AEW and NEW have shown similar efficacy to hypochlorite, at equivalent free chlorine concentrations, against *Escherichia coli*, *Listeria innocua*, and *Salmonella choleraesuis* in apple (*Malus domestica* L.) slices artificially inoculated with these bacteria (Graça *et al*., 2011). Other studies have demonstrated the effectiveness of electrolyzed water as a disinfectant against *E. coli* in cut apple and melon (Wang *et al*., 2006), *Botryosphaeria berengeriana* in cut pear (*Pyrus communis* L.) (Al-Haq *et al*., 2002), and *Penicillium expansum* during apple handling and processing (Okull and Laborde, 2004).

Hydrogen-rich water

Hydrogen-rich water (HRW) is a practical and safe alternative to hydrogen gas for various applications, including postharvest treatment of fruits and vegetables (Dong *et al*., 2023a). Many physiological and developmental processes, including the postharvest preservation of horticultural products, depend on gas transfer molecules such as hydrogen sulfide (H_2S) and methane (CH_4) (Fang *et al*., 2021). Several studies have demonstrated the beneficial effects of H_2S (Hu *et al*., 2014) and nitric oxide (NO) (Lai *et al*., 2011) in extending the shelf life of strawberries (*Fragaria* × *ananassa* Duch.) and tomatoes (*Solanum lycopersicum* L.), respectively. Furthermore, H_2 can regulate the antioxidant defense system, mitigating abiotic stresses such as high salinity and low temperature. Additionally, H_2 is involved in regulating postharvest biochemical and physiological behavior.

In kiwifruit (*Actinidia deliciosa* Liang), HRW reduces lipid peroxidation and delays the ripening process, thus maintaining quality and extending postharvest life (Hu *et al*., 2014). A 50 % HRW solution was found to effectively maintain the chlorophyll content in pak choi (*Brassica rapa* subsp. *chinensis* L.), and when combined with vacuum precooling, it also helped maintain antioxidant compounds while reducing the rate of weight loss (An *et al*., 2021). In okra (*Abelmoschus esculentus* L.), HRW maintained cell wall biosynthesis by regulating genes related to cellulose, hemicellulose, and pectin at different times during storage, which helped the fruit to retain its firmness and delay softening (Dong *et al*., 2023a).

One disadvantage of conventional HRW is the short residence time of H_2 in water, as well as its low solubility. However, nanobubbles are an emerging technology that can increase the residence time and content of H_2 in water. Hydrogen nanobubble water (HNW) has been applied in preharvest and other areas, such as water treatment. The vase life of cut carnation flowers (*Dianthus caryophyllus* L.) was prolonged by regulating nuclease and protease activities through the postharvest application of HNW (Li *et al*., 2021). However, further research is needed to evaluate the effectiveness of this technology for postharvest applications in other horticultural products.

Essential oils and plant extracts

Synthetic fungicides are associated with environmental and human health risks. To replace chemical treatments, essential oils (EO) and plant extracts have emerged as safe alternatives over the last two decades. Plants contain bioactive compounds that exhibit biological activity against pathogenic microorganisms, including phytopathogenic fungi, oomycetes, and bacteria. With more than 250,000 plant species worldwide, plant extracts and essential oils offer considerable potential for postharvest applications in a variety of fruits and vegetables (El Khetabi *et al*., 2022). Essential oils are produced as secondary metabolites in various parts of aromatic plants, including leaves, fruits, seeds, flowers, stems, roots, buds, and bark (Aftab and Hakeem, 2021). However, EOs can be photodegradable and volatile, which may reduce their long-term effectiveness. As a result, EOs are often tested in combination with other technologies (Table 1).

Table 1. Recent studies on essential oils (EOs) and plant extracts as postharvest treatments for fruits and vegetables.

Product	EO Treatment	Results	Limitations/notes	References
Postharvest washing of fresh produce	Thyme *(Thymus vulgaris* L.), oregano (*Origanum vulgare* L.), cinnamon (*Cinnamomum verum* J. Presl), and clove (*Syzygium aromaticum* L.)	Reduced foodborne pathogens, strongly inhibiting *E. coli*, *Salmonella*, and *L. monocytogenes*.	Need for standardization of EO concentrations and application methods.	(Pizzo *et al*., 2023)
Apple (*Malus domestica* L.)	Lemongrass (*Cymbopogon citratus* (DC.) Stapf) with poly(lactic acid) nanocapsules	Treated fruits showed smaller bitter rot lesions compared to non-capsulated EO and control.	Potential cost and complexity of nanocapsule production.	(Antonioli *et al*., 2020)
Jackfruit (*Artocarpus heterophyllus* Lam.)	Vetiver (*Vetiveria zizanioides* L.) and basil (*Ocimum basilicum* L.)	Reduced rot caused by *P. notatum* and *R. microsporus* on the jackfruit surface.	Requires further testing for commercial application.	(Atif *et al*., 2020)
Guava (*Psidium guajava* L.)	Gum Arabic (GA) with cinnamon	10 % GA + 1 % cinnamon EO preserved firmness, color, pH, flavor index, SSC, carotenoids, and chlorophylls during cold storage.	Synergistic effects of GA and EO need more exploration.	(Etemadipoor *et al*., 2019)
Strawberry (*Fragaria* × *ananassa* Duch.)	Chitosan/citrus /silver nanoparticle films and gamma irradiation	Composite films showed less weight loss than controls. Gamma irradiation reduced firmness and decay over 12 d.	Combined effects of EO, chitosan, and nanoparticles need further study	(Shankar *et al*., 2021)
Peach (*Prunus persica* L.)	Lavender (*Lavandula angustifolia* Mill.), rosewood (*Aniba rosaeodora* Ducke), dill weed (*Anethum graveolens* L.), and fennel (*Foeniculum vulgare* Mill.)	Rosewood EO in vapor phase effectively reduced decay and maintained weight loss and total soluble solids at room temperature and refrigeration.	Variability in effectiveness depending on EO concentration and application method.	(Lin *et al*., 2022)
Dragon fruit (*Selenicereus undatus* (Haw.) D.R. Hunt)	Ginger (*Zingiber officinale* Roscoe), turmeric (*Curcuma longa* L.), and dukung anak (*Alpinia galanga* L.) extracts	10 g L^{-1} controlled anthracnose; higher concentrations (≥15 g L^{-1}) may cause phytotoxicity and worsen diseases.	Determination of optimal concentrations for efficacy without phytotoxicity.	(Bordoh *et al*., 2020)
Apple	Neem (*Azadirachta indica* A. Juss.), fennel, lavender, thyme, pennyroyal (*Mentha pulegium* L.), salvia (*Salvia officinalis* L.), and asafetida (*Ferula assafoetida* L.) extracts	Neem extract (25 %) reduced disease severity by 89.11 % against *Botrytis cinerea*.	Variability in effectiveness among different extracts.	(Gholamnezhad, 2019)

PHYSICAL AND ENVIRONMENTAL PRESERVATION METHODS

Controlled atmosphere storage

Controlled atmosphere storage (CAS) was developed as a complement to refrigeration and is widely used for a variety of fruits and vegetables (Fang and Wakisaka, 2021). Among postharvest storage techniques, CAS is a popular choice. This method involves maintaining optimal gas concentrations by continuously adding or removing gases during the storage of unpackaged produce (Kirtil and Oztop, 2016). By modifying the surrounding atmosphere, CAS alters the internal gaseous composition of the product, which in turn affects cell metabolism. Most research on CAS in fruit and vegetables involves combining it with other technologies, such as modified atmosphere packaging (MAP), 1-methylcyclopropene (1-MCP), high-pressure carbon dioxide (H-CO_2), argon-modified atmosphere packaging (MAP-Ar), and MAP with zinc oxide (ZnO), among others (Fang and Wakisaka, 2021) (Table 2). Combined with cold storage, CAS reduces metabolic activity, inhibits enzymatic reactions, and effectively extends the shelf life of fruits and vegetables (Falagán and Terry, 2018).

Table 2. Recent research on controlled atmosphere storage of fruit and vegetables.

Product	Treatment	Storage time	Results	Limitations/notes	References
Apple (*Malus domestica* L.)	1.2 kPa O_2, 2 kPa CO_2 94 ± 2 % relative humidity (RH), 1.5 ± 0.1 °C	240 d	Reduced ester production and volatile profile quality.	May affect flavor and aroma profile of apples.	(Anese *et al*., 2020)
Apple	2–3 % O_2, 1–1.5 % CO_2 90–95 % RH, 0 ± 0.5 °C,	210 d	Improved quality and prevented pericarp browning.	Potential variability in response depending on apple variety.	(Gao *et al*., 2023)
Apple	<2 % O_2, <1 % CO_2 99 % RH, 1.5–2 °C	>150 d	Preserved phenolic compounds for long-term storage.	Requires precise control of gas levels to avoid quality deterioration.	(Bílková *et al*., 2020)
Pear (*Pyrus communis* L.)	1.0 % O_2 and 2.2 % O_2, ~0.05 % CO_2	8-10 months	Quality improved by 2.2 % O_2 for pears harvested at 48.01 N firmness, and by 1 % O_2 for those at 42.19 N firmness or lower.	Effectiveness of O_2 concentration varies with harvest firmness.	(Dong *et al*., 2023b)
Grape (*Vitis vinifera* L.)	6 % O_2, 10 % CO_2 95 % RH, 4 °C	42 d	Decreased weight loss, decay incidence, and ethylene production; maintained antioxidant activity, phenolic compounds, and firmness.	Requires careful monitoring to avoid excessive CO_2 damage.	(Shahkoomahally *et al*., 2021)

Table 2. Continued.

Product	Treatment	Storage time	Results	Limitations/notes	References
Dragon Fruit (*Selenicereus undatus* (Haw.) D.R. Hunt)	2 kPa O_2, 5 kPa CO_2 6 ± 0.5 °C	50 d	Maintained acidity and reduced scale yellowing.	Optimal conditions may vary with different dragon fruit varieties.	(Ho *et al*., 2021)
Cabbage (*Brassica oleracea* L.)	2 % O_2, 5 % CO_2 93 % RH, 0 °C	150 d	Reduced weight loss, trimming loss, and decay incidence; maintained pH, soluble solids, moisture, and reduced sugar content.	Long storage times require stringent control of environmental conditions.	(Choi *et al*., 2020)
Cabbage	2 % O_2, 2 % CO_2 95 % RH, 2 °C	100 d	Maintained vitamin C, total phenolics, and total glucosinolates; significantly inhibited total aerobic bacterial growth compared to control.	Requires optimization for different cabbage cultivars and storage conditions.	(Kang *et al*., 2019)
Beans (*Phaseolus vulgaris* L.)	1.5 kPa O_2, 9 kPa CO_2 40–60 % RH, 20 °C	180 d	Observed changes in galactose, starch, and sucrose pathways; no changes in amino acid or lipid metabolism.	Potential for physiological changes affecting long-term quality.	(Coelho *et al*., 2020)
Pecan nuts (*Carya illinoinensis* (Wangenh.) K.Koch)	2 kPa O_2 combined or not with CO_2 40 or 80 kPa 10 °C	12 months	Higher luminosity, lower acidity, TBARS, and peroxide than control; no significant differences were observed between 40 and 80 kPa CO_2.	Optimal CO_2 concentration requires further study for different nut varieties.	(Ribeiro *et al*., 2023)
Figs (*Ficus carica* L.)	3 % O_2, 15 % CO_2 90–95 % RH, 0 °C	28 d	Decreased respiration and decay rates; higher sugar and organic acid content compared to control.	Requires precise control of gas composition to avoid flavor and texture degradation.	(Dogan and Erkan, 2023)

To ensure the effectiveness of CAS, several factors must be taken into account, including the type of product (fruit species and cultivar), its climacteric behavior, storage temperature, stage of maturity, quality at harvest, pre-storage treatments, and gas concentrations (Valdez-Fragoso and Mújica-Paz, 2016). Like any postharvest technology, CAS can cause tissue damage under certain conditions, such as excessively low oxygen or excessively high carbon dioxide concentrations. When oxygen levels are too low, anaerobic respiration and fermentation are induced, leading to the formation of off-flavors and toxic compounds such as alcohols and aldehydes, which can ultimately cause tissue death. This process typically begins in the central part of the fruit (Ntsoane *et al*., 2019). Conversely, excessively high carbon dioxide levels can produce damage similar to chilling injury, including internal and surface browning, pitting, and tissue softening (DeEll *et al*., 2016).

Modified atmosphere packaging

The respiratory behavior of fresh postharvest commodities and the subsequent development of ripening and senescence are influenced by temperature, the atmosphere that surrounds the product during storage, and the concentration of gases that have a high effect on its metabolism, such as ethylene, water vapor, O_2, and CO_2 (Castellanos and Herrera, 2017). By regulating temperature and the gaseous composition of the atmosphere surrounding fruits and vegetables, it is possible to slow biochemical processes and thereby extend shelf life. Likewise, the growth and activity of microorganisms are strongly influenced by environmental conditions and can be controlled by modifying these parameters (del Valle *et al*., 2009; Sandhya, 2010; Caleb *et al*., 2012).

In modified atmosphere packaging (MAP), the food is packaged, and the gas composition inside is modified to specifically extend the product's shelf life. This modification can be achieved in two ways: in active MAP, the gas mixture is adjusted at the beginning of the packaging process, whereas in passive MAP, the internal atmosphere is altered over time through the natural respiration of the product and the selective permeability of the packaging film (Kirtil and Oztop, 2016).

Organoleptic characteristics are important in consumer purchasing decisions, and storage or packaging under modified atmospheres can significantly influence these attributes. (Thompson, 2015). During food distribution, temperature fluctuations commonly occur, and a modified atmosphere in packaged food can lead to excessive O_2 depletion and CO_2 accumulation, leading to metabolic disorders and reduced shelf life (Rodriguez-Aguilera *et al*., 2009). Adjusting moisture content, together with temperature control and a specific atmospheric composition, has proven effective in maintaining the quality of fruits and vegetables and extending their shelf life (Falagán and Terry, 2018).

Gas absorbents and release agents are added to the packaging bag to remove excessive ethylene, CO_2, and moisture. This allows for timely replenishment of O_2, maintaining a suitable gas environment for preservation. These technologies, known as active packaging, commonly incorporate antibacterial and deoxidizing agents such as chitosan and nisin. However, these chemicals may contaminate food during long-term storage, posing a risk to consumers' health (Chang *et al*., 2023). Active packaging can preserve the quality of food for an extended period, delay or prevent oxidative, microbial, and enzymatic spoilage, reduce contamination and weight loss, and preserve the color and texture during storage (Park *et al*., 2018).

When designing a MAP system, it is important to consider factors affecting both the metabolism of the produce and the permeability of the packaging to gases. These factors include the type of produce and its ripening stage, storage conditions, and specific characteristics of the packaging system. For the packaged product, it is important to determine its transpiration rate, oxygen consumption, and CO_2 and ethylene generation rates under the given packaging conditions. Additionally, identifying the optimal gas concentrations and relative humidity levels that enhance shelf life is necessary (Castellanos and Herrera, 2017) (Table 3).

Table 3. Recent research on modified atmosphere packaging (MAP) for fruit and vegetables: efficacy and limitations.

Product	Treatment	Storage time	Results	Limitations/Notes	References
Tomato (*Solanum lycopersicum* L.)	14.9–16.7 % O_2, 4.2–7.3 % CO_2 95 %, 4 °C	14 + 3–8 d at 20 °C	Reduced chilling injury and extended shelf life.	Temperature fluctuations can affect effectiveness.	(Park *et al*., 2018)
Mulberry (*Morus alba* L.)	10 % O_2, 5 % CO_2, 85 % Ar 90 ± 5 % relative humidity (RH), 4 ± 1 °C	12 d	Reduced weight loss, maintained juice content, and resulted in higher soluble solids content, but had no effect on sensory profile.	Requires precise control of gas composition.	(Tinebra *et al*., 2021)
Strawberry (*Fragaria × ananassa* Duch.)	5–10 % O_2, 10–15 % CO_2 90–95 % RH, 4 ± 1 °C	18 d	Decelerated chemical spoilage and controlled microbial spoilage.	Sensitivity to CO_2 levels may vary among different strawberry varieties.	(Kahramanoğlu, 2019)
Jujube (*Ziziphus jujuba* Lam.)	25 % O_2, 5 % CO_2 85 ± 5 % RH, 2 ± 1 °C	9 + 35 d of cold storage	Ineffective in maintaining weight and firmness, or reducing browning.	Not suitable for long-term storage without additional treatments.	(Moradinezhad and Dorostkar, 2021)
Pistachio (*Pistacia vera* L.)	10 % O_2, 90 % N_2 85–90 % RH, 5 °C	45 d	Reduced weight loss and aflatoxin production, and effectively controlled hull color deterioration.	Potential for uneven gas distribution within packaging.	(Rezaiyan Attar *et al*., 2023)
Lettuce (*Lactuca sativa* L.)	97 % N_2 and 3 % O_2. CO_2 90 % RH, 4 °C	20 d	Reduced respiration, transpiration, water loss, and deterioration.	Needs consistent temperature control to avoid spoilage.	(Soltani Firouz *et al*., 2021)
Tomato	10 % O_2, 10 % CO_2 91 % RH, 6 °C	21 d	Retarded color development, firmness loss, and decay.	Varietal differences may impact effectiveness.	(Olveira-Bouzas *et al*., 2021)
Mango (*Mangifera indica* L.)	7 % CO_2, 3 % O_2, 90 % N_2 13 ± 1 °C	30 d	Delayed pulp yellowing and biochemical changes, and maintained firmness and free moisture content.	High CO_2 concentrations can cause off-flavors.	(Wei *et al*., 2021)

Table 3. Continued.

Product	Treatment	Storage time	Results	Limitations/Notes	References
Wolfberry (*Lycium barbarum* L.)	5 % O_2, 10 % CO_2 0 ± 0.5 °C	28 d	Maintained physiological quality, and reduced weight loss, decay index, and color change.	Optimal conditions need to be determined for different storage durations.	(Liang *et al*., 2022)
Apricot (*Prunus armeniaca* L.)	40 % O_2, 20 % CO_2	6 + 28 d of cold storage	Decreased weight loss and total soluble solids, maintained hardness and chemical properties, but caused no signs of decay.	High oxygen levels may increase respiration rate.	(Dorostkar *et al*., 2022)
Lychee (*Litchi chinensis* Sonn.)	5 % O_2, 20 % CO_2, 75 % N_2 90 ± 5 % RH, 5 ± 1 °C	9 d	The treatment prevented browning, and maintained the pericarp color, vitamin content, flavor, and microbiological quality.	Prevented browning, maintained pericarp color, vitamin content, flavor, and microbiological quality.	(Passafiume *et al*., 2023)
Sweet cherry (*Prunus avium* L.)	5 % O_2, 10 % CO_2 80–85 % RH, -1 to +1 °C	120 d	Decreased decay rate, reduced polyphenol oxidase and peroxidase activity, and maintained firmness, nutrition, and taste.	Requires precise temperature control to prevent freeze damage.	(Xing *et al*., 2020)

Irradiation

Irradiation is a safe method in which food is exposed to radiation for a specific period to eliminate pathogenic microorganisms, parasites, and fungi. This technology helps prevent sprouting, delay ripening, eliminate insects, and sterilize products. Some advantages are its superior effectiveness to fungicides in the inactivation of pathogens and minimal or negligible sensory changes in the product. In addition, irradiation does not leave chemical residues in the product or make it radioactive and allows sterilization without contact. However, although irradiation is considered an energy-efficient and safe process for the consumer and the environment, there is still low acceptance of irradiated foods due to lack of consumer awareness. Other disadvantages include high capital costs, localized radiation hazards, and taste changes due to oxidation of lipids in the food (Jeong and Jeong, 2017; Bhatnagar *et al*., 2022).

Radiation can be either ionizing or non-ionizing, depending on the intensity of the energy transmitted. Non-ionizing radiation is a type of energy that can travel in space in the form of electromagnetic waves at a certain wavelength. This radiation comprises a portion of the electromagnetic spectrum from 1 to 3×10^{15} Hz, with a long wavelength (>100 nm) and low photon energy (<12.4 eV). It is only able to stimulate one molecule or atomic electron and is therefore not normally dangerous. Some sources of non-ionizing radiation are extremely low-frequency electromagnetic fields, radiofrequency, infrared, microwave, and ultraviolet, the latter being one of the most investigated radiations in postharvest of fruits and vegetables (Bisht *et al*., 2021).

Ultraviolet (UV) radiation lies outside the visible light spectrum and is classified as highly energetic non-ionizing radiation. It can be absorbed by microorganisms, where it induces biochemical alterations in enzymes or nucleic acids or activates specific molecules that form phototoxins, disrupting physiological processes. The effectiveness of UV radiation ranges from 89 to 99.999% against bacteria, fungi, and viruses, depending on factors such as microorganism type, radiation dose, exposure duration, and environmental conditions (Jalbout and Dgheim, 2019; Khan *et al*., 2022). Based on wavelength, UV radiation is divided into three regions: UV-C (200–280 nm, shortwave), UV-B (280–320 nm, medium wave), and UV-A (320–400 nm, longwave). In postharvest applications, UV-C treatment typically involves exposing produce to UV-C lamps emitting at 254 nm, the wavelength most effective in damaging microbial DNA. However, excessive exposure can compromise product quality, leading to surface damage such as browning or scorching (Murray *et al*., 2019).

Ionizing radiation, in contrast, possesses high energy, capable of removing electrons from atoms, thereby forming ions. This type of radiation is characterized by very short wavelengths and includes X-rays, gamma rays, and electron beams (Bisht *et al*., 2021). Ionizing radiation impacts microorganisms and food products with direct and indirect effects. The direct effect involves damage to cellular components, such as carbohydrates, lipids, and DNA. The indirect effect involves free radicals and reactive species, including hydroxyl radicals, hydrogen atoms, and hydroelectrons from water radiolysis, that react with cells and food components (Bhatnagar *et al*., 2022).

Several studies have demonstrated the effectiveness of irradiation as a postharvest treatment for food. UV-C radiation doses of 0.6–6 kJ m^{-2} reduced 2.2–3.1 and 2.3–3.5 log CFU per fruit, respectively, for cocktail mixtures of *Salmonella enterica* and *E. coli* O157:H7 on the surface of tomato (Mukhopadhyay *et al*., 2014). Similarly, strawberries treated with gamma irradiation at 1 and 1.5 kGy exhibited significantly extended storage lives (5.75 and 7.75 d, respectively) compared with non-irradiated controls (3.25 d), without altering key chemical quality parameters such as soluble solids, titratable acidity, or pH (Majeed *et al*., 2014). In the case of X-rays, exposure of whole melons to a 2 kGy dose achieved a 5-log CFU reduction across all tested pathogens (*E. coli* O157:H7, *L. monocytogenes*, *S. enterica*, and *Shigella flexneri*) without affecting the color or firmness of the fruits (Mahmoud, 2012).

Cold plasma

Plasma is an electrically neutral gas containing numerous ionized particles and can be artificially generated through energy sources such as electrical discharges, radio frequencies, or microwaves (Ekezie *et al*., 2017). Among novel postharvest technologies, cold plasma has shown high efficacy in sterilizing fruits and vegetables while maintaining or even improving their quality under certain conditions (Chen *et* *al*., 2020). Most studies have reported minimal or no impact on the physical, chemical, nutritional, and sensory attributes of different products, giving it a clear advantage over conventional heat treatments. Moreover, cold plasma is an affordable and eco-friendly technology (Pankaj *et al*., 2018).

Cold plasma was effective in inactivating microorganisms in blueberries but affected color and anthocyanins in treatments with longer exposure time (Lacombe *et al*., 2015). In strawberries, cold plasma caused a reduction in aerobic mesophilic bacteria, molds, and yeasts, while firmness, color, and respiration rate were not affected (Misra *et al*., 2014). Similarly, in cherry tomatoes, there was no effect on color, firmness, pH, and total soluble solids with cold plasma application, but there was a significant reduction in *E. coli* and *L. innocua*, as well as a decrease in mesophilic bacteria, molds, and yeasts (Ziuzina *et al*., 2016).

EDIBLE COATINGS AND FILMS

An edible coating is defined as a continuous matrix composed of edible and food-safe compounds that forms directly around the food and can be safely consumed by the consumer. These coatings are typically applied by dipping or spraying the product. In contrast, edible films or biofilms are thin layers usually pre-formed on plates or molds (casting method) or by extrusion, serving as the primary protective envelope for the food. Edible coatings and films extend the shelf life of foods by forming a semi-permeable barrier to water vapor and gases, which reduces weight loss and slows metabolic activity in fruits and vegetables. Additionally, these formulations can incorporate active substances, such as antioxidants and natural antimicrobial agents, helping to preserve food quality and safety throughout transport, marketing, and consumption (Pérez-Gago and Palou, 2016).

The main ingredients used in edible coating formulations are proteins (casein, soy protein, whey protein), polysaccharides (cellulose and its derivatives, starch, pectin, carrageenans, gums, chitosan), and lipids (fatty acids, mono- and diglycerides of fatty acids, natural waxes), either alone or in combinations (Bautista-Baños *et al*., 2017). In addition, certain food additives, such as plasticizers, emulsifiers, and active substances such as antioxidants, vitamins, and antimicrobial agents, can be added to formulations to improve the physical properties of formulations and enhance the microbiological, nutritional, and organoleptic properties of foods (Ansorena *et al*., 2018). The use of natural antimicrobials in both coatings and edible films, such as essential oils, chitosan, herbal extracts, plants, and spices, has been extensively studied for controlling microorganisms in food (Irkin and Esmer, 2015; Etxabide *et al*., 2017).

CONCLUSIONS

The deterioration of fruits and vegetables during the postharvest period depends on several physiological and environmental factors. The development of treatments and technologies complementary to refrigeration can prevent or delay physicochemical and microbiological deterioration. Ozone and electrolyzed water stand out for their effectiveness in eliminating microbes while remaining safe for consumers. Modified atmosphere packaging and edible coatings primarily preserve physicochemical and sensory quality, and when enriched with antimicrobial agents, they also enhance microbiological safety. Cold plasma has emerged as a promising technology, demonstrating strong activity against pathogenic bacteria and fungi with no negative impact on product quality. The effectiveness of any given approach depends on the fruit species and cultivar, its physiological condition at harvest, and storage conditions. Consequently, targeted studies are essential, particularly to assess the potential of emerging technologies for extending the shelf life of fresh produce.

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