American Journal of Biochemistry and Biotechnology

Review

Research Progress on Non-Thermophysical Fresh Keeping Technology of Fruits and Vegetables Based on Nutrition and Safety

[1]Shuai Han, [2]Hongfang Cai, [1]Youzhi Wu, [3]Haitao Yu and [1]Haihua Cong

[1]*College of Food and Drug, Shanghai Zhongqiao Vocational and Technical University, China*
[2]*College of Biology and Food Engineering, Changshu Institute of Technology, China*
[3]*College of Food Science and Technology, Nanjing Agricultural University, China*

Article history
Received: 05-09-2022
Revised: 18-11-2022
Accepted: 12-01-2023

Corresponding Author:
Hongfang Cai
College of Biology and Food Engineering, Changshu Institute of Technology, China
Email: caihongfang@cslg.edu.cn

And

Haihua Cong
College of Food and Drug, Shanghai Zhongqiao Vocational and Technical University, China
Email: conghh@shzq.edu.cn

Abstract: With the rapid development of the economy and the improvement of living standards, people not only have an increasing demand for fresh fruits and vegetables but also have become increasingly strict on the nutrition, safety, and quality of fruits and vegetables. However, the characteristics of high nutrition and high moisture make them easily susceptible to microbial infection, which can seriously reduce their nutritional value and economic value and even cause food safety problems. Therefore, from the perspective of nutrition and safety, this study examines the application and research of non-thermal physical preservation technologies, such as packaging, irradiation, and cold plasma, in the postharvest storage of fruits and vegetables, and forecasts the research and development trends of fruit preservation technology.

Keywords: Postharvest Preservation, Nutritional Value, Packaging, Irradiation, Cold Plasma

Introduction

Fruits and vegetables are widely loved by consumers because of their rich nutritional value and physiological effects. But harvested fruits and vegetables are still living organisms, carrying out necessary physiological metabolic processes. Moreover, affected by the environment and the nutrition and moisture of fruits and vegetables, post-harvest rot, quality deterioration, and microbial infection are easy to occur (Pinela and Ferreira, 2017; Nxumalo *et al*., 2021). According to the latest statistics from the food and agriculture organization of the United Nations (http://www.fao.org) (Fig. 1), global vegetable and fruit production rank fifth and seventh respectively. According to the annual data of the national bureau of statistics (https://data.stats.gov.cn), the total domestic output of vegetables and fruits in 2020 reached 749.129 and 286.9236 m tons in China respectively. According to the report of the 2018 China vegetable and fruit physical preservation and industrial chain value enhancement seminar, the fruit loss rate in developed countries is between 3-5%, while the postharvest fruit loss rate in China is as high as 20%, which seriously affects the economic value of fruits. Therefore, how to prolong the fresh keeping period of fruits and vegetables and maintain their high quality and safety is a hot topic for researchers engaged in postharvest preservation technology of fruits and vegetables.

Fruit and vegetable preservation technology can be divided into physical preservation, chemical preservation, and biological preservation. Traditional preservation techniques, such as heat treatment and chemical treatment, can provide effective preservation effects, but lead to the decline of fruit sensory quality and the loss of nutrients (Rawson *et al*., 2011). Moreover, heat treatment and chemical treatment cannot completely and effectively target all pathogenic microorganisms and the infection of microorganisms will bring danger and harm to human health and the social environment (Escalona *et al*., 2015). Hence, to meet the freshness, nutrition, and safety of fruits and vegetables, non-heat-treated fresh-keeping technology has been widely concerned and studied by scholars and enterprises. These non-thermal technologies, such as active packaging, irradiation, and cold plasma, are fantastic choices for the reason that they mitigate damage to the quality of fruits and vegetables (Hernández-Hernández *et al*., 2019). For instance, (Pace *et al*., 2020) demonstrated that active packaging containing oxalic acid significantly reduced respiration rate, leaf edge browning, and electrolyte leakage, preserving the visual quality of fresh cut lettuce. This study reviews the current application research progress of several types of non-thermal preservation technologies based on the premise of ensuring the freshness, safety, and nutrition of fruits and vegetables. It aims to provide scientific researchers with guidance for the research and development of non-thermal preservation technology, which could be employed by the fruit and vegetable industry for fresh market use and juice processing and help production practitioners to improve the fresh keeping effect of fruits and vegetables by using non-thermal fresh-keeping technology.

Packaging Technology

The packaging of food is not only conducive to prolonging the fresh-keeping period but also beneficial to the protection of food from the external environment in the process of market circulation. At the same time, with the development of science and technology, especially nanotechnology and artificial intelligence, environment friendly food packaging materials, and intelligent packaging have attracted more and more attention from researchers (Hannon *et al*., 2015).

Modified Atmosphere Packaging (MAP)

Fruits and vegetables are still complete organisms after harvest, undergoing respiratory metabolism and energy metabolism under normal environmental conditions. MAP inhibits the respiration rate of fruit by reducing the proportion of oxygen and increasing the proportion of carbon dioxide, thereby reducing the consumption rate of the substrate. Especially for climacteric fruits and vegetables, ethylene, as a plant hormone, plays a very important role in the ripening and aging process of fruits and vegetables. The hypoxic environment of MAP can significantly reduce the biosynthesis of ethylene, thereby delaying the ripening and senescence of fruits and vegetables and maintaining their higher nutritional value of fruits and vegetables (Sandhya, 2010).

Modified atmosphere packaging is widely used in the preservation of fresh fruits and vegetables or lightly processed fruits and vegetables to achieve the effect of extending shelf life and maintaining quality (Table 1). For different varieties, the changes in gas composition ratio will have different effects. As proof, Wang and Long (2014) showed that modified atmosphere packaging containing 1.8-8.0% O_2 reduced the respiration rate of cherries and the degradation of organic acids and effectively maintained the flavor of cherries; while Li *et al*. (2012) used MAP (O_2 80%) significantly increased the polyphenol content of pear fruit; (Oms-Oliu *et al*., 2008) used a high concentration of oxygen to inhibit the enzymatic reaction and maintain a higher fruit firmness of melon fruit. In addition, the effect of modified atmosphere packaging is also significantly related to the packaging material and storage temperature. The air permeability of packaging materials is an important factor affecting the effect of modified atmosphere packaging and the reason why the effect of modified atmosphere packaging is regulated by temperature is that it directly affects the metabolic rate of harvested vegetables (Zhang *et al*., 2016). Modified atmosphere packaging can not only affect the physiology of fruits and vegetables after harvest but also effectively prevent the infection and destruction of fruits and vegetables, such as mango (Poubol and Izumi, 2005), papaya (Waghmare and Annapure, 2013), strawberries (Van der Steen *et al*., 2002), etc., (Table 1).

Active Packaging (AP)

Active packaging refers to a packaging technology that adds auxiliary materials to the packaging system to improve the storage environment, thereby maintaining the quality and safety of food and extending its shelf life of food (Mihindukulasuriya and Lim, 2014). With the continuous research and development of active packaging technology, increasing numbers of researchers have begun to explore the application of active packaging in the preservation of fruits and vegetables (Table 2). Packaging made of Polypropylene/Ethylene Vinyl Alcohol (PP/EVOH) film containing essential oils can significantly restrain the growth and reproduction of pathogenic microorganisms Escherichia coli, Salmonella, and Listeria monocytogenes, thereby that can improve the safety of salad and extend its shelf life (Muriel-Galet *et al*., 2012). The Ag^+ based active membrane showed a significant inhibitory effect on the proliferation of acidophilic heat-resistant bacteria (Nobile *et al*., 2004). Li *et al*. (2011) developed a package prepared by coating PVC film with nano-ZnO powder, which can effectively suppress the browning rate of fresh-cut apples and maintain the quality better. It can be seen that active packaging can not only effectively maintain fruit quality, but also significantly inhibit microbial infection and delay fruit ripening and senescence.

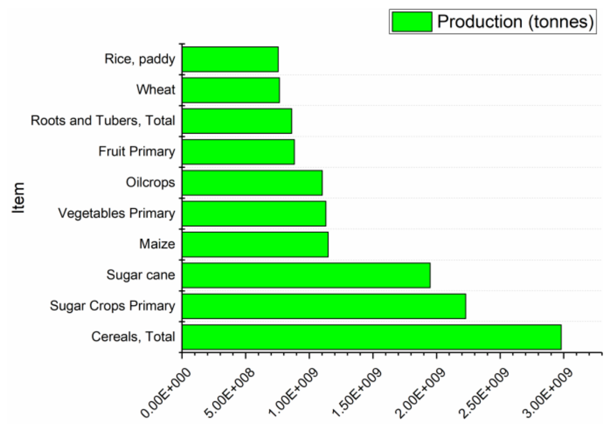

Fig. 1: Global production of major crops

Table 1: Application of MAP in the preservation of postharvest fruits and vegetables

Object	Technology	Optimal condition	Effects	Remaining nutritional value	References
Apple	MAP	Calcium ascorbate + MAP	Delay fruit ripening and senescence	Higher Vc content and antioxidant properties	Aguayo *et al*. (2010)
Mango	MAP	60 kPa O_2 5°C	Depressed breathing rate; inhibit browning	ns	Poubol and Izumi (2005)
Pear	MAP	80% O_2	Increase polyphenol content	Higher polyphenol	Li *et al*. (2012)
Tomato	MAP	10% O_2 +10% CO_2	Delayed color volution; reduced the firmness loss and decay rate	Slightly lower TSS and TA at end of storage; higher lycopene and β-carotene	Olveira-Bouzas *et al*., (2021)
Straw berry	MAP	5% O_2 +15% CO_2	Highest fruit firmness and the lowest weight loss;	TSS and TA are slightly higher then the control	Blaszczyk *et al*. (2022)
Pepper	MAP	MAP	Less fungal proliferation	ns	Frans *et al*. (2021)

Vc: Vitamin C/ascorbic acid; TSS: Total Soluble Solids; TA: Total Acid; kPa: Kilopascal; O_2: Oxygen; CO_2: Carbon dioxide; C_2H_4: Ethylene; ns: Not significant

Table 2: Application of AP in the preservation of postharvest fruits and vegetables

Object	Technology	Optimal condition	Effects	Remaining nutritional value	References
Straw berry	AP	Oxygen absorber	Hold fruit firmness; reduce rot rate	Higher TSS	Aday and Caner (2013)
Straw berry	AP	Oregano essential oil	Reduce respiration rate; maintain firmness	Higher TSS and TA	Li *et al*. (2020)
Grape	AP	EOs-β-cd inclusion Complex	Reduce weight loss, Microbial growth	Higher TA and TSS	Lopez-Gomez *et al*. (2020)
Nectarine	AP	EOs-β-cd inclusion complex	Higher hardness; better sensory quality	Higher TA and TSS	Lopez-Gomez *et al*. (2020)
Lettuce	AP	EOs-β-cd inclusion complex	Less weight loss; better sensory quality	Higher TA and TSS	Lopez-Gomez *et al*. (2020)

Absorber: Strong adsorption capacity for adsorbate
EOs-β-cd inclusion complex: β-cyclodextrin-essential oils inclusion complex

Although there has been a lot of research in the field of active packaging, only a few antibacterial and antioxidant packaging technologies have been put on the market and most of the research focuses on the screening of antibacterial and antioxidants.

Intelligent Packaging (IP)

Intelligent packaging is a packaging system with smart functions. It can assist in precise artificial control through functions such as detection, recording, tracking, feedback, and warning, to prolong the storage period of fruits and vegetables and maintain higher quality (Ahvenainen and Hurme, 1997). With the development of science and technology, new packaging systems have been rapidly developed and extensively studied. Mills and Hazafy (2008) developed a UV-B-activated oxygen indicator using nanoparticulate tin oxide as a Semiconductor Photosensitizer (SCP). In addition to chemical substances as receptors, some biosensors use biological materials as receptors, such as enzymes, antibodies, antigens, bacteriophages, and nucleic acids. Based on the principle of biosensors, SIRA technologies (USA) has developed a packaging barcode technology that alerts consumers or retailers if a product has been exposed to adverse conditions and poses a safety hazard (Ghaani *et al*., 2016). Based on the hydrolysis of esters, a ripeness indicator for aroma esters was developed for the first time by Hort Research (New Zealand) specifically for pears (Janjarasskul and Suppakul, 2018). At present, there are still huge challenges in the field of intelligent packaging. For example, there is a lack of indicators with high sensitivity and specificity and how to ensure their accuracy and stability.

Irradiation Technology

Irradiation technology, as a new type of physical non-thermal processing technology, mainly utilizes the radiation chemical and radiation microbiological effects produced by the radiation source, so as to achieve the purpose of sterilization, inhibition of germination, and delay of ripening and senescence of fruits and vegetables (Lung *et al*., 2015). Previous studies by some international authoritative institutions believed that irradiation technology can be used as a safe and efficient treatment method to replace the fumigation of chemical reagents for the preservation of fruits and vegetables (Pinela and Ferreira, 2017). With the rapid advancement of technology, the International Codex Alimentarius Commission (CAC) issued the "International General Standard for Irradiated Foods" and lifted the limit of the maximum absorbed dose of 10 kilograys (kGy) in food irradiation processing. Not only that, irradiation has the advantages of strong penetrating ability, easy control of the reaction, and simple processing flow, so it has great research value and application prospects. Tables 3-6 presents several examples of the application of irradiation techniques such as γ-ray irradiation, Electron Beam Irradiation (EBI), ultraviolet, Pulsed Light (PL), and cold plasma in the preservation of harvested vegetables.

Gamma Ray Irradiation

Ionizing radiation is to use of radiation sources of 60 cobalt (^{60}Co) or 137 cesium (^{137}Cs) to treat food or packaging materials to achieve the purpose of maintaining quality and prolonging the storage period. Among them, ^{60}Co-γ ray has the advantages of strong penetrating ability, uniform irradiation intensity, and operational reliability. Moreover, it is currently the most widely used irradiation processing technology at home and abroad.

Gamma-ray irradiation can effectively kill pathogenic microorganisms and prevent the infection of fruits and vegetables by microorganisms. The results of (Hussain *et al*., 2019) indicated that 0.9 kGy irradiation treatment can significantly inhibit the growth and reproduction of yeast and mold. Not only that, γ-ray irradiation can effectively delay the ripening and senescence of fruits and vegetables and significantly maintain their nutritional quality of fruits and vegetables (Table 3). Studies have shown that within a certain dose range, the respiration rate of postharvest fruits decreases with the increase of irradiation dose, which may be caused by the fact that irradiation reduces the activity of enzymes related to respiration and metabolism (Boynton *et al*., 2006). The results of (Maraei and Elsawy, 2017) illustrated that compared with the control, appropriate γ-ray irradiation effectively reduced the weight loss rate of strawberry fruit, maintained higher total phenolic content and antioxidant capacity, and thus maintained better nutritional quality. Through comparison, it is found that the optimal dose of γ-ray irradiation applied to fruits and vegetables of different species is different. The reason for this phenomenon mainly depends on the optimal dose that can be absorbed by fruits and vegetables and the absorbed dose is related to its quality, density and thickness, and other factors.

Electron Beam Irradiation (EBI)

Different from ionizing gamma rays with a radiation source, electron beam irradiation is to generate electron beams with a certain energy through an electron accelerator and then irradiates the object. Compared with γ-ray irradiation, electron beam irradiation has the following advantages: (1) No radioactive waste is generated and there is no hidden danger of environmental pollution; (2) The processing speed is fast and the product performance is less degraded; low cost to build and operate.

With the continuous development and improvement of electron beam irradiation technology, it has been widely used in many fields. It can be seen from Table 4 that electron beam irradiation can reduce microorganisms, reduce the loss of nutrients and maintain higher storage quality in fruits and vegetables. Schmidt *et al*. (2006) found that low-dose electron beam irradiation could significantly inhibit the reproduction of Salmonella in tomato fruit. The results of (Truc *et al*., 2021) showed that electron beam irradiation could defer the decline of firmness of postharvest mango, delay the increase of Total Soluble Solids (TSS) and stay the ripening and senescence of mango. Although there are many studies on the effect of EBI on the preservation of fruits and vegetables after harvest, a lot of research is needed on the response effect of specific quality parameters of fresh fruits and vegetables on the dose of EBI. At the same time, it is necessary to increase publicity and promotion work to promote the commercial application of this technology.

Ultraviolet (UV) and Pulsed Light (PL)

Ultraviolet rays are electromagnetic waves with frequencies between visible light and X-rays, with wavelengths ranging from 10 to 400 nm. According to the wavelength range, ultraviolet rays can be divided into low frequency long-wave ultraviolet (UV-A, wavelength 320 ~ 400 nm), intermediate frequency medium-wave ultraviolet (UV-B, wavelength 280 ~ 320 nm), high-frequency short wave ultraviolet (UV-C, Wavelength 100 ~ 280 nm) and ultra-high frequency ultraviolet (EUV, 10 ~ 100 nm). Among them, the main wavelength band that causes biological effects is short wave ultraviolet rays ranging from 100 to 280 nm. Syamaladevi *et al*. (2015) showed that UV-C irradiation treatment can effectively reduce the expansion of Penicillium on the surface of the apple, cherry, and strawberry fruits. In addition, UV-C treatment can effectively inhibit the production of tomato ethylene, delay the decline of firmness and then retard fruit ripening and senescence (Severo *et al*., 2015). It can be seen that UV-C irradiation can not only promote the resistance of fruits and vegetables to postharvest diseases but also effectively delay the ripening and senescence of fruits and vegetables.

Pulse strong light is the use of an inert gas discharge light source in the frequency range of 200 ~ 1100 nm to generate high power, short term strong broad-spectrum pulsed light radiation, also known as high-intensity pulsed ultraviolet light, strong light pulse, broad-spectrum white light, etc. In the field of food sterilization, a large number of studies have proved that pulsed light can effectively inactivate microorganisms. The research of (Aguiló-Aguayo *et al*., 2013) indicated that PL treatment effectively inhibited the nutrient loss of tomato fruit. Ramesh *et al*. (2012) found that PL treatment significantly increases the total phenolic content and antioxidant capacity of elderberry. Charles *et al*. (2013) showed that PL treatment resulted in higher firmness and flavonoid content in fresh cut mangoes, effectively delaying fruit softening and nutrient loss. At present, most of the research focuses on the study of PL treatment on the safety and nutritional quality of fruits and vegetables. However, the molecular regulation mechanism of PL in regulating the quality of fruits and vegetables needs to be further explored.

Cold Plasma (CP)

Plasma is the fourth state of matter after solid, liquid, and gas. When the applied voltage reaches the breakdown voltage, the gas molecules are ionized, resulting in a mixture of electrons, ions, atoms, and atomic groups. In the process of low-temperature plasma discharge, although the temperature of electrons is high, the temperature of heavy particles is very low and the whole system is in a low-temperature state, so it is called cold plasma, also called non-equilibrium plasma.

The generation of cold plasma mainly includes glow discharge, corona discharge, dielectric barrier discharge, radio frequency discharge, and other methods. The research of cold plasma technology has been greatly developed in the fields of semiconductors, the coal chemical industry, the synthesis of new substances and new materials, and the food industry. Cold plasma is rich in a mass of active substances, such as ions, electrons, molecules, and free radicals, which have the ability to kill microorganisms. The experimental result of (Yong *et al*., 2015) proved that CP treatment could effectively deal with Salmonella typhimurium, Escherichia coli, and Listeria on the surface of the cheese. The experimental result of (Tappi *et al*., 2019) found that CP treatment could effectively alleviate the browning of fresh cut apples. Wang and Long (2014) detected that CP can reduce the rot rate of blueberries and induce the activity of antioxidant enzymes in blueberries through its bactericidal effect, thereby improving the quality of blueberries during storage. Therefore, CP can not only effectively destroy pathogenic microorganisms on the surface of fruits and vegetables, but also significantly preserve the storage quality of fruits and vegetables (Table 7).

Table 3: Application of gamma irradiation in the preservation of postharvest fruits and vegetables

Object	Technology	Optimal condition	Effects	Remaining nutritional value	References
Grape	γ-ray	0.5-1.0 kGy (Helwani) 1.5-2.0 kGy (Baladi)	50% longer shelf-life	nm	Al-Bachir (1999)
Papaya	γ-ray	1.8-2.1 kGy	Curb corruption; extend shelf-life	Higher chlorophyll	Hussain *et al*. (2019)
Tomato	γ-ray	1-4 kGy	Lower weight loss	Higher TSS	Gyimah *et al*. (2020)
Jujube	γ-ray	1.0 kGy	Enhance antioxidant potential	Higher ascorbic acid and total phenol content	Jat *et al*. (2022)
Fresh-cut peach	γ-ray	up to 1.0 kGy	Extend shelf-life	ns	Colletti *et al*. (2022)
Pomegranate	γ-ray	1.0 kGy	Reduce the population of bacteria, fungi and yeasts; increase the shelf-life	ns	Ashtari *et al*. (2019)

kGy: Kilogray; nm: No mention

Table 4: Application of EBI in the preservation of postharvest fruits and vegetables

Object	Technology	Optimal condition	Effects	Remaining nutritional value	References
Mango	EBI	0.5 kGy	Inhibit chlorophyll degrading enzyme activity; enhance antioxidant capacity	Higher chlorophyll	Nguyen *et al*. (2021)
Mango	EBI	0.5 kGy	Alleviate disease; maintain quality	Higher TA; lower TSS	Truc *et al*. (2021)
Mango	EBI	0.5 kGy +13°C	higher firmness	Higher contents of cell wall polysaccharides; lower content of water-soluble pectin	Nguyen *et al*. (2021)
Kiwifruit	EBI	0.5 kGy +1°C	Keep higher quality	Higher TA, TSS, and Vc content	Zhou *et al*. (2015)
Kiwifruit	EBI	0.5 kGy +0-1°C	Higher firmness; improve activity of antioxidant enzymes;	Reduce the content of malondialdehyde lower TSS content	Li *et al*. (2021)
Straw berry	EBI	1.0 kGy +4°C	Reduce the population of fungi and the bacterial mesophilic; extend the shelf-life of up to 7 days	Lower total phenolic and total flavonoid contents	Barkaoui *et al*. (2021)

Table 5: Application of UV in the preservation of postharvest fruits and vegetables

Object	Technology	Optimal condition	Effects	Remaining nutritional value	References
Grape	UV-B	5.98, 9.66 kJ m^{-2} d^{-1}	Induction of phenol production	Higher levels of polyphenols	Martínez-Lüscher *et al*. (2014)
Straw berry	UV-C	4.1 kJ m^{-2}	Maintains hardness, inhibits mature aging	Less TSS and anthocyanins	Li *et al*. (2014)
Broccoli florets	UV-B	1.5 kJ m^{-2}	Delay the yellowing; increase antioxidant capacity	Higher indole-type glucosinolates and hydroxycinnamates contents	Duarte-Sierra *et al*. (2020)
Tomato	UV-A	6.0 kJ m^{-2}	Enhance antioxidant activity	Higher contents of total phenol	Dyshlyuk *et al*. (2020)
Sweet cherry	Chitosan + UV-B + UV-C	21.6 kJ m^{-2}	Reduce weight loss; highest fruit firmness	Higher vitamin C and total phenolic compounds	Abdipour *et al*. (2020)

Table 6: Application of PL in the preservation of postharvest fruits and vegetables

Object	Technology	Optimal condition	Effects	Remaining nutritional value	References
Fig	PL	90~300 s	Stimulates the accumulation of anthocyanins	of More anthocyanins	Rodov *et al*. (2012)
Tomato	PL	1~8 J cm^{-2}	Enhances antioxidant capacity	Higher contents of antioxidants	Pataro *et al*. (2015)
Persimmon	PL	2 J cm^{-2} or 6 J cm^{-2}	Provoke antioxidant capacity	No impact on TSS and vitamin C; higher contents of total phenols	Denoya *et al*. (2020)
Straw berry	PL	3 J cm^{-2}	Slightly reduce the level of Salmonella	Not significant	Cao *et al*. (2019)
Apricot	PL	200 J 60 s	Inhibit microbial growth; increase antioxidant capacity; reduce cell structure damage	Higher total phenols, total flavonoids	Hua *et al*. (2022)

Table 7: Application of cold plasma in the preservation of postharvest fruits and vegetables

Object	Technology	Optimal condition	Effects	Remaining nutritional value	References
Blueberry	CP	Spray volume 4 cfm, ambient air volume 7 cfm, working distance 7.5 cm, duration 60 s	Reduce rot rate and maintain a higher edible quality	ns	Lacombe *et al*. (2015)
Fresh-cut apple	CP	Plasma-activated water treatment with a sinusoidal voltage of 7.0 kHz and an the amplitude of 8 kV for 5 min	Inhibit the growth and reproduction of microorganism	ns	Liu *et al*. (2020)
Fresh-cut mango	CP	75 kV for 3 min using a Dielectric Barrier Discharge (DBD) generator	Inhibits the ROS generation and membrane lipid peroxidation and the growth of total microbial counts	Higher TSS, TA carotenoids	Yi *et al*. (2022)
Soybean sprouts	CP	cold-plasma-activated water	Sprout length and fresh weight increased by 41.07,11.24% respectively	Higher total amino acid and contents of isoflavone	Ji *et al*. (2022)

Summary and Outlook

With rapid economic and social development, people's demand for fresh fruits and vegetables is increasing. However, issues such as food safety and postharvest quality have seriously affected the circulation and economic value of harvested fruits and vegetables. On the premise of ensuring food safety, the non-thermophysical fresh keeping technology not only holds the better sensory quality and nutritional value of the harvested vegetables but also effectively postpones their maturity and aging. Based on the characteristics of safety, efficient and green non-thermal physical preservation technology has received extensive attention. However, the vast majority of studies mainly discuss its effects on the physiological quality and fresh-keeping effect of post-harvest fruits and vegetables. In the future, the following aspects should be strengthened: (1) To explore the combined application of various non-thermophysical fresh-keeping technologies on the quality and preservation of post-harvest fruits. (2) From the perspective of transcriptional regulation, the molecular mechanism of preservation technology to maintain postharvest fruit quality and delay ripening and senescence was explored; (3) Based on the latest scientific research results, develop non-thermal Physical preservation equipment, accelerate the transformation of scientific and technological achievements and significantly improve the market circulation and economic value of fresh fruits and vegetables.

Funding Information

This study was supported by the "Chen Guang" project supported by the shanghai municipal education commission and shanghai education development foundation (19CGB26), The natural science foundation of the Jiangsu higher education institutions of China (22KJD550001), and Class B funding of shanghai municipal savings plan (2022).

Author's Contributions

Shuai Han: Initiated the concept of the article and wrote.

Hongfang Cai: Initiated the concept of the article and contributed to the summary and outlook.

Youzhi Wu and Haitao Yu: Contributed to the proofread of the manuscript.

Haihua Cong: Provided modification suggestions and polished the manuscript.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues are involved.

References

Abdipour, M., Malekhossini, P. S., Hosseinifarahi, M., & Radi, M. (2020). Integration of UV irradiation and chitosan coating: A powerful treatment for maintaining the postharvest quality of sweet cherry fruit. *Scientia Horticulturae*, 264. https://doi.org/10.1016/j.scienta.2020.109197

Aday, M. S., & Caner, C. (2013). The shelf-life extension of fresh strawberries using an oxygen absorber in the biobased package. *LWT-Food Science and Technology*, *52*(2), 102-109. https://doi.org/10.1016/j.lwt.2012.06.006

Aguayo, E., Requejo-Jackman, C., Stanley, R., & Woolf, A. (2010). Effects of calcium ascorbate treatments and storage atmosphere on antioxidant activity and quality of fresh-cut apple slices. *Postharvest Biology and Technology*, *57*(1), 52-60. https://doi.org/10.1016/j.postharvbio.2010.03.001

Aguiló-Aguayo, I., Charles, F., Renard, C. M., Page, D., & Carlin, F. (2013). Pulsed light effects on surface decontamination, physical qualities and nutritional composition of tomato fruit. *Postharvest Biology and Technology*, *86*, 29-36. https://doi.org/10.1016/j.postharvbio.2013.06.011

Ahvenainen, R., & Hurme, E. (1997). Active and smart packaging for meeting consumer demands for quality and safety. *Food Additives & Contaminants*, *14*(6-7), 753-763. https://doi.org/10.1080/02652039709374586

Al-Bachir, M. (1999). Effect of gamma irradiation on storability of two cultivars of Syrian grapes (Vitis vinifera). *Radiation Physics and Chemistry*, *55*(1), 81-85. https://doi.org/10.1016/S0969-806X(98)00295-3

Ashtari, M., Khademi, O., Soufbaf, M., Afsharmanesh, H., & Sarcheshmeh, M. A. A. (2019). Effect of gamma irradiation on antioxidants, microbiological properties and shelf-life of pomegranate arils cv. 'Malas Saveh'. *Scientia Horticulturae*, 244, 365-371. https://doi.org/10.1016/j.scienta.2018.09.067

Barkaoui, S., Mankai, M., Miloud, N. B., Kraiem, M., Madureira, J., Verde, S. C., & Boudhrioua, N. (2021). E-beam irradiation of strawberries: Investigation of microbiological, physicochemical, sensory acceptance properties and bioactive content. *Innovative Food Science & Emerging Technologies*, 73. https://doi.org/10.1016/j.ifset.2021.102769

Blaszczyk, J., Bieniasz, M., Nawrocki, J., Kopec, M., Mierzwa-Hersztek, M., Gondek, K., . . . Bogdal, S. (2022). The effect of harvest date and storage conditions on the quality of remontant strawberry cultivars grown in a gutter system under covers. *Agriculture-Basel*, 12(8). https://doi.org/10.3390/agriculture12081193

Boynton, B. B., Welt, B. A., Sims, C. A., Balaban, M. O., Brecht, J. K., & Marshall, M. R. (2006). Effects of low dose electron beam irradiation on respiration, microbiology, texture, color and sensory characteristics of fresh cut cantaloupe stored in modified-atmosphere packages. *Journal of Food Science*, *71*(2), S149-S155. https://doi.org/10.1111/j.1365-2621.2006.tb08918.x

Cao, X. N., Huang, R. Z., & Chen, H. Q. (2019). Evaluation of Food Safety and Quality Parameters for Shelf-Life Extension of Pulsed Light Treated Strawberries. *Journal of Food Science, 84*(6), 1494-1500. https://doi.org/10.1111/1750-3841.14613

Charles, F., Vidal, V., Olive, F., Filgueiras, H., & Sallanon, H. (2013). Pulsed light treatment as new method to maintain physical and nutritional quality of fresh-cut mangoes. *Innovative Food Science & Emerging Technologies*, *18*, 190-195. https://doi.org/10.1016/j.ifset.2013.02.004

Colletti, A. C., Denoya, G. I., Budde, C. O., Gabilondo, J., Pachado, J. A., Vaudagna, S. R., & Polenta, G. A. (2022). Induction of stress defense response and quality retention in minimally processed peaches through the application of gamma irradiation treatments. *Postharvest Biology and Technology, 194*. https://doi.org/10.1016/j.postharvbio.2022.112084

Denoya, G. I., Pataro, G., & Ferrari, G. (2020). Effects of postharvest pulsed light treatments on the quality and antioxidant properties of persimmons during storage. *Postharvest Biology and Technology, 160*. https://doi.org/10.1016/j.postharvbio.2019.111055

Duarte-Sierra, A., Hasan, S. M. M., Angers, P., & Arul, J. (2020). UV-B radiation hormesis in broccoli florets: Glucosinolates and hydroxy-cinnamates are enhanced by UV-B in florets during storage. *Postharvest Biology and Technology, 168*. https://doi.org/10.1016/j.postharvbio.2020.111278

Dyshlyuk, L., Babich, O., Prosekov, A., Ivanova, S., Pavsky, V., & Chaplygina, T. (2020). The effect of postharvest ultraviolet irradiation on the content of antioxidant compounds and the activity of antioxidant enzymes in tomato. *Heliyon, 6*(1). https://doi.org/10.1016/j.heliyon.2020.e03288

Escalona, V. H., Hinojosa, A., Char, C., Villena, P., Bustamante, A., & Saenz, C. (2015). Use of alternative sanitizers on minimally processed watercress harvested in two different seasons. *Journal of Food Processing and Preservation*, *39*(6), 1287-1298. https://doi.org/10.1111/jfpp.12347

Frans, M., Aerts, R., Ceusters, N., Luca, S., & Ceusters, J. (2021). Possibilities of modified atmosphere packaging to prevent the occurrence of internal fruit rot in bell pepper fruit (Capsicum annuum) caused by *Fusarium* spp. *Postharvest Biology and Technology, 178*. https://doi.org/10.1016/j.postharvbio.2021.111545

Ghaani, M., Cozzolino, C. A., Castelli, G., & Farris, S. (2016). An overview of the intelligent packaging technologies in the food sector. *Trends in Food Science & Technology*, *51*, 1-11. https://doi.org/10.1016/j.tifs.2016.02.008

Gyimah, L. A., Amoatey, H. M., Boatin, R., Appiah, V., & Odai, B. T. (2020). The impact of gamma irradiation and storage on the physicochemical properties of tomato fruits in Ghana. *Food Quality and Safety, 4*(3), 151-157. https://doi.org/10.1093/fqsafe/fyaa017

Hannon, J. C., Kerry, J., Cruz-Romero, M., Morris, M., & Cummins, E. (2015). Advances and challenges for the use of engineered nanoparticles in food contact materials. *Trends in Food Science & Technology*, *43*(1), 43-62. https://doi.org/10.1016/j.tifs.2015.01.008

Hernández-Hernández, H. M., Moreno-Vilet, L., & Villanueva-Rodríguez, S. J. (2019). Current status of emerging food processing technologies in Latin America: Novel non-thermal processing. *Innovative Food Science & Emerging Technologies*, *58,* 102233. https://doi.org/10.1016/j.ifset.2019.102233

Hua, X. W., Li, T. T., Wu, C. E., Zhou, D. D., Fan, G. J., Li, X. J., . . . Wu, Z. H. (2022). Novel physical treatments (Pulsed light and cold plasma) improve the quality of postharvest apricots after long-distance simulated transportation. *Postharvest Biology and Technology, 194*. https://doi.org/10.1016/j.postharvbio.2022.112098

Hussain, P. R., Rather, S. A., Suradkar, P. P., & Ayob, O. (2019). Gamma irradiation treatment of quince fruit (*Cydonia oblonga* Mill): Effect on post-harvest retention of storage quality and inhibition of fungal decay. *Journal of Radiation Research and Applied Sciences*, *12*(1), 118-131. https://doi.org/10.1080/16878507.2019.1618588

Janjarasskul, T., & Suppakul, P. (2018). Active and intelligent packaging: The indication of quality and safety. *Critical Reviews in Food Science and Nutrition*, *58*(5), 808-831. https://doi.org/10.1080/10408398.2016.1225278

Jat, L., Lakhawat, S. S., Singh, V., Meena, R., Choudhary, J. L., & Gathala, S. (2022). Postharvest gamma-irradiation treatment enhance nutritional and antioxidant potential of Indian jujube (*Ziziphus mauritiana* Lamk) fruit. *Scientia Horticulturae*(301-), 301. https://doi.org/10.1016/j.scienta.2022.111127

Ji, W. M., Li, M., Yang, T. B., Li, H. Y., Li, W. X., Wang, J., & Ma, M. (2022). Effect of cold plasma on physical-biochemical properties and nutritional components of soybean sprouts. *Food Research International, 161*. https://doi.org/10.1016/j.foodres.2022.111766

Lacombe, A., Niemira, B. A., Gurtler, J. B., Fan, X., Sites, J., Boyd, G., & Chen, H. (2015). Atmospheric cold plasma inactivation of aerobic microorganisms on blueberries and effects on quality attributes. *Food Microbiology*, *46,* 479-484. https://doi.org/10.1016/j.fm.2014.09.010

Li, D., Luo, Z., Mou, W., Wang, Y., Ying, T., & Mao, L. (2014). ABA and UV-C effects on quality, antioxidant capacity and anthocyanin contents of strawberry fruit (*Fragaria ananassa* Duch.). *Postharvest Biology and Technology*, *90*, 56-62. https://doi.org/10.1016/j.postharvbio.2013.12.006

Li, L., Song, W., Shen, C., Dong, Q., Wang, Y., & Zuo, S. (2020). Active packaging film containing oregano essential oil microcapsules and their application for strawberry preservation. *Journal of Food Processing and Preservation*. https://doi.org/10.1111/jfpp.14799

Li, R. J., Yang, S. X., Wang, D., Liang, J., Huang, T. Z., Zhang, L., & Luo, A. W. (2021). Electron-beam irradiation delayed the postharvest senescence of kiwifruit during cold storage through regulating the reactive oxygen species metabolism. *Radiation Physics and Chemistry, 189*. https://doi.org/10.1016/j.radphyschem.2021.109717

Li, W. L., Li, X. H., Fan, X., Tang, Y., & Yun, J. (2012). Response of antioxidant activity and sensory quality in fresh-cut pear as affected by high O_2 active packaging in comparison with low O_2 packaging. *Food Science and Technology International, 18*(3), 197-205. https://doi.org/10.1177/1082013211415147

Li, X., Li, W., Jiang, Y., Ding, Y., Yun, J., Tang, Y., & Zhang, P. (2011). Effect of nano-ZnO-coated active packaging on quality of fresh-cut 'Fuji'apple. *International Journal of Food Science & Technology*, *46*(9), 1947-1955. https://doi.org/10.1111/j.1365-2621.2011.02706.x

Liu, C., Chen, C., Jiang, A., Sun, X., Guan, Q., & Hu, W. (2020). Effects of plasma-activated water on microbial growth and storage quality of fresh-cut apple. *Innovative Food Science & Emerging Technologies, 59,* 102256. https://doi.org/10.1016/j.ifset.2019.102256

Lopez-Gomez, A., Ros-Chumillas, M., Buendia-Moreno, L., & Martinez-Hernandez, G. B. (2020). Active cardboard packaging with encapsulated essential oils for enhancing the shelf life of fruit and vegetables. *Frontiers in Nutrition, 7*. https://doi.org/10.3389/fnut.2020.559978

Lung, H. M., Cheng, Y. C., Chang, Y. H., Huang, H. W., Yang, B. B., & Wang, C. Y. (2015). Microbial decontamination of food by electron beam irradiation. *Trends in Food Science & Technology*, *44*(1), 66-78. https://doi.org/10.1016/j.tifs.2015.03.005

Maraei, R. W., & Elsawy, K. M. (2017). Chemical quality and nutrient composition of strawberry fruits treated by γ-irradiation. *Journal of Radiation Research and Applied Sciences*, *10*(1), 80-87. https://doi.org/10.1016/j.jrras.2016.12.004

Martínez-Lüscher, J., Torres, N., Hilbert, G., Richard, T., Sánchez-Díaz, M., Delrot, S., ... & Gomès, E. (2014). Ultraviolet-B radiation modifies the quantitative and qualitative profile of flavonoids and amino acids in grape berries. *Phytochemistry*, *102*, 106-114. https://doi.org/10.1016/j.phytochem.2014.03.014

Mihindukulasuriya, S. D. F., & Lim, L. T. (2014). Nanotechnology development in food packaging: A review. *Trends in Food Science & Technology*, *40*(2), 149-167. https://doi.org/10.1016/j.tifs.2014.09.009

Mills, A., & Hazafy, D. (2008). A solvent-based intelligence ink for oxygen. *Analyst*, *133*(2), 213-218. https://doi.org/10.1039/B713450A

Muriel-Galet, V., Cerisuelo, J. P., López-Carballo, G., Lara, M., Gavara, R., & Hernández-Muñoz, P. (2012). Development of antimicrobial films for microbiological control of packaged salad. *International Journal of Food Microbiology*, *157*(2), 195-201. https://doi.org/10.1016/j.ijfoodmicro.2012.05.002

Nguyen, T. T., Uthairatanakij, A., Srilaong, V., Laohakunjit, N., Kato, M., & Jitareerat, P. (2021). Impact of electron beam irradiation on the chlorophyll degradation and antioxidant capacity of mango fruit. *Applied Biological Chemistry*, *64*(1), 1-13. https://doi.org/10.1186/s13765-021-00592-8

Nobile, M. D., Cannarsi, M., Altieri, C., Sinigaglia, M., Favia, P., Iacoviello, G., & D'agostino, R. (2004). Effect of Ag-containing nano-composite active packaging system on survival of Alicyclobacillus acidoterrestris. *Journal of Food Science*, *69*(8), E379-E383. https://doi.org/10.1111/j.1365-2621.2004.tb09899.x

Nxumalo, K. A., Aremu, A. O., & Fawole, O. A. (2021). Potentials of medicinal plant extracts as an alternative to synthetic chemicals in postharvest protection and preservation of horticultural crops: A review. *Sustainability*, *13*(11), 5897. https://doi.org/10.3390/su13115897

Olveira-Bouzas, V., Pita-Calvo, C., Vazquez-Oderiz, M. L., & Romero-Rodriguez, M. A. (2021). Evaluation of a modified atmosphere packaging system in pallets to extend the shelf-life of the stored tomato at cooling temperature. *Food Chemistry, 364*. https://doi.org/10.1016/j.foodchem.2021.130309

Oms-Oliu, G., Martínez, R. R. M., Soliva-Fortuny, R., & Martín-Belloso, O. (2008). Effect of superatmospheric and low oxygen modified atmospheres on shelf-life extension of fresh-cut melon. *Food Control*, *19*(2), 191-199. https://doi.org/10.1016/j.foodcont.2007.03.009

Pace, B., Capotorto, I., Palumbo, M., Pelosi, S., & Cefola, M. (2020). Combined effect of dipping in oxalic or in citric acid and low O_2 modified atmosphere, to preserve the quality of fresh cut lettuce during storage. *Foods*, *9*(8), 988. https://doi.org/10.3390/foods9080988

Pataro, G., Sinik, M., Capitoli, M. M., Donsì, G., & Ferrari, G. (2015). The influence of post-harvest UV-C and pulsed light treatments on quality and antioxidant properties of tomato fruits during storage. *Innovative Food Science & Emerging Technologies*, *30*, 103-111. https://doi.org/10.1016/j.ifset.2015.06.003

Pinela, J., & Ferreira, I. C. (2017). Non-thermal physical technologies to decontaminate and extend the shelf-life of fruits and vegetables: Trends aiming at quality and safety. *Critical Reviews in Food Science and Nutrition*, *57*(10), 2095-2111. https://doi.org/10.1080/10408398.2015.1046547

Poubol, J., & Izumi, H. (2005). Physiology and microbiological quality of fresh-cut mango cubes as affected by high-O_2 controlled atmospheres. *Journal of Food Science*, *70*(6), m286-m291. https://doi.org/10.1111/j.1365-2621.2005.tb11448.x

Ramesh, M., Valérie, O., & Mark, L. (2012). Effect of pulsed ultraviolet light on the total phenol content of elderberry (*Sambucus nigra*) fruit. *Food and Nutrition Sciences*, *2012*. https://doi.org/10.4236/fns.2012.36104

Rawson, A., Patras, A., Tiwari, B. K., Noci, F., Koutchma, T., & Brunton, N. (2011). Effect of thermal and non-thermal processing technologies on the bioactive content of exotic fruits and their products: Review of recent advances. *Food Research International*, *44*(7), 1875-1887. https://doi.org/10.1016/j.foodres.2011.02.053

Rodov, V., Vinokur, Y., & Horev, B. (2012). Brief postharvest exposure to pulsed light stimulates coloration and anthocyanin accumulation in fig fruit (*Ficus carica* L.). *Postharvest Biology and Technology*, *68*, 43-46. https://doi.org/10.1016/j.postharvbio.2012.02.001

Sandhya. (2010). Modified atmosphere packaging of fresh produce: Current status and future needs. *LWT-Food Science and Technology*, *43*(3), 381-392. https://doi.org/10.1016/j.lwt.2009.05.018

Schmidt, H. M., Palekar, M. P., Maxim, J. E., & Castillo, A. (2006). Improving the microbiological quality and safety of fresh-cut tomatoes by low-dose electron beam irradiation. *Journal of Food Protection*, *69*(3), 575-581. https://doi.org/10.4315/0362-028X-69.3.575

Severo, J., Tiecher, A., Pirrello, J., Regad, F., Latché, A., Pech, J. C., ... & Rombaldi, C. V. (2015). UV-C radiation modifies the ripening and accumulation of ethylene response factor (ERF) transcripts in tomato fruit. *Postharvest Biology and Technology*, *102,* 9-16. https://doi.org/10.1016/j.postharvbio.2015.02.001

Syamaladevi, R. M., Adhikari, A., Lupien, S. L., Dugan, F., Bhunia, K., Dhingra, A., & Sablani, S. S. (2015). Ultraviolet-C light inactivation of Penicillium expansum on fruit surfaces. *Food Control*, *50*, 297-303. https://doi.org/10.1016/j.foodcont.2014.09.006

DOI: 10.3844/ajbbsp.2023.55.64

Tappi, S., Ragni, L., Tylewicz, U., Romani, S., Ramazzina, I., & Rocculi, P. (2019). Browning response of fresh cut apples of different cultivars to cold gas plasma treatment. *Innovative Food Science & Emerging Technologies*, *53*, 56-62. https://doi.org/10.1016/j.ifset.2017.08.005

Truc, N. T., Uthairatanakij, A., Srilaong, V., Laohakunjit, N., & Jitareerat, P. (2021). Effect of electron beam radiation on disease resistance and quality of harvested mangoes. *Radiation Physics and Chemistry*, *180*, 109289. https://doi.org/10.1016/j.radphyschem.2020.109289

Van der Steen, C., Jacxsens, L., Devlieghere, F., & Debevere, J. (2002). Combining high oxygen atmospheres with low oxygen modified atmosphere packaging to improve the keeping quality of strawberries and raspberries. *Postharvest Biology and Technology*, *26*(1), 49-58. https://doi.org/10.1016/S0925-5214(02)00005-4

Waghmare, R. B., & Annapure, U. S. (2013). Combined effect of chemical treatment and/or Modified Atmosphere Packaging (MAP) on quality of fresh-cut papaya. *Postharvest Biology and Technology*, *85*, 147-153. https://doi.org/10.1016/j.postharvbio.2013.05.010

Wang, Y., & Long, L. E. (2014). Respiration and quality responses of sweet cherry to different atmospheres during cold storage and shipping. *Postharvest Biology and Technology*, *92*, 62-69. https://doi.org/10.1016/j.postharvbio.2014.01.003

Yi, F., Wang, J. M., Xiang, Y., Yun, Z., Pan, Y. G., Jiang, Y. M., & Zhang, Z. K. (2022). Physiological and quality changes in fresh-cut mango fruit as influenced by cold plasma. *Postharvest Biology and Technology, 194*. https://doi.org/10.1016/j.postharvbio.2022.112105

Yong, H. I., Kim, H. J., Park, S., Alahakoon, A. U., Kim, K., Choe, W., & Jo, C. (2015). Evaluation of pathogen inactivation on sliced cheese induced by encapsulated atmospheric pressure dielectric barrier discharge plasma. *Food Microbiology*, *46*, 46-50. https://doi.org/10.1016/j.fm.2014.07.010

Zhang, M., Meng, X., Bhandari, B., & Fang, Z. (2016). Recent developments in film and gas research in modified atmosphere packaging of fresh foods. *Critical Reviews in Food Science and Nutrition*, *56*(13), 2174-2182. https://doi.org/10.1080/10408398.2013.819794

Zhou, H., Ye, Z., & Shi, C. (2015). Effects of high-energy electron irradiation on the preservation of kiwifruit. *China Agricultural Science Bulletin*, *31*, 133-138.