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Preserving freshness: innovations for fresh-eating fruit distribution and damage prevention - A review

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Abstract: The preservation of fresh-eating fruit within the supply chain is of paramount for maintaining freshness and minimizing resource waste. This article elucidates a comprehensive and integrated approach to fruit loss prevention and preservation techniques which collectively can substantially prolong the shelf life of fresh-eating fruits across various supply chain contexts. Here we show that the proposed solution emphasizes the development of real-time damage monitoring systems, innovative sensors for fruit freshness detection, and predictive methods for quality degradation and estimating shelf life. Additionally, we advocate for fundamental research to support the creation of smart, lightweight, sustainable, shockproof packaging systems. These packaging systems aim to utilize recyclable and biodegradable materials, contributing to environmental sustainability. In conclusion, this study establishes a scientific foundation for innovative solutions in the preservation and damage avoidance of fresh-eating fruits within the supply chain. By considering diverse factors and proposing a holistic approach, we anticipate substantial advancements in preserving the freshness of fruits.

Keywords: Fresh fruit, Packaging, Mechanical damage, Fruit quality, Sustainability

1 Introduction

Fruits, contributing a staggering 887 million metric tons annually to the global economy and diets worldwide, are categorized into fresh and dried types. Fresh fruits can be categorized into those intended for immediate post-harvest consumption and those subjected to subsequent processing. The former category, including tomatoes, peaches, and strawberries, encompasses vital bioactive compounds such as vitamins, polyphenols, and trace elements that play a significant role in influencing human health (Liu et al., 2023a). Research reveals the health advantages of daily fresh fruit intake, linking it to improved glycemic control in diabetics (Wu et al., 2022) and reduced cardiovascular risks, with a 40% decrease in cardiovascular death and a 34% drop in coronary events (Du et al., 2016). For instance, studies have highlighted the cardioprotective effects of polyphenol-rich *Musa balbisiana*, commonly known as banana (Kumari et al., 2020).

However, maintaining the quality of fresh fruits throughout the supply chain remains a significant challenge (Al-Dairi et al., 2022). Post-harvest activities, including picking, cleaning, packaging, and transportation, greatly impact fruit quality, particularly for climacteric fruits, which exhibit increased respiration rates post-harvest, influencing their shelf life (Zhang et al., 2023). The variance in respiration patterns distinguishes fruits into climacteric and non-climacteric types. Climacteric fruits, such as bananas and apples, exhibit a notable increase in respiration post-harvest, often accompanied by a surge in ethylene production, which significantly influences their subsequent ripening process (Zhu et al., 2020).

In addition to the challenges posed by post-harvest handling, environmental factors also play a significant role in the preservation of fresh fruits. Climate conditions during cultivation and storage greatly impact fruit quality and shelf life, with temperature and humidity levels being key determinants (Alam et al., 2023; Lufu et al., 2020). Extreme temperatures can accelerate ripening processes or induce chilling injury, while improper humidity levels can lead to moisture loss or promote mold growth (Al-Dairi et al., 2023). Furthermore, exposure to ethylene gas, whether from natural sources or artificial sources, can hasten fruit ripening and senescence, necessitating meticulous control measures throughout the supply chain (Shah et al., 2023). Understanding the complex interplay between environmental factors and fruit physiology is critical for developing effective preservation strategies that mitigate quality degradation and ensure consumer satisfaction.

Similarly, the uneven global distribution of fresh fruits necessitates cross-regional transport to meet diverse consumer demands, yet this journey often causes mechanical damage, affecting up to 30% of soft fresh fruits (Opara and Fadiji, 2018). Long-distance transportation can lead to tissue softening, nutrient loss, and wilting, further impacting fruit quality (Hua et al., 2023).

To address these challenges, this paper aims to comprehensively review literature on damage prevention techniques and preservation technologies throughout the supply chain. It seeks to delve into existing strategies for safeguarding the quality and freshness of fresh-eating fruits during transportation and storage. Additionally, it aims to outline future research directions to enhance the longevity and quality maintenance of fresh fruits.

2 Critical factors affecting fruit freshness

Post-harvest, fruits, as living tissues, undergo a continuum of physiological and biochemical transformations involving respiration-both aerobic and anaerobic-alongside ethylene emission and transpiration processes (Li et al., 2020). These intricate changes significantly influence enzyme activity, antioxidant capacity, flavor profile, and visual appearance of the fruit.

These alterations are governed by a multitude of factors, both intrinsic and extrinsic (as illustrated in Fig. 1). Intrinsic factors, encompassing fruit varieties, ripening stages, and harvest seasons, interplay with extrinsic elements such as temperature, humidity, and storage conditions. The collective impact of these factors contributes to pulp tissue softening, oxidative browning, nutrient depletion, and alterations in taste, presenting considerable obstacles for consumers in selecting fresh fruits (Strouwen et al., 2022).

Localized mechanical damage further exacerbates post-harvest physiological and biochemical changes including tissue browning, reduction in antioxidant enzyme activity, and acceleration of the oxidative degradation of lipid membranes. These effects manifest as a dulled surface luster and nutrient loss in fresh fruits (Pathare and Al-Dairi, 2021). Moreover, mechanical damage can disrupt cell integrity, leading to increased susceptibility to pathogen invasion and decay, thereby shortening shelf life and compromising fruit quality (Li et al., 2024). The presence of bruises, cuts, or punctures detracts from the visual appeal of fruit and serves as an entry point for microbial spoilage, hastening deterioration and rendering fruit unfit for consumption (Alegbeleye et al., 2022). A summary of the physiological and biochemical indices affected by mechanical damage in fresh fruits is presented in Table 1.

2.1 Respiration

Post-harvest, fresh fruits undergo respiration, a critical process that drives physiological metabolism (Zhang et al., 2022). Respiration serves as a constant energy source, facilitating biochemical reactions within living tissues. Fruits with heightened respiration undergo accelerated energy expenditure, hastening the depletion of stored starch or sugars, resulting in nutrient loss and decay (Xylia et al., 2022).

Climacteric fruits exhibit a surge in respiration rate during ripening, reaching a peak before declining, while non-climacteric fruits manifest a consistent decline in respiration throughout growth and maturation (Liu et al., 2023b). Aerobic respiration of organic compounds yields CO_2, H_2O, and substantial energy, while anaerobic conditions foster nutrient breakdown into metabolites like ethanol and pyruvic acid, with fewer energy benefits and the accumulation of browning compounds (Andrzejczak et al., 2020). Anaerobic respiration accelerates fruit aging, intensifying nutrient engagement and metabolic processes required for life maintenance.

Mitochondria, the hub of fruit respiration, drive tissue metabolism via the electron transport chain (ETC), leading to oxygen consumption and reactive oxygen species (ROS) release (Hou et al., 2019). ROS accumulation induces oxidative damage to cell membranes, electrolyte leakage, heightened malondialdehyde (MDA) production, compromised antioxidant capacity, tissue oxidation, browning, and the generation of distinct odors (Cao et al., 2023). This imbalance between ROS and antioxidants promotes fruit deterioration. Moreover, the energy liberated from this metabolism expedites the breakdown of macromolecular sugars and glucose utilization. Fruit type, variety, maturity, damage degree, and mechanical treatment influence post-harvest respiration, with mechanical damage often causing physiological and metabolic disruptions that impede storage and transportation (Brar et al., 2020). Mechanical injuries induce “wound respiration,” elevating the respiratory rate by introducing more oxygen into damaged tissues, leading to increased nutrient and weight loss. Mechanical injuries in persimmons result in H_2O_2 accumulation, decreased SOD enzyme activity, and the generation of volatile compounds (Novillo et al., 2014).

Empirical studies suggest that mechanical damage exacerbates CO_2 release and the accumulation of volatile compounds in apples and yellow peaches, while also enhancing ethylene production and tissue softening in fruits such as apricots and kiwis (Li et al., 2018; Yang et al., 2020; Xia et al., 2020). However, certain fruits, like strawberries, may exhibit no substantial changes in quality due to limited vibration frequency, duration, and storage time (Chaiwong and Bishop, 2015). Bananas subjected to mechanical damage experience altered respiratory climacteric peaks, accelerating ripening, and compromising storage (Maia et al., 2014). Consequently, research focusing on identifying respiratory inhibitors and innovative packaging methods to regulate post-harvest fruit respiration is crucial in extending fresh fruit shelf life.

Furthermore, respiration contributes to the production of volatile compounds, which can significantly impact fruit quality and sensory attributes. The volatile compounds generated during respiration, such as esters, aldehydes, and alcohols, contribute to the characteristic aroma and flavor of fruits (Li et a., 2023; Pott et al., 2020). However, excessive volatile compound accumulation, often exacerbated by mechanical damage, can lead to off-flavors, undesirable odors, and accelerated senescence, ultimately diminishing consumer acceptance and marketability (Lin et al., 2021; Pott et al., 2020). Volatile changes and related biosynthesis in "Red Fuji" apples caused by post-harvest mechanical damage were investigated by Lin et al. (2021). Similarly, vibration damage to strawberries (Rao et al., 2020) and compression damage to peaches (Yang et al., 2020) resulted in a significant change in volatile organic compounds.

Understanding of the interplay between respiration and volatile compound production is indispensable for formulating strategies aimed at mitigating post-harvest quality deterioration and extending fruit shelf life. Moreover, the regulation of respiration through targeted interventions, such as controlled atmosphere storage or the application of respiratory inhibitors, presents promising avenues for enhancing fruit preservation and maintaining freshness throughout the supply chain.

2.2 Transpiration

Transpiration, the release of water vapor from fresh fruit surfaces to the surrounding environment, hinges significantly on the fruit's surface integrity and the ambient temperature and humidity. Typically comprising 70% to 95% water, high-moisture fresh fruits are prone to dehydration during storage via transpiration, leading to tissue wilting, skin wrinkling, and loss of luster (Xanthopoulos et al., 2017). Excessive transpiration can accelerate the dehydration process, resulting in decreased fruit quality, reduced marketability and shortened shelf life.

Non-climacteric berries like raspberries, mulberries, and blueberries generally exhibit higher transpiration rates compared to climacteric fruits such as apples, plums, and peaches. Water loss from post-harvest fruit elevates the concentration of soluble solids in tissue cells, stimulating respiratory metabolism. Excessive water evaporation enhances the activity of hydrolases like chlorophylase and pectinase, hastening the degradation of quality-related compounds like chlorophyll and pectin, causing alterations in hardness, color, and flavor (Moggia et al., 2017). Moreover, excessive water loss triggers ethylene synthesis and accelerates its release in fresh fruits.

Mechanical damage can disrupt the integrity of fruit exocarp tissue, leading to substantial water evaporation, quality decline, pulp hardening, surface defects, and unpleasant taste (Jalali et al., 2017). Post-harvest weight loss primarily stems from the transpiration of fresh fruits. For instance, prolonged vibration between 1 Hz and 200 Hz resulted in mechanical damage to grapes, leading to reduced soluble solid content, decreased titratable acidity, and compromised quality after 30 days of storage (Jung et al., 2018). Mangos exposed to vibration frequencies of 20, 30, and 40 Hz experienced weight reductions of approximately 9%, 10%, and 12%, respectively, after 28 days of refrigerated storage (Costa et al., 2021). Similarly, kiwi fruits, subjected to simulated impact damage by falling from a height of 0.5 meters, displayed a maximum weight loss of 5.83% after 10 days, which was lower compared to grapes and mangoes (Xia et al., 2020; Jung et al., 2018; Costa et al., 2021). Zhu et al. (2022) assessed the weight loss of apple fruits subjected to various compression forces during storage. Specifically, fruits exposed to compression forces of 0, 40, 80, 160, 320, and 640 N exhibited weight loss rates of 0.6%, 0.61%, 0.68%, 0.76%, 0.89%, and 1.2% within a 16-day span, respectively. Notably, the weight loss rate increased with the degree of damage, demonstrating a linear upward trend throughout the storage duration. The accelerated weight loss could be attributed to the damage-induced increase in water transpiration from the fruit.

Optimization of mechanical treatment methods, such as controlling vibration frequency and collision intensity, coupled with alterations in the fruit's microenvironment (temperature and humidity), during post-harvest treatments, can effectively slow down fresh fruit transpiration. This approach extends fruit freshness and preserves nutrient content for longer durations, contributing to overall consumer satisfaction and reducing food waste along the supply chain.

2.3 Ethylene generation

During the post-harvest phase, the dynamics of endogenous hormones, particularly ethylene, in fresh fruits undergo notable changes. Once ethylene accumulates within fruits and reaches a specific threshold, it is emitted into the surrounding environment as exogenous ethylene. This process triggers a self-perpetuating cycle of ripening and senescence, as exogenous ethylene catalyzes further endogenous ethylene production. Ethylene, recognized as a phytohormone, significantly modulates the sensory attributes and physiological aspects of fresh fruits. Functioning as a natural ripening agent, ethylene orchestrates biochemical processes including chlorophyll degradation synthesis of pigments responsible for color changes, and modifications in flavor compounds (Pathak et al., 2017). Additionally, ethylene plays a vital role in regulating respiration rates, influencing the overall maturation and ripening of fruits, thus impacting their post-harvest quality (Pathak et al., 2017). In addition to its role in ripening, ethylene escalates peroxidase activity and malondialdehyde content in fruit cells, impacting cell membrane permeability and reducing pulp tissue antioxidants, thereby accelerating respiration.

Mechanical damage sustained by fresh fruits during post-harvest stages intensifies the release and accumulation of ethylene, hastening the processes of fruit softening and aging (Ai et al., 2021). For instance, apricots subjected to mechanical damage and stored for eight days exhibited a 59.46% increase in ethylene production. The increased ethylene release stimulated the secretion of secondary metabolites, resulting in the formation of a protective callus to reduce further damage and enhance antioxidant capacity and peroxidase activity in the affected tissues. Similar findings were observed in mechanically damaged tomatoes, showing an 85% to 400% increase in ethylene release based on storage temperatures (Mutari and Debbie, 2011). Grapes, subjected to mechanical damage and stored for 30 days, displayed an 11.54% increase in ethylene production (Jung et al., 2018). Lu et al. (2019) conducted a study to investigate the effect of vibration on storage quality and the expression of ethylene biosynthesis-related enzyme genes in harvested apple fruit stored at (4 ± 1) °C and (20 ± 2) °C. The reported results revealed that vibration significantly increased ethylene production in the stored apple fruit, likely due to the mechanical stimulation induced by vibration triggering the activation of ethylene biosynthesis pathways.

Climacteric fresh-eating fruits tend to undergo a more rapid increase in ethylene production after harvesting compared to non-climacteric fresh-eating fruits. This difference is attributed to variations in the efficiency of ethylene synthesis enzymes, such as 1-aminocyclopropane-1-carboxylic synthase (ACC). Non-climacteric fruits typically have lower enzymatic efficiency and fewer ethylene receptor (ETR) genes contributing to ethylene production (Chen et al., 2018). To maintain freshness, it is recommended to implement strategic measures, such as using ethylene inhibitors or absorbents, during post-harvest storage and transportation to minimize ethylene production in fruits. In addition to ethylene regulation, exploring novel methods such as gene editing techniques offers promising prospects for extending the post-harvest life of fruits. By targeting specific genes involved in ripening and senescence pathways, researchers have the potential to develop fruit varieties with enhanced resistance to mechanical damage and reduced ethylene production, thereby extending shelf life without compromising quality (Adaskaveg and Blanco-Ulate, 2023). Furthermore, the development of advanced sensor technologies to monitor ethylene levels in real-time enables timely interventions, mitigating its effects on fruit quality.

2.4 Handling and Storage

The post-harvest freshness and quality of fruits are significantly influenced by the handling and storage temperatures. Effective temperature management during these stages is crucial, as it directly affects the physiological and biochemical processes within fruits. Moreover, temperature fluctuations during these stages can significantly alter the metabolic activity within fruits, influencing processes such as respiration rates, enzyme activity, and the degradation of cellular components (Duan et al., 2020).

Optimal handling practices, particularly during harvesting and post-harvest processing are imperative to mitigate mechanical damage and preserve fruit integrity. Mechanical injury can trigger physiological and metabolic disorders, accelerating the onset of undesirable reactions in fruits, leading to compromised storage and transportation capabilities (Brar et al., 2020). For instance, certain fruits, such as apples, exhibit surface color differences and altered sensory qualities post-mechanical damage, affecting overall market value (Hussein et al., 2020). Mechanical damage can also instigate the accumulation of reactive oxygen species (ROS) in fruit tissues, promoting oxidative stress and compromising antioxidant defenses, further accelerating deterioration (Montes et al., 2022).

Storage temperature plays a pivotal role in dictating the shelf life and quality retention of fresh fruits. Varied temperatures influence the rate of physiological processes like respiration, transpiration, and ethylene production (Li et al., 2022). For instance, refrigeration at specific temperatures such as 12 °C and 20 °C intensifies ethylene production in tomatoes, escalating the fruit's aging process (Mutari and Debbie, 2011). Additionally, mangoes subjected to different vibration frequencies demonstrated varied weight losses, exhibiting a decrease ranging from approximately 9% to 12% over 28 days under different storage conditions (Costa et al., 2021). Similarly, varying storage temperatures also affect the respiration rates of fruits, thereby impacting their shelf life and sensory attributes (Jung et al., 2018). Inappropriate storage conditions markedly accelerated the degradation of chemical constituents and adversely affected the nutritional and biochemical properties of strawberries, including the retention of amino acids (AA), total phenolic content (TPC), and antioxidant capacity (ANC) (Ktenioudaki et al., 2019).

The impact of temperature on fruit freshness is also tied to transpiration rates. Elevated temperatures can hasten transpiration, resulting in water loss, subsequent tissue wilting, and wrinkling, thereby affecting fruit quality (Cheng et al., 2021). This water loss also triggers the accumulation of soluble solids, altering the fruit's texture and taste (Moggia et al., 2017). Optimal temperature slows down transpiration rates and also regulates enzymatic activity, hormonal balance, and metabolic pathways crucial for maintaining fruit quality. Therefore, meticulous temperature control during handling, storage, and transportation stages is vital to minimize physical damage, control physiological processes, and maintain fruit freshness. Implementing strategic adjustments in storage conditions, such as temperature modulation and microenvironment control, can effectively extend the shelf life and maintain the quality of fresh fruits.

3 Fresh-keeping methods and technologies for fresh-eating fruit

Presently, a spectrum of methods and technologies is utilized for fresh fruits, encompassing low-temperature preservation, air conditioning, irradiation, the use of preservation agents or films, modified atmosphere packaging (MAP), active and intelligent packaging, as well as coatings (See Table 2). Generally, the preservation duration achieved by low-temperature refrigeration and irradiation tends to be comparatively shorter than that achieved through air conditioning, controlled atmosphere (CA) storage or the use of preservation agents. Large-scale storage facilities typically utilize low-temperature environments, air conditioning, and CA methods, whereas transportation and retail stages within the supply chain predominantly rely on low-temperature preservation and the use of preservation agents such as antimicrobial pads. However, an emerging trend involves the integration of multiple techniques, such as MAP, active and intelligent packaging, and coatings, which, when tailored to specific fruit varieties, harvest timings, and storage conditions, offer heightened efficacy in extending the shelf life of fresh fruits (Fang and Wakisaka. 2021).

Moreover, advancements in preservation technologies continue to evolve, with ongoing research focusing on innovative approaches to prolonging fruit freshness. Novel methods such as high-pressure processing, pulsed electric field treatment, and ozone treatment are being explored for their potential to enhance microbial safety and extend shelf life without compromising fruit quality (Saikumar et al., 2024; Brito and Silva, 2024; Varalakshmi, 2021). Additionally, the development of biodegradable and sustainable packaging materials aims to reduce environmental impact while maintaining product integrity during storage and transportation (Petkoska et al., 2021). By leveraging the synergies between traditional and emerging preservation techniques, the industry can effectively meet the increasing demand for fresh fruits while ensuring the highest quality and safety standards across the entire supply chain.

3.1 Low temperature fresh-keeping technology

Low-temperature preservation stands as a traditional yet integral technique in the postharvest storage of fresh fruits, primarily involving the placement of these fruits within a controlled low-temperature environment. This practice effectively restricts molecular migration within cellular structures, subsequently lowering tissue respiration and metabolic rates while also inhibiting the growth and proliferation of microorganisms (Yang et al., 2021; Hu et al., 2016). Various methods fall under low-temperature preservation, encompassing refrigeration (0 to 10 °C), ice temperature storage (freezing point to 0 °C), micro-freezing (-3 to -2 °C), and freezing (< -18 °C) (Yang et al., 2021; Hu et al., 2016). The effects of low-temperature preservation on fresh fruits are diverse and encompass a spectrum of outcomes (See Table 2).

Refrigeration, commonly utilized for fruits prone to cold injury, requires careful temperature control to prevent quality deterioration such as core lesions, skin markings and potential texture changes or flavor alterations (Vincent et al., 2020). For instance, tomatoes are best stored within the range of 7 to 10 °C, while bananas and mangoes fare optimally between 9 and 13 °C. Pomegranates exhibit reduced respiration rates when stored between 5 and 10 °C for 4 to 16 weeks, enhancing freshness and extending shelf life (Deng et al., 2020). Nevertheless, specific temperature variations can impact fruit characteristics, as observed in strawberries, that exhibit a significantly prolonged shelf life when stored at 0 °C but experience increased decay at 10 °C (Ikegaya et al., 2020).

Ice temperature preservation, storing fruits within a narrow range from their tissue's freezing point to 0 °C, ensures organized water molecules within tissue cells, reducing free water available for microorganisms without damaging cells (Yang et al., 2021). Studies comparing near-freezing storage with 0 °C storage for cherries and apricots have shown improved quality and decreased deterioration at the near-freezing temperature (Zhao et al., 2019; Fan et al., 2018). Micro-freezing preservation at -3 to -2 °C is particularly suitable for drupe fruits with outer skins like lychee and longan, optimizing storage quality and reducing costs in large-scale storage (Hu et al., 2016). Frozen preservation, with temperatures maintained below -18 °C enhances nutritional value but alters the fruit's acceptability upon thawing due to cell rupture and water loss (Bulut et al., 2018; Liu et al., 2019). This method is suitable for ingredient extraction rather than immediate consumption.

Combining low-temperature preservation with other methods, such as ϒ-irradiation, ozone treatment or heat, has shown promising results in reducing decay rates and maintaining quality (Zhen et al., 2016; Xue et al., 2015). These combinations offer potential for extending storage periods and preserving fruit quality throughout the supply chain, thereby reducing postharvest losses and meeting the increasing demand for fresh, high-quality fruit.

3.2 Modified atmosphere, active and intelligent packaging

Modified atmosphere preservation technology regulates gas concentrations like O_2, N_2 and CO_2 in enclosed environments (e.g., sealed bags), trays or in bulk form where fresh fruits are stored. This approach effectively moderates respiration intensity, ethylene release, and organic matter conversion rates, while also minimizing moisture loss and inhibiting microbial growth, thereby extending the shelf life of fruits and maintaining their quality (Li et al., 2015). Various approaches, including traditional cave and kiln storage, along with modern controlled atmosphere storage like equilibrium modified atmosphere packaging, constitute typical methods (Li et al., 2015).

The gas composition in modified atmosphere preservation typically comprises low O_2 (1% - 5%) and high CO_2 (3% - 20%) concentrations, advantageous in reducing fruit respiration, inhibiting surface microorganism growth, mitigating undesirable odors and slowing down enzymatic browning processes (Amaro et al., 2012). Notably, apricots stored in a closed environment with 5% CO_2, 10% O_2, and 85% N_2 experienced significantly lower mass loss compared to those in natural conditions, showcasing a 98% reduction in mass loss rate (Muftuoğlu et al., 2012). Pears stored in an airtight environment with 12.3% O_2 and 5.6% CO_2 lasted up to 4 months without significant taste differences compared to strawberries in a gas environment of 10% CO_2 and 11% O_2 (Wang and Sugar, 2013).

Studies comparing vacuum and controlled atmosphere preservation on fresh dates showed a 5.66-day longer shelf life in vacuum storage (Moradinezhad and Dorostkar, 2020). However, the combined use of modified atmosphere preservation with low-temperature storage results in higher costs, limiting its application for fruits with lower commodity value like tomatoes and persimmons. Regarding active intelligent and antimicrobial packaging, several studies have explored their applications in fruit preservation. Active packaging involves incorporating active substances or systems into packaging materials to extend shelf life or improve food quality. For instance, oxygen scavengers or carbon dioxide emitters in packaging can modulate the internal atmosphere, enhancing fruit preservation (Biji et al., 2015). Intelligent packaging incorporates sensors or indicators to monitor freshness or provide information on product quality. These technologies, when integrated into fruit packaging, offer real-time monitoring of freshness, ensuring better quality and reducing food wastage.

Antimicrobial packaging incorporates antimicrobial agents to inhibit microbial growth, thereby enhancing fruit shelf life. Essential oils, bacteriocins, and nanoparticles incorporated into packaging materials have shown promising antimicrobial effects against spoilage microorganisms (Duan et al., 2020). These innovative packaging technologies are continuously evolving, showing potential in extending the shelf life and preserving the quality of various fruits throughout the supply chain.

3.3 ϒ-irradiation

The preservation method involving irradiation utilizes ionizing radiation to eliminate pathogenic microorganisms and spoilage bacteria, disrupting their enzyme activity, hindering tissue physiological processes, and retarding ripening in fresh fruits (Farkas and Mohácsi-Farkas, 2011). The effects of irradiation on fresh fruits, typically employing ultraviolet and gamma rays, are outlined in Table 3. Usual radiation doses applied to fresh fruits are below 3 kGy, as higher doses may induce nutritional loss and reduce fruit firmness. For instance, exposure to ultraviolet-C radiation for 10 minutes at a light dosage of 3.1 J/cm^2 and an emission wavelength of 254 nm led to a decrease of 3.8 ± 0.2 $\log_{10}$ CFU/mL in *Escherichia coli* for apples (Corrêa et al., 2020). Additionally, 600 Gy of Co60 radiation extended the shelf life of pears by one day (Abolhassani et al., 2013). Notably, blueberries treated with 400 Gy rays exhibited fewer molds on their surface compared to those treated with methyl bromide fumigation (Thang et al., 2016).

Studies have highlighted the impact of UV-C irradiation on the expression of genes associated with phenolic compound accumulation, resulting in elevated total phenolic compounds, flavonoids, flavanols, anthocyanins, and antioxidant activities in grapes (Sheng et al., 2018). Grapefruit subjected to an irradiation dose of 1 kJ m^{-2} displayed approximately 20% and 35% increases in total phenol and anthocyanin content, respectively (Maurer et al., 2017). Similarly, sweet cherries exposed to 0.046 W m^{-2} light-emitting diode for 10 days exhibited heightened phenylalanine ammonia lyase (PAL) enzyme activity and increased anthocyanin content in the pulp tissue (Kokalj et al., 2019). However, the suitability of the irradiation method varies among fruits. For instance, the seedless Kishu lacks certain protective phenolic compounds, leading to potential alterations in appearance and firmness during irradiation (Ornelas-Paz et al., 2017).

Gamma irradiation (ϒ- irradiation), particularly at higher doses like 1.0 kGy, effectively inhibits spore germination and fungal growth on Citrus Satsuma but may induce fruit damage and the release of soluble contents (Bisht et al., 2021). Combining a low gamma irradiation dose of 0.4 kGy with 10 ppm sodium dichloro-s-triazinetrione demonstrated potent antifungal activity against green mold decay, emphasizing the potential synergy between various technologies (Bisht et al., 2021). Considering fruit type, maturity level, and irradiation dose becomes crucial when utilizing irradiation technology for fruit preservation.

3.4 Edible and antimicrobial coatings

Edible coatings offer a promising technique to extend the freshness of fruits by forming a protective layer over the fruit surface. These coatings, made from natural polymers like proteins, polysaccharides, or lipids, act as barriers against moisture loss, gas exchange, and microbial spoilage (Fernández-Pan et al., 2012). Moreover, integrating antimicrobial agents into these coatings enhances their preservation abilities.

The application of edible coatings, such as chitosan, alginate, or whey protein, effectively retards moisture evaporation from fruits, thereby reducing shriveling and extending shelf life (Salarbashi et al., 2018). These coatings create a shield that mitigates gas exchange, slowing down respiration and delaying ripening processes in fruits. Antimicrobial agents incorporated into these coatings offer added protection by inhibiting microbial growth and decay. For instance, natural compounds like essential oils or plant extracts, with inherent antimicrobial properties, have been used in coatings to combat fungal or bacterial spoilage in fruits (Souza et al., 2021). The incorporation of antimicrobial agents aids in controlling pathogenic microbes and prolongs the storage duration of fruits.

The application of edible coatings containing antimicrobial agents has been observed to reduce microbial load, inhibit mold growth, and decrease enzymatic activity in fruits, thereby significantly contributing to preserve freshness and extend the fruit shelf life (Kumar et al., 2020). These coatings serve as an innovative approach, offering dual benefits of moisture retention and microbial inhibition, ensuring the preservation and quality of fresh fruits for extended periods. Edible coatings, like grape seed functional coatings applied to strawberries, have proven effective in slowing weight loss and extending the freshness of the fruit during storage (Yıldırım-Yalçın et al., 2022).

In recent years, nanotechnology has emerged as a promising avenue for extending the freshness of fruits, offering innovative solutions to enhance shelf life and maintain quality. Nanoemulsions, nanoparticles, and nanocomposite coatings are among the nanotechnology-based approaches being explored for their potential to inhibit microbial growth, reduce oxidative stress, and slow down physiological processes in fruits (Sagar et al., 2022). Nanoemulsions, consisting of nanoscale droplets of oil dispersed in water, can be loaded with natural antimicrobial agents or antioxidants to create stable formulations that can be applied as coatings or dips to fruits. Nanoparticles derived from natural active ingredients, such as nano-titanium and nano-silver, embedded in biopolymer films or PE films, exhibit promising potential in delaying the aging process of fresh fruits due to their stability, controlled release, and high surface area (Mistriotis et al., 2015; Sridhar et al., 2021). Moreover, nanoparticles exhibit strong antimicrobial properties that help preserve fruits during storage and transportation. Nanocomposite coatings, formed by incorporating nanoparticles into edible polymers, offer an effective barrier against oxygen, moisture, and microbial contaminants, thereby extending the shelf life of fruits while minimizing the need for synthetic preservatives. As research in nanotechnology continues to advance, these innovative approaches hold great promise for revolutionizing fruit preservation practices and meeting the evolving needs of the food industry and consumers. However, it is crucial to consider the potential toxicity of these nanoparticles and their environmental impact before their application.

3.5 Preservatives

Preservation techniques significantly contribute to extending the shelf life of fresh fruits. These methods typically include chemical synthetic and natural preservatives (Table 4). Common chemical preservatives like 1-methylcyclopropene (1-MCP) are synthetic compounds that prevent ethylene release, effectively prolonging fruit shelf life. On the other hand, natural preservatives, such as plant essential oils and melatonin extracted from plants, have gained traction due to safety and environmental concerns associated with synthetic options, aligning with the growing demand for sustainable and eco-friendly preservation methods.

Melatonin, naturally present in various plants, fruits, and vegetables, has demonstrated promising preservation effects. Studies have shown its effectiveness in delaying changes in strawberry properties, including color, firmness, and chemical composition, resulting in reduced decay and weight loss, while enhancing essential health-promoting compounds like phenolics and flavonoids in strawberries (Liu et al., 2018). Melatonin treatment also delays the respiratory climacteric peak and ripening process in bananas (Hu et al., 2017).

3.6 Cold plasma (CP)

Cold plasma is a nonthermal process with significant potential applications for preservation and decontamination, offering relative advantages to prolong the shelf life of fresh produce, including fruits (Pan et al., 2021). Plasma, the fourth state of matter following solid, liquid, and gas, is described as a quasi-neutral ionized gas consisting of particles including photons, free electrons, positive or negative ions, excited or non-excited atoms, and molecules (Chen et al., 2020). Typically, common gases like air, oxygen, nitrogen, or a blend of noble gases such as helium, argon, and neon are employed in cold plasma applications. Plasma can be generated through various energy application methods, such as electricity, lasers, microwaves, radiofrequency, magnetic fields, and both alternating and direct currents (Ma et al., 2017).

Cold plasma treatment has been successfully applied to enhance safety and extend the availability of fresh-eating fruit (Pan et al., 2019). Microbial infection and endogenous enzymatic browning are pivotal factors contributing significantly to the decay of fresh produce. This enzymatic process can rapidly induce deterioration, ultimately leading to the development of undesirable or unacceptable organoleptic attributes, rendering the produce unsuitable for consumption. CP treatment demonstrated remarkable efficacy in suppressing the growth of *Botrytis cinerea*, consequently enhancing the preservation of blueberries (Zhou et al., 2019). In another study, Rana et al. (2020) explored the impact of CP treatment on microbial inactivation, physicochemical properties, and shelf-life extension of strawberry fruit during extended in-package storage at room temperature (25°C) and refrigerated conditions (4°C). The results revealed a significant 2-log reduction in the microbial count of strawberries, along with an increase in total phenolic content and antioxidant activity following CP treatment. Similar findings were reported by Giannoglou et al (2021), who noted the effectiveness of CP in reducing microorganisms, with a decrease in total viable count by approximately 0.9 log CFU/g in strawberries. Additionally, the authors observed an increase in phenolic compounds and antioxidant activity by approximately 20.9% and 16.5%, respectively.

CP technology, particularly in microorganism inactivation, provides distinct benefits due to its eco-friendly attributes, minimal hazardous substance emissions, and capability to inhibit the formation of long-lasting harmful compounds. Likewise, CP sterilization is renowned for its consistent and replicable process. Nevertheless, it is crucial to acknowledge certain limitations, such as high initial investment costs, the necessity for stringent safety protocols, specialized equipment requirements, and the importance of adequate training (Kaur et al., 2024; Ucar et al., 2021). Moreover, while CP shows promise in preserving fruit quality, the specific mechanisms underlying its effectiveness remain incompletely understood, thus presenting a potential gap for further research.

4 Damage prevention technologies of fresh-eating fruit in the supply chain

Damage prevention methods commonly employed in the production of fresh-eating fruits include measures to prevent damage during production process, picking, and packaging (An et al., 2022). These three categories of damage prevention methods are of great significance in reducing the rate of decay as well as raising consumers acceptance of fresh-eating fruits (Li and Thomas, 2014). The first line of defense against product spoilage and to minimize loss throughout plant growth process from the root is loss prevention in the production process and harvesting (Ha and Lu, 2019). However, damage prevention for fresh fruits after harvesting and transit to the point of sale generally depends on high-quality packaging (Lin et al., 2022). Inadequate packing methods can expose fruits to varying levels of compression, impact, vibration and puncture mechanical damage (Li et al., 2017). Compression damage on a fruit surface typically manifests as a deep indentation or a relatively large browning area, while impact damage tends to be internal and may not be immediately obvious on the surface. Vibration damage often appears as multiple regions unevenly distributed on the fruit surface, influenced by random abrasion during transportation. Puncture damage, on the other hand, usually exhibits a small and deep puncture hole on the fruit surface (See Fig. 2). Combining various damage prevention techniques can effectively reduce the mechanical damage rate of fresh-eating fruit. This approach takes into account factors such as genetics, environmental conditions, and physiological factors that contribute to fruit deterioration.

Post-harvest processing comprises essential stages such as pre-cooling, packaging, transportation, and storage. The packaging methodology applied to fresh fruit significantly influences the degree of post-harvest damage (Jiao et al., 2021). Hence, exploring various packing techniques is critical in mitigating harm to freshly harvested fruits. Figure 3 showcases the prevailing technologies utilized in packaging for the prevention of damage during postharvest handling of fresh fruits.

4.1 Combined packaging damage prevention technology with corrugated box and partition

Figure 3a illustrates the composition of the packaging structure, primarily comprised of a corrugated box, corrugated partitions, and expandable polyethylene (EPE) foam net. In this setup, each fruit is initially enveloped within EPE foam nets and then positioned within isolated spaces defined by corrugated partitions. During transportation, external forces can induce vibrations, impacts, or collisions within the integrated packaging box containing the fruits (Pathare and Opara, 2014).

The wavy structure of the corrugated core paper in the box and the cushioning provided by the EPE foam net facilitate an elastic deformation-recovery process that mitigates the impact of external forces on the fruit (Dayyani et al., 2015). Moreover, the use of corrugated partitions creates individual compartments for each fruit, restricting their movement and reducing the likelihood of inter-fruit collisions, thereby minimizing the risk of mechanical damage during transit. This specific method is commonly applied to spherical fresh fruits such as apples and pears.

Studies by Fadiji et al. (2016a) on corrugated box packaging with rectangular ventilation holes, oriented at a 45° angle, indicated that these configurations were less susceptible to damage during transportation compared to boxes with horizontally oriented circular ventilation holes. Additionally, research by Liu and Yang (2022) highlighted that a corrugated box with a flute height of 2.5 mm and 50 flutes exhibited a maximum compressive strength of 1.27 kN under critical conditions of 60 °C ambient temperature and 60% humidity. It was observed that the effectiveness of corrugated boxes in preventing damage decreased beyond this threshold.

4.2 Combined packaging damage prevention with corrugated box and EPE porous foam compartment

Figure 3b illustrates the packaging configuration composed mainly of a corrugated box, EPE porous foam compartments, and EPE foam nets. Each fruit is individually enveloped with EPE foam nets and housed within a separate cavity isolated by EPE porous foam compartments. During transit, these porous foam compartments effectively restrict the movement of each fruit within the corrugated box, preventing collisions both among fruits and with the partition wall. This significantly reduces the mechanical damage incurred during transportation (Wang et al., 2022).

Moreover, this packaging method is versatile, capable of accommodating fruits with varying diameters due to the resilient and adaptable nature of the porous foam (An et al., 2023). Despite its effectiveness, there is a scarcity of scientific literature discussing this integrated approach to mitigating damage during packaging for fruits with diverse size variations.

4.3 Combined packaging damage prevention with corrugated box and corrugated honeycomb cardboard

Figure 3c displays the packaging arrangement, comprising a corrugated box, corrugated honeycomb cardboard, corrugated partitions, and EPE foam nets. The placement of the corrugated honeycomb cardboard is adjacent to the inner wall of the corrugated box. All other structural components and packaging methodologies mirror those depicted in Figure 3a.

Compared to the preceding packaging methods, the honeycomb paperboard features a hollow three-dimensional regular hexagonal structure, enhancing its resistance to external impacts during transportation, especially on rugged mountainous roads. This attribute makes it a preferred choice to quickly package fruits prone to mechanical damage in remote areas (Kmita-Fudalej et al., 2022).

Study discovered that a 100 mm × 100 mm honeycomb sandwich panel loses its cushioning capability under out-of-plane dynamic compression conditions at a strain of 8.4 mm/mm and a pressure of 0.082 MPa (Wang and Bai, 2015). Research by Subhani (2019) demonstrated that after curing at 110°C for two hours, the flexural strength of the honeycomb paperboard reached 57 MPa. This integrated packaging's anti-damage technique diverges from previous research approaches. Notably, there is a lack of scientific literature exploring the effectiveness of honeycomb paperboard in protecting fresh fruits from damage.

4.4 Combined packaging damage prevention with corrugated box and air column bag

Figure 3d illustrates the packaging composition, primarily comprising corrugated boxes and air column bags. These bags, when fitted snugly on the inner side and delicately contoured to match the equatorial plane of the fruit, significantly enhance the protection against mechanical damage during transit.

The combined packaging structure operates as an effective shield for fruits, particularly large, delicate, and vibration-sensitive varieties like cantaloupes, watermelons, and muskmelons. External forces impacting the corrugated box during transportation are effectively diffused through the air column bags, minimizing the impact on fruits nestled within them. Research by Wang and Lu (2013) demonstrates that air column bags, with a film thickness of 75 μm and a single air column diameter of 40 mm, possess a cushioning coefficient (C) of approximately 5 under 60 kPa stress, highlighting their robust buffering capability. Despite this, there remains a conspicuous absence of scientific literature delving into the specific application of air column bags in safeguarding fresh fruits, indicating an unexplored area within current research.

4.5 Combination packaging damage prevention with foam box, vacuum bag, foam tray and EPE foam net

Figure 3e depicts the packing structure, which is primarily of foam box, sponge sheet, vacuum bag, foam tray, and an EPE foam net. Each fruit is first wrapped with EPE foam nets and placed on sponge board and foam tray, then placed together into vacuum bag. Each strawberry is fixed in the groove of the foam tray and the sponge sheet in the vacuum bag absorbing the water vapor produced by fruit transpiration and respiration. The oxygen concentration in the vacuum bag is low, reducing the consumption of organic matter in the fruit itself. The impact force that may suddenly act on the foam box during transportation is eventually transmitted to the sponge sheet between the interior of the foam box and vacuum bag gap, thus fruits are less affected by any external force. Strawberries, cherries, and other fresh fruits with high commodity value are frequently transported over long distances using this combined packaging damage protection system. According to Sujeetha et al. (2020), the respiration rate of the fruit tissue of pomegranates packed in high-density polyethylene vacuum bags can be reduced at a low temperature of 4 °C. The vacuum effect also immobilizes the pomegranate fruit, preventing collisions between them, and the final vacuum-packed fruits have a shelf life of up to 15 days. With the same external force, the mechanical damage of pear fruit packed in polystyrene (PS) foam trays and pear fruit packed in kraft pulp trays was not noticeably different (Wang et al., 2022). Additionally, Fadiji et al. (2016a) discovered that apples packed in pulp trays had mechanical damage at a rate that was almost 50% lower than apples packed in plastic bags. The combined packaging damage avoidance technology stated in this article has no scientific literature report to the best of our knowledge.

4.6 Combined packaging damage prevention technology with foam box and inflatable packaging air bag

Figure 3f depicts a packaging configuration centered on a foam box, an inflatable packaging air bag, and an ice bag. The inflatable packaging bag boasts a dual-layered structure with an inner bag that can be inflated between the outer and inner layers. Specifically designed for the combined packaging, the inflatable bag conforms closely to the fruit's exposed surface due to its softness, while its ventilation apertures facilitate the release of water vapor generated by the fruit's respiration or transpiration.

This integrated packaging system serves to further mitigate mechanical damage during transit. Upon sudden impact on the foam box, the energy from the impact force is absorbed by the gas-filled air bag, preventing immediate transmission of force to the fruit itself (Liu et al., 2023b). Fresh fruits such as grapes, mangoes, and ginseng fruits commonly benefit from this anti-damage packaging method.

5 Technologies for supply chain fruit freshness monitoring

Numerous publications have extensively covered technologies for monitoring fruit freshness and preservation across the supply chain, a topic not detailed in this review. These encompass diverse indicators, sensors, data carriers, and instruments utilized for assessing and tracking the degree of fruit freshness and deterioration. Figure 4 illustrates the commonly used quality testing indicators for fruits in the supply chain. Categorized by monitoring principles, these technologies include imaging systems (such as computer vision, hyperspectral imaging, multispectral imaging, thermography, and X-ray imaging), sensors, smart packaging, spectroscopy (spanning ultraviolet, visible, infrared, and Raman spectroscopy), as well as other methods like electronic nose and acoustic impulse (Wang et al., 2017; Beshai et al., 2020; Onwude et al., 2020).

Imaging-based approaches, notably computer vision systems, have gained popularity owing to their non-destructive, contactless nature, particularly when integrated with artificial intelligence (AI) and the Internet of Things (IoT) (Ni et al., 2020; Abayomi-Alli et al., 2023; Huang et al., 2023). These methods are utilized throughout the supply chain to classify, grade, assess quality, detect defects, and estimate internal properties of fruits (Palumbo et al., 2022a). For instance, using JPEG image processing, the maturity degree of plums was determined based on color, with less than a 2.4% error rate (Kaur et al., 2018). Similarly, correlations were found between RGB indices of images and fruit chemical properties, such as strong correlations between fruit acidity and mean green color intensity ($R^2 = 0.9966$). Studies on strawberry ripening stages revealed strong correlations between titratable acidity and data from spectroscopy and image analysis, indicating the potential of these technologies for rapid fruit acidity evaluation and ripening stage assessment (Pearson correlation coefficient = 1 for fruit titratable and image analysis data) (Palumbo et al., 2022b).

The Internet of Things (IoT) enables remote control of objects through the use of smart materials like RFID tags and sensors, marking the present and future advancements in fruit quality control and monitoring. Smart packaging integrates both active and intelligent components. Active packaging materials, which absorb or release substances such as moisture, gas, antimicrobial, and antioxidant compounds, are employed to enhance food quality and extend shelf life. Simultaneously, intelligent packaging utilizes components like sensors, RFID tags, barcodes, and indicators to monitor various factors such as temperature, gas, pH, humidity, and ripeness. This combined approach plays a pivotal role in comprehensive food quality control and monitoring within the packaging, ensuring optimal conditions for freshness and preservation (Beshai et al., 2020; Alam et al., 2021; Shao et al., 2021). Multi-sensors developed for real-time monitoring of factors like temperature, humidity, O_2, CO_2, and ethylene changes in cherry transportation microenvironments exemplify the extensive applications of sensor (Zhang et al., 2020). While sensor applications in monitoring fruit freshness are expansive, the challenge lies in developing sustainable, safe, and miniature sensors capable of detecting and automatically implementing corrective measures. Despite advancements, continuous innovative research is imperative in this domain.

6 Future research directions

Fresh fruit preservation across the supply chain stands as a pivotal measure in minimizing quality degradation and financial losses. Current technologies primarily focus on reducing respiration, transpiration, and hormone release in fresh fruits. Low-temperature storage and functional compounds emerge as popular methods, especially in combining techniques for effectively storing fresh-eating fruits. Transportation packaging predominantly utilizes partitions, corrugated boxes, and active packaging to prevent both fruit damage and package integrity issues. Despite these advancements, current anti-loss and preservation technologies fail to entirely eliminate fresh fruit loss.

Future advancements in this domain must prioritize the development of environmentally friendly packaging materials that align with fruit ripening states and types. This includes research into ecologically sustainable, recyclable, and biodegradable materials that minimize environmental impact while safeguarding fruits with high economic value. Additionally, understanding the relationship between mechanical damage and fruit quality deterioration requires more comprehensive research, spanning molecular-level investigations and real-time monitoring systems. Such advancements will aid in predicting quality degradation and shelf life under dynamic loads while focusing on non-destructive, automated fruit freshness monitoring techniques.

Although packing techniques such as inflated airbags and air column bags effectively reduce mechanical damage during transportation, further investigation is necessary to examine the influence of air volume within these bags on fruit integrity. Moreover, the use of vacuum bags for long-distance shipment, resulting in anaerobic respiration and subsequent fruit spoilage, requires further investigation, especially concerning correlations with transit distance. Despite the positive aspects of current fresh-keeping technologies, such as extended shelf life and waste reduction, they are plagued by drawbacks like high costs and environmental contamination. To address these challenges, multidimensional research that combines modern technologies such as the Internet of Things (IoT) and big data with novel preservation methods and rapid, accurate monitoring systems for fresh fruits is imperative. This forward-looking approach will pave the way for advanced, sustainable, and efficient fresh fruit preservation methods, mitigating losses and promoting industry growth.

Credit authorship contribution statement

Jincheng Yu: Conceptualization, Investigation, Resources, Data curation, Writing-original draft, Writing-review & editing. Minggang Wang: Writing-review & editing. Zhiguo Li: Writing-review & editing, Supervision, Funding acquisition, Project administration. Fideline Tchuenbou-Magaia: Writing-review & editing, Supervision. Ali Abas Wani: Writing-review & editing, Supervision. Pengfei Zhu: Supervision. Yande Liu: Writing-review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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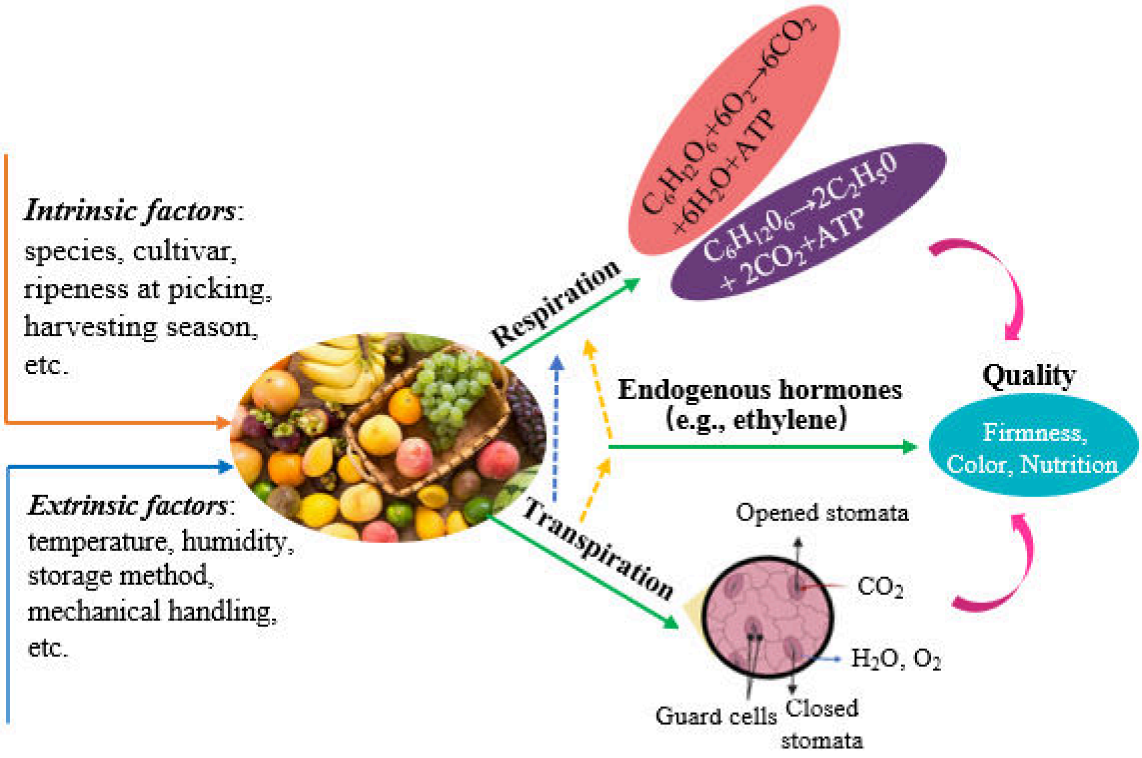

Fig. 1 Physiological and biochemical changes in fresh-eating fruit

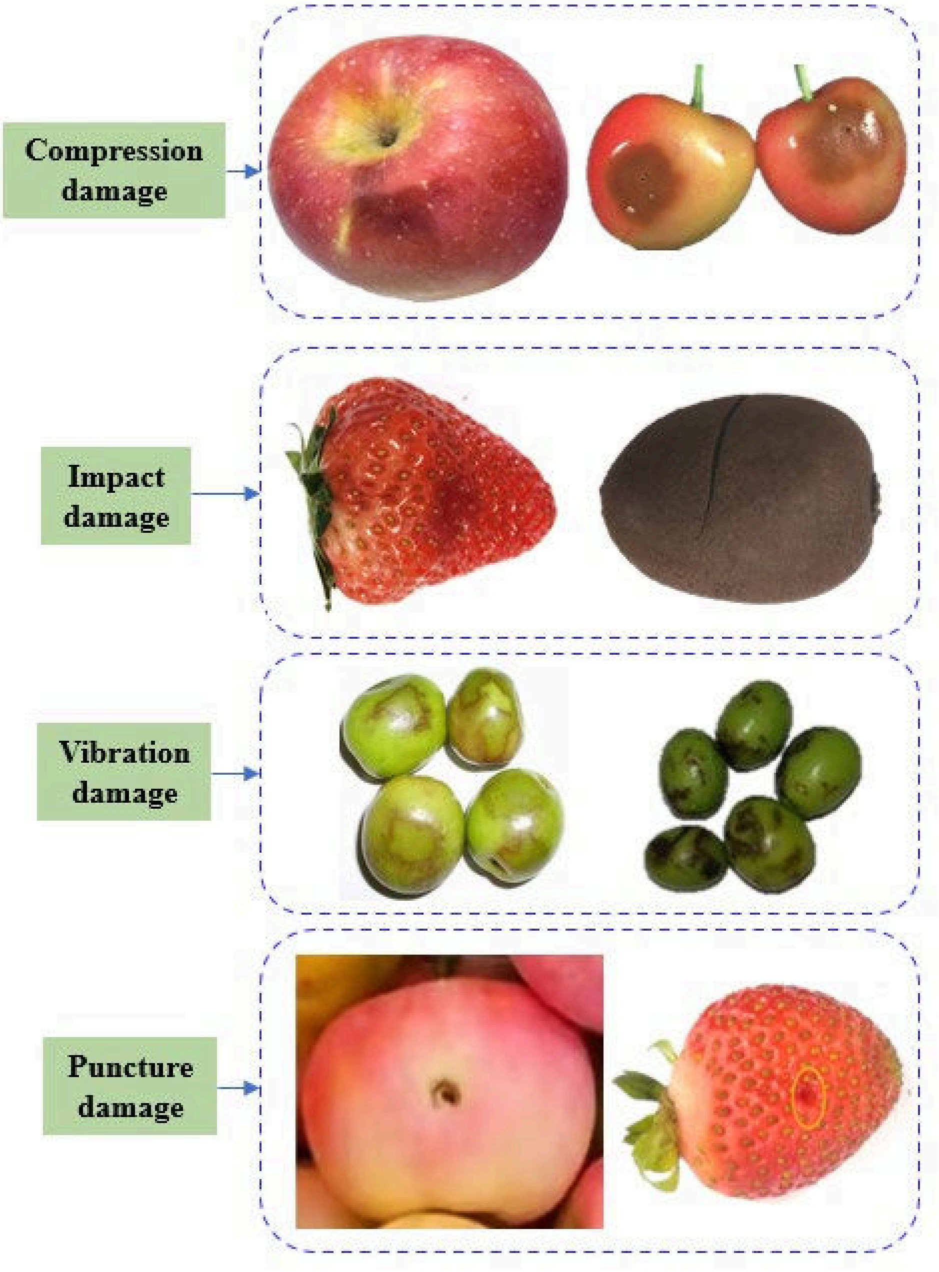

Fig. 2 Various types of mechanical damage to fruits

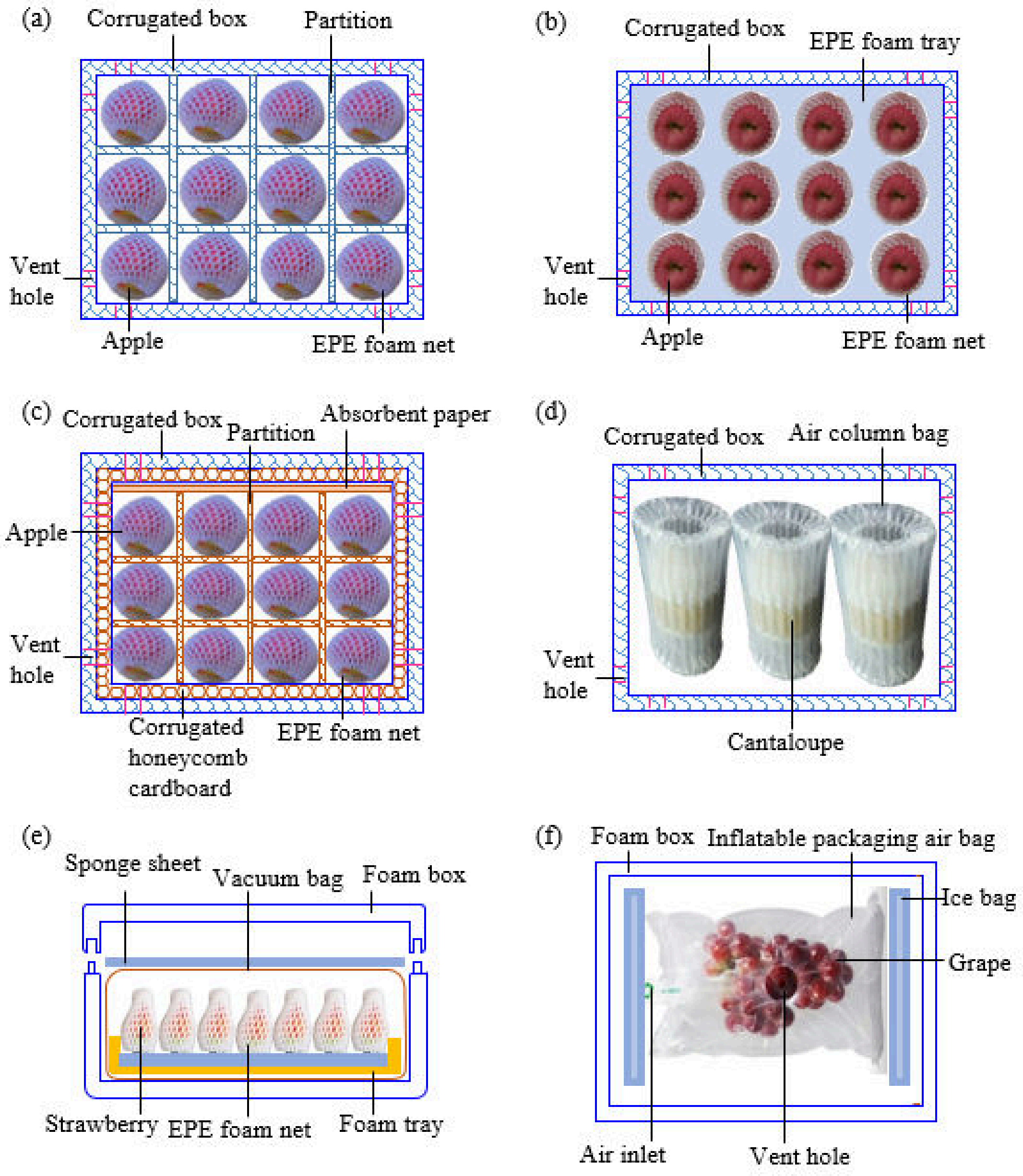

Fig. 3 Several packaging types of fruit. (a) apple packaged by corrugated box and partition; (b) apple packaged by corrugated box and EPE foam tray; (c) apple packaged by corrugated box and honeycomb cardboard; (d) cantaloupe packaged by corrugated box and air column bag; (e) strawberry packaged by foam box, vacuum bag, foam tray and EPE foam net; (f) grape packaged by foam box and inflatable packaging air bag.

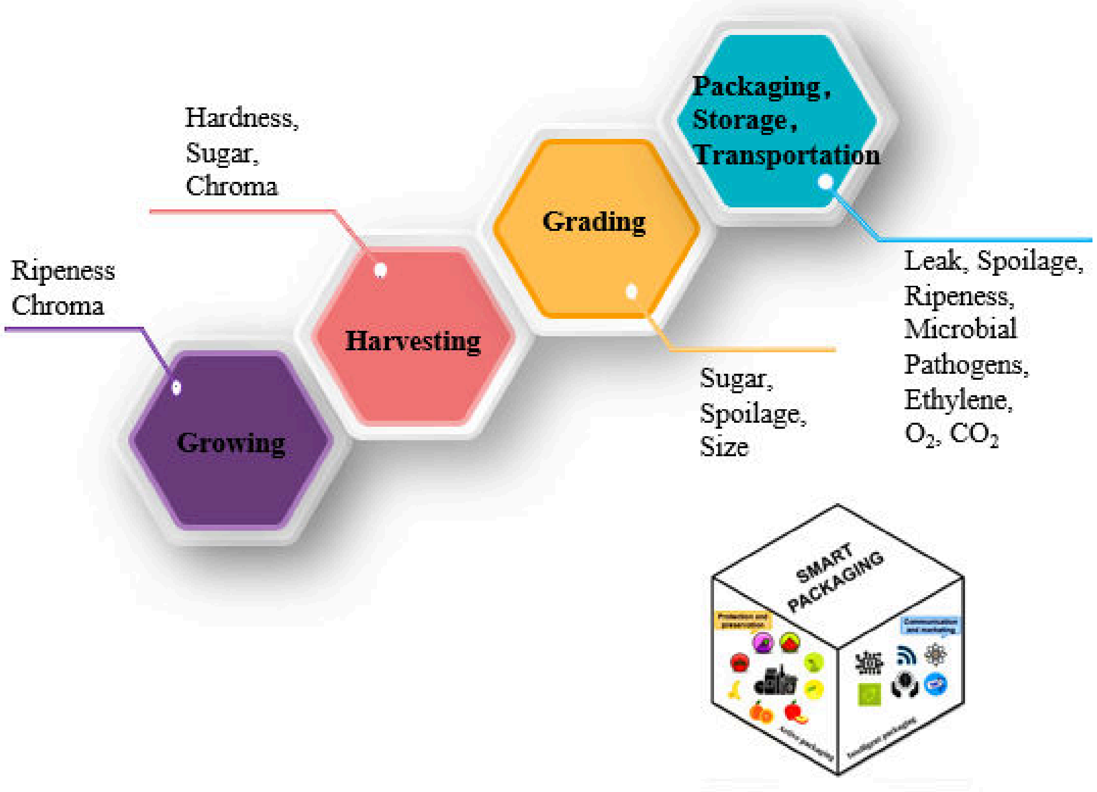

Fig. 4 Fruit quality parameters for each stage in the supply chain

Table 1 Some physiological and biochemical changes of damaged fresh-eating fruit

Respiration	Fruit type	Some physiological and biochemical changes	References
Climacteric	Pear	Rate of water loss ↑; hardness and SSC content ↓; TA content ↑; PG and cellulase activities ↑; protopectin, total pectin, cellulose, relative conductivity, morbidity rate ↑; color change.	Pathare and Al-Dairi. (2021)
	Apple	Respiratory rate ↑; hardness, SSC and TA contents ↓; browning degree and MDA content ↑; aroma components content (e.g., ethyl acetate, alcohol, aldehyde, acid, and alkene) ↑	Li *et al*. (2018)
	Tomato	Respiratory rate, ethylene production, juice loss rate and maturity ↑; hardness, cell integrity, cell wall rigidity, sugar, aldehyde and acid contents ↓; lycopene content ↓; relative conductivity, and PG and PME activities →; color change and tissue collapse.	Buccheri and Cantwell. (2014) Mutari and Debbie. (2011)
	Banana	Fruit quality and pulp starch content ↓; electrolyte leakage rate, PPO and POD activities, rate of color evolution of peel and conversion rate of starch to sugar ↑; advance of fruit respiration peak.	Maia *et al*. (2014)
	Peach	5-hexyldihydro-2(3H)-furanone, tetrahydro-6-pentyl-2H-pyran-2-one, Pentadecane, ethyl caproate, ethyl acetate, ethyl trans-4-decenoate and 4-(Z)-octenoic acid methyl ester ↑.	Yang *et al*. (2020)
	Kiwifruit	Respiration rate, ethylene production, MDA content, electrolyte leakage, H_2O_2 content and superoxide radical ↑; mass, and CAT, SOD and POD activities ↓.	Xia *et al*. (2020)
	Persimmon	Browning rate, ROS accumulation of flesh and acetaldehyde content ↑; SOD activity ↓; flesh pinkish-bruising occurred in flesh.	Novillo *et al*. (2014)
	Mango	Mass loss and browning rate ↑; pulp hardness ↓; SSC and TA →; color change.	Costa *et al*. (2021)
Non-climacteric	Strawberry	Relative conductivity, butanoic acid and methyl ester content ↑; acetic acid-hexyl ester, 1-hexanol, 2-hexen-1-ol-acetate, (E)-dodecane and decane content ↑; TSS, TA, hardness and mass loss →.	Cao *et al*. (2022) Chaiwong and Bishop. (2015)
	Blueberry	Ethylene production, respiration rate and decay rate, softening rate, relative content of alcohol in aromatic component ↑; hardness, SOD, CAT activity, SSC, TA, flavonoid content, total phenol content and relative content of ester ↓.	Moggia *et al*. (2017) Xu *et al*. (2021)
	Litchi	TSS, respiration rate, ethylene release and ethylene production ↑; acidity ↓; color change.	Kumar *et al*. (2016)
	Grape	Quality and SSC content ↓; ethylene production ↑.	Jung *et al*. (2018)

Note: SSC: soluble solids content; TA: titratable acid; PG: polygalacturonase; PME: pectin methyl esterase; MDA: malondialdehyde; PPO: polyphenol oxidase; POD: peroxidase; CAT: catalase; SOD: superoxide dismutase; ROS: reactive oxygen species; TSS: total soluble solids; H_2O_2: hydrogen peroxide; ↑: increase; ↓: decrease; →: constant.

Table 2 Effect of low temperature preservation and modified atmosphere preservation on the fresh-eating fruit

Type of fresh-keeping	Fresh-eating fruit	Treatment conditions	Fresh-keeping performance	Reference
Low temperature preservation	Orange	5.8 ℃	TSS/TA ↑; softening rate, mass loss rate and flavonoid reduction rate ↓.	Deng *et al.* (2020)
	Cherry	-1.9 °C ~ 0 °C	Respiration rate, softening rate, mass loss rate, MDA content, LOX activity, fruit cracking rate, total phenol and flavonoid reduction rate ↓; TSS/TA, ascorbic acid content and antioxidant capacity ↑; chroma →.	Zhao *et al.* (2019)
	Strawberry	-27 °C and -23 °C; 0 ~ 10 ℃	Fruit quality, ascorbic acid, total phenol content, antioxidant capacity, anthocyanins and aroma compounds ↑; color change →.	Bulut *et al.* (2018)
	Apricot	-2.1 ~ -1.7 °C	Respiration rate, ethylene production, decay rate and MDA content ↓; TSS/TA, ascorbic acid content, antioxidant capacity, total carotenoid content, total phenol content and flavonoid reduction rate ↑; color change.	Fan *et al.* (2018)
	Peach	-0.7 °C	Antioxidant capacity ↑, maintaining cell Membrane stability and postharvest quality ↑, extend shelf life ↑.	Liu *et al.* (2013)
	Blueberry	-1.6 ~ 0.4 °C	Respiration rate, ethylene production rate, catalase and lipoxygenase activity ↓; shelf life ↑.	Xue *et al.* (2015)
Controlled atmosphere preservation	Cherry	16% O_2 and 20% CO_2 in PET plastic bag	Respiration rate, ethyl acetate content, browning rate, softening rate and color change rate ↓; VOCs change (alcohols and aldehydes) →.	Cozzolino *et al.* (2019)
	Jujube	21% O_2 and 0.03% CO_2 in low-density polyethylene bag	Mass loss, total soluble fruit solids, browning index and softening rate ↓; total phenolic compounds, vitamin C, sensory evaluation and shelf life ↑.	Moradinezhad and Dorostkar. (2020)

Note: TSS: total soluble solids; TA: titratable acid; MDA: malondialdehyde; LOX: Lipoxygenase; VOCs: volatile organic compounds; ↑: increase; ↓: decrease; →: constant.

Table 3 Effect of irradiation preservation on the fresh-eating fruit

Fresh-eating fruit	Treatment conditions	Fresh-keeping performance	Reference
Apple	Ultraviolet ray (100 ~ 280 nm)	Staphylococcus aureus ↓	Corrêa *et al.* (2020)
	Ultraviolet ray (219 kJ m^{-2})	Peel flavonoids and hydroxycinnamon contents ↑	Assumpção *et al.* (2018)
Pear	400 ~ 600 Gy γ rays	TA, TSS and ripening time ↓	Abolhassani *et al.* (2013)
Sweet cherries	Light (blue light)	Anthocyanin content and PAL activity ↑	Kokalj *et al.* (2019)
	400 Gy γ rays	Fruit surface Salmonella and Listeria monocytogenes level ↓	Thang *et al.* (2016)
Blueberries	Ultraviolet ray (4 kJ m^{-2})	Anthocyanin content, SOD and APX activities ↑	Xu *et al.* (2016)
	400 Gy γ rays	Fruit surface Salmonella and Listeria monocytogenes level ↓	Thang *et al.* (2016)
Citrus	1.0 kGy γ rays	Growth rate of green mold ↓	Jeong *et al.* (2016)
Grapes	400,600, 800 Gyγ Co60 rays	Sweetness ↑	Kim *et al.* (2014)
	Ultraviolet ray (3.6 kJ m^{-2})	Phenolic compounds and accumulation of phenolic metabolites ↑	Sheng *et al.* (2018)
	Ultraviolet ray (1 kJ m^{-2})	SOD and CAT activities, glutathione reductase and guaiacol peroxidase induction time, total phenols and anthocyanins contents ↑	Maurer *et al.* (2017)
Pineapple	400 ~ 600 Gy γ rays	Browning time of pulp ↑; TA/TSS, antioxidant dose and ascorbic acid concentration →	Jenjob *et al.* (2017)
Tomato	Ultraviolet ray (100~ 400 nm); Light (red and blue)	Antioxidant capacity, flavonoid, phenolic, β-carotene, lycopene, lutein and total carotenoid contents ↑	Mditshwa *et al.* (2017) Dyshlyuk *et al.* (2020) Baenas *et al.* (2021)
Mango	Ultraviolet ray (5 kJ m^{-2})	Ascorbic acid and phenolic compounds ↑	Jiang *et al.* (2015)

Note: TSS: total soluble solids; TA: titratable acid; CAT: catalase; SOD: superoxide dismutase; APX: aseorbateperoxidase; ↑: increase; ↓: decrease; →: constant.

Table 4 Effect of preservatives/agent/film preservation on the fresh-eating fruit

Fresh-eating fruit	Treatment conditions	Fresh-keeping performance	Reference
Papaya	O_3	Total soluble solids, ascorbic acid, β-carotene, lycopene and antioxidant and anti- free radical activities ↑	Ali *et al.* (2014)
Kiwi fruit	1-MCP; O_3	Regulate ethylene production and carotenoid content ↑, Chlorophyll content and biosynthesis of endogenous ethylene ↓	Liu *et al.* (2021) Minas *et al.* (2018)
Banana	Melatonin	Ethylene biosynthesis ↓, retard maturation	Hu *et al.* (2017)
	Thyme oil	Weight loss↓, retain color and hardness →; growth and reproduction of anthrax ↓	Vilaplana *et al.* (2018)
Blueberries	Melatonin	Malondialdehyde and hydrogen peroxide ↓; slowing down the activities of polyphenol oxidase, guaiacol peroxidase and lipoxygenase ↓; accumulation of polyphenols, flavonoids, anthocyanins and ascorbic acid ↑	Magri and Petriccione. (2022)
Fresh jujube	Melatonin	rate of color change and hardness decrease ↓; Phenol synthesis gene expression and phenol compound level ↑	Wang *et al.* (2021)
Cherry	Melatonin	Endogenous melatonin content, antioxidant enzyme activity and ascorbic acid level ↑	Wang *et al.* (2019)
Mango	Melatonin	Mango hardness, ascorbic acid, phenolic compounds and antioxidant activity ↑; PPO activity ↓, CAT and POD activities ↑	Rastegar *et al.* (2020)
Pomegranate	Melatonin	PAL activity ↑, accumulation of total phenols and anthocyanins ↑, antioxidant capability ↑	Aghdam *et al.* (2020)
Citrus	Melatonin	Active oxygen scavenging capacity ↑, resistance of Citrus Fruits to green mold ↑	Lin *et al.* (2019)
Apple	Melatonin	Ethylene production ↓; POD, SOD and CAT activities ↑	Onik *et al.* (2021)
Strawberry	Grape seed extract, cross-linked corn starch, grape juice	Respiration rate ↓, Ascorbic acid, anthocyanin, total phenol content and antioxidant activity ↑	Yıldırım-Yalçın *et al.* (2022)
Pitaya	Peppermint oil, activated carbon	Fungi and rotten fungi on fruit surface ↓, storage fruit hardness, bract green, titratable acid value and total phenol content ↑	Chaemsanit *et al.* (2018)
	Plant oil-based coating; Carnauba base coating	Atrophy of exocarp ↓	Razali *et al.* (2021)
Sweet orange	Carnauba wax and polyethylene synthetic wax	Weight loss and hardness loss of brazilian palm coated fruit are less, and polyethylene coated fruit is brighter	Njombolwana *et al.* (2013)
Litchi	Shellac loaded tannic acid film	Browning and decay rate, polyphenol oxidase and guaiacol activity of litchi ↓	Ma *et al.* (2021)
Seabuckthorn	160 OTR oriented polypropylene film	Soluble solids →; antioxidant activity, fruit firmness ↑	Li *et al.* (2015)

Note: PPO: polyphenol oxidase; POD: peroxidase; CAT: catalase; SOD: superoxide dismutase; ↑: increase; ↓: decrease; →: constant.

Preserving freshness: innovations for fresh-eating fruit distribution and damage prevention – A review

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