

REVIEW

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Sustainable persimmon valorization through integrated postharvest technologies, packaging, and product innovations

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Abstract

Postharvest losses remain a significant barrier to global food security and sustainability. This review positions persimmon (*Diospyros kaki*) as a model fruit for sustainable innovation, examining its potential through three interconnected pillars: preservation technologies, packaging strategies, and value-added product development. The climacteric properties and limited seasonality of persimmon hinder its commercialization but also create opportunities for innovation. Evidence indicates that preservation methods such as edible coatings, modified atmosphere packaging, ethylene inhibition, and advanced drying and extraction techniques can effectively delay softening, reduce microbial spoilage, and extend shelf life. Concurrently, packaging solutions using biopolymeric materials, active components, and tailored mechanical protection have been shown to mitigate physiological disorders and transport-related damage. Furthermore, persimmon by-products are a valuable resource for recovering dietary fiber, pectin, carotenoids, phenolic compounds, antimicrobial tannins, biopolymeric films, nanoparticles, and bioenergy, enabling multiple valorization pathways. Collectively, these findings suggest that combining postharvest technologies with by-product valorization strategies can significantly reduce food loss and waste while generating high-value products. This review highlights the importance of holistic approaches that integrate postharvest innovation with environmental responsibility, offering insights applicable to other perishable crops.

Keywords Persimmon (*Diospyros kaki*), Circular economy, Sustainability, Postharvest preservation, Food packaging, Value-added products

1 Introduction

According to the FAO [1] Food loss and waste (FLW) refer to the reduction in the quantity or quality of food available for consumption. Whereas food loss results from the choices and behaviors of food suppliers along the food supply chain, excluding retail, food service, and consumers, food waste results from decisions and actions by retailers, food service suppliers, and consumers. Thus, food losses occur at the stages of



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production, post-harvest, and processing, while food waste occurs from retail to the final consumption [1, 2].

FAO estimates that 14% of post-harvest food, excluding retail/consumption, is lost globally [3]. The United Nations Sustainable Development Goals (SDGs) of the 2030 Agenda outline increased awareness of this matter. One of the primary objectives is to “Ensure sustainable production and consumption patterns” (SDG 12). It is essential to recognize that the SDGs are interlinked. For instance, reducing food loss and waste (FLW) can contribute to achieving several other goals, such as “Zero Hunger” (SDG 2), “Clean Water and Sanitation” (SDG 6), “Climate Action” (SDG 13), and “Life Below Water” and “Life on Land” (SDGs 14 and 15, respectively).

In this context, the European Circular Economy Action Plan is another important initiative joining efforts to minimize, prevent, and add value to waste, reducing resource depletion and greenhouse gas emissions, and promoting sustainability and positive climate action [4]. For successful reduction of post-harvest injuries, investments are needed in sustainable production programs, qualified technical support, and knowledge production to promote good agricultural practices. It is increasingly urgent to adopt sustainable and efficient management of these resources to ensure their availability for future generations [5]. However, these inputs must be processed early in the supply chain to prevent senescence, develop food packaging solutions, and create innovative, value-added products aligned with the principles of the circular economy.

It is therefore urgent that we consider global food systems holistically, encompassing not only production and consumption but also food processing, packaging, transportation, food services, and retail, among other components. In this scenario, investing in new techniques for processing fruits and vegetables is essential to prevent food loss. This approach is part of a broader, integrated solution to the problem. In this review, the persimmon (*Diospyros kaki* L.) is used as a case study to contextualize this dilemma.

The commercialization of persimmons occurs in the form of fresh fruit; as it is a seasonal fruit, it is produced only for a specific period throughout the year [6, 7]. Persimmon exhibits climacteric behavior, characterized by rapid ethylene production and a high respiration rate, resulting in a limited marketable period and rapid fruit deterioration [8]. In Brazil, persimmon production is intense from February to July, with peaks in April and May [9]. China is the world’s largest producer of persimmons, followed by Korea, Spain, Japan, and Brazil [10], with an average annual production of 157,000 kg [3]. However, there is significant post-harvest loss during the short, intense harvest of this fruit; statistical reports indicate that Brazil loses approximately 20% of its total production [3].

Review articles concerning persimmons (*Diospyros kaki*) predominantly examine specific facets of their production and utilization, with a particular focus on chemical composition, bioactive compounds, health-related properties, and the development of food products derived from persimmons [11–13]. Furthermore, these articles emphasize post-harvest technologies, encompassing storage conditions, treatments for astringency removal, and processing methodologies [14, 15]. To the best of our knowledge, there is currently no comprehensive review that concurrently addresses preservation technologies, packaging strategies, and the creation of value-added products, all within the integrated framework of a circular economy, to mitigate post-harvest losses and enhance value.

This review examines current strategies for persimmon preservation and valorization, with a focus on preservation technologies, packaging solutions, and the development of value-added products within the circular economy framework. The integration of these dimensions provides insight into how to reduce food loss and waste while generating economic and environmental benefits. This approach distinguishes this review from previous publications and offers a transferable framework applicable to persimmons and other highly perishable fruits.

2 Fresh fruit quality, postharvest challenges, and preservation technologies of persimmon

Persimmon is appreciated for its sensory characteristics, excellent nutritional quality, and wide range of applications in various industrial sectors [11]. It is nutritionally composed of high moisture content (78.29 g 100 g⁻¹), carbohydrates (18.83 g 100 g⁻¹), especially glucose (7.31 g 100 g⁻¹), fructose (6.04 g 100 g⁻¹), and dietary fiber (3.86 g 100 g⁻¹) [11], with emphasis on pectin (84,2% of galacturonic acid) [16] and mucilage [12].

Micronutrients and phytochemicals are also found in abundance in different persimmon cultivars, e.g., potassium, magnesium, vitamins A and C, gallic acid, malic acid, condensed tannins, lycopene, β and α carotene, and lutein [11, 12]. Given the bioactive properties of these compounds of persimmon, as well as their positive effects on human health, and their capacity to prevent chronic non-communicable diseases [17, 18]. There is a tendency to improve the processing of persimmon and its residues, enhancing its use and reducing losses, especially in off-season periods [12, 19].

In 2022, around 4.4 million tons of persimmons were produced in the world; Azerbaijan and Brazil were responsible for about 4% of this total, and China had the most significant production (corresponding to 76% of the total output), followed by the Republic of Korea (5%) and Japan (5%). Persimmon losses in that same year accounted for about 20% of production in Brazil, 17% in Uzbekistan and Japan, 10% in the Republic of Korea, and only 5% in China [3]. In 2020, world production of persimmons showed a slight reduction compared to previous years, totaling approximately 4.2 million tons [3].

Thus, despite the lack of more recent data, the trend is that the persimmon production chain in many countries has encountered greater difficulties, thereby increasing loss rates. These data reinforce the importance not only of taking action to reduce losses throughout the production chain, especially in the post-harvest stages, but also of developing strategies to produce value-added persimmon products in Brazil and in all countries where this fruit is produced on a large scale.

Among the effects of senescence in fruits, excessive softening is a crucial determinant of their commercial value and shelf life. Briefly, the process begins with water loss, followed by the induction of genes involved in ethylene formation, which, in turn, causes cell wall degradation via enzymatic action. Excessive softening is characterized by degradation of the cellular microstructure, resulting in decreased pulp firmness and a gradual weight loss. Given persimmons' climatic requirements, their post-harvest period is characterized by an increased rate, posing challenges for handling, transportation, and export [14, 15, 20].

Several strategies have been investigated to delay the softening of persimmons. Modified atmosphere packaging (MAP) and treatment with 1-Methylcyclopropene (1-MCP) can delay the softening of persimmon through the control of ethylene production [14,

21, 22]. Jung et al. [21] observed that the natural lipid compound lysophosphatidylethanolamine (LPE) prolonged the freshness of persimmons by interfering with molecular mechanisms involved in the softening process. Specifically, LPE suppressed the expression of softening-related genes such as *ACSI*, *ACO1*, and *ERF24* (associated with ethylene synthesis and responses), as well as *DkUGD1*, *DkCHI3*, and *DkB-CHI1* (associated with starch degradation and sugar metabolism). Researchers observed this effect during fruit growth, after harvest, and even after extended post-harvest cold storage, demonstrating the significant potential of this technique for further exploration, including for overseas export trade. Another study found that combining heat treatment at 50 °C with immersion in a 1% carboxymethyl-chitosan (CM-C) solution was effective in maintaining the cold storage quality of persimmon, especially up to 40 days, based on freshness parameters such as soluble solids content, total titratable acid, firmness, soluble tannin, protopectin, peroxidase, polyphenol oxidase, and relative electrical conductivity [22]. Thus, this study demonstrated that combining different techniques can help extend the shelf life and expand the sales area of persimmons, reducing waste and economic losses.

During transportation, vibration damage can occur due to collisions between fruits and/or between fruits and the surrounding environment, resulting in impact, abrasion, and compression injuries [23, 24]. Mir and Shahbazi [25], further investigated the effects of different simulated vibration frequencies on persimmons, focusing on their impact on physical (weight, geometric mean diameter, surface area, and volume), mechanical (firmness and rupture force), and chemical properties (pH and total soluble solids) of fresh persimmons over 4 days at 20 °C. Among the main results, persimmons exposed to vibration frequencies of 5–15 Hz showed higher weight losses (2.12–3.26%) than control fruits (0.83%), along with greater increases in pH (21–33% vs. 7%) and total soluble solids (38–55% vs. 24%). At the same time, geometric mean diameter, surface area, volume, firmness, and rupture force decreased as vibration frequency increased [25]. Even the samples exposed to the lowest study vibration frequency (5 Hz) showed greater negative impacts on their properties than the control samples (without vibration stress) [25].

Martineli et al. [26] developed transport packaging with an exclusive format for persimmons and found that this packaging extended shelf life by up to 13 days compared to wooden and cardboard boxes, maintaining consumer acceptance and sensory quality up to the ninth day, whereas acceptance of fruits packed in wooden crates and cardboard boxes declined from the first and fifth days, respectively. These studies highlighted the importance of adopting strategies to improve transportation conditions and packaging types for persimmons, thereby maintaining quality, increasing shelf life, and reducing avoidable fruit losses [25, 26].

Proper post-harvest management is a key factor in the development of curing in persimmons [27]. Questions about the reactions that promote browning remain poorly elucidated. However, the mechanically induced damage in persimmon fruits seems to trigger the darkening of the pulp through the oxidation and polymerization of phenolic compounds by enzymatic action. In parallel, astringent fruits seem to be less sensitive to this disorder than fruits submitted to the astringency removal process, and the degree of tannin solubility seems to be a crucial factor in the manifestation of this disorder.

Han et al. [28] noted that deastringency treatment with a CO₂ atmosphere, although effective and convenient, often causes persimmon to brown rapidly. After CO₂ treatment, the authors observed an accumulation of insoluble tannins (from 1.64 ± 0.13 g/

kg in the control group to 9.22 ± 0.22 g/kg in the treated group), acetaldehyde generation, a decrease in phenolic compound content (from 13.19 ± 0.90 to 7.24 ± 0.047 g/kg), a reduction in phenylalanine ammonia lyase activity (from 175.33 ± 4.03 U/g in the control group to 136.83 ± 5.06 U/g in the treated group), an increase in polyphenol oxidase activity (from 3.94 ± 0.33 U/g in the control group to 22.22 ± 0.14 U/g in the treated group), superoxide dismutase activity (from 1.12 ± 0.024 to 2.91 ± 0.074 U/g), peroxidase activity (from 0.49 ± 0.011 to 22.79 ± 0.91 U/g), catalase activity (from 1.33 ± 0.05 to 53.00 ± 0.99 U/g), and malondialdehyde activity (from 3.08 ± 0.38 μ mol/kg in the control group to 6.09 ± 0.41 μ mol/kg in the treatment group). The levels of ascorbic acid (1.93-fold) and flavonoids (1.28-fold) also increased, demonstrating that these compounds play important roles in the browning process of persimmon fruit. The commercialization of persimmons is closely linked to their visual quality; therefore, the occurrence of blackened tissues, in addition to the deleterious effect on their appearance, can cause rotting during storage [26].

Fungal diseases are among the primary factors contributing to the decline in persimmon production. The main ones are caused by fungi such as *Alternaria alternata* and *Botrytis cinerea*. The disease can manifest itself as discoloration of the rind or as black, firm, dry patches of varying sizes and shapes found below the calyx or anywhere on the surface of the fruit's rind. Often, symptoms develop over prolonged storage periods [15, 29].

Another disease that can affect persimmon, under Brazilian conditions and worldwide, is anthracnose caused by species of the genus *Colletotrichum*. In persimmon, anthracnose can infect flowers, buds, branches, leaves, as well as unripe and ripe fruits, but the main damage to yield is due to premature fruit drop [29, 30]. Although uncommon, other fungi can also cause disease; for example, *Penicillium expansum*, *Rhizopus stolonifer*, *Cladosporium* spp., *Trichoderma* spp., and *Mucor piriformis* [31, 32].

As discussed previously, the harvest of persimmons is short and intense in different regions worldwide [33, 34], which hinders its development and appreciation. Therefore, adopting techniques to preserve post-harvest quality is crucial for extending the fruit's supply period and reducing price seasonality. In addition, reducing persimmon losses through tools that delay its maturation and preserve its quality throughout the production and supply chain is of great interest, as it can mitigate environmental, social, and economic impacts [11, 13].

Given the mechanisms that govern the physiology and biochemistry of persimmon maturation and the factors that hinder its commercialization, techniques need to be developed to delay browning, inhibit pathogen growth and ripening, and inhibit the biosynthesis or action of ethylene. Furthermore, such approaches must consider and preserve the physical, nutritional, and sensory aspects [35–37].

2.1 Postharvest preservation techniques and their effects on persimmon quality

Several studies have been published in recent years, proposing chemical and physical approaches to extend the storage life of persimmons. Postharvest management strategies involve a variety of thermal, non-thermal, and chemical/hormonal treatments aimed at preserving quality, maintaining nutritional and sensory properties, and enhancing the retention of bioactive compounds [34, 38–43]. Table 1 highlights recent studies that

Table 1 Persimmon preservation strategies developed to increase its storage life

Applied technology	Cultivar	Impact on persimmon quality	Refer-ences
Cold storage after high hydrostatic pressure treatment	Persimmon fruit cv. "Rojo Brillante"	HHP treatment does not prevent the loss of total phenolic, carot-enoid content, and antioxidant capacity in persimmon samples stored at 4 °C for 28 days	[34]
Cold storage com-bined with hot water and calcium lactate	Persimmon fruit cv. 'Karaj'	Maintenance of antioxidant properties, soluble tannin, carot-enoid, and ascorbic acid levels stored at 1 °C for 40 days	[38]
Freeze-drying	Persimmon fruit cv. "Rojo Brillante"	The freeze-drying process maintains bioactive compound levels during storage for 3 months	[39]
Inside-out heat-shock via microwave	Persimmon fruit cv. "Huoshi"	After storing persimmons for 9 days at 25 °C, it can be concluded that the heat shock treatment helps to remove astringency, reduce cellulose and pectin degradation, and inhibit cellulase activity. It enhances postharvest persimmon quality by improv-ing fruit firmness and sensory attributes	[40]
Freezing	Persimmon fruit cv. "Daebong"	Freezing at -20 °C and – 80 °C for 15 to 60 days is a potential method for removing persimmon astringency without deterio-rating fruit quality. During storage, the soluble tannin content decreased, while the physicochemical parameters remained unchanged	[41]
Exogenous ap-plication of hydro-gen sulfide and γ-aminobutyric acid	Persimmon fruit cv. "Karaj"	Persimmon fruit treated with H ₂ S and GABA exhibited lower chilling injury manifested by lower peel browning, accompanied by higher total soluble solids (TSS) and titratable acidity (TA) dur-ing storage at 2 °C for 45 days	[42]
Methyl jasmonate treatment	Persimmon fruit cv. "Karaj"	Postharvest treatment of MeJA significantly decreases the CI of persimmon stored for 120 days at 1 °C. Additionally, it preserves physicochemical characteristics, maintains total phenolic com-pounds, and enhances antioxidant capacity	[43]

have explored strategies to extend persimmon storage life, such as refrigeration and freeze-drying [26, 44].

Cold storage combined with high hydrostatic pressure modifies persimmon tissue microstructure, breaking some cell walls and organelle membranes, which enhances the extractability of carotenoids in astringent tissues and potentially increases their bioac-cessibility [34]. Although HHP preserves sensory quality and facilitates bioactive com-pound release, this non-thermal treatment also may lead to a significant decrease in phenolic content. Garcia-Cayela et al. [34] observed that during storage, HHP-treated persimmons continue to lose total phenolics, independently of pressurization time, and carotenoid levels diminish similarly in both treated and control fruits over 28 days. While cold storage combined with hot water and calcium lactate treatments effectively maintain firmness and overall fruit quality [38]. Hot water treatments alleviate internal browning and delay senescence by modulating enzymatic activities (e.g., catalase, ascor-bate peroxidase, peroxidase, pectin methylesterase, and polygalacturonase), whereas cal-cium lactate improves textural attributes without causing bitterness, as observed with calcium chloride [38].

Freeze-drying preserves persimmon slices by removing water at low temperatures, but due to the thermoplastic behavior of the resulting amorphous matrix, phase transitions from a glassy to rubbery state can lead to textural loss [39]. Understanding water sorp-tion isotherms and critical water activity values is essential to ensure stability of physi-cal properties and bioactive compounds during storage [39]. Inside-out heat-shock via

microwave offers rapid, uniform heating with minimal nutrient loss and reduced enzymatic activity [40]. This method delays fruit softening and postharvest ripening more efficiently than conventional outside-in heat treatments, although its mechanisms in persimmons require further study [40]. Tang et al. [45] proposed a freezing pretreatment at -80°C prior to vacuum microwave drying of persimmons to mitigate browning and improve texture, appearance, and physical properties.

Freezing treatments have been shown to remove astringency by decreasing soluble tannins and increasing insoluble tannins without compromising overall fruit quality [41]. For example, storage at -20°C decreased soluble tannins from 4.59 to 3.52 mg/g DW, and at -80°C from 4.18 to 3.34 mg/g DW, compared with 11.68 mg/g DW in control fruits. These treatments produce non-astringent fruits suitable for long-term preservation.

Chemical and hormonal postharvest treatments, including exogenous applications of hydrogen sulfide (H_2S), γ -aminobutyric acid (GABA) [42], and methyl jasmonate (MeJA) [43], have been used to modulate fruit physiology and enhance quality during storage. The H_2S and GABA act as signaling molecules that alleviate chilling injury, retard senescence, and maintain firmness, while promoting antioxidant enzyme activity and the accumulation of phenolic compounds, flavonoids, and anthocyanins. While MeJA, a plant hormone applied exogenously, enhances cold tolerance, activates heat shock proteins, increases antioxidant enzyme activities, and modulates membrane fatty acid composition, collectively reducing chilling disorders and preserving overall persimmon quality.

In summary, these postharvest preservation techniques, thermal, non-thermal, freezing, and chemical/hormonal treatments, demonstrate complementary mechanisms to maintain persimmon quality. They help preserve firmness, color, bioactive compound content, and antioxidant activity, while reducing astringency, chilling injury, and senescence, ultimately extending shelf life and marketability.

3 Packaging strategies for persimmons: technology, design, and sustainability

This topic examines various packaging strategies for persimmons, focusing on the technologies, designs, and sustainability aspects of these methods.

Nearly half of Europe's plastic production is used for packaging. Nevertheless, reliance on fossil-based polymers with limited biodegradability has become a significant contributor to environmental damage and potential health risks [46]. In response to these issues, innovative packaging technologies have been developed, including active, smart, and edible systems designed to interact directly with fruits, vegetables, and their surroundings [47]. Active packaging includes functional agents like antimicrobials, oxygen scavengers, and ethylene absorbers to slow spoilage and suppress microbial growth [46]. Conversely, smart packaging uses indicators or sensors to track freshness, gas levels, and temperature, providing real-time updates on product quality [47]. Edible coatings and biopolymeric films, often made from polysaccharides, proteins, or lipids [48], act as semi-permeable barriers that help reduce moisture loss, respiration, and oxidative reactions [49]. These innovations work together to extend shelf life, preserve firmness, flavor, and nutritional value, and reduce postharvest waste. They also support sustainability by cutting plastic use and promoting a circular economy [50, 51]. Recent reviews highlight

that these new packaging systems improve preservation, build consumer confidence, and enhance food safety, making them crucial tools in the modern supply chain for perishable crops such as persimmons [47, 49, 51].

The role of packaging in prolonging the postharvest life of persimmons is crucial, as it effectively slows their climacteric ripening and softening. Persimmons undergo rapid ethylene-mediated softening after harvest, resulting in a short marketable window and high perishability [52]. The creation of controlled microenvironments and protective barriers by packaging strategies has been demonstrated to mitigate these effects. For instance, the application of MAP in combination with ethylene action inhibitors has been shown to retard persimmon ripening. In the 'Youhou' sweet persimmons, studies have shown that applying 1-MCP followed by MAP significantly reduces chilling injury and helps maintain higher fruit firmness during cold storage [53]. This effectiveness is attributed to the ability of these methods to inhibit ethylene action and reduce oxygen availability, which, in turn, slows respiration and softening of the fruit. These findings highlight the combined effectiveness of ethylene inhibition and atmosphere modification in extending persimmon shelf life. However, it is essential to note that while MAP has been observed to alleviate persimmon's cold-storage disorders, it may not eliminate them if conditions are suboptimal [14, 53]. The optimal packaging atmosphere must be tailored to the physiology of the persimmon tree, which is typically characterized by moderate oxygen (O₂) and elevated carbon dioxide (CO₂) levels. This is necessary to delay the onset of senescence without inducing off-flavors or flesh browning (chilling injury). In practice, even passive MAP (natural atmosphere modification within a semi-permeable package) has shown benefits in refrigerated persimmon storage, improving firmness retention over time [44]. Overall, controlling the gas composition around the fruit constitutes a cornerstone of persimmon packaging strategies, particularly in managing ethylene and respiration-driven softening.

A variety of edible coatings and films have been researched as alternatives or supplements to conventional packaging for persimmons, using bio-based polymers to create a thin protective layer on the fruit. These coatings function as semi-permeable barriers to moisture and gases, thereby reducing water loss, slowing respiration, and delaying oxidative reactions. Polysaccharide and gum-based coatings have been especially successful. The study by Elabd and Gomaa [35] demonstrated that a guar gum-based edible coating significantly extended the shelf life of persimmon by minimizing weight loss and preserving firmness [35]. In this study, the application of 0.5% guar gum reduced weight loss to 0.96%, whereas the control (uncoated samples) showed a weight loss of 2.4% after 3 days of storage. This treatment also had a positive effect on persimmon firmness, maintaining a firmness of 4.6 N compared with the control, which exhibited a firmness of 2.3 N after 15 days of storage [35]. Similarly, Results from Saleem et al. [52] indicated that persimmons coated with 10% gum arabic exhibited ripening, as evidenced by a 1.57-fold reduction in physiological weight loss, 1.32-fold lower membrane leakage (indicating reduced membrane degradation), and a 1.99-fold lower ripening index compared with uncoated controls during storage. These findings reinforce the role of gum arabic in maintaining structural integrity and slowing senescence. Furthermore, the coated fruits exhibited a higher retention of ascorbic acid (decrease was lesser in 1.4-fold than noncoated fruits) and phenolics (higher 1.44-fold TPC than the noncoated control), on day 20 suggesting a preservation of their nutritional and antioxidant properties [52].

Another natural coating material identified as potentially useful is Aloe vera gel. Findings from the Aloe vera coating study revealed that high concentrations of Aloe vera gel markedly delayed fruit softening, confirming its effectiveness as a natural preservative barrier. Aloe-coated fruits exhibited significantly less weight and firmness loss during 20 days at ambient temperature, alongside lower malondialdehyde (a lipid peroxidation marker) accumulation and higher antioxidant enzyme activity relative to untreated fruit [52]. The findings of this study suggest that Aloe vera gel, rich in polysaccharides and bioactive compounds, creates a moisture-retentive, antioxidative barrier that slows senescence. The effectiveness of composite coatings that combine polysaccharides and other bio-based gums can be further enhanced. For instance, researchers have experimented with mixtures such as tragacanth gum and Aloe vera, which have been shown to yield synergistic effects in suppressing persimmon respiration and ethylene production whilst maintaining fruit firmness and nutritional quality [8]. It is noteworthy that edible coatings typically assist in preserving TA and retarding the increase in TSS, thereby influencing the ripening index of persimmon fruits [8, 52]. The selection of appropriate coating concentrations and formulations is crucial, as overly thick coating can create anaerobic conditions or off-flavors. However, studies to date have reported that properly formulated edible coatings are both sensory-neutral and effective in preserving persimmon quality [35, 52].

In addition to passive coatings, active coating formulations have been developed to impart antimicrobial or antioxidative functions, thereby extending the shelf life of persimmon. One such innovation involves incorporating nanoparticles or natural extracts into the edible film matrix. The study by Saekow et al. [37] demonstrated that applying carboxymethyl cellulose (CMC) coating infused with zinc oxide nanoparticles (ZnO-NPs) successfully extended shelf life and suppressed disease, confirming the dual functionality of nanocomposite coatings in persimmon preservation. Results indicated that the CMC-ZnO coating significantly reduced weight loss (CMC, 10.4%; CMC-ZnO, 9.9% vs. 14.8% control) and respiration rate, thereby helping maintain higher firmness levels. This finding suggests that ZnO nanoparticles enhance the barrier properties of CMC coatings while providing antimicrobial protection. In addition, the onset of black spot disease, which is caused by *Alternaria* fungus, was significantly delayed in coated fruit in comparison to uncoated fruit [37]. The ZnO-NPs in the coating are likely to exert antimicrobial action against fungal spores and promote antioxidative effects that protect the fruit's cellular integrity. It is worth noting that the nanocomposite coating did not have a detrimental impact on the fruit's appearance; instead, it provided a protective layer that was almost invisible to the naked eye. In a similar vein, silver nanoparticles (AgNPs) synthesized from persimmon processing by-products have been investigated as active packaging additives. As demonstrated by Ramachandraiah et al. [54], AgNPs derived from persimmon peel and calyx extracts can be incorporated into a biodegradable alginate film without compromising its mechanical properties. The resulting nanocomposite film demonstrated enhanced antioxidant capacity and has been proposed for use in food packaging to inhibit microbial growth on produce surfaces [54]. Although the direct application of AgNP-infused films to persimmon fruit has not yet been documented, possibly also due to legal and food-safety constraints, this approach demonstrates that persimmon waste can be upcycled into active packaging components, thereby aligning with the principles of the circular economy. In addition to nanoparticles, other natural

agents (e.g., essential oils or plant extracts with antimicrobial properties) could be incorporated into persimmon packaging.

To date, the existing literature on active packaging specifically for persimmons is limited. However, well-known solutions from other climacteric fruits (such as ethylene-absorber sachets containing potassium permanganate or activated clay) are likely applicable. The incorporation of an ethylene scavenger into persimmon packaging material could slow ripening, particularly during long-distance shipping. This deceleration can be attributed to the continuous removal of ethylene gas, a by-product of persimmon storage, by scavenger. In general, edible and active coatings offer a biodegradable, consumable packaging option that can significantly retard persimmon softening, maintain nutritional quality, and reduce microbial spoilage [35, 37]. These coatings frequently utilize edible biopolymers, such as pectin (a predominant component of persimmon), starch derivatives, gums, and chitosan, thereby aligning with consumer demand for natural and safe postharvest treatments.

It is essential to recognize the importance of physical protection during the handling and transportation of persimmon packaging. Persimmons are relatively delicate fruits. As they reach maturity, the flesh of the fruit softens and becomes susceptible to bruising and internal ruptures when subjected to mechanical stress. It is essential to note that vibration- and impact-induced damage during transportation can lead to rapid deterioration in quality, even with a cold chain and protective coatings. Simulated transit vibration tests have demonstrated that persimmons exposed to repeated vibrations exhibit accelerated deterioration in quality. Fruit subjected to vibration frequencies exhibited significantly higher weight loss, increased pH (indicating loss of acidity), and higher TSS (suggesting advanced ripening), alongside reduced firmness and rupture force, compared to non-vibrated controls [25]. As the vibration intensity increased, these negative changes became more pronounced, with severe softening and volume reduction observed at higher frequencies [25]. Furthermore, mechanical jolts have been demonstrated to trigger physiological disorders in persimmon flesh.

Impact bruising has been linked to the development of flesh browning and gelling in persimmons, particularly if they have undergone CO₂ deastringency treatment, which renders the flesh more susceptible to oxidative darkening [27]. It is therefore vital that the packaging design minimizes movement and provides adequate cushioning for the fruit, considering the product's specific needs. Innovations in transport packaging for persimmons have led to quantifiable improvements.

Martineli et al. [26] developed an optimized persimmon transport container featuring an exclusive cavity design (a thermoformed tray and a recycled polyethylene frame with fiber reinforcement) tailored to the fruit's shape and size. This specialized packaging significantly reduced the movement and impact of the fruit during transit. As a result, persimmons shipped in the new design maintained their sensory quality much longer than those in standard crates: consumer acceptance for appearance remained high for ~ 9 days in the new packaging (versus only 1–5 days for fruits in traditional wooden or cardboard boxes), and overall shelf life was extended by up to 13 days relative to conventional packaging [26]. Custom packaging achieved this by preventing abrasion and compression damage, thereby slowing external shriveling and internal textural breakdown.

Other studies on packaging materials also emphasize the importance of cushioning and stabilizing fruits. Foam inserts, corrugated dividers, or bio-based padding can

absorb shocks and vibrations, thereby reducing the incidence of bruising. It is also beneficial to limit the stacking height and secure the load to avoid excessive pressure on the bottom layers. For persimmons, each layer of fruit is often separated with soft liners or trays in commercial packs, which helps distribute forces. The evidence clearly indicates that improved mechanical protection in packaging extends persimmon postharvest life and improves firmness and visual quality retention [25, 26]. In summary, these studies demonstrate that integrating shock-absorbing design features, such as molded trays, padding materials, and tight-fit compartments, is essential for minimizing transport-induced losses and maintaining persimmon quality throughout the supply chain.

From a sustainability and circularity perspective, the challenge is to achieve these preservation benefits with minimal environmental cost. Persimmons, like many fresh produce items, have historically been sold with little to no packaging (aside from bulk crates), which raises the question: Is additional packaging justified? The answer depends on balancing the packaging's footprint against the food waste reduction it enables. Persimmon production is resource-intensive (land, water, energy for inputs), and any fruit lost to spoilage carries a hidden environmental burden. If a small amount of packaging can prevent a much larger amount of fruit waste, the net ecological outcome is often favorable. Indeed, life-cycle assessments in food supply chains have shown that the carbon and water footprints of the food typically far exceed those of the packaging protecting it [55]. In the case of persimmons, using a 15–20 g plastic tray or a biopolymer film to prevent the waste of 150 g of fruit is ordinarily a beneficial trade-off, given the greenhouse gas emissions saved. However, it should be noted that the net benefit of such measures depends on two factors: first, the packaging's efficacy in reducing waste, and second, the use of environmentally sustainable materials. The issue of overpackaging, defined as the excessive or unnecessary use of plastics, can erode consumer trust and even increase waste.

Recent research has successfully recovered high-methoxyl pectin from Rojo Brillante persimmon waste and suggested its suitability for film-forming and coating applications [16]. Conversely, as previously mentioned, persimmon by-products have been transformed into nanoparticles and integrated into films, thereby enhancing functionality without the utilization of petroleum-based additives [54]. Concurrently, other research in the field of fruit by-products (e.g., the incorporation of *Opuntia* cactus flour into starch films) has demonstrated that agricultural waste can enhance the mechanical strength of films and impart antioxidant activity, thereby reducing reliance on synthetic polymers or additives [56]. In the future, a holistic life-cycle assessment (LCA) approach is recommended for the implementation of new packaging for persimmons. Such assessments encompass a comprehensive evaluation of raw material production, manufacturing processes, transportation logistics, and end-of-life considerations. Ultimately, these findings suggest that any innovation, whether an edible coating, a nano-enabled film, or a new tray, must demonstrate a net positive outcome by extending shelf life and reducing fruit losses enough to offset the environmental impacts of its production and disposal.

In summary, persimmons benefit from a multifaceted packaging strategy (as shown in Fig. 1) that combines atmosphere management, edible coatings, active functionalization, and mechanical protection, all while adhering to sustainability goals. The following design guidelines distill best practices for persimmon packaging:

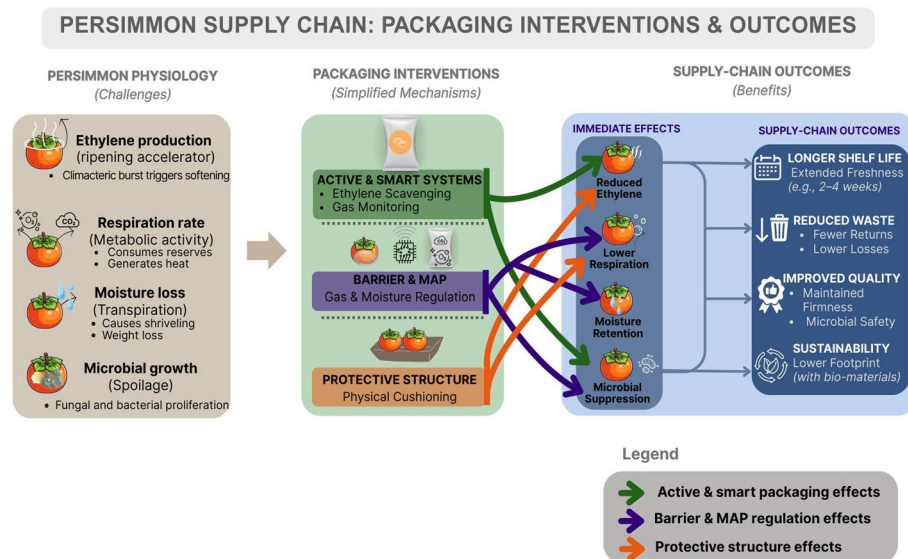


Fig. 1 Framework summarizing persimmon postharvest challenges, packaging interventions, immediate physiological responses, and resulting supply chain outcomes

- **Cushioning & shock absorption:** Use fruit-specific trays, padding (e.g., foam or biofoam liners), and secure stacking to minimize vibration and impact damage. This preserves firmness and prevents internal bruising during transit [25, 26].
- **Modified atmosphere control:** Implement MAP with appropriate gas permeability or active gas modulation to reduce O_2 and elevate CO_2 around the fruit. This slows respiration and ethylene action, delaying ripening and chilling injury (especially when combined with 1-MCP treatment) [53]. Ensure the gas mix is optimized to avoid CO_2 -induced flesh browning.
- **Edible coatings:** Apply natural edible coatings (e.g., gum arabic, Aloe vera gel, pectin-based, or chitosan coatings) to individual fruits. These coatings act as an “invisible film,” reducing moisture loss and oxidation. They effectively maintain firmness and nutritional quality without the need for synthetic packaging and are safe for consumption [8, 52].
- **Active packaging elements:** Incorporate ethylene scavengers (sachets or ethylene-absorbing films) inside persimmon packages to actively remove ethylene and further slow the climacteric ripening. Similarly, consider antimicrobial inserts or coating additives (e.g., ZnO or essential oil emitters) to suppress decay and extend shelf life, provided they are proven safe and effective for persimmons [37].
- **Sustainable materials & design:** Favor packaging made from recyclable or compostable materials. Bio-based and biodegradable films (e.g., those made from starch, polylactic acid, or persimmon-derived polysaccharides) and fiber/pulp trays can replace conventional plastics, thereby reducing environmental impact. Design packages for easy separation of materials (for recycling) and minimal excess material, while still protecting the fruit. Continually assess whether the added packaging yields a net reduction in food waste; the goal is to prevent more waste (and emissions) than the packaging generates.

By implementing these strategies, the persimmon supply chain can reduce postharvest losses and deliver high-quality fruit to consumers over longer distances and for longer storage durations. It should be noted that packaging is just one component of an integrated postharvest approach: it works best in concert with other preservation methods (Topic 1 of this review, e.g., cold storage, treatments) and feeds into the valorization efforts (Topic 3, value-added products) by ensuring that more fruits meet quality standards for processing and sale. When appropriately used, packaging innovations for persimmons exemplify sustainable technological solutions that extend shelf life, improve economic returns, and minimize environmental footprint, aligning with the broader goals of a more sustainable circular bioeconomy for food packaging concepts.

4 Generation of technological and biotechnological value-added products from persimmon within circular economic principles

Interest in the development of value-added products has been growing substantially among both small and large producers, as this sector enables them to utilize excess fresh raw materials to manufacture ready-to-eat products, capture losses from non-tradable products, offer customers more options, and, above all, increase profitability. Especially for persimmons, significant improvements have been made in post-harvest techniques and storage methods; however, seasonality remains a significant disadvantage. In this way, the development of technologically innovative and sustainable persimmon products has gained special attention [40, 57, 58].

Several persimmon-derived products are being developed, including dried persimmons, smoothies, sauces, juices, and purees for making jellies, cakes, pastries, breads, and even biodegradable food coating materials. In addition, because of the growing cultivation and industrialization of this fruit and the generation of waste, which consists mainly of peel and stem, some research has focused on the use of persimmon waste to produce vinegar, persimmon husk flour to be used as functional food ingredients, fibers from the bark, and extracts [11, 19, 59].

The recovery of industrial persimmon waste may also be used as a substrate for the growth of microorganisms and the production of secondary metabolites of commercial interest. There is considerable interest in developing technologies for energy production that utilize agro-industrial biomass as raw material. Bioethanol, for example, is the most used biofuel worldwide, and it can be used alone or mixed with other conventional fuels, as it has the advantage of reducing CO₂ emissions and pollutants in the atmosphere. Current trends in the production of this biofuel focus on the development of processes to obtain bioethanol from renewable resources at reasonable costs: particularly, waste containing lignocellulosic and cellulosic materials could be used as a raw material [19, 60].

A different approach for the valorization of persimmon involves the potential application of crude extracts with specific active principles, naturally present in this food matrix, for the manufacture of functional products, nutraceuticals, cosmeceuticals, and other high-value products [61, 62].

Currently, extraction can be performed using conventional and alternative methods, including enzymes, pressurized liquids, ultrasound, microwaves, pulsed electric fields, supercritical fluids, and other treatments. The disadvantages presented by conventional extraction (large solvent and energy consumption, and a long production cycle)

are increasing interest in exploring new methods and technologies. Green extraction technologies, such as autoclave and ultrasonic extraction, are increasingly employed to improve extraction efficiency while providing economic and environmental benefits [63–66].

Studies indicate that ultrasonic extraction can increase the yield of bio-compounds, including carotenoids, betalains, and polyphenols, from diverse matrices as it acts by producing cavitation in the biological matrix, as well as shock waves and mixing phenomena [64, 67]. Autoclaving was recently introduced and has been shown to extract bioactive substances more efficiently than previously studied methods. This method uses pressure and temperature, enhancing the contact between the solvent and the raw material, thus increasing the extraction yield [68].

Figure 2 illustrates how the application of different processing and extraction methods, either individually or in combination, promotes specific physical, chemical, and biological mechanisms that enable the generation of multiple value-added products from persimmon fruit within a circular economy framework.

In this context, Table 2 summarizes the main bioactive compounds and value-added products obtained from persimmon, highlighting the processing and extraction techniques employed, the types of compounds recovered, products developed, and their respective applications. Physical and chemical processing strategies, such as high hydrostatic pressure, thermal treatments, and acid extraction, have been successfully applied to recover carotenoids and pectin [6, 16]. The incorporation of persimmon flours and extracts into food matrices has enabled the development of functional products, including pasta, bakery items, and confectionery, enriched with polyphenols and dietary fiber and associated with improved nutritional and technological properties [18, 69, 70].

Biotechnological and green synthesis approaches further demonstrate the versatility of persimmon, notably through the production of AgNPs and the development of biodegradable films with antimicrobial activity, underscoring the potential of persimmon valorization within circular economy frameworks [54, 72, 73]. In addition, persimmon-derived tannins and phenolic extracts have shown promising bioactivities, such as antimicrobial effects and modulation of glycemic response, supporting their application in nutraceuticals and functional foods [66, 68]. Finally, non-food applications, including eco-friendly textile dyeing and environmental remediation through activated carbon production, further highlight persimmon as a renewable and multifunctional resource for the generation of value-added products [78, 79].

Within the food system, the recovery of FLW implies that a significant portion of the edible food has already been wasted within the food supply chain, resulting in lost money and resources. However, in the context of the circular economy in food systems, the underlying principle is that sustainability is directly linked to economic growth. Therefore, the idea is not only to use underutilized agriproducts, but also to recover by-products and avoid losses by reintroducing them into the economic cycle, taking full advantage of their value and utility along the chain [80, 81]. However, integral valorization, process efficiency, biorefinery strategies, zero-waste economy, and the cradle-to-cradle design model represent new perspectives that must be better structured and rethought to encourage greener, sustainable production processes [82, 83]. In this sense, the circular economy promises to be an efficient option in the medium and long term for

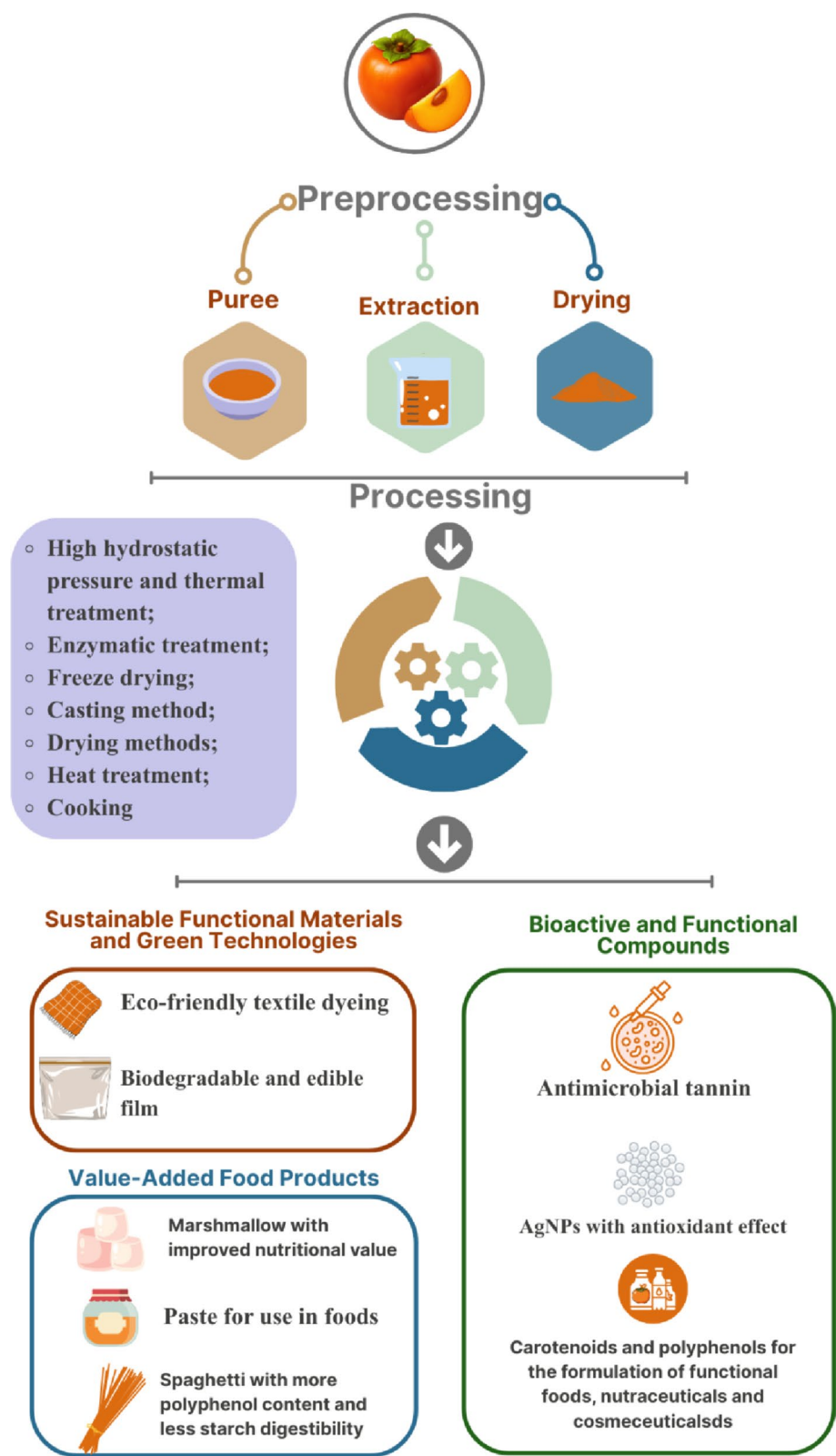


Fig. 2 Applying different methods or combining them can yield numerous value-added products from persimmon fruit

Table 2 Bioactive compounds and value-added products derived from persimmon, including processing, extraction methods and applications

Compound or product	Processing/extraction method	Application	References
Carotenoids and carotenoid esters	High hydrostatic pressure and thermal treatment	Functional ingredients; nutritional enrichment	[6]
Pectin	Acid extraction and purification	Soluble dietary fiber; prebiotic ingredient; film-forming material	[16]
Polyphenol-rich food ingredients (dietary fiber)	Incorporation of persimmon flour into pasta	Functional spaghetti with reduced starch digestibility	[18]
Silver nanoparticles	Green synthesis using persimmon by-products	Antimicrobial additives incorporated into biodegradable food packaging films	[54]
Dietary fiber and polyphenols Food product	Incorporation of persimmon paste	Bakery products with improved physical properties	[69]
	Drying and formulation	Marshmallow with improved nutritional value	[70]
Carotenoids	Juice processing and extraction	Nutraceutical ingredients; functional beverages	[71]
Biopolymeric packaging materials	Film formation using persimmon pulp	Biodegradable edible films for food packaging applications	[72]
Biopolymeric packaging materials	Food ingredient (Persimmon powder)	Antibacterial biodegradable films for food packaging	[73]
Insoluble and soluble fiber fractions	Drying and milling	Commercial fiber ingredient for food formulations	[74]
Persimmon tannins	Extraction of tannin-rich fractions	Management of postprandial hyperglycemia	[75]
Polyphenols and dietary fiber	Drying and milling of persimmon by-products	Functional food applications	[76]
Condensed tannins	Extraction of tannin-rich extracts	Antimicrobial activity against methicillin-resistant <i>Staphylococcus aureus</i>	[77]
Peel extract as a reductant for indigo dyeing	Aqueous thermal extraction	Eco-friendly textile dyeing	[78]
Activated carbon	Thermal treatment and activation	<i>Diospyros kaki</i> seeds to high surface area activated carbon for removing atrazine from synthetic solutions and river waters	[79]

management and recovery, and it should suggest solutions to overcome difficulties, such as the reuse of this waste during implementation [11, 84, 85].

5 Limitations and research gaps

Although circular economic approaches offer considerable potential for the persimmon food system, including by-product valorization into functional ingredients and bioenergy, most proposed recovery strategies remain at an early stage of technological development. Approaches such as edible coatings, active packaging, and bioactive or nanoparticle-based treatments have been mainly evaluated at laboratory or pilot scale, with limited evidence of industrial scalability and robustness. This indicates a research gap in industrial validation and highlights the need for future studies focusing on scale-up, process integration, and long-term performance under real processing conditions.

Economic and regulatory aspects are also insufficiently addressed in the current literature. While many studies emphasize functional and physicochemical performance, comprehensive techno-economic analyses, regulatory assessments, and consumer acceptance evaluations are often absent. Future research should therefore integrate economic feasibility and regulatory compliance considerations alongside technological development to enable realistic commercialization pathways.

Environmental sustainability assessments within persimmon-based food systems remain fragmented. Key environmental impacts related to greenhouse gas emissions, land use, water consumption, energy demand, transportation, and cold storage are frequently overlooked or assessed in isolation, despite their relevance to sustainability outcomes [86]. This limitation reveals a need for future research adopting a systems-based perspective that captures the whole value chain from agricultural production to end-of-life management. Closely related to this issue is the limited availability of comprehensive LCA studies tailored to persimmon supply chains. Existing analyses often rely on partial system boundaries, restricting their ability to identify environmental trade-offs and risks of burden shifting. Future work should focus on developing standardized, product-specific life-cycle inventories and assessment frameworks for persimmon-derived products.

Finally, despite the growing relevance of digitalization in sustainable food systems, the application of digital product passports remains unexplored. The absence of structured and verifiable lifecycle data limits traceability and accountability [87, 88]. Future research should investigate the integration of digital product passports as tools for life-cycle data management, sustainability monitoring, and policy alignment, as suggested in broader circular-economy and manufacturing contexts.

6 Conclusion

This review highlights the transformative potential of persimmons as a model for sustainable innovation in the food system. The synthesized evidence indicates that postharvest preservation strategies, including edible and active coatings, modified atmosphere packaging, ethylene management, and controlled processing techniques, are effective in delaying ripening, reducing physiological disorders, and minimizing microbial decay. Additionally, tailored packaging designs that combine atmosphere control, mechanical protection, and bio-based materials contribute to extended shelf life and reduced transport-related losses. Beyond concerns related to persimmon freshness, persimmon by-products have been identified as valuable feedstocks for the recovery of functional fibers, pectin, carotenoids, polyphenols, antimicrobial tannins, and biopolymeric materials, as well as for the production of AgNPs and second-generation bioethanol. Overall, these findings indicate that persimmon valorization is not limited to food applications but also includes promising opportunities in packaging, nutraceuticals, cosmetics, and environmental sectors. Importantly, the integration of preservation technologies with by-product valorization aligns strongly with circular economy principles, offering concrete pathways to reduce food loss and waste while increasing economic value. However, this review also identifies critical gaps, including the limited industrial-scale implementation of emerging technologies, the lack of comprehensive life-cycle assessments, and insufficient evaluation of economic and regulatory feasibility. The environmental and social implications of packaging interventions must be critically evaluated to ensure that they contribute positively to the food system. Future research should focus on life cycle assessments, regulatory feasibility, and scalable applications to fully realize the potential of persimmon-based technologies. Ultimately, the approaches discussed here provide a replicable framework for other perishable fruits, promoting resilient, circular, and economically sustainable food systems.

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Author contributions

C.M.S. contributed to the conceptualization, data curation, and writing of the original draft, as well as the preparation of Figure 2. J.R.V.M., T.S.P.S., and A.S.B. were responsible for the literature review, data collection, and writing of the original draft. P.M.F. contributed to the data curation and writing of the original draft, including its review and editing. M.S. worked on the packaging and sustainability sections and was involved in funding acquisition. A.E.C.F. contributed to conceptualization, data curation, funding acquisition, resource management, writing (review and editing), supervision, and project administration. All authors reviewed and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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