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REVIEW ARTICLE

Edible coatings: Classification, applications and innovations in food preservation

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Abstract

The health of every individual heavily depends on the consumption of fruits. Although fruits are exceptionally healthy, their perishable characteristics pose difficulties for prolonged storage. Ineffective post-harvest techniques can impede the supply chain, leading to considerable losses for producers. Therefore, there is an urgent need to reduce post-harvest losses to enhance agricultural productivity. Conventional post-harvest treatments involving synthetic chemicals are increasingly being recognized for their potential negative impacts on human health. In response, the use of bio-based edible coatings derived from plant materials is gaining significant attention and encouragement. Edible coatings effectively extend the shelf life of fruits by controlling oxidation, moisture loss and gas exchange. Coatings enriched with bioactive materials create an additional protective layer that slows down respiration rates, thereby prolonging the freshness of the fruits. This review provides an abridged overview of edible coatings, discussing their applications and classifications and concludes by emphasizing chitosan as one of the most effective compounds. Additionally, the review explores innovative materials and nanotechnology-based edible coatings, along with their application techniques for various fruits. These advancements aim to address supply chain challenges and enhance food security.

Keywords

edible coatings; fruits; postharvest; pre-harvest; shelf life

Introduction

Fruits are vital to human nutrition, providing a significant source of energy, dietary fiber and essential micronutrients, including minerals, vitamins, phytochemicals and flavonoids (1). In recent years, the importance of horticultural products in daily diets has increased substantially due to their health benefits, which include flavor compounds, antioxidants and crucial nutrients (2). Furthermore, the post-harvest treatment market has experienced strong growth, with the market size expected to increase from $1.59 billion in 2023 to $1.74 billion in 2024, at a compound annual growth rate (CAGR) of 9.7% (3). Fruits, especially those with high water content

(≥75%), are highly perishable and prone to rapid deterioration due to factors such as transpiration, insect damage, respiration and microbial activity (4).

Fruits are classified based on their maturation mechanisms into climacteric and non-climacteric types. Climacteric fruits, such as bananas, mangoes and apples, undergo significant post-harvest ripening driven by ethylene, while non-climacteric fruits, like grapes, citrus and strawberries, cease ripening once harvested, requiring different storage and handling techniques. Climacteric fruits ripen rapidly after harvest, becoming more susceptible to microbial infections and spoilage (5). This accelerated ripening and subsequent deterioration present considerable challenges for postharvest handling, leading to significant economic losses and food insecurity. Currently, only 30% of total fruit production is consumed, with postharvest losses being even more pronounced in developing nations. These losses highlight the critical need for effective postharvest management to reduce waste and enhance food security (6).

Several factors influence the shelf life of fresh produce, including the variety of the crop, its maturity level, the ripening phase and handling practices. External conditions, such as atmospheric factors (ethylene levels, temperature, O_2, CO_2) and stress factors, also play a significant role in the preservation of fruits. Issues such as moisture loss, microbial deterioration and enzymatic browning intensify further complicate the preservation of fruit quality during handling, storage and transportation. Citrus fruits, such as lemons and blood oranges, are particularly susceptible to chilling injuries during cold storage. For example, lemons may develop internal cavities, skin discoloration and brown sunken spots on the peel after prolonged exposure to cold. Blood oranges are especially vulnerable to cold stress, exhibiting chilling injury symptoms at temperatures as low as 5°C, which can lead to significant quality degradation (7).

To address these challenges, bio-based edible coatings have been developed as a solution to extend the shelf life of fruits and vegetables (8). The amalgamation of edible coatings with nanotechnology breakthroughs presents numerous advantages, such as enhanced water barrier attributes, augmented mechanical strength and regulated release of bioactive compounds . Natural coatings, derived from biodegradable sources such as waxes, gums and plant extracts, provide both consumer safety and environmental sustainability. In contrast, synthetic coatings, often made from petrochemical components, require stricter safety regulations to ensure their suitability for human health and the environment. The growing consumer preference for natural coatings, using ingredients like beeswax and carnauba wax, is driven by increasing interest in eco-friendly and natural products (9).

Chitosan's ability to form films allows it to create a semi-permeable layer on fruits, effectively controlling gas exchange and reducing respiration rates. This property prolongs ripening and maintains fruit quality longer than other bio-based polymers, such as alginate, which may lack equivalent control over gas permeability. Regulating respiration is crucial for extending the shelf life of fruits during storage and transportation (10). This review offers an in-depth analysis of the effects of these compounds on prolonging the shelf life of fruits, emphasizing their roles in reducing postharvest losses, enhancing fruit quality and tackling global issues with food security and sustainability.

Edible coating

The use of edible coatings in China dates back to the 12th century. However, it wasn't until 1922 that edible coatings were officially recognized, with the introduction of fruit waxing, which was later applied commercially to both vegetables and fruits (11). These coatings were developed as a safer alternative to hazardous synthetic chemicals that could pose risks to consumer health. Made from biological or chemical substances, edible coatings are applied in one or more layers to the surface of products (12).

Edible coatings are thin, consumable layers made from naturally derived materials. Their primary function is to create a protective barrier that reduces moisture loss, regulates gas exchange and prevents microbial spoilage of fruits. This helps preserve the freshness and overall quality of fruits during storage, as shown in Fig. 1. The sensory attributes of the fruit should remain unaffected by the edible coating, which typically has a thickness of less than 0.3 mm (13). Materials commonly used in edible coatings, such as polysaccharides, proteins and lipids, offer distinct advantages. For example, polysaccharides are known for their excellent gas barrier properties, while lipids are effective in reducing moisture loss due to their hydrophobic nature (10).

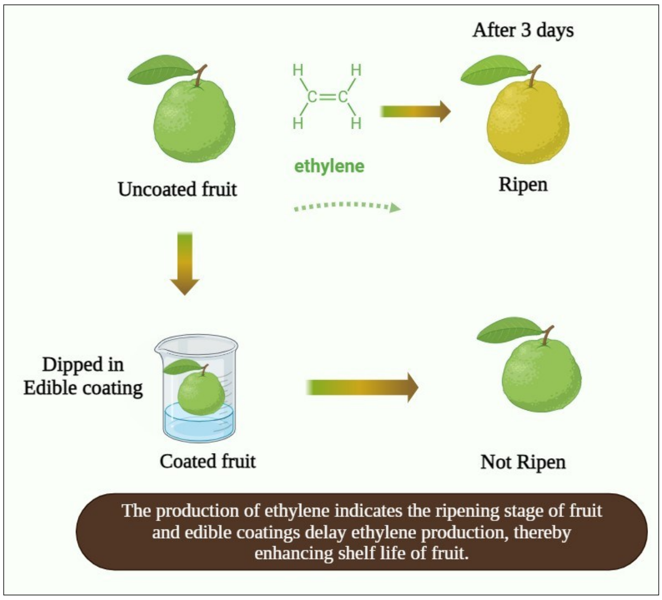

Fig.1. Impact of edible coatings on fruit shelf life.

Edible coating (classification based on composition)

Edible coatings are widely used in the food industry to enhance shelf life, quality and safety. Chitosan, when applied to fruits like apples, provides strong antimicrobial properties but dissolves under acidic conditions. Pectin, commonly used on citrus fruits, helps reduce moisture loss but is less effective in high-moisture environments. Alginate, often used for fresh produce, retains moisture but offers limited gas barrier properties. Cellulose, applied to cheese, prevents oxidative spoilage but limits moisture exchange. Starch, used on tomatoes, adds visual appeal but has weak moisture barrier properties. Wax, such as carnauba wax, extends fruit shelf life but can hinder respiration if over-applied (14). Edible coatings are classified into four categories based on their composition: lipids, hydrocolloids, composites and active ingredients, as shown in Fig. 2.

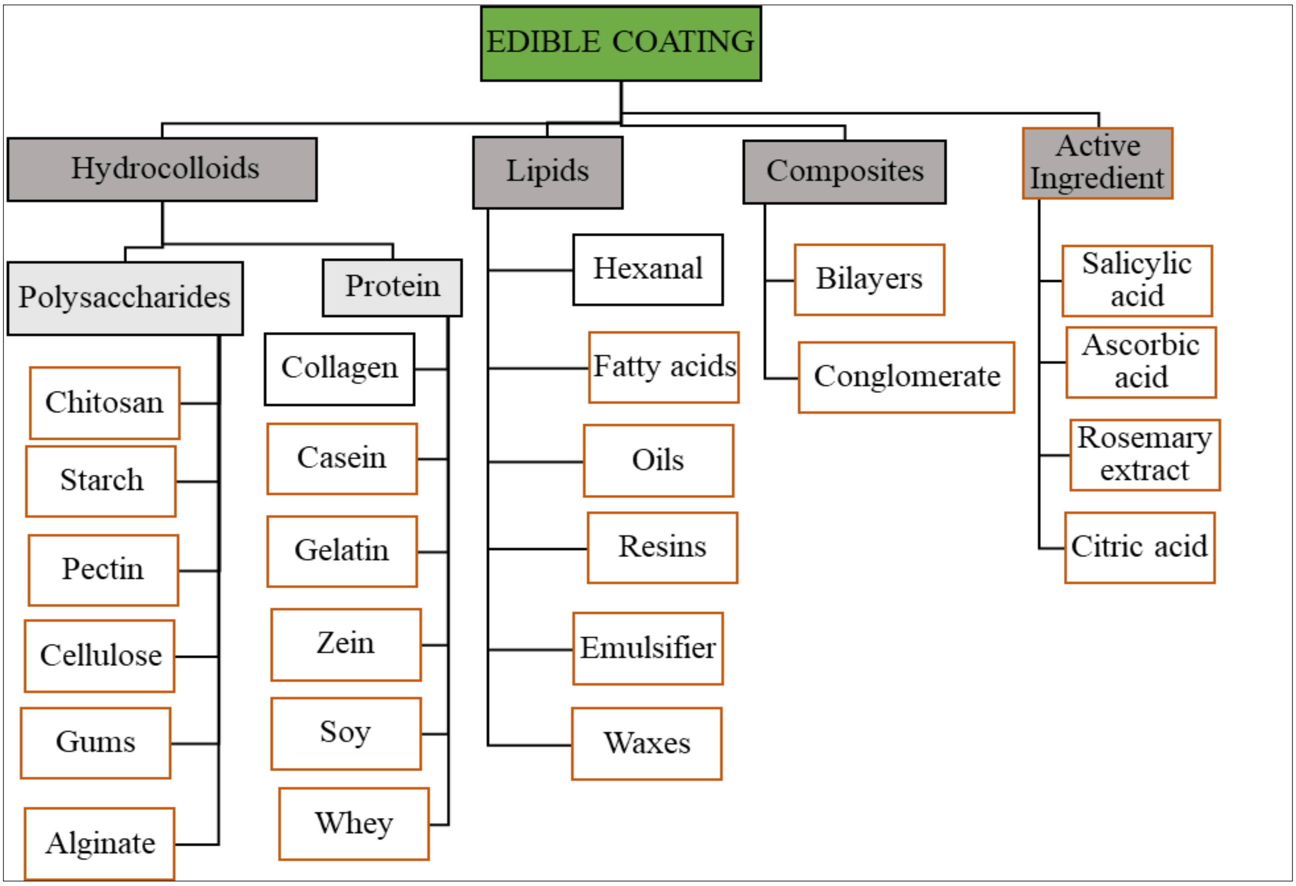

Fig. 2. Different types of edible coating.

Hydrocolloids

Hydrocolloids, water-attracting polymers derived from plants, animals and microbes, have a wide range of applications, particularly in coating solutions for fruits. They are used to coat food items without affecting their texture, flavor and color during preservation. Typically, they are either partially or completely soluble in water and their primary function is to increase viscosity (15). These hydrocolloids are classified into two categories based on their composition: polysaccharides and proteins.

Polysaccharides: The primary polysaccharides commonly used in the formulation of edible coatings for fruits include chitosan, carrageenan, alginate, cellulose, gellan gum and pullulan (10). While these coatings generally have limited moisture barrier properties due to their solubility in water, they offer relatively low oxygen permeability. Polysaccharide-based edible coatings are typically applied to fresh or minimally processed fruits to create a modified atmosphere that reduces the respiration rate. These coatings also improve the mechanical handling properties of the fruits (16).

Chitosan, derived from chitin found in the exoskeletons of crustaceans, is an edible polymer widely used in the development of coatings for fruits (17). It provides mechanical strength similar to that of natural gums and has high viscosity. Chitosan forms clear, transparent films that act as a barrier to oxygen while being highly permeable to carbon dioxide, offering protection against a range of microorganisms (18).

Pectin, a naturally occurring substance in fruits, is used in the production of high-quality coatings. These coatings maintain stability even at temperatures up to 180°C. Additionally, pectin can be dissolved in polyvinyl alcohol to enhance its characteristics (19).

Cellulose is one of the most naturally abundant materials, composed of long chains of a hydroglucose polymer. Methyl cellulose, a specific type of polysaccharide, is frequently used in coating formulations. As the primary structural component of plants, cellulose is the most prevalent complex carbohydrate worldwide. Cellulose can be adapted through chemical modifications to produce ether-ester films (20).

Gums are water-insoluble substances widely utilized in various applications. A blend of guar gum is often used to create uniform coatings with strong adhesive properties, even in moist conditions. Polysaccharide-based gums, primarily derived from the endosperm of plant seeds in the Leguminosae family, are rich in galactomannans composed mainly of the monosaccharides mannose and galactose. The structure varies by plant source, with mannose forming linear chains linked to glucopyranosyl residues as side chains (21). Polysaccharides are extracted from seed gums, including guar, locust bean, tara and tamarind (22).

Alginate exhibits advantageous characteristics for culinary applications. Its distinctive colloidal properties render it excellent as a stabilizer, thickening, suspending agent, coating or film former and gel former (23). Alginate is widely used across industries, including food, beverage, textiles, printing and pharmaceuticals (24). In edible coatings, alginate functions as a thickening agent, stabilizer, emulsifier, chelating agent, encapsulant, swelling agent and suspending agent. Its ability to swell and its water solubility are essential characteristics for handling fresh-cut fruits with high moisture content on their surfaces (25).

Coatings based on protein : Protein-based bio-coatings, derived from both plant and animal sources, are known for their hydrophilic nature, which makes them less effective as barriers against water vapor. However, they offer favorable organoleptic properties (26). A study found that proteins and polysaccharides are commonly used as structural components in bio-based coatings due to their abundance (27). Coatings made from protein materials are generally more neutral in flavor, transparent and bland compared to those formulated with lipid materials (28).

Collagen is a naturally occurring macromolecule found in the dermal layers and hides of mammals (such as bovine and porcine), as well as in avian and aquatic species. It is widely used as an edible coating material due to its biodegradable, non-toxic and non-antigenic properties. Additionally, collagen is highly valued for its exceptional mechanical strength, oil resistance, oxygen barrier capabilities and biocompatibility. Its versatility also allows it to serve as a carrier for a variety of compounds and additives (29).

Casein, a protein sourced from milk, exhibits superior mechanical and barrier properties compared to polysaccharides, due to its excellent ability to form cohesive coatings. Ascorbic acid enhances the antioxidant properties of casein coatings through several mechanisms. It acts as a free radical scavenger by donating electrons to neutralize harmful radicals, thereby preventing oxidative damage. Additionally, ascorbic acid chelates metal ions such as iron and copper, reducing their catalytic role in oxidative reactions and stabilizing the coating. It also works synergistically with other antioxidants, regenerating compounds like tocopherols to increase the overall antioxidant efficacy. Moreover, ascorbic acid enhances emulsion stability, safeguarding food goods from oxidative deterioration by establishing stable interfaces. Ascorbic acid levels typically decline during fruit aging due to the enzymatic action of ascorbic acid oxidase. Therefore, enriching coatings with ascorbic acid is recommended to help maintain the fruit's ideal antioxidant levels (30).

Gelatin is a protein polymer derived from animal sources, including skins, bones, connective tissues and fish skins, through partial hydrolysis of collagen. This process involves treating raw animal materials with dilute acid or alkali, which breaks down the crosslinking in the collagen matrix, resulting in a substance known as "warm water-soluble collagen," commonly referred to as gelatin. Gelatin films are extensively utilized to preserve meat and other food items by providing a covering that prolongs shelf life and sustains quality . It was also reported that zein protein has low solubility in water but readily dissolves in aqueous alcohol and glycol ester solutions (31). These properties make zein an ideal material for producing coatings due to its strong binding and adhesive capabilities.

Corn zein protein is highly efficient in preventing color changes, preserving firmness and extending the shelf life of fruits. Additionally, it exhibits exceptional oxygen barrier properties. Coatings made with corn zein show remarkable resistance to water vapor, offering barrier capabilities that are approximately 800 times more effective than those of other coating materials and wrapping films.

Soybean protein materials are well-suited for use in edible coatings due to their low permeability to oxygen and carbon dioxide, as well as their cost-effectiveness (32). When combined with other components, these materials have been used to extend the shelf life of eggplants and walnut kernels (33).

Whey protein isolates (WPI) can be converted into flexible and transparent films that offer excellent barrier properties against gases, aroma compounds and oils, outperforming those made from polysaccharides and lipids. However, these films have limited mechanical strength and high-water vapor permeability due to the significant presence of hydrophilic amino acids in their composition (34). A study found that a whey protein-based emulsion coating reduced weight loss and browning in fresh-cut apples by 26.55% and 46.39%, respectively, thus improving freshness during storage. Another study showed that a composite coating of WPI and wax increased dry matter content and fruit hardness compared to WPI alone. While WPI is biodegradable and suitable for various foods, its moisture absorption in humid environments undermines its barrier properties. Additionally, WPI's low tensile strength limits its protective ability, especially in high humidity, reducing its long-term effectiveness (35).

Coatings based on lipids

The quality of fruits has been preserved using edible coatings made from lipids, which provide a shiny and lustrous finish. Examples of lipid materials include beeswax and carnauba wax. One of the key properties of lipids is their water resistance (36). Wax coatings offer superior moisture barriers compared to both lipid-based and non-lipid coatings. However, the thickness and greasiness of oil, fat and wax-based coatings can make them challenging to apply to fruit surfaces and may impart a rancid flavor (37).

Hexanal is naturally synthesized by certain plant species, with linoleic and linolenic acids acting as biological precursors for its synthesis. The biosynthesis of hexanal involves metabolic pathways associated with lipoxygenase (LOX) and hydroperoxide lyase (HPL). The enzymes responsible for this process include LOX, HPL, lipolytic acyl hydrolase and (E, Z)-2,3-enal isomerase. Hexanal treatment has demonstrated efficacy in prolonging the shelf life of fruits by suppressing phospholipase D (PLD) activity (38).

Fatty acids enhance the flexibility of lipid coatings by acting as plasticizers, disrupting the film's crystalline structure, which increases molecular mobility and prevents cracking. Unsaturated fatty acids provide greater flexibility than saturated ones. Additionally, fatty acids improve adhesion by reducing surface tension, promoting better wetting and spreading on the fruit and creating a more effective barrier against moisture loss and gas exchange. A commercial example of this is the use of fatty acid-based coatings on apples, which reduce water loss and maintain firmness, thereby extending shelf life. Lipid-based coatings serve as both moisture and oxygen barriers, contributing to the long-term preservation of food quality. These coatings can be applied to a wide range of products, including confectionery, fruits, vegetables, dairy items, chocolates, cereals, poultry, fish, frozen goods and dried products. In recent years, lipid-based films and coatings have gained significant attention for their functional attributes and nutritional benefits (39).

Bioactive compounds, such as essential oils, have been used as food preservatives (40) and can be incorporated into edible coatings to enhance their efficacy in preserving fruit quality and reducing microbial spoilage, thereby extending shelf life.

Shellac is a natural resinous substance produced by the scale insect *Kerria lacca*, consisting of a mixture of resin, pigment and wax (41). It is highly valued for its excellent film-forming properties and water resistance, making it widely used in coatings and functional materials. In the food industry, shellac functions as a glazing agent, improving the aesthetic of items like confectionery, chocolates and fruits, while also offering a moisture barrier. Referred to as "confectioner's glaze," it is approved by the FDA and aids in minimizing moisture loss, thereby prolonging shelf life . However, over time, shellac's brittleness and susceptibility to self-esterification can compromise its integrity, causing it to crack. Its solubility in alkaline media and organic solvents further limits its use. Additionally, because shellac is derived from insects, it is excluded from vegetarian products, leading to the search for plant-based alternatives (42).

Carnauba wax, a plant-derived lipid, is widely used in food applications, particularly as an edible coating to extend the postharvest shelf life of various horticultural commodities. In the food industry, it is primarily employed as a glazing agent for fruits and confections. It is commonly applied to apples and citrus fruits to provide a shiny finish while serving as a moisture barrier. Carnauba wax, owing to its natural origins and hypoallergenic characteristics, presents an attractive alternative to synthetic coatings. Designated as a safe food additive by both the FDA and EFSA, it is utilized in an array of products, including chocolates and baked goods . Additionally, its biodegradable nature supports the growing consumer demand for sustainable food practices (43).

Coatings based on composite

Composite or multicomponent coatings consist of lipid-based materials, such as polysaccharides and proteins. These composites are divided into two categories: conglomerates and bilayer composites. Bilayer composites are made up of two layers, each formed from mixtures of one or more materials, such as lipid/lipid, polysaccharide/protein, protein/protein, or lipid/polysaccharide (44). Conglomerates are created by combining two or more biopolymers to form a homogeneous layer, which combines the key attributes of each component. Typically, conglomerate edible coatings are made by blending biopolymers like polysaccharides (e.g., starch, chitosan and pectin), proteins (e.g., gelatin, casein) and lipids (e.g., waxes, oils). This blend forms a cohesive layer that leverages the strengths of each biopolymer. For example, polysaccharides provide film-forming properties, proteins contribute structural strength and lipids offer moisture barrier capabilities. Recent research on edible coatings for fruits has focused on innovative combinations of natural materials to enhance preservation and quality. These biodegradable coatings act as protective barriers, extending shelf life by reducing moisture loss, gas exchange and decay while preserving sensory qualities. Commonly used biopolymers include polysaccharides, proteins and lipids, which are often combined to optimize mechanical strength and moisture barrier properties. Studies have shown that coatings with cassava starch and essential oils significantly reduce water loss and enhance antioxidant properties in fresh-cut apples, while beeswax and chitosan coatings improve the quality and appearance of strawberries by reducing decay rates (45).

Active ingredient

Active ingredients refer to substances incorporated into coating formulations that serve specific purposes beyond providing structure or texture. These ingredients are typically added to enhance the coating's properties or to impart additional functionalities, such as improving the shelf life of fruits, enhancing food safety, improving sensory attributes, or offering nutritional benefits (10).

Salicylic acid (SA) is recognized as a signalling molecule that regulates various physiological processes and induces systemic resistance (46). A study reported that SA reduced metabolic activity and slowed the hydrolysis of complex carbohydrates into soluble solids content (SSC), thereby delaying the increase of SSC in tomato fruits (47).

Ascorbic acid (AA) and its analogs have been the subject of numerous studies on fruits, with concentrations typically ranging from 0.5% to 4% (w/v). The anti-browning effects of ascorbic acid have been tested on various fresh-cut fruit products under a wide range of conditions (22). Additionally, AA is rich antioxidant and helps to minimize the loss of vitamin C. Studies have shown that AA treatment is particularly beneficial for kiwi fruit, as it helps maintain its quality during storage, making it an important strategy for post-harvest handling. Similarly, AA has been effective in preserving the quality of many other fruits, demonstrating its versatility and broad applicability across different fruit varieties (48).

Rosemary extract is becoming increasingly popular as a bio-based coating for fruits due to its beneficial properties and functional uses. Derived from the rosemary plant (Rosmarinus officinalis), this natural compound is rich in antioxidants and essential oils, which enhance its effectiveness in food preservation. A study examined the impact of rosemary extract, a natural antimicrobial agent, on Fuji apples (49). The results showed that the coating significantly reduced microbial proliferation, preserved fruit firmness and minimized browning, thus improving both the shelf life and overall quality of the apples.

Citric acid also exhibits antimicrobial properties, inhibiting the growth of spoilage microorganisms and pathogens on fruit surfaces. Its primary advantage lies in extending the shelf life of fruits while ensuring their safety during storage and transit. A study explored the effects of calcium chloride and citric acid, both individually and in combination, on the quality of pineapples during storage (50). The researchers found that coatings infused with citric acid effectively preserved fruit firmness, inhibited microbial growth and slowed the decline of sensory characteristics, ultimately enhancing the quality of pineapples (51).

Chitosan

The term "chitin" is derived from the Greek word "chitosan," signifying "a protective covering. coatings are highly regarded in the field of food preservation, particularly among hydrocolloids and lipids, due to their exceptional characteristics that surpass those of other edible coatings. One of the key advantages of chitosan is its strong antimicrobial activity, which effectively inhibits the growth of microbes and significantly extends the shelf life of perishable fruits (52). Chitosan is also recognized as generally recognized as safe (GRAS) by the US FDA, further enhancing its appeal as an edible coating and it has been widely explored in various studies (53). While other hydrocolloids have limited applications, chitosan's versatility allows it to meet a broad range of food preservation needs. Research has shown that chitosan treatment effectively prolongs the shelf life of various fruits by slowing decay. It has proven particularly effective for strawberries, mangoes, bananas and sweet cherries, reducing microbial loads and preserving sensory attributes. Additionally, chitosan coatings have been found to improve storage conditions for fruits such as longan and apples, highlighting its broad applicability (54).

Recently, the food industry has shown considerable interest in using chitosan-based edible coatings as an innovative packaging material for food products (55). Chitosan is typically extracted from the shells of marine crustaceans and is widely used in various industrial and medical applications. Industrial chitosan (poly-β-1,4-N-acetyl-D-glucosamine) is produced by chemically deacetylating chitin, which is extracted from the exoskeletons of arthropods. Edible chitosan films exhibit excellent oxygen permeability and serve as effective barriers against water (56). Chitosan has proven successful in controlling fungal diseases that degrade fruit quality during storage (57). Table 1 outlines the pre-harvest application of chitosan, which has been effective in extending shelf life and improving various quality attributes (58-64). Similarly, postharvest chitosan treatments, as presented in Table 2, have demonstrated significant improvements in quality parameters and extended the shelf life of produce (65-71).

Impact of chitosan on respiration rate and physiological loss in weight

Chitosan has proven highly effective in reducing physiological weight loss in fruits such as strawberries (72). The application of chitosan coatings significantly mitigated weight loss in fruits throughout the storage period. Research on mangoes (*Mangifera indica* cv. Dashehari) revealed that chitosan coatings at concentrations of 0.5% and 1.0% effectively reduced weight loss to 5.82% and slowed the ripening process. Chitosan-treated mangoes maintained greater firmness, measuring 15.50 N after 21 days of storage, compared to untreated fruits, which exhibited lower firmness. This effect is attributed to the semi-permeable membrane formed by chitosan, which alters the internal atmosphere of the fruit and reduces gas exchange. These changes significantly delay the climacteric peak, helping to prevent rapid deterioration (73).

Impact of chitosan on peroxidase activities and polyphenol oxidase

Chitosan coatings significantly inhibited the accumulation of anthocyanins, flavonoids and total phenolic content, whether a 1% or 2% glutamic acid solution was applied alongside the

Table 1. Impact of pre-harvest chitosan spray treatment on the shelf life of fruits

Fruits	Variety	Pre harvest spray treatment	Shelf life of treated fruits in days	Reference
Apricot	Armenian plums	Chitosan 0.01%, 0.05% or 0.25%	Fruits treated with a 0.25% chitosan as pre-harvest spray were stored for 16 days while fruits treated with a 3% chitosan pre-harvest spray were sustained for 70 days in cold storage.	(58)
Barhi dates	*Phoenix sp*	Chitosan 1, 2 and 3 g/L & nano-chitosan 1, 2 and 3 cm^3 /L and $CaCl_2$ 1, 2 and 3 g/L	Fruits treated with a 3% chitosan as pre-harvest spray were sustained in cold storage for 70 days.	(59)
Mango	*Mangifera sp*	Chitosan 0.5, 1.0 and 1.5%	Fruits treated with a 1.5% chitosan as pre-harvest spray were prolonged at 25°C for 12 days.	(60)
Peach	'Florida prince'	Chitosan at 0.5 and 1.0% & $CaCl_2$ at 2 and 4%	Fruits treated with a pre-harvest spray of 1% chitosan and 4% $CaCl_2$ were prolonged for 35 days under ambient conditions.	(61)
Rambutan	'Malwana special'	40 ppm concentration of chitosan fungicide and copper chitosan and chitosan oligomer	Fruits treated with a pre-harvest spray of 40 ppm chitosan were stored for 7 to 10 days.	(62)
Raspberries	'Autumn Bliss'	Chitosan 0.5, 1.0 or 2.0%	Fruits treated with a pre-harvest spray of 2% chitosan were sustained at 0°C and 90% RH, extending their shelf life up to 12 days.	(63)
Straw berry	Camarosa	Calcium chloride (@ 0.5%, 1.0% and 1.5%) and chitosan (@ 5g/L and 6g/L)	Fruits treated with a pre-harvest spray of chitosan were sustained at 7°C for 7 days.	(64)

Table 2. Effect of chitosan coating on postharvest shelf life of fruits

Fruits	Variety	Coating	Shelf life of treated fruits in days	Reference
Acid lime	*Citrus sp*	Essential oil of *Cinnamomum camphora* (CCEO) loaded in nanoemulsion of chitosan coating	Fruits dipped in a nanoemulsion chitosan were sustained for 5 days after harvest.	(65)
Apricot	*Prunus sp*	Chitosan and chitosan nanoparticles (CHNPs)	Fruits dipped in chitosan and chitosan nanoparticles were sustained for 9 days at room temperature (25 ± 3° C) and 30 days in cold storage (5 ± 1°C).	(66)
Blue berry	*Vaccinium sp*	Chitosan/thyme oil coating combined with UV-C	Fruits coated with a chitosan/thyme oil mixture and exposed to UV-C were maintained at 4°C for 56 days.	(67)
Kiwi fruit	*Actinidia sp*	Chitosan 0.6%, 0.8% and 1%	Fruits treated with 1% chitosan were maintained at 5 ± 1°C for 10 days.	(68)
Mango	"Kent"	Hot water (HW) and 1% chitosan coating	Fruits dipped in 1% chitosan were retained at 13 ± 0.5° C and 85%-90% relative humidity for 28 days.	(69)
Orange	*Citrus sp*	SA 1%, chitosan 0.5% supplemented with nano (ZnO) (0.50 g/L)	Fruits dipped in a chitosan and nano ZnO combination were retained for 20 days.	(70)
Sour sop	*Annona sp*	Chitosan cinnamon essential oil coating	Fruits coated in chitosan and cinnamon essential oil are kept at 16°C for 11 days.	(71)

chitosan (74). Additionally, chitosan demonstrated a partial inhibitory effect on peroxidase activity and suppressed the proliferation of polyphenol oxidase (PPO). Acting as effective protective barriers, chitosan coatings help mitigate lipid oxidation and carefully regulate flavor compounds, gas exchange and moisture retention, thereby preserving and enhancing food quality. In control groups, PPO activity increased after two days of storage, while chitosan-treated samples exhibited reduced PPO activity over the same period. Chitosan indirectly reduced polyphenol oxidase activity, minimized rapid water loss in litchi and lowered the respiration rate, which collectively contributed to reduced bio-heat generation (75).

Effect of chitosan on fruit firmness

In a study, it was observed that chitosan coatings markedly enhanced fruit firmness, with treated fruits exhibiting superior flesh firmness assessments relative to untreated counterparts across all experimental groups. The initial firmness of the fruits was preserved following chitosan application, with substantial changes becoming evident on the sixth day of storage. In contrast, non-coated fruits exhibited a gradual softening trend throughout the storage period. Fruits coated with 1.5% chitosan demonstrated superior flesh firmness compared to those treated with 1% chitosan, indicating a clear difference between the two concentrations. Similar improvements in firmness associated with higher chitosan concentrations have been observed in studies involving tomatoes and papayas (76). A detailed study on the impact of chitosan coatings on plums showed that chitosan effectively preserved fruit firmness at around 78% and reduced weight loss by approximately 52% during storage, compared to untreated control groups. The key factor in these results was the reduction in respiration rates, which helped slow down the metabolic processes that typically cause deterioration. Additionally, the study highlighted that chitosan coatings not only maintained firmness but also enhanced the overall quality of the fruit (77).

Impact of chitosan on fruit colour

Chitosan coatings help to preserve the external colour of fully ripe strawberries by reducing moisture loss. These coatings significantly decrease moisture loss, preserving the fruit's firmness and overall quality by forming a semi-permeable barrier that slows respiration and minimizes exposure to environmental factors that cause color degradation. This helps maintain the bright red color, enhancing market value. Moreover, higher temperatures accentuate the color differences between coated and untreated strawberries, making the visual quality more pronounced. Chitosan also helps retain AA during storage, reducing enzymatic browning and further preserving color integrity. Variations in factors such as AA, sugar profiles, peroxidase activity and other phenolic compounds-key substrates for enzymatic browning-can lead to the formation of dark-colored pigments (78).

Impact of chitosan on antibacterial activity

Antibacterial composite films made from chitosan or hydroxypropyl methylcellulose, enhanced with essential oils (such as lemon, tea tree, or bergamot), were applied to inoculated agar plates as a model for solid food systems. The study demonstrated that chitosan films enriched with essential oils effectively inhibited the growth of bacteria, including *Escherichia coli*. The antibacterial activity of the chitosan films was significantly enhanced against Gram-positive bacteria, with the essential oils proving more effective than the polymer alone. Moreover, there is considerable evidence suggesting that chitosan combined with essential oils can significantly extend the storage life of certain fruits and vegetables, including table grapes (79) and sweet peppers (80).

Pre-harvest applications of chitosan sprays offer significant benefits by enhancing fruit quality and reducing susceptibility to diseases. Research indicates that these treatments improve fruit firmness and reduce weight loss during storage, helping to maintain overall quality while acting as a protective barrier. Additionally, pre-harvest chitosan triggers plant defense mechanisms, decreasing infection rates from diseases such as *Botrytis cinerea* (81). Post-harvest chitosan treatments aim to preserve fruit quality after harvest. Chitosan coatings effectively reduce fungal rot and extend the shelf life of various fruits. The antimicrobial and antioxidant properties of these coatings inhibit pathogen growth and help maintain the fruit's physicochemical properties during storage. They are particularly effective in extending the shelf life of fruits like raspberries and strawberries, enhancing their marketability (82). While pre-harvest sprays focus on disease prevention and improving fruit quality, post-harvest applications help control decay and maintain freshness during storage.

Novel material as edible coating

Consumers are increasingly seeking healthier food options with preserved quality and environmentally friendly packaging, driving research into new methods and techniques. Significant efforts are being made to create and analyze novel materials that incorporate innovative components as binding agents. Additionally, new processing systems are being tested to optimize costs, functional properties and bio-based coatings (83). The findings related to these innovative materials are presented below.

Whole grain flours

Legume flours are ideal for film formation due to their high protein and starch content. Additionally, some legume flours are rich in fats, providing a valuable source of minerals, proteins and vitamins, often cost-effective price. Mung bean flour, known for its functional properties and biodegradability, is particularly suitable for various fruit applications. For example, edible coatings made from mung bean starch significantly enhance the shelf life of cut papaya by maintaining freshness and reducing spoilage. Furthermore, mung bean protein-based coatings effectively reduce weight loss and fungal contamination in fruits, extending their shelf life during storage. Research also shows that edible coatings based on mung bean flour help preserve the quality of various fruits by improving texture and moisture retention (84).

Fruits and vegetables residues

Peel residue has been developed and characterized using a blend of flour from ripe banana peels and corn starch (85). By-products from citrus fruits also serve as excellent film-forming materials. In particular, grapefruit albedo has demonstrated beneficial functional properties in the films produced. Similar results were observed for films created from pomelo peel flour (86).

Root plants

Starches derived from tubers and roots, like sweet potatoes, cassava and potatoes, have shown promising results as coatings and edible films. Researchers are also exploring the potential of flour and starch from less common root crops for these applications. For example, achira flour has been investigated as an innovative material for film formation. Citrus fruits, including oranges and lemons, have shown significant preservation benefits when coated with green composite coatings made from root plant residues. These coatings effectively reduce postharvest spoilage rates and slow down fruit respiration, thereby extending the overall shelf life of citrus fruits (87).

Plant gums

In recent years several naturally occurring gum exudates from plants, including gum Arabic, gum karaya, gum ghatti, mesquite gum and tragacanth gum, have drawn interest for potential applications. Gum Arabic, a historically significant natural gum with a lineage of over 5000 years, is well acknowledged for its use in sectors such as food, paint and textiles. It provides emulsification, stabilization, thickening and binding capabilities (88). In a specific study, Gum Arabic coatings were applied to strawberries to enhance their shelf life and preserve sensory qualities, including taste and texture, during cold storage. The results showed a significant reduction in spoilage and an extended storage duration, highlighting the potential of Gum Arabic as a natural preservative. Additionally, gum Arabic serves as a protective coating that extends the shelf life of food items, such as pecan nuts, by reducing their greasy and damp appearance.

Advanced edible coating through nanotechnology

Nanotechnology offers an advanced strategy for enhancing the delivery systems of targeted plant extracts, including vitamins, essential oils and polyphenols, known for their antibacterial and antioxidant properties. The submicron scale of these systems is used to modify gas transport characteristics and facilitate the release of natural compounds, while also improving mechanical performance, durability, transparency and antimicrobial activity. Nanotechnology significantly enhances edible coatings by incorporating nanoparticles that improve mechanical strength, create cohesive and resilient coatings and better withstand environmental stressors, thus reducing spoilage rates. The addition of inorganic nanoparticles enhances barrier properties against moisture and gas, slowing respiration and microbial growth and leading to an extended shelf life for fruits and vegetables. Metal-based nanoparticles, such as silver and zinc oxide, provide antimicrobial properties, enhancing food safety and shelf life. Recent advancements include the development of nanoemulsions to enhance the delivery of bioactive compounds, as well as composite coatings combining different nanoparticles, such as chitosan with silver, for improved microbial control and flexibility. Moreover, there is a growing trend toward using biodegradable materials in these coatings, with innovations that combine plant-derived compounds and nanomaterials to create eco-friendly options that enhance food safety while remaining fully biodegradable (89). Nanotechnology encompassed all systems with dimensions smaller than a micron. Carbon nanotubes have emerged as a promising addition to edible coatings for citrus fruits due to their remarkable properties. Research has shown that incorporating carbon nanotubes into these coatings improves their mechanical strength and barrier functionality, helping to retain the fruit's moisture while exhibiting antibacterial properties, which contribute to lower spoilage rates during storage (90).

Substances with significant potential for polymeric nano systems have been integrated into edible coatings alongside essential oils known for their antimicrobial properties. For example, nanoparticles of lemongrass oil and turmeric oil were combined to form alginate-chitosan nanocapsules. Additionally, lemongrass oil was encapsulated in cellulose acetate nanocapsules using the nanoprecipitation technique. This method creates nanocapsules that effectively concentrate active lemongrass oil while preserving its integrity and bioactivity. The cellulose acetate-based nanocapsules demonstrate strong antibacterial properties, making them ideal for food applications, particularly for extending the shelf life of perishable products like fruits. Furthermore, this encapsulation technique enhances the stability of the volatile compounds in lemongrass oil, thereby boosting its effectiveness in food packaging (91). Recently, the essential oil of *Zataria multiflora* was encapsulated in chitosan nanoparticles to produce a coating material that enhanced antioxidant activity and extended the shelf life of cucumbers (92). Traditional chitosan coating methods, such as dipping in chitosan gel, have been compared with nanoparticle applications. The use of nanoparticles on apples resulted in a non-continuous coating that reduced moisture content, increased surface interaction and exhibited a stronger antimicrobial effect against microorganisms (93).

Different techniques of edible coatings application

An edible coating is a layer placed to a product's surface, which can be either a single layer or a multilayer film, composed of biological or chemical constituents (94). Presented herein are several techniques for the application of bio-based edible coatings to the surfaces of fruit.

Dipping

The dipping technique is one of the simplest methods for applying edible coatings, involving three steps: immersion and dwelling, deposition and evaporation (95). After removing the excess coating solution, the food is typically dried either at room temperature or using a drying system. Research indicates that multiple factors such as immersion duration, withdrawal speed, number of dipping cycles, parameters of the coating solution (including density, viscosity and surface tension) and drying conditions substantially influence the density and morphology of coatings produced via dipping (96).

Spraying

The spraying technique involves dispersing fine droplets onto the outer surface of fruits utilizing a nozzle system. This approach includes three main types of spraying: air-assisted airless atomization, pressure atomization and air spray atomization. Spray technology allows for multilayer applications of interlayer solutions and uniform coatings with consistent thickness. Known for its low viscosity, this method produces thicker coatings compared to the dipping method. In the electro-spraying process, a strong electric field generates charged droplets, ranging from micrometric to sub-micrometric sizes, with a narrow size distribution. Spray coating is widely used to apply edible coatings in a fine mist over the surfaces of fruits, making it ideal for irregularly shaped varieties like grapes and tomatoes. Studies focused on grape preservation have found that using biodegradable coatings applied through spraying help retain firmness and significantly reduce moisture loss. Similarly, research on tomatoes indicates that antimicrobial coatings applied via spraying effectively minimize spoilage and extend shelf life (97).

Electro spraying

Electro-spraying is an advanced technique for applying bio-based substances to fruits and other food items. In this process, an electric field generates a fine mist or aerosol, which is then evenly deposited onto the fruit's surface. This method offers precise control over droplet size and distribution, making it particularly effective for coating irregularly shaped items. Electro -spraying facilitates uniform coverage, reduces material wastage and allows for meticulous control of both coating thickness and composition. A recent study examined the antimicrobial effects of edible coatings applied via electro-spraying on various fruits, such as peaches and plums. Results indicated that these coatings, infused with bioactive compounds, effectively inhibited microbial growth, thereby extending the fruit's shelf life. This research emphasized the advantages of electro-spraying, highlighting its capacity to form efficient coatings that also enhance food safety by reducing spoilage from bacteria and fungi (98).

Panning

The panning method, also known as pan coating, is a traditional technique for applying bio-based coatings to fruits and other food products. In this process, the product is placed in a rotating drum or pan, where the coating material is gradually added until reaching the desired thickness. The coating adhered to the fruit's surface through repeated tumbling and agitation within the pan. Research has explored the application of panning techniques specifically for minimally processed fruits, showing that these coatings effectively prevent moisture loss and microbial contamination in items like sliced apples and packaged berries. The protective film formed by the coatings helps preserve fruit quality and enhances shelf stability, making this method beneficial for the food industry (99).

Brushing

The brushing method for applying bio-based edible coating to fruits involves manually spreading a prepared coating solution over the fruit's surface using a brush or similar tool. This method offers benefits such as precision and flexibility, making it particularly suitable for small-scale or artisanal fruit production. However, it requires higher labour input compared to other methods and is impractical for large-scale industrial applications. A recent study examined the effectiveness of hot water brushing (HWB) as a method for disinfecting organic citrus fruits, aiming to reduce postharvest decay. The results indicated that HWB effectively minimized fungal spoilage while preserving essential quality traits, such as firmness and flavour. This approach highlights how brushing, when combined with suitable treatments, can enhance fruit freshness practically and efficiently (100).

Future perspective

The future of edible coatings for extending fruit shelf life lies in leveraging nanotechnology to boost functionality, tailoring formulations for specific fruits, exploring innovative application methods, sourcing sustainable ingredients, incorporating active packaging and addressing scalability and commercialization challenges. This progress is driven by innovation, collaboration and sustainability, aiming to reduce food waste, strengthen food security and meet evolving consumer demands. Interdisciplinary collaboration and the adoption of emerging technologies will benefit all stakeholders in the fresh produce supply chain.

Careful monitoring of interactions between fruits and coatings is essential to prevent the inclusion of undesired compounds. Key objectives should include prioritizing nanotechnology, exploring cost-effective base materials and developing labour-efficient techniques. Emphasis should be placed on designing customized edible coatings compatible with a variety of products to maximize shelf life. Future research must address existing knowledge gaps and introduce innovative coating applications that improve functionality and sensory qualities. Additionally, assessing the technological readiness of bio-based coating solutions for broader adoption is crucial.

Conclusion

This review highlights the crucial role of chitosan coatings in extending the post-harvest life of fruit crops, emphasizing their advantages in sustainable storage management. Chitosan, a biopolymer, forms a protective edible matrix that minimizes water loss, inhibits microbial growth and reduces oxidative degradation while enhancing structural firmness and decreasing decay. Edible coatings, often formulated with chitosan, waxes and bioactive natural extracts, serve as effective barriers against moisture and microbes, helping to preserve the sensory, nutritional and visual qualities of fruits. When combined synergistically with other treatments, chitosan coatings further optimize post-harvest quality by reducing respiration rates and improving the stability and integrity of various fruits.

The integrated use of these bio-preservative treatments improves texture retention, reduces spoilage and maintains overall fruit quality. However, their effectiveness depends on factors such as fruit type, application method and storage conditions. Future research should focus on optimizing formulations and delivery techniques while evaluating their effectiveness across a broader range of fruit crops. Collectively, these innovative technologies offer eco-friendly, sustainable solutions for extending fruit shelf life, minimizing post-harvest losses and supporting global food security.

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Authors' contributions

PJ played a significant role in conceptualizing the review, conducting the literature search and writing the original draft. KRV contributed to the overall direction of the review and methodology design and provided supervision throughout the manuscript development. AND organized and synthesized the literature, contributed to data analysis and participated in manuscript formatting. VJ contributed to data visualization, manuscript formatting and reviewing the manuscript. RAK assisted in the literature review, helped with data summarization and contributed to manuscript editing. KG played a key role in writing parts of the original draft, reviewing the manuscript and editing for intellectual content. IGL critically evaluated the content, provided technical input and refined the structure of the manuscript. TUM assisted in literature selection and data interpretation and provided expert guidance on specific thematic areas. TA provided insights on the scope, organized thematic sections and reviewed the final draft.

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