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POSTHARVEST PRESERVATION OF FRUITS AND VEGETABLES BY NATURAL BASED EDIBLE COATINGS – A REVIEW

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ABSTRACT

The market demand for fruits and vegetables is substantial due to their high nutritional value. However, their perishable nature results in relatively short shelf life. Approximately 40% of produce is lost due to damage from insects, microorganisms, and adverse conditions during harvesting, transportation, and storage. Consequently, preservation of fruits and vegetables presents a significant global challenge. Various preservation methods have been applied to fruits and vegetables, with particular interest in biopolymers (polysaccharides, proteins, lipids, etc.) and their combinations with plant-derived products that possess diverse biological activities, renewability, and environmental compatibility. These coatings act as protective barriers, reducing moisture loss, delaying ripening, and inhibiting microbial growth, thereby extending the shelf life of produce. Polysaccharides such as chitosan, alginate, and cellulose derivatives are widely used due to their film-forming properties and biocompatibility. Proteins like gelatin and casein, as well as lipids such as beeswax and carnauba wax, are also employed to enhance the mechanical and barrier properties of the coatings. Additionally, plant-derived compounds such as essential oils, polyphenols, and flavonoids are incorporated into these coatings to provide antioxidant and antimicrobial benefits, further improving preservation efficacy. By leveraging the potential of biopolymers and plant-derived compounds, the development of advanced edible coatings can significantly contribute to the global effort to preserve perishable produce and meet the increasing demand for fresh and nutritious fruits and vegetables. This review presents the applications of natural edible coatings for postharvest preservation of fruits.

Keywords: Biopolymers, edible coatings, natural preservatives, postharvest preservation, shelf life extension.

INTRODUCTION

Tropical fruits play a vital role in global agriculture, supplying 62% of the world's fresh fruit. Asia dominates production, contributing 86% of the global output, with Southeast Asia being a key producer (Md Nor & Ding, 2020). Vietnam, with its favorable climate, cultivates major fruit types, including mangoes, bananas, dragon fruit, oranges, and guava, each grown on over 10,000 hectares. Post-harvest losses and quality degradation of agricultural products, particularly fruits and vegetables, are significant challenges, especially in tropical climates like Vietnam. High moisture content and soft textures make these products highly perishable, with post-harvest losses exceeding 40%, compared to 20% for cereals and 30% for dairy and fish products. Mechanical damage, environmental conditions, and microbial spoilage further exacerbate these losses (Ratikanta Maiti, 2018). Unlike staple crops, fresh fruits and vegetables contain high moisture levels and soft textures, making them easily susceptible to bruising and microbial (fungi, bacteria) spoilage, which can lead to complete loss of the product (Bautista-Baños *et al.*, 2016). Globally, biotechnological advancements have introduced transformative solutions to these challenges. For instance, genetic engineering techniques have enabled the development of crop varieties with delayed ripening characteristics and suppressed ethylene biosynthesis, thereby extending shelf life and enhancing resistance to pathogenic agents. These innovations highlight the potential of modern science in improving postharvest preservation methods. However, in Vietnam, the application of these high-tech solutions remains constrained by inadequate infrastructure, regulatory barriers, and high implementation costs. Current preservation methods include drying, cold storage, irradiation, and chemical treatments. Among these, edible coatings made from natural polymers (polysaccharides, proteins, and lipids) combined with antioxidants and antimicrobial agents have shown high effectiveness. These materials are eco-friendly, non-toxic, biodegradable, and align with global trends toward sustainable practices. The primary objective of this article is to review and analyze existing literature on edible coatings and their applications in postharvest preservation. By synthesizing current research findings, the paper aims to provide a comprehensive understanding of the roles, mechanisms, and potential of edible coatings in extending the shelf life and maintaining the quality of fruits and vegetables after harvest. The selection criteria for this review focus on peer-reviewed journal articles related to postharvest physiological changes in fruits and vegetables, preservation methods, and, in particular, the application of edible coatings. Reviewing studies from the past 10 years provides a broad and continuous overview of the development and progress in this field.

PHYSIOLOGICAL CHANGES AND PATHOGENIC THREATS IN FRUITS AND VEGETABLES

Following harvest, fruits and vegetables maintain metabolic activity through ongoing respiration, consuming stored organic compounds and undergoing complex physical (water evaporation, weight loss, heat generation), physiological (ethylene production, respiration), and biochemical changes (chemical composition alterations, nutrient degradation) that collectively contribute to quality deterioration (Kambhampati, 2019). These processes are particularly pronounced in Vietnam's agricultural context, where approximately 1.3 million hectares of tropical and subtropical fruit trees yield around 8 million tons annually. The Mekong Delta alone contributes about 50% of the total cultivation area and 60% of the national fruit production. Despite Vietnam's position as ASEAN's third-largest fruit and vegetable exporter (USD 7.12 billion in exports, 2024), postharvest losses exceed 40% (Hodges et al., 2011), driven by the inherent perishability of produce (70-95% water content) and multiple interacting factors: mechanical damage during handling creates entry points for microbial invasion; continued physiological activity accelerates ripening and senescence; and tropical environmental conditions (25-35°C, 80-95% RH) favor pathogen proliferation. Microbial infections are a major cause of post-harvest losses, with common pathogens including fungi (*Alternaria* spp., *Botrytis* spp., *Penicillium* spp., *Rhizopus* spp.) and bacteria (*Pseudomonas* spp., *Erwinia* spp.). These microorganisms cause diseases such as gray mold rot (*Botrytis cinerea*), blue mold rot (*Penicillium* spp.), and soft rot (*Erwinia carotovora*), which significantly reduce the quality and marketability of produce.

POST-HARVEST PRESERVATION METHODS FOR FRUITS AND VEGETABLES

Post-harvest preservation is essential for maintaining the quality and extending the shelf life of agricultural products by preventing spoilage, degradation, and physical damage. It not only ensures product quality for domestic consumption and export but also enhances economic efficiency and promotes sustainable agricultural development. In Vietnam, post-harvest losses remain high due to the limited application of modern technologies, with most exports being fresh and unprocessed. Therefore, advancing preservation technologies is crucial to reduce losses, improve farmers' incomes, and increase the added value of agricultural products. Currently, various preservation methods are applied depending on the characteristics and intended use of each product (Table 1). Traditional techniques such as drying help reduce moisture content and inhibit microbial growth, although they may negatively affect sensory quality (Dao, 2020). Cold storage maintains low temperatures to slow down respiration and metabolic processes, making it suitable for many fruits and vegetables; however, it does not eliminate microorganisms and may cause chilling injuries (Dao, 2020). Irradiation, a non-thermal method, effectively eliminates insects and microorganisms as an alternative to chemical treatments, yet it incurs high operational costs and may cause slight physical changes in products (Ferrier, 2010). Chemical preservation employs physiological inhibitors, antioxidants, and antimicrobial agents, offering rapid and large-scale effectiveness, though potential risks to human health and the environment remain a concern (Cantín *et al*., 2012). Modern preservation technologies such as the cells alive system (CAS)—which combines rapid freezing with magnetic fields—and controlled atmosphere (CA) or modified atmosphere (MA) storage help reduce respiration rates, maintain freshness, and extend shelf life. Modified atmosphere packaging (MAP) and edible coatings are also used to minimize water loss, preserve natural texture and color, and are particularly suitable for small-scale applications (Chong *et al*., 2013). Additionally, Hyokan technology from Japan utilizes high voltage and low current intensity to inhibit oxidation and microbial growth without causing water crystallization, thereby prolonging storage time despite high initial and maintenance costs (Doan *et al*., 2018). Recently, cold plasma has emerged as a promising technology due to its ability to inactivate microorganisms through reactive oxygen and nitrogen species while preserving product quality at low temperatures. It has been effectively applied in surface decontamination, packaging, and equipment sanitation; however, challenges such as high costs, limited penetration depth, and the formation of ozone or by-products need to be addressed (Kaur *et al*., 2024). Moreover, there is a growing interest in biological preservation, which employs microbial systems or natural antimicrobial compounds such as lactic acid bacteria (LAB) and bacteriocins. Owing to their non-toxic nature, thermal stability, and broad-spectrum antibacterial activity, LAB are considered safe and effective biological preservatives for fruits and vegetables, representing a sustainable and environmentally friendly approach in post-harvest preservation (Kaur *et al*., 2024).

Table 1. Effectiveness of edible coatings in extending shelf life and preserving postharvest quality of tropical fruits.

Fruit	Type of coating used	Effectiveness	References
Mango	Chitosan-based coating (dip-coating)	Better aroma and more sweetness in coated mangoes, remain green, hard, and fresh after 14-days at 30°C, 40–50% RH, while uncoated mangoes were fully ripened after 7-8 days, anaerobic fermentation occurred for the coated mangoes after 14 days of storage, no weight los for the coated and control samples: TSS was lower in coated samples.	Prashanth *et al*., 2016
	Carnauba wax	Shelf life extended by 7 days at 21°C, 55% RH; improved firmness; reduced water loss; enhanced eating quality; fruits appeared shiny and turgid.	Dang *et al*., 2008
Guava	Beeswax + hydroxypropyl methylcellulose	20% beeswax coating significantly extended shelf life of 'Pedro Sato' guavas by at least 6 days. The hydrophobic coating acted as a semi-permeable barrier, reducing water loss and delaying ripening.	Formiga *et al*., 2022
	Lipid nanoparticles from Candeuba wax + xanthan gum (dip-coating)	Guavas coated with wax-derived lipid nanoparticles retained higher firmness (14.3 N after 30 days) than uncoated guavas (24.7 N after 10 days), effectively extending shelf-life.	Zambrano-Zaragoza *et al*., 2013
Banana	1.5% Chitosan	Reduced decay rate (~10.3%), decreased moisture loss, extended shelf life (16.2 days), maintained pH and titratable acidity better than control.	Gol & Ramana Rao, 2011
	Chitosan + gibberellic acid	Lowest decay rate (9.9%), longest shelf life (~17.2 days), better chlorophyll retention, slower increase in TSS and total sugar content.	Gol & Ramana Rao, 2011

EDIBLE COATINGS

Fruits and vegetables, when exposed to air, are highly susceptible to moisture loss, oxidative reactions, and microbial invasion, leading to spoilage, texture degradation, color changes, flavor alterations, and nutritional loss. These challenges are particularly pronounced in hot and humid climates, where the conditions exacerbate the deterioration process. To address these issues, edible coatings have emerged as a promising post-harvest preservation technology. These coatings are thin layers of material applied to the surface of produce via dipping, spraying, or brushing, creating a barrier that limits moisture evaporation, O_2 penetration, and solute migration (Dhall, 2013; Manisha Ch. Momin, 2021; Raghav *et al*., 2016). Furthermore, widespread commercialization faces obstacles including production costs, scalability limitations, and potential sensory alterations of coated products.

Advantages and disadvantages of edible coatings

Edible coatings play an important role in maintaining the post-harvest quality of fruits and vegetables by preserving nutritional components, firmness, and weight, thereby extending shelf life. Their ability to incorporate active substances such as antimicrobials, antioxidants, and vitamins into the polymer matrix enhances both safety and functionality. Additionally, because these coatings are edible, they help reduce the use of plastic packaging and support environmental sustainability. Improper coating thickness or material selection, however, can disrupt respiration or encourage microbial growth, issues that can be addressed through process optimization. As one of the most practical and scalable preservation methods, edible polymer films act as semi-permeable barriers that limit moisture loss, delay ripening, and maintain quality—an approach proven effective for extending the shelf life of Vietnam's high-value export fruits.

Edible coatings for post-harvest preservation of fruits and vegetables

Edible coatings operate on a principle similar to MAP, but with the added requirement that the coating materials are consumable and must possess specific functional properties. These coatings are typically composed of natural biopolymers—such as polysaccharides, proteins, and lipids—combined with surfactants and plasticizers to create a sustainable and effective solution for post-harvest preservation. The performance of edible coatings depends on their mechanical, barrier, and optical properties, which regulate gas exchange (O_2 and CO_2) and control water vapor evaporation, thereby extending shelf life and maintaining the quality of fruits and vegetables (Raghav *et al*., 2016). Edible coatings are broadly classified into three categories: hydrocolloids (polysaccharides and proteins), lipids (fatty acids, waxes, and resins), and composite coatings (combinations of hydrocolloids and lipids). However, each type of biopolymer has its own advantages and limitations in terms of physical, chemical, and storage properties, necessitating careful selection based on the specific requirements of the produce and storage conditions. In recent years, the development of composite and bilayer coatings has gained significant attention. These advanced coatings combine the beneficial properties of different materials to overcome the limitations of single-component systems. For example, composite coatings may integrate water-resistant lipids with gas-permeable polysaccharides or combine proteins with carbohydrates or lipids. Notable examples include coatings made from lipids and hydroxypropyl methylcellulose

(Hagenmaier & Shaw, 1990); methyl cellulose (MC) and lipids (Greener & Fennema, 1989); MC and fatty acids (Sapru & Labuza, 1994); zein from corn casein and lipids (Avena-Bustillos & Krochta, 1993; gelatin and soluble starch (Arvanitoyannis *et al*., 1997); gelatin and fatty acids; soy protein and gelatin; soy protein and PLA (Manisha Ch. Momin, 2021; Raghav *et al*., 2016).

Protein-based edible coatings

Protein-based edible coatings are derived from plant (e.g., corn zein, soy) and animal sources (e.g., gelatin, casein). Their morphology and permeability can be adjusted by pH modification. However, their hydrophilic nature limits water vapor barrier properties, which can be improved by combining proteins with polysaccharides or lipids, or by adding hydrophobic components. To enhance mechanical strength, plasticizers or chemical treatments (e.g., cross-linking agents like formaldehyde, glutaraldehyde or glyoxal) are applied. Antimicrobial agents such as nisin, gallic acid, and essential oils from lemon, orange, cinnamon, thyme, clove, and oregano can also be incorporated. Furthermore, antioxidants like α-tocopherol, ascorbic acid, ferulic acid, or natural extracts (e.g., red grape extracts or tea polyphenols) are commonly included to improve the functional properties of the coatings (Calva-Estrada *et al*., 2019). Among protein sources, gelatin has been the most extensively studied due to its excellent film-forming ability and effectiveness as a protective barrier against light and oxygen. Fish gelatin, derived from fish skin—a major by-product of the fish processing industry—has gained attention as a sustainable alternative to bovine and porcine gelatin, addressing both social and health-related concerns.

Polysaccharide-based edible coatings

Polysaccharides, the most abundant macromolecules in nature, are widely used to produce biodegradable films and coatings for post-harvest preservation due to their excellent barrier properties against O_2 and CO_2 (under low to moderate humidity) and high tensile strength, comparable to synthetic polymers. However, their hydrophilic nature results in poor water vapor resistance, which can be mitigated by combining polysaccharides with hydrophobic materials (e.g., lipids or resins) or through chemical modifications such as cross-linking. Additionally, polysaccharide-based coatings are often enhanced with antimicrobial, antifungal, or antioxidant agents to improve their functionality and expand their application potential (Cazón *et al*., 2017; Ferreira *et al*., 2016).

Polysaccharides are derived from various sources, each with unique properties and applications.

i) Animal-derived polysaccharides, such as gelatin, chitin, and chitosan. Chitosan, obtained from the deacetylation of chitin found in crustacean shells, is one of the most widely used polysaccharides due to its non-toxicity, biodegradability, biocompatibility, and strong antimicrobial activity. Chitosan inhibits the growth of fungi (e.g., *Alternaria alternata*, and *Penicillium* spp.) and bacteria by interacting with microbial cell membranes, altering permeability, and causing leakage of intracellular components (Duan *et al*., 2019). However, chitosan films have high water permeability and are not heat-resistant, often requiring blending with thermoplastic polymers (e.g., poly (butylene succinate)) or cross-linking agents (e.g., glutaraldehyde) to enhance mechanical and moisture-resistant properties (Elsabee & Abdou, 2013). Furthermore, to improve moisture resistance, chitosan can be cross-linked with agents such as formaldehyde, glutaraldehyde, or genipin to reduce solubility and swelling. When processing chitosan films, additional antimicrobial, antioxidant agents, and additives like flavors, colors, nutrients, vitamin E, or oleic acid can be incorporated to extend shelf life and enhance the nutritional value of fruits and vegetables without significantly altering their antifungal and moisture-resistant properties.

ii) Plant-derived polysaccharides are widely applied in food packaging, including coatings for fruits and vegetables, with examples such as starch, cellulose derivatives, pectin, and aloe vera. Starch is an abundant and cost-effective biopolymer, and starch-based films are transparent, odorless, and exhibit excellent oxygen (O_2) barrier properties. However, their hydrophilicity limits water resistance, which can be improved by combining with hydrophobic substances like resins or plasticizers (e.g., sorbitol). Starch coatings are commonly used to preserve fruits such as apples, strawberries, and tomatoes (Raghav *et al*., 2016). Cellulose, another abundant natural polymer, is insoluble in water. To enhance its solubility, it can be modified into derivatives such as carboxymethyl cellulose (CMC) or MC. These cellulose derivatives exhibit excellent film-forming properties and are typically odorless, tasteless, transparent, flexible, and resistant to oils and fats while allowing permeability to moisture and O_2. The mechanical and barrier properties of cellulose-based films depend on their molecular weight: the higher the molecular weight, the better these properties (Avena-Bustillos & Krochta, 1993). However, cellulose-based films tend to be relatively expensive (Dhall, 2013). Aloe vera gel exhibits antifungal activity against fungi such as *Aspergillus flavus*, *A. niger*, *Penicillium gladioli*, and *Fusarium oxysporum*, as well as antimicrobial activity against pathogens like *Escherichia coli* and *Salmonella typhimurium*. Its bioactive compounds, including saponins, acemannan, and anthraquinones, contribute to these properties, though the precise mechanism of action remains unclear. As an edible coating, aloe vera gel reduces respiration rates, water loss, and spoilage, while extending shelf life and delaying senescence in fruits like cherries and grapes (Serrano *et al*., 2006). It also controls oxidative browning and microbial growth. However, its instability—due to enzymatic hydrolysis of polysaccharides and color changes upon exposure to air and light—limits its use unless stored at low temperatures or combined with additives (Suriati *et al*., 2018). Combining aloe vera gel with additives like ascorbic acid, glycerol, or $CaCl_2$ enhances its effectiveness. Additionally, blending it with materials such as chitosan, starch, or alginate improves postharvest quality. (Suriati *et al*., 2018). Pectin, a group of polysaccharides derived from plants, is one of the main components of plant cell walls found in fruits and vegetables. Pectin is soluble in acid and water and is primarily used as a gelling agent in jam, fruit juice, and pie fillings, as well as a stabilizer in dairy drinks and yogurts. Due to its gelling properties, the use of pectin as a material for creating edible coatings has been investigated in recent years. Pectin-based films have good gas barrier properties but poor water resistance, although they have been utilized to slow moisture loss and lipid migration. Edible coatings made from pectin exhibit moisture loss control properties similar to alginate films (Cazón *et al*., 2017).

iii) Polysaccharides derived from seaweed (alginate, agar, carrageenan, etc.) or microorganisms (xanthan gum, gellan gum, pullulan, etc.) are also commonly used for edible coatings on fruits and other foods. Alginate, extracted from brown algae, forms durable films with enhanced mechanical properties when cross-linked with calcium (Cazón *et al*., 2017). Carrageenan is a hydrophilic natural polysaccharide extracted from red seaweed (Rhodophyceae). Carrageenan coatings are used to reduce water evaporation, control gas exchange, and prevent discoloration in fruits, thereby maintaining texture and extending shelf life.

Lipid-based edible coating

Lipid-based coatings have been widely used for decades to preserve the quality of fruits and vegetables post-harvest. These coatings are primarily composed of waxes and oils, including animal-derived waxes (e.g., beeswax, shellac, and lanolin), plant-derived waxes (e.g., carnauba, candelilla, rosin, palm oil, and rice bran oil), as well as mineral oils, paraffin wax, fatty acids, and monoglycerides (Dhall, 2013). Due to their hydrophobic nature, lipid-based coatings are highly effective in reducing water loss, which is critical for maintaining the freshness and weight of fruits and other food products. Additionally, these coatings help mitigate respiration rates, extend shelf life, and enhance the visual appeal of fruits and vegetables by providing a glossy finish. However, the hydrophobic characteristics of lipids often result in thicker and more brittle coatings with inferior mechanical properties, such as low flexibility and tensile strength. To overcome these limitations, lipids are frequently combined with other film-forming agents, such as proteins or polysaccharides (e.g., cellulose derivatives). This combination improves the mechanical and barrier properties of the coatings, making them more versatile and effective (Manisha Ch. Momin, 2021). It is important to note that the production of lipid-based edible coatings typically requires the use of solvents and high temperatures, which can pose challenges in terms of scalability and environmental impact.

Table 2. Characteristics of some types of edible coatings used for fruit preservation.

Edible Coating	Advantages	Disadvantages	References
Protein-based films			
Zein	Good film-forming properties, effective moisture and gas barrier	Water-insoluble, high brittleness	Hassan *et al*., 2018; Luangapai *et al*., 2019; Sharma et al., 2019
Gluten	Elastic and adhesive film, effective barrier	Water-insoluble, potential allergen	Hassan *et al*., 2018; Luangapai *et al*., 2019; Sharma et al., 2019)
Whey	Good oxygen (O_2) and carbon dioxide (CO_2) barrier, oil-resistant, transparent	Poor moisture barrier	(Jamróz *et al*., 2019; Sharma *et al*., 2019
Gelatin	Low cost, transparent, good mechanical properties	Poor moisture barrier	Hassan *et al*., 2018; Luangapai *et al*., 2019; Sharma *et al*., 2019

Polysaccharide-based films			
Chitosan	Effective O_2 and CO_2 barrier, antimicrobial, transparent, flexible	Alters product flavor at high concentrations, high water permeability	Hassan *et al*., 2018; Jamróz *et al*., 2019; Mujtaba *et al*., 2019; Palou *et al*., 2015; Sharma *et al*., 2019; Valencia-Chamorro *et al*., 2011
Starch	Tasteless, transparent, can block O_2 and CO_2	High water absorption, weak mechanical strength	Galgano *et al*., 2015; Hassan *et al*., 2018; Jamróz *et al*., 2019; Sharma *et al*., 2019)
Methylcellulose	Oil and water resistance, odorless, tasteless, transparent	Low O_2 barrier, expensive	Galgano *et al*., 2015; Hassan *et al*., 2018; Lin & Zhao, 2007
Alginate	Can block O_2 and CO_2, transparent, good film-forming properties	High water permeability	Jamróz *et al*., 2019; Lin & Zhao, 2007; Luangapai *et al*., 2019
Pectin	Good O_2 and CO_2 barrier	Poor water vapor barrier, low mechanical strength	Jamróz *et al*., 2019
Pullulan	Effective O_2 and CO_2 barrier, oil-resistant, good mechanical strength	Low solubility in water	Jamróz *et al*., 2019
Lipid-based films			
Wax	Excellent moisture barrier	Affects sensory properties of the product	Embuscado & Huber, 2009; Hassan *et al*., 2018
Shellac	Glossy surface, effective O_2, CO_2, and ethanol barrier	Not generally recognized as safe (GRAS) certified	Hassan *et al*., 2018

According to Table 2, protein-based coatings (e.g., zein, gluten, whey, and gelatin) demonstrate superior gas barrier properties and mechanical strength but often suffer from brittleness and poor moisture resistance (Hassan *et al*., 2018; Sharma *et al*., 2019). Certain proteins like gluten may also pose allergenicity risks. In contrast, polysaccharide-based coatings (e.g., chitosan, starch, methylcellulose (MC), and alginate) offer flexibility, antimicrobial activity, and effective gas modulation, yet most exhibit high water vapor permeability (Jamróz *et al*., 2019; Valencia-Chamorro *et al*., 2011). Lipid-based coatings (e.g., waxes, shellac) excel in moisture barrier performance but may compromise sensory attributes or lack regulatory approvals (Embuscado & Huber, 2009). The choice of edible coatings for fruits and vegetables depends on factors such as respiration rate, storage temperature, and optimal O_2 and CO_2 levels. Ideal coatings should allow higher CO_2 permeability than O_2. Each coating material—protein, polysaccharide, or lipid—has unique advantages and limitations based on its physical, chemical, and biological properties. Recent advancements focus on composite and bilayer coatings, which combine materials to enhance functionality. Composite coatings mix polysaccharides, proteins, and/or lipids (e.g., lipids with hydroxypropyl methylcellulose, casein with lipids, gelatin with starch) to improve permeability and mechanical strength (Hagenmaier & Shaw, 1990); lipid and MC (Greener & Fennema, 1989); MC and fatty acids (Sapru & Labuza, 1994); casein and lipids (Avena-Bustillos & Krochta, 1993); gelatin and starch; gelatin and fatty acids; soy protein and gelatin; soy protein and polylactic acid (Rhim *et al*., 2007). Bilayer coatings, on the other hand, combine the water-resistant properties of lipid-based coatings with the gas permeability of polysaccharide-based coatings to enhance the barrier properties of the films (Dhall, 2013; Manisha Ch. Momin, 2021; Raghav *et al*., 2016). The foregoing analysis demonstrates that edible coating selection must be dynamically tailored to the physiological characteristics of each agricultural commodity and specific storage conditions. No single coating material can be universally optimized for all applications. Instead, the most promising contemporary solution lies in the development of composite or bilayer coating systems, which effectively mitigate individual limitations while synergistically enhancing functional properties. This advanced approach significantly expands practical applications for extending the postharvest shelf life of perishable fresh produce.

Processing and production of edible coatings

Following the selection of an appropriate film-forming formulation, the method of applying the coating to the fruit surface plays a crucial role in determining the functionality and performance of edible coatings. Among various application techniques, dipping is the simplest and most widely used, involving three main stages: immersion and holding, deposition, and solvent evaporation (Tavassoli-Kafrani *et al*., 2016). Post-application, the excess coating is typically removed and the product is dried either under ambient conditions or using a dryer (Andrade *et al*., 2012). The properties of the resulting coating—such as morphology and thickness—are significantly influenced by factors including immersion time, withdrawal speed, number of dipping cycles, and characteristics of both the coating solution (e.g., viscosity, surface tension, density) and the fruit surface, as well as drying parameters. However, dipping may lead to excessively thick layers, which can impede fruit respiration, compromise surface integrity, and degrade coating functionality. Additionally, the potential contamination of the coating solution by microorganisms and dirt from the fruit surface poses challenges for industrial-scale applications. Another limitation is the high volume of coating solution required per unit mass of product (Lin & Zhao, 2007).

The spreading technique is more suitable for high-viscosity formulations, with coating efficiency dependent on parameters such as wettability, spreading rate, substrate characteristics, drying conditions, and surface geometry (Kumar & Prabhu, 2007). As this method often requires manual application (e.g., brushing), operator skill significantly affects coating uniformity and thickness. In spraying techniques, atomized droplets are distributed onto the fruit surface through different mechanisms, including air spray, pressure atomization, and air-assisted airless atomization (Andrade *et al*., 2012). Spraying enables uniform multilayer coating applications and offers better control over layer thickness compared to dipping, particularly when using low-viscosity solutions (Huber & Embuscado, 2009). Electrospraying employs a high-voltage electric field to generate monodisperse micro- or submicron-sized droplets (Khan *et al*., 2014). This method allows precise control over droplet size and coating thickness by adjusting solution viscosity and flow rate (Jaworek & Sobczyk, 2008). Layer-by-layer deposition utilizes electrostatic interactions between charged polyelectrolytes and the food surface, allowing the formation of chemically or physically bonded multilayer films. Such multilayer structures enhance coating compactness and stability, demonstrating improved effectiveness in fruit preservation, particularly with polysaccharides and charged biopolymers capable of hydrogen and covalent bonding (Skurtys *et al*., 2010). Lastly, cross-linking involves establishing covalent or non-covalent bonds between polymer chains to enhance film compactness and stability. Coatings are generally applied via dipping, spraying, or spreading, followed by the addition of a cross-linking agent. This technique improves mechanical strength, chemical and thermal resistance, and barrier properties (Guo *et al*., 2015). Protein-based materials are often preferred over polysaccharides due to their higher density of functional groups, which favor cross-linking interactions (Dai *et al*., 2020).

Post-harvest losses, including weight loss, nutrient depletion, texture changes, and microbial spoilage, are mitigated by incorporating additives into coatings. These additives must be non-toxic, eco-friendly, and compatible with coating materials. They can be applied as i) separate packaging agents (e.g., volatile essential oils), ii) dispersed within packaging materials during extrusion or casting, iii) coatings formed by dipping produce into additive solutions chitosan and aloe vera gel inherently possess antimicrobial properties. Other additives include organic acids (e.g., lactic, citric acids), metals (e.g., Ag, ZnO), bacteriocins (e.g., nisin), and plant-derived compounds (e.g., cinnamon, oregano oils) (Campos *et al*., 2011). Organic acids reduce pH and disrupt microbial activity but may alter coating properties through plasticization (Campos *et al*., 2011).

Plant extracts and essential oils: Recent years have seen a growing interest in the potential of plant-derived products, such as extracts, essential oils, and phenolic compounds, to control fungal diseases. With diverse antifungal and antibacterial activities and biodegradable properties, these products have wide applications in preserving fruits and vegetables when combined with edible coating materials. Among these, essential oils from medicinal and culinary plants are most frequently applied. Compounds in essential oils, such as terpenoids, carotenoids, coumarins, and curcumin—especially linear hydrocarbons, monoterpenes, and sesquiterpenes—exhibit lipophilic properties, enabling them to penetrate cell membranes, disrupt cell walls, and inhibit microbial growth (Benchaar et al., 2008). Combinations of essential oils and biodegradable polymers (e.g., proteins, natural gums, modified starches, and lipids) can not only prevent moisture, O_2, and CO_2 exchange but also inhibit spoilage in fruits and vegetables. The quality, shelf life, and stability of fresh produce are significantly enhanced when coating materials are combined with antioxidants, antimicrobial agents, or other functional additives derived from plants. This approach represents an environmentally friendly trend in food preservation technology for post-harvest fruits and vegetables (Campos *et al*., 2011; Dao, 2020).

Essential oils and natural compounds from plants such as thyme (*Thymus*), oregano (*Origanum*), clove (*Syzygium*), peppermint (*Mentha*), and eucalyptus (*Eucalyptus*) exhibit antioxidant properties. The key active components include phenols like carvacrol from oregano (Milos, 2000), thymol from thyme (Lee *et al*., 2005), eugenol from cloves (Lee & Shibamoto, 2001), and terpenoids like menthol from peppermint (Shan *et al*., 2005) and eucalyptol from eucalyptus (Amakura *et al*., 2002). The antioxidant activity of these compounds closely resembles that of α-tocopherol or vitamin C, primarily due to the presence of hydroxyl groups in the benzene ring. Additionally, the position and quantity of hydroxyl groups may correlate with their relative toxicity to microorganisms, with increased hydroxylation leading to enhanced toxicity (Cowan, 1999). For essential oils lacking phenolic groups, such as peppermint oil, it is believed that the mechanism of action involves membrane disruption by lipophilic compounds (Pandey *et al*., 2017).

Plant-derived antioxidants (e.g., tocopherol, ascorbic acid, tea polyphenols) are effective alternatives to synthetic antioxidants like butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT), offering both antioxidant and antimicrobial benefits to foods (Silva-Weiss *et al*., 2013). Empirical evidence confirms that edible coatings are effective in extending shelf life and preserving the postharvest quality of tropical fruits. In Vietnam, practical adoption depends on technological readiness, economic feasibility, and supply chain conditions. According to Table 3, for guava, the use of beeswax–cellulose blends appears more feasible than lipid nanoparticle systems, which face barriers related to cost and infrastructure. Empirical evidence in Table 1 confirms that, for mangoes, carnauba wax exhibits greater commercial potential than chitosan-based coatings due to a lower risk of anaerobic fermentation and easier integration into export processing (Dang *et al*., 2008; Jongsri *et al*., 2016). Experiments on bananas have demonstrated that chitosan combined with gibberellic acid shows high potential (Gol & Rao, 2011); however, it requires a sustainable food-grade chitosan supply, ideally derived from domestic seafood by-products. Overall, simple wax- and chitosan-based formulations are the most immediately applicable in Vietnam, whereas advanced systems require further validation at pilot scale and economic assessment prior to large-scale deployment.

TREND OF EDIBLE COATINGS IN POST-HARVEST PRESERVATION METHODS

Development of new coating materials and additives from natural sources

Edible coatings derived from polysaccharides have been extensively utilized in the food industry due to their ability to protect and extend the shelf life of products. Among them, chitosan is the most widely applied polysaccharide for fruit coating because of its effectiveness in reducing dehydration, enzymatic browning, and fungal decay.

Table 3. Edible coatings with added bioactive and functional ingredients for extending the shelf life of guava.

Coating material	Composition	Effect of coating	References
Chitosan	Cassava starch, essential oils, glycerol	Excellent microbiological qualities in terms of mould counts and yeast at room temperature. Delayed the ripening process, maintained firmness, reduced browning and inhibited colour development in coated guavas as compared to uncoated guavas during storage for 10 days.	De Aquino *et al*., 2015
Chitosan	Poly-vinyl-pyrrolidine, salicylic acid, aqueous CH3COOH	Reduce browning in guava fruit, minimized water loss, and improved antioxidant activities during fifteen days storage in an ambient environment (27 ± 1^{o}C).	Lo'ay & Taher, 2018
Chitosan	Citric acid, glycerol	Sensorial characteristics were preserved along with fungistatic and fungicidal action during storage because of the chitosan-citric acid coating. Maintained post-harvest guava quality by lowering oxygen and/or elevating carbon dioxide while suppressing ethylene production.	Nascimento *et al*., 2020
Carboxymethylcellulose (CMC)	Citric acid, glycerol, *Azadirachta indica* L. leaf extract	Maintained fruit quality for 15 days storage period with lowered weight loss (11.19%) and higher moisture content (57.15%) as compared to uncoated references.	Refilda *et al*., 2022

Nevertheless, other natural polysaccharides such as starch, cellulose, carrageenan, pullulan, and gums also possess significant potential for application. Emerging materials that warrant further investigation include lignocellulose and hemicellulose extracted from red pine (*Pinus densiflora*), cellulose obtained from sugarcane bagasse and cotton fibers, as well as alginate mixtures with carbohydrates, zein protein, and fish gelatin. The utilization of agricultural by-products, such as pectin from apples and carrots or gelatin from fish skin, can contribute to the development of environmentally friendly coating materials with inherent antioxidant and antimicrobial properties (Md Nor & Ding, 2020; Samad Bodbodak, 2016). In addition to the selection of polysaccharide sources, the incorporation of natural additives plays a crucial role in enhancing film functionality. Hydrophobic and plasticizing agents such as stearic acid, oleic acid, glycerol, and essential oils are often incorporated to improve flexibility and reduce water sensitivity. Moreover, antioxidants, antimicrobial agents, and probiotics can be embedded into edible coatings to enhance their preservative effects. For instance, cinnamic acid and sulfites act as anti-browning agents, while propionates, benzoates, sorbates, and essential oils from medicinal plants help control postharvest fungal diseases. Recently, edible coatings incorporating LAB have gained attention due to their production of natural antimicrobial metabolites. However, challenges remain regarding scalability, mechanical strength, water solubility, and sensory impacts. Despite these limitations, edible coatings represent a promising approach to prolong the postharvest life and maintain the quality of fruits and vegetables, offering a sustainable and biodegradable solution for modern food packaging systems. (Md Nor & Ding, 2020).

Nanotechnology applications in edible coating for postharvest preservation

Nanotechnology significantly enhances edible coatings through nanoemulsions, nanoparticles, and nanocomposites, enabling controlled release of bioactive compounds such as essential oils, antioxidants, and antimicrobial agents. Nanoemulsions are particularly effective for encapsulating lipophilic substances (e.g., oregano oil, omega-3, β-carotene), while biodegradable polymers (chitosan, starch, alginate) and inorganic nanomaterials (TiO_2, ZnO, and Ag) provide robust antibacterial properties. Studies demonstrate that nano-coatings incorporating chitosan or aloe vera effectively prolong the shelf life of tropical fruits like mangoes, bananas, and citrus. Beyond coatings, nanotechnology enables advanced applications, including (i) antimicrobial nanoparticles for freshness preservation, (ii) nanocomposite coatings with enhanced barrier and antibacterial functions, (iii) active/smart packaging for ethylene/O_2 scavenging and humidity control, and (iv) nanosensors for real-time ripeness monitoring via volatile compound detection (e.g., ethylene). However, challenges persist regarding nanomaterial safety and scalable production, necessitating further research to balance efficacy with environmental and health concerns (Baranwal *et al*., 2018; Chang *et al*., 2025). Despite its great potential, the application of nanotechnology in food packaging still faces challenges, particularly regarding the safety of inorganic nanoparticles (e.g., TiO_2, ZnO, Ag), which may pose health and environmental risks. The absence of unified regulations, along with high production costs and technical complexity, also limits large-scale adoption. Smart packaging and nanosensors introduce additional concerns about data accuracy and consumer acceptance. Therefore, further interdisciplinary research is essential to ensure safe, cost-effective, and sustainable integration of nanotechnology into the food industry.

Commercialized edible coatings and their potential for hard-skinned tropical fruits

Edible coating formulations have been successfully commercialized to extend fruit shelf life, reduce moisture loss, and enhance visual quality. For instance, Semperfresh™ effectively minimizes water loss while maintaining gas exchange, resulting in firmer, greener cherries and fresher pears with reduced weight loss and color degradation, without hindering natural ripening. Such coatings are not only suitable for soft fruits but also show great potential for hard-skinned tropical fruits such as jackfruit, soursop, and durian, particularly for peeled and pre-packaged segments that require microbial protection and freshness maintenance during retail display. The economic feasibility of edible coatings plays a critical role in their commercialization. Production cost analysis typically includes direct materials (e.g., chitosan, glycerol), indirect materials (e.g., cleaning solvents), labor, and overheads such as energy and equipment depreciation. Cost determination methods—absorption or direct costing—depend on whether fixed costs are incorporated. Major cost drivers include processing technology, equipment scale, and raw material characteristics, with material and energy costs being decisive factors (Radev & Kurshumov 2024). From a regulatory perspective, the classification of antimicrobial coating agents differs globally. The U.S. FDA recognizes several organic acids (acetic, citric, lactic, malic, propionic, tartaric) and essential oils as generally recognized as safe (GRAS) substances (Doores, 1993). while the EU permits coatings containing natural waxes, pectins, and gums (Dhall, 2013).

The production costs of ten edible coating formulations (EFC1–EFC10) were evaluated based on ingredient composition, component cost, and labor inputs. Results indicated considerable variation depending on the type and proportion of raw materials used. EFC1, composed of chitosan (0.025), acetic acid (0.006), glycerol (0.25), 1M sodium hydroxide (0.01), and distilled water (0.709), had a total cost of €0.889/100 g/mL, including €0.518 for labor. EFC2 (chitosan 0.02, 0.25N HCl 0.01, glycerol 0.005, and distilled water 0.965) and EFC3 (calcium chloride 0.02 and distilled water 0.98) were among the lowest-cost formulations, at €0.715 and €0.663/100 g/mL, respectively. In contrast, formulations with high-value oils or waxes exhibited significantly higher costs. EFC4 (moringa oil 0.8, beeswax 0.2) reached €26.78/100 g/mL, while EFC5 (paraffin wax 0.75, toluene 0.25) and EFC6 (CMC 0.01, glycerol 0.3, distilled water 0.69) cost €1.276 and €0.917/100 g/mL, respectively. Protein- and gel-based coatings, such as EFC7 (gelatin 0.05, aloe vera gel 0.95), had a total cost of €2.702/100 g/mL due to the high price of aloe vera extract. EFC8 (beeswax 0.03, Frytol® oil 0.97) was more economical at €0.835/100 g/mL, whereas EFC9 (shellac wax 0.4, distilled water 0.6) and EFC10 (candelilla wax 0.03, gum arabic 0.04, jojoba oil 0.0015, pomegranate polyphenols 0.00015, distilled water 0.9283) cost €1.399 and €1.003/100 g/mL, respectively. Cost data further show that low-cost formulations such as EFC2 (€0.715/100 g/mL), EFC3 (€0.663/100 g/mL), and EFC8 (€0.835/100 g/mL) are suitable for large-scale tropical fruit exports (e.g., mango, dragon fruit, banana), using readily available domestic materials like chitosan, beeswax, and vegetable oils. (Radev & Kurshumov 2024). Medium- and high-cost formulations (e.g., paraffin wax, aloe vera, moringa oil) may be viable for premium or organic markets despite higher production costs. Compared to MAP and CA systems–which require high capital investment–edible coatings offer a low-cost, adaptable, and scalable alternative for extending fruit shelf life and maintaining export quality.

CONCLUSION

The demand for fresh fruits and vegetables in daily life has been increasing due to their exceptional nutritional benefits. However, due to their perishable nature, fruits and vegetables often suffer significant postharvest losses caused by intrinsic factors and external conditions. One effective method to improve their quality and extend shelf life is the application of edible coatings. Packaging materials derived from biopolymers such as polysaccharides, proteins, and lipids, sourced from animals, plants, and marine algae, are being extensively researched and developed. When producing edible coatings, these biopolymers are often combined with antimicrobial agents, antioxidants, and other active components in the form of blends or composites to enhance preservation capabilities, maintain quality, and prolong storage duration. These bioactive agents, derived from plant sources, are environmentally friendly and safe for public health. However, for widespread industrial application, further scientific research and practical trials are necessary, including the evaluation of new processes, assessment of safety and toxicity, compliance with regulations, and consumer preference studies.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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