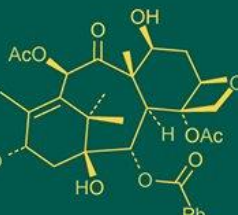
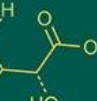
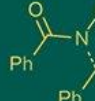


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Next-generation edible coatings and nano-packaging for fruits: A smart approach to shelf-life extension and postharvest safety

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Abstract

The need for sophisticated post-harvest preservation technology has increased due to the worldwide demand for high-quality, minimally processed, and safe fruits. Even if they can be somewhat successful, conventional techniques like chemical treatments and refrigeration are linked to health dangers, excessive energy usage, and environmental issues. The eco-friendliness and versatility of emerging technologies, especially edible coatings and nano-packaging, have attracted a lot of interest. Natural biopolymer-based edible coatings work as semi-permeable barriers that restrict microbial growth, respiration, and moisture loss. By improving barrier qualities, antibacterial activity, and controlled release mechanisms, nano-packaging improves these activities. Smart packaging systems, nano-emulsions, and bioactive coatings are examples of recent developments that provide improved preservation and real-time monitoring. This study offers a thorough and critical examination of next-generation edible coatings and nano-packaging technologies, with an emphasis on their composition, processes, uses, and function in fruit postharvest safety and shelf-life extension. There is also discussion of issues including consumer acceptability, scalability, toxicity hazards, and regulatory problems. In order to create intelligent and sustainable food preservation systems, future views place a strong emphasis on integrating nanotechnology, biotechnology, and artificial intelligence.

Keywords: Edible coatings, Nano-packaging, Fruit preservation, Postharvest technology, Nanotechnology, Shelf-life extension, Food safety, Biopolymers

1. Introduction

Fruit post-harvest losses are a major worldwide problem with profound effects on environmental preservation, economic sustainability, and food security. Because of their high moisture content, delicate texture, and ongoing metabolic activity long after harvest, fruits are extremely perishable commodities. In contrast to processed foods, fresh fruits continue to be physiologically active, going through processes like transpiration, respiration, and ethylene production that speed up senescence, ripening, and eventual spoiling (Nair *et al.*, 2023; Ghidelli & Pérez-Gago, 2024) [9, 5]. Fruits are more sensitive during storage, transit, and marketing because these biological processes are further impacted by environmental factors as temperature, humidity, and handling techniques. Food loss and waste have increased to worrying proportions worldwide. The Food and Agriculture Organization (FAO) estimates that 14% of food is wasted between harvest and sale, with fruits and vegetables making up a sizable share because of their perishability (FAO, 2024). These losses are made worse in underdeveloped nations by poor postharvest handling techniques, a lack of cold chain systems, and inadequate infrastructure. Beyond the effects on the economy, postharvest losses worsen environmental conditions by raising greenhouse gas emissions and squandering important natural resources including energy, water, and land (Kumar *et al.*, 2024) [14]. Physiological, biochemical, and microbiological factors are the main causes of fruit degeneration after harvest. In terms of physiology, transpiration causes moisture loss, weight loss, and textural deterioration, whereas respiration causes the depletion of organic substrates. Browning and quality degradation are caused by biochemical enzymatic processes such polyphenol oxidase activity. In terms of microbiology, fruits are particularly vulnerable to deterioration by bacteria and fungus, such as *Penicillium*, *Aspergillus*, and *Botrytis* species, which can compromise food safety in addition to lowering quality (Oliveira *et al.*,

2024; Singh *et al.*, 2023)^[10, 15]. To reduce postharvest losses, conventional preservation techniques including refrigeration, controlled environment storage, and chemical preservatives have been widely used. Although it takes a lot of energy and might not be available everywhere, refrigeration slows down metabolic processes. Although chemical preservatives are useful in reducing microbial development, there are issues with toxicity, chemical residues, and consumer health (Jurić *et al.*, 2024)^[18]. Additionally, because typical plastic packaging is not biodegradable, it contributes considerably to environmental pollution while being extensively utilized. A paradigm change toward the creation of environmentally benign, biodegradable, and sustainable preservation solutions has occurred in response to these difficulties. Among them, nano-packaging and edible coatings have shown promise as substitutes.

Applying thin layers of edible materials directly to fruit surfaces creates a semi-permeable barrier that controls gas exchange, minimizes moisture loss, and prevents microbial development (Alemu, 2025; Sharma *et al.*, 2024)^[1, 14]. Usually made of natural biopolymers including polysaccharides, proteins, and lipids, these coatings are frequently enhanced in their performance by the addition of bioactive substances like antioxidants and antibacterial agents.

By using nanoparticles to enhance package performance, nano-packaging, on the other hand, offers a major breakthrough in food preservation technology. Materials with improved mechanical strength, barrier qualities, and antibacterial activity can be created thanks to nanotechnology. For example, the potential of nanoparticles like silver, zinc oxide, and nanoclays to prevent microbial growth and increase shelf life has been extensively researched (Ramya *et al.*, 2025; Thakur *et al.*, 2024)^[12, 17]. Additionally, nanosensors provide real-time food quality and safety monitoring, which helps to design intelligent packaging solutions, while nanoemulsions enable the regulated release of active chemicals (McClements, 2023; Chan *et al.*, 2025)^[8, 3]. According to recent studies, traditional edible coatings are giving way to multipurpose nano-enabled systems that combine safety, monitoring, and preservation capabilities into one platform. By lowering reliance on artificial packaging materials, these cutting-edge technologies not only improve the physicochemical and microbiological stability of fruits but also support sustainability objectives. (Tasnim *et al.*, 2025; Zhang *et al.*, 2025)^[16, 20]. The safety and consumer acceptance of these technologies are further improved by the use of natural antibacterial agents like plant extracts and essential oils. Regulatory approval, cost-effectiveness, scalability, and public perception are some of the obstacles to the widespread use of edible coatings and nano-packaging, despite their great promise. Comprehensive risk evaluation and standardization are also required due to concerns about the toxicity and safety of nanomaterials (Bremenkamp & Gallagher, 2025)^[2]. However, it is anticipated that continued developments in food engineering, nanotechnology, and material science will solve these issues and make it easier for these creative solutions to be commercialized. Combining edible coatings with nano-packaging, which offers a sustainable and efficient method to reduce postharvest losses, enhance food safety, and meet the growing need for environmentally friendly packaging

solutions, may transform fruit preservation. This research aims to provide a comprehensive overview of these cutting-edge technologies with a focus on their methodology, uses, advantages, and future prospects.

2. Postharvest Physiology and Deterioration Mechanisms

Even after being harvested, fresh fruits continue to be metabolically active and go through a number of physiological, biochemical, and microbiological changes that eventually affect their quality and shelf life. Both intrinsic (such fruit type, development stage, and composition) and extrinsic (like temperature, humidity, and storage conditions) elements affect these interconnected processes. Designing successful preservation techniques, such as edible coatings and nano-packaging systems, requires an understanding of these principles.

2.1 Respiration and Senescence

One of the most important physiological processes affecting the quality and shelf life of postharvest fruit is respiration. Adenosine triphosphate (ATP), coupled with carbon dioxide and water as byproducts, is produced by oxidizing organic substrates such sugars, organic acids, and lipids. The overall respiratory response can be summed up as follows:

Carbon dioxide + Water + Energy (ATP) = Glucose + Oxygen

Fruits continue to breathe after harvest, but without the assistance of the plant system, which causes stored substrates to be depleted and senescence to develop. Fruits with greater respiration rates often have shorter shelf lives because the rate of respiration is closely correlated with the pace of degradation (Nair *et al.*, 2023)^[9].

Based on their respiration patterns, fruits are divided into climacteric (like apples, bananas, and mangos) and non-climacteric (like citrus and strawberries) varieties. Climacteric fruits undergo fast metabolic changes, including starch hydrolysis, cell wall disintegration, and color transformation, which are linked to the climacteric peak, a sudden rise in respiration rate during ripening (Ghidelli & Pérez-Gago, 2024)^[5]. On the other hand, following harvest, non-climacteric fruits exhibit a slow decrease in respiration. The last stage of fruit growth, known as senescence, is marked by loss of structural integrity, membrane deterioration, and cellular disintegration. Senescence at the cellular level is characterized by oxidative stress, reactive oxygen species (ROS) buildup, lipid peroxidation, and enzyme-mediated breakdown of cell wall constituents such cellulose and pectin (Jurić *et al.*, 2024)^[18]. Softening, taste loss, and reduced nutritional value are the results of these alterations. Respiration rates are greatly influenced by environmental variables including temperature and oxygen availability. Reduced metabolic activity at lower temperatures slows respiration and increases shelf life. Cold storage and packing in a changed environment are based on this idea. However, anaerobic respiration brought on by an extreme drop in oxygen levels might result in off odors and a decline in quality (Kumar *et al.*, 2024)^[14].

2.2 Transpiration and Moisture Loss

The process by which fruit surfaces release water vapor into the surrounding air is known as transpiration. It is a significant contributor to quality degradation and

postharvest weight loss. Fruits have a high water content (about 80-95%), and even a small amount of moisture loss can have a big impact on their marketability. Vapor pressure differential between the fruit's surface and the surrounding atmosphere are the main cause of water loss by diffusion. The rate of transpiration is influenced by variables including temperature, relative humidity, air velocity, and surface features (Shaifali *et al.*, 2024)^[13].

- The following are some effects of moisture loss:
- Reduced weight that results in financial losses
- The visual quality is affected by shriveling and wrinkling.
- Reduced turgor pressure causes a loss of stiffness.
- Textural deterioration affects customer acceptability

Transpiration causes turgidity to be lost at the cellular level, which causes tissues to relax and cells to collapse. This is especially important for fruits that are extremely susceptible to dehydration, such as strawberries, grapes, and green fruits. By creating a moisture barrier on the fruit's surface, edible coatings significantly reduce transpiration. Because lipid-based coatings are hydrophobic, they are particularly good at reducing water vapor transfer (Sharma *et al.*, 2024)^[14].

2.3 Production of Ethylene

Fruit ripening and senescence are mostly controlled by the gaseous plant hormone ethylene. Key enzymes including ACC synthase and ACC oxidase are involved in the Yang cycle, which produces it from the amino acid methionine. During ripening, climacteric fruits produce a significant amount more ethylene, which sets off a series of physiological and biochemical changes that include:

- Degradation of the cell wall, resulting in softness
- Color changes due to carotenoid production and chlorophyll degradation
- Starch is converted to sugars to increase sweetness.
- The creation of taste and fragrance compounds

Additionally, ethylene functions as an autocatalytic hormone, which accelerates the ripening process by stimulating additional ethylene synthesis (Oliveira *et al.*, 2024)^[10].

Non-climacteric fruits, on the other hand, do not show a climacteric increase in respiration and release minimal amounts of ethylene. They can still react to exposure to ethylene from the outside, though, which could hasten degeneration. In postharvest technologies, ethylene management is a crucial tactic. Edible coatings, controlled environment storage, and ethylene scavengers are among methods that assist limit ethylene levels and postpone ripening. By altering gas permeability and adding ethylene inhibitors, nano-enabled coatings can successfully prevent ethylene action, according to recent research (Ramya *et al.*, 2025)^[12].

2.4 Microbial Spoilage

One of the main reasons fruits lose quality and safety after harvest is microbial deterioration. Fresh fruits' high moisture content (80-95%), availability of nutrients including sugars and organic acids, and optimal pH levels make them perfect for microbial development. Together, these elements facilitate the growth of a variety of microorganisms, such as bacteria, yeasts, and fungus (Oliveira *et al.*, 2024)^[10].

Fruit deterioration is mostly caused by fungal diseases, which are frequently linked to taxa including *Penicillium*, *Aspergillus*, *Botrytis*, and *Rhizopus*. Fruit tissues are invaded by these fungi through wounds or natural holes made during harvesting, handling, or transportation. Once established, they release extracellular enzymes such as proteases, cellulases, and pectinases that break down the components of cell walls, causing tissue maceration and obvious deterioration (Nair *et al.*, 2023)^[9]. Some fungal species not only cause physical degeneration but also create mycotoxins, which can seriously harm consumers' health.

While less obvious than fungal deterioration, bacterial decomposition is just as important. Fruits can become contaminated by bacteria including *Salmonella*, *Erwinia*, and *Pseudomonas* by inappropriate handling, dirt, or water. These microbes are involved in the development of slime, off smells, and soft rot. Microbial contamination is a serious problem for food safety as pathogenic bacteria can cause foodborne illnesses (Singh *et al.*, 2023)^[15]. Microbial growth is significantly influenced by environmental factors. One of the most important variables is temperature, as higher temperatures speed up enzyme activity and microbial growth rates. Another factor that affects spoiling is relative humidity; excessive humidity encourages the development of fungi and the generation of spores. Furthermore, the type of microorganisms that predominate depends on the availability of oxygen, with aerobic circumstances encouraging fungal development (Kumar *et al.*, 2024)^[14].

Numerous postharvest techniques have been developed to reduce microbial spoiling. Among these, nano-packaging techniques and edible coatings have demonstrated a great deal of potential. Essential oils, organic acids, and plant extracts are examples of antimicrobial agents that can be carried by edible coatings. (Zhang, L., *et al.*, 2025)^[20]. These chemicals prevent bacteria development by rupturing cell membranes and interfering with metabolic activities. Additionally, because of their large surface area and capacity to produce reactive oxygen species, nano-enabled coatings containing nanoparticles like zinc oxide and silver show increased antibacterial activity (Thakur *et al.*, 2024; Zhang *et al.*, 2025)^[17, 20].

3. Edible Coatings: Functional Design and Composition

By creating a thin, edible layer on the top of fresh fruits, edible coatings have become a potential postharvest technique. In addition to acting as carriers for functional additives, these coatings are intended to act as semi-permeable barriers that control mass transfer processes including gas exchange and moisture migration. Their ability to prolong shelf life and preserve fruit quality is largely dependent on their content and structural design.

3.1 Functional Properties and Definition

Thin layers of edible ingredients placed directly to the surface of food goods, especially fruits, to improve their quality, safety, and shelf life are known as edible coatings. Edible coatings, as contrast to traditional packaging, integrate into the food and are ingested with it (Alemu, 2025)^[1]. The following functional characteristics of edible coatings play a major role in determining their efficacy:

3.1.1 Characteristics of Barriers

Gases including oxygen (O₂), carbon dioxide (CO₂), and water vapor are selectively blocked by edible coatings. They

slow down ripening and lower respiration rates by regulating gas permeability. But the perfect coating needs to be balanced since too little oxygen can cause anaerobic respiration, which can result in unpleasant tastes. (Sharma *et al.*, 2024)^[1].

3.1.2 Mechanical Properties

For the coating to remain intact during handling and storage, it must be mechanically strong and flexible. Coatings must be able to stick to the fruit's surface without splitting, peeling, or deforming.

3.1.3 Optical Properties

Since coatings shouldn't detract from fruits' aesthetic appeal, transparency and gloss are crucial for consumer acceptability.

3.1.4 Beneficial Activity

Bioactive substances including antimicrobials, antioxidants, and nutraceuticals are frequently added to contemporary edible coatings, allowing them to actively improve food safety and nutritional value (Jurić *et al.*, 2024)^[18].

3.2 Biopolymer Compounds in Edible Coatings

The kind and mix of biopolymers utilized in edible coatings determine their performance. Proteins, lipids, polysaccharides, and their composites are the broad categories into which these materials are divided.

3.2.1 Polysaccharide-Based Coatings

Because of their superior film-forming capacity and gas barrier qualities, polysaccharides are frequently utilized in edible coatings. However, they are less efficient as moisture barriers due to their hydrophilic nature (Dhaka *et al.*, 2021)^[22].

Chitosan: One of the most researched polysaccharides for edible coatings, chitosan is produced from chitin. It is biodegradable, has strong antibacterial action, and may form films. By rupturing cell membranes and interfering with microbial metabolism, chitosan coatings prevent microbial development. They are appropriate for fruits like apples and strawberries since they are very efficient against fungal diseases (Nair *et al.*, 2023)^[9].

- **Starch:** Starch-based coatings are widely accessible and reasonably priced. They offer easy customization, biodegradability, and good oxygen barrier qualities. Native starch films, however, are fragile and moisture-sensitive. Plasticizers like glycerol are frequently used to increase flexibility in order to get around this restriction (Kumar *et al.*, 2024)^[14].
- **Pectin:** Because it works well with fruit matrices, pectin, a polysaccharide produced from plants, is frequently utilized in fruit coatings. It is very helpful for covering chopped fruits since it gels when calcium ions are present. Although pectin-based coatings aid in retaining firmness and minimizing moisture loss, they must be combined with other substances to improve mechanical strength (Wu *et al.*, 2024)^[19].
- **Polysaccharide Limitations:** Despite their benefits, polysaccharide coatings' hydrophilic nature makes them poorly resistant to water vapor transport. This reduces their ability to stop moisture loss, hence they must be used in conjunction with hydrophobic materials.

3.2.2 Protein-Based Coatings

The improved film-forming ability, mechanical strength, and flexibility of protein-based edible coatings have drawn a lot of attention in postharvest technologies. These coatings, which are made from naturally occurring proteins like whey, casein, and soy protein, may create continuous, cohesive films that stick to fruit surfaces. Because of their structural features, they can operate as semi-permeable barriers that control gas exchange and lessen oxidative degradation (Jurić *et al.*, 2024)^[18].

The molecular makeup of protein-based coatings is primarily responsible for their functioning. Amino acid chains, which make up proteins, can connect through disulfide bonds, hydrophobic interactions, and hydrogen bonds. These proteins unfold and rearrange into a three-dimensional network upon denaturation, which is usually brought on by heat or pH shifts, producing stable and homogeneous films. Their mechanical qualities and integrity during handling and storage are enhanced by this structural configuration (Kumar *et al.*, 2024)^[14].

- **Film-Forming Capability:** When whey protein solutions dry, they can create cohesive, uniform films. Increased intermolecular connections brought about by heat-induced denaturation result in stronger and more consistent films. These films effectively cover and protect fruit surfaces because they stick to them nicely (Alotaibi *et al.*, 2018)^[10].
- **Oxygen Barrier Properties:** Whey protein coatings' low oxygen permeability is one of their main advantages. Lipid oxidation and enzymatic browning are two oxidative processes that are lessened by the dense protein network's restriction of oxygen diffusion. This is especially helpful for preserving fruits' color, taste, and general quality when they are being stored (Sharma *et al.*, 2024)^[14].
- **Nutritional Value:** The nutritional profile of coated fruits is improved by the abundance of important amino acids found in whey protein. This is in line with customer desire for food items that are both functional and health-promoting.
- **Casein:** A protein produced from milk, casein creates flexible, robust films with high barrier qualities. To improve flexibility and lessen brittleness, it is frequently used with plasticizers.

Soy protein is a plant-based substitute that is becoming more and more well-liked since it is affordable and sustainable. It has moderate barrier qualities, good mechanical strength, and biodegradability. However, for better performance, protein-based coatings may need to be cross-linked or blended with lipids since they may not be very resistant to water vapor (Jurić *et al.*, 2024)^[18].

Restrictions and Strategies for Modification

Whey protein coatings have various drawbacks despite their benefits, mostly because they are hydrophilic. They are typically ineffective in keeping out water vapor, which can lead to moisture loss and decreased efficacy in situations with high humidity. Moreover, without the use of plasticizers, protein films might become brittle (Eca *et al.*, 2014)^[25].

Numerous modification tactics have been proposed to solve these issues. These include the application of cross-linking methods to fortify the protein network, the use of

plasticizers like glycerol to increase flexibility, and the addition of lipids to improve moisture resistance. The use of nanoparticles to enhance barrier qualities and provide antibacterial efficacy is another recent development (Zhang *et al.*, 2025)^[20].

3.2.3 Coatings Based on Lipids

The main reason lipid-based coatings are utilized is because of their superior moisture barrier qualities. They efficiently lessen the passage of water vapor since they are hydrophobic (Azarakhs *et al.*, 2024)^[23].

- **Waxes:** Fruit coats frequently include natural waxes including paraffin, carnauba wax, and beeswax. They offer longer shelf life, better gloss and look, and high moisture resistance. Citrus fruits and apples are frequently coated with wax to improve appearance and minimize water loss (Das *et al.*, 2013)^[26].
- **Fatty Acids:** The hydrophobicity of coatings is enhanced by the use of fatty acids and their derivatives. To improve moisture barrier qualities, they are frequently used to composite coatings.
- **Limitations of Lipids:** Lipids have weak gas barrier qualities and can cause anaerobic respiration when employed alone, despite their effectiveness in avoiding moisture loss. As a result, they are usually mixed with proteins or polysaccharides (Kumar *et al.*, 2020)^[29].

3.2.4 Edible Composite Coatings

Composite coatings are created by mixing two or more elements to get over the drawbacks of separate biopolymers. To attain higher functioning, these systems combine the

benefits of each component. They increased stability and durability, balanced gas and moisture barrier qualities, mechanical strength, and the capacity to add bioactive ingredients.

For instance

Lipid + polysaccharide = increased resistance to moisture

Protein with polysaccharide results in increased mechanical strength.

In order to further improve performance, nanoparticles are added to biopolymer matrices in nano-composite coatings, which are the subject of recent study. These coatings have better barrier qualities, regulated active agent release, and enhanced antibacterial action (Zhang *et al.*, 2025)^[20]. Additionally, natural additives like probiotics, antioxidants, and essential oils may be included into composite coatings, making them multipurpose systems that can handle safety and preservation issues (Oliveira *et al.*, 2024)^[10].

3.3 Design Considerations and Critical Analysis

The formulation, structural characteristics, and compatibility of edible coatings with the particular fruit matrix all have a major role in how well they extend the shelf life and guarantee the quality of fresh fruits (Silva-Weiss *et al.*, 2013)^[28]. Finding the ideal balance between gas permeability and moisture barrier qualities is a crucial part of coating design. Coatings should decrease respiration and oxidation by reducing oxygen ingress, but too much restriction might create anaerobic conditions that cause physiological problems and off-flavors (Alemu, 2025)^[1].

Table 1: Design Considerations and Critical Analysis

Design Factor	Explanation	Significance in Fruit Preservation	Potential Limitations	Recommended Approaches	References
Gas Permeability	Ability of coating to control oxygen and carbon dioxide transfer	Helps regulate respiration and delays ripening processes	Excessively low oxygen levels may induce anaerobic metabolism and off-flavors	Develop coatings with balanced permeability tailored to specific fruits	(Alemu, 2025) ^[1]
Moisture Resistance	Capacity to limit water vapor movement from fruit surface	Prevents dehydration, weight loss, and shriveling	Hydrophilic coatings (e.g., polysaccharides) offer poor moisture resistance	Combine with hydrophobic substances such as waxes or lipids	(Kumar <i>et al.</i> , 2024) ^[14]
Material Selection	Choice of coating components such as polysaccharides, proteins, or lipids	Determines barrier efficiency and compatibility with fruit physiology	Single-component systems often lack multifunctionality	Use multi-component or composite coatings for improved performance	(Kumar <i>et al.</i> , 2024) ^[14]
Mechanical Stability	Strength and flexibility of the coating layer	Ensures durability during handling, storage, and transport	Films may become brittle or crack under stress	Incorporate plasticizers and apply cross-linking techniques	(Jurić <i>et al.</i> , 2024) ^[18]
Surface Adhesion	Ability of coating to uniformly adhere to fruit surface	Ensures complete coverage and consistent protection	Weak adhesion may lead to uneven coating and reduced effectiveness	Optimize formulation and application techniques (e.g., dipping or spraying)	(Jurić <i>et al.</i> , 2024) ^[18]
Functional Additives	Inclusion of compounds such as antimicrobials and antioxidants	Enhances protection against microbial spoilage and oxidation	High concentrations may alter taste, aroma, or appearance	Optimize dosage and use controlled-release systems	(Oliveira <i>et al.</i> , 2024) ^[10]
Economic Feasibility	Cost-effectiveness and scalability of coating formulation	Determines suitability for commercial adoption	Advanced materials (e.g., nano-coatings) may be expensive	Focus on low-cost, biodegradable, and scalable materials	(Thakur <i>et al.</i> , 2024; Jafarzadeh <i>et al.</i> , 2020) ^[17, 29]
Safety and Regulations	Compliance with food safety standards and regulations	Ensures consumer safety and market approval	Concerns regarding toxicity of certain nanomaterials	Conduct thorough risk assessments and follow regulatory guidelines	(Thakur <i>et al.</i> , 2024) ^[17]
Consumer Acceptance	Public perception of edible coatings and novel technologies	Influences market success and adoption	Resistance to unfamiliar or nano-based materials	Promote awareness and use natural, clean-label ingredients	(Alemu, 2025) ^[1]

4. Edible Coatings' Action Mechanism

In order to prolong shelf life and preserve postharvest quality, edible coatings serve as protective layers that are

directly placed to the surface of fruits. Physical, chemical, and biological processes work together to minimize degradation and maintain sensory qualities. These coatings

provide both passive and active protection by acting as semi-permeable barriers and carrying useful chemicals (Brito *et al.*, 2019)^[30].

4.1 Gas Exchange Regulation

The control of gas exchange between the fruit and its surroundings is one of the main processes of edible coverings. After being harvested, fruits continue to breathe, taking in oxygen (O₂) and expelling carbon dioxide (CO₂). The respiration rate is lowered by edible coatings because they produce a semi-permeable barrier that limits carbon dioxide outflow and oxygen input (Alemu, 2025)^[1]. Ripening and senescence are two metabolic processes that are postponed by this controlled atmospheric impact (Mahcene *et al.*, 2020)^[31]. Maintaining the ideal balance is crucial, though, because too much oxygen restriction can cause anaerobic respiration, which builds up ethanol and bad tastes. As a result, the coating's permeability needs to be adjusted to the respiration characteristics of certain fruits (Kumar *et al.*, 2024)^[14].

4.2 Reduction of Moisture Loss

One of the main causes of fruit weight loss, shriveling, and textural deterioration is moisture loss via transpiration. By preventing the transfer of water vapor, edible coatings lower transpiration rates and preserve cellular turgidity. Because they are hydrophobic, lipid-based coatings are very good at reducing moisture loss. However, by regulating both moisture and gas exchange, composite coatings that mix lipids with proteins or polysaccharides offer a more balanced strategy (Sharma *et al.*, 2024)^[14]. Edible coatings help keep fruits firm and enhance their appearance by retaining their water content.

4.3 Microbial Growth Inhibition

The capacity of edible coatings to inhibit microbial growth is another important mechanism. Fruits are particularly vulnerable to bacterial and fungal deterioration. Essential oils, organic acids, and plant extracts are examples of antimicrobial compounds that may be used in edible coatings to prevent bacteria development through a variety of mechanisms (Becerril *et al.*, 2020)^[32]. These antimicrobial substances prevent colonization and spoiling by rupturing microbial cell membranes, interfering with enzyme function, and blocking nutrition intake. Furthermore, since they may produce reactive oxygen species and harm microbial cells, nano-enhanced coatings with nanoparticles like zinc oxide or silver show increased antibacterial action (Thakur *et al.*, 2024)^[17].

4.4 Antioxidant Activity and Delay of Oxidative Reactions

Fruit quality degradation, including enzymatic browning and nutritional content loss, is caused by oxidative processes. Antioxidants that counteract free radicals and lessen oxidative damage, such as ascorbic acid, phenolic compounds, and plant extracts, can be added to edible coatings. Edible coatings efficiently postpone enzymatic activities mediated by enzymes like polyphenol oxidase by restricting oxygen availability and provide antioxidant protection (Chalandar *et al.*, 2017)^[33]. This aids in preserving fruits' nutritional value, color, and taste while they are being stored (Oliveira *et al.*, 2024)^[10].

4.5 Ethylene Regulation and Internal Atmosphere Modification

By changing gas diffusion, edible coatings have an impact on the interior environment of fruits, which in turn impacts ethylene production and sensitivity (Khamis *et al.*, 2017)^[34]. A crucial hormone in fruit ripening, especially in climacteric fruits, is ethylene. Edible coverings can inhibit ethylene production and postpone ripening processes by lowering oxygen availability and raising carbon dioxide levels. To further regulate ripening and increase shelf life, some sophisticated coatings additionally include ethylene scavengers or inhibitors (Jurić *et al.*, 2024)^[18].

4.6. Bioactive Compounds Released Under Control

The purpose of contemporary edible coatings is to serve as bioactive chemical delivery vehicles. These include nutraceuticals that are delivered gradually over time, antioxidants, and antibacterial agents (Fateixa *et al.*, 2009)^[35]. Throughout the storage duration, the regulated release system guarantees continuous protection against oxidative degradation and microbiological spoilage. Specifically, nano-structured coatings improve these chemicals' stability and release efficiency, which improves overall preservation performance (Zhang *et al.*, 2025; Fernández-López *et al.*, 2019)^[20, 21].

5. Nano-Packaging Technologies

Food preservation has advanced significantly with the use of nano-packaging technology, especially for fresh fruits. These systems improve the functional characteristics of packaging, such as mechanical strength, barrier effectiveness, antimicrobial activity, and real-time monitoring capabilities, by integrating materials at the nanoscale (1-100 nm). Nano-packaging solutions, in contrast to traditional packaging, are intended to actively engage with food items and their surroundings, extending shelf life and guaranteeing safety (Tripathi *et al.*, 2021)^[36].

5.1 Composites of nanomaterials

A polymer matrix, usually made of biodegradable biopolymers like starch, cellulose, or chitosan, is combined with nanoparticles to create nanocomposites, which are hybrid materials. The structural and functional qualities of packing materials are greatly enhanced by the use of nanoparticles. Advanced materials known as nanocomposites are created by adding nanoscale particles (1-100 nm) to a polymer matrix. These polymers are usually biodegradable substances like starch, chitosan, cellulose, or proteins used in food packaging and edible coatings. as nanoparticles are included into these matrices, the materials' mechanical, functional, and physical characteristics are greatly enhanced as compared to traditional packaging techniques (Zhang *et al.*, 2025)^[20].

5.1.1 Function and Mechanism

Gas and moisture transport is made more compact and convoluted by nanoparticles like nanoclays, metal oxides (like zinc oxide and titanium dioxide), and silver nanoparticles. Fruits' respiration and dehydration processes are slowed as a result of the decreased permeability to oxygen and water vapor (Zhang *et al.*, 2025)^[20]. Furthermore, packing materials are more resilient to ripping, distortion, and environmental stress because to nanocomposites' increased mechanical strength. This is especially crucial for storage and transit.

Enhancement of Barrier: Nanoparticles make it difficult for moisture and gasses to pass through the substance. As a result, permeability is decreased because oxygen and water vapor must travel a longer, more difficult path through the package. Fruits' respiration rates and moisture loss are thereby greatly reduced (Kumar *et al.*, 2024)^[14].

Mechanical Strength Improvement: By improving intermolecular interactions, nanofillers fortify the polymer matrix. Increased tensile strength, elasticity, and resistance to mechanical stress result from this, making the package more resilient during handling and transit.

Antimicrobial Activity: Some nanoparticles have inherent antibacterial qualities. Consider silver nanoparticles (AgNPs). Zinc oxide nanoparticles (ZnO), DNA, and microbial cell membranes are all affected. It damages microbial cells by producing reactive oxygen species. By preventing the formation of spoilage microbes, these systems help prolong fruit shelf life. There are nanoparticles with inherent antibacterial activity. For instance, zinc oxide nanoparticles produce reactive oxygen species that prevent microbial development, whereas silver nanoparticles damage microbial cell membranes and obstruct DNA replication. According to Thakur *et al.* (2024)^[17], these characteristics aid in decreasing spoiling and increasing shelf life. For fruits like apples, strawberries, and grapes, nanocomposite coatings and films are frequently employed to preserve firmness, prevent microbial contamination, and lessen weight loss (Shah *et al.*, 2010)^[37].

5.2 Nanoemulsions

Nanoemulsions are colloidal systems made up of tiny droplets (usually between 10 and 500 nm in diameter) scattered over another immiscible liquid, such water and oil. Because these systems improve the transport and stability of bioactive substances, they are being utilized more and more in edible coatings and packaging (Mou *et al.*, 2008)^[38].

5.2.1 The Function and Mechanism

Because of their tiny droplet size, nanoemulsions have more surface area, which improves their interaction with microbial cells and increases the bioavailability of active ingredients. Antimicrobial agents, antioxidants, and essential oils can be delivered more effectively as a result (McClements, 2023)^[8]. Additionally, nanoemulsions show kinetic stability, which guarantees equal distribution of active substances and prevents phase separation. For constant performance to be maintained while being stored, this stability is essential (Jafari *et al.*, 2007)^[39].

5.2.2 Controlled Release of Bioactive Compounds

The capacity of nanoemulsions to deliver regulated and prolonged release of encapsulated substances is one of their main benefits. This minimizes spoiling over time by ensuring extended antibacterial and antioxidant action (Panwar *et al.*, 2024)^[11]. Fruits including berries, citrus fruits, and mangoes are frequently coated with nanoemulsion-based materials. Without compromising sensory qualities, they aid in lowering microbial growth, postponing oxidation, and enhancing overall fruit quality (Akbas *et al.*, 2018)^[40].

5.3 Nanosensors

Advanced parts of smart packaging systems that track food quality in real time are called nanosensors. These sensors provide important information on the safety and freshness of

fruits by detecting changes in environmental and biochemical factors (Petriccione *et al.*, 2014)^[41]. Volatile organic compounds (VOCs) emitted during spoiling, temperature and humidity variations, and gas composition (O₂, CO₂, ethylene) are some of the signs that nanosensors detect. These sensors provide ongoing food condition monitoring by converting chemical or physical data into quantifiable outputs (Chan *et al.*, 2025)^[3].

Nanosensor Types:

- **Gas sensors:** Track ripening by detecting ethylene levels
- **Biosensors:** Determine the presence of microorganisms
- **Temperature-time indicators:** Monitor the state of storage

Benefits and Uses: The benefits of nanosensors include reduced food waste, improved supply chain management, early spoiling detection, and real-time freshness monitoring. Packaging techniques for expensive products, such berries and exotic fruits, are increasingly using nanosensors (Gohlani *et al.*, 2012)^[42]. They offer digital or visual indications that aid in the evaluation of product quality by manufacturers, merchants, and consumers (Mihafu *et al.*, 2020)^[43].

5.4 Nanoemulsions

Nanoemulsions are colloidal dispersions made up of two immiscible liquids, commonly water and oil, in which one phase is distributed as minuscule droplets inside the other, often ranging in size from 10 to 500 nm. Emulsifying agents like biopolymers or surfactants reduce droplet agglomeration and improve stability in these systems (McClements, 2023)^[8]. Nanoemulsions have special physicochemical characteristics, such as increased surface area, optical transparency, and improved kinetic stability, because to their nanoscale droplet size. Nanoemulsions are excellent for food applications because, in contrast to traditional emulsions, they are resistant to flocculation, coalescence, and gravity separation.

Nanoemulsions are mostly utilized in fruit preservation as transporters for bioactive substances such vitamins, antioxidants, essential oils, and antibacterial agents. Antimicrobial efficacy is strengthened by the tiny droplet size, which facilitates better dispersion and more contact with microbial cells. Furthermore, nanoemulsions enable the continuous and regulated release of active ingredients, guaranteeing extended defense against oxidative deterioration and spoiling (Panwar *et al.*, 2024)^[11]. Edible coatings based on nanoemulsions have been used extensively on berries, citrus fruits, and mangos. Without impairing flavor or appearance, these coatings aid in lowering microbial growth, postponing oxidation, and preserving sensory quality. Additionally, nanoemulsions increase hydrophobic chemicals' solubility and bioavailability, increasing their efficacy in food systems. Despite their benefits, large-scale uses of food-grade surfactants need addressing issues such formulation stability, cost, and regulatory considerations.

6. Sustainability and Environmental Impact of Edible Coatings

Because edible coatings are biodegradable, have a less environmental impact, and can reduce food waste, they have drawn a lot of interest as sustainable substitutes for

traditional food packaging. Edible coatings provide an environmentally benign solution in line with the concepts of the circular economy as worries about plastic pollution and resource depletion grow on a worldwide scale.

6.1 Plastic Waste Reduction

The potential of edible coatings to lessen reliance on synthetic plastic packaging is one of its most significant environmental benefits. Because they are not biodegradable and accumulate in ecosystems, traditional packaging materials—especially petroleum-based plastics contribute greatly to environmental contamination. Edible coatings, on the other hand, are made from naturally occurring biopolymers such lipids, proteins, and polysaccharides that are safe for the environment and biodegradable (Kumar *et al.*, 2024) ^[44]. Edible coatings can drastically cut down on the usage of plastic films, trays, and wraps by acting as main or supplemental packaging. This lessens the pressure on the environment and the production of solid trash.

6.2 Eco-Friendly Nature and Biodegradability

Renewable materials that naturally break down without producing hazardous residues make up edible coatings. Materials that come from plants or animals, such starch, chitosan, gelatin, and pectin, are easily biodegradable in the natural world. Because of this, they are a sustainable substitute for synthetic polymers that linger in the environment for many years (Alemu, 2025) ^[1]. Additionally, compared to traditional plastic manufacturing, the creation of edible coatings often uses less energy, which reduces carbon emissions.

6.3 Reduction of Food Waste

Food waste is a significant worldwide problem with social, economic, and environmental ramifications. By lowering respiration, moisture loss, and microbial deterioration, edible coatings help fruits last longer on the shelf. These coatings minimize postharvest losses during storage, transportation, and retail by preserving quality and postponing degradation (Jurić *et al.*, 2024) ^[18]. Reducing food waste also indirectly reduces greenhouse gas emissions related to the production, processing, and disposal of food. Edible coatings are therefore essential to enhancing the sustainability of the food chain.

6.4 Utilizing Renewable and Natural Resources

Most edible coatings are made from renewable resources, such as waste materials and agricultural byproducts. For instance, fruit peels are used to extract pectin, and crab shells are used to get chitosan. Using these by-products promotes sustainable resource management while also adding value to waste resources (Sharma *et al.*, 2024) ^[14]. This strategy is in line with the circular economy's tenets, which call for the recycling and reuse of waste resources to produce goods with additional value.

6.5 Environmental Restrictions and Difficulties

Edible coatings provide benefits, but they also have certain sustainability issues. Certain biopolymers may require substantial agricultural inputs, such as water and energy, in order to be produced on a big scale. Furthermore, the use of nanoparticles in sophisticated coatings raises questions about possible toxicity and environmental safety if improperly controlled (Thakur *et al.*, 2024) ^[17]. Furthermore,

the cost-effectiveness and scalability of edible coatings continue to be important concerns that need to be resolved for their broad use.

7. Conclusion

A revolutionary development in postharvest fruit preservation, next-generation edible coatings and nano-packaging technologies provide a sustainable and multipurpose solution to the world's problems with food loss, safety, and environmental impact. These systems effectively regulate physiological functions including respiration, transpiration, and ethylene production by combining natural biopolymers with nanotechnology. They also prevent microbial development and oxidative degradation. This dual purpose keeps fruits' sensory and nutritional qualities intact while also extending their shelf life.

Intelligent and active packaging solutions are becoming more prevalent, as seen by the transition from traditional coatings to nano-enabled and bioactive systems. Nanosensors provide real-time monitoring capabilities that improve quality assurance across the supply chain, nanoemulsions facilitate effective administration and controlled release of bioactive substances, and nanocomposites increase mechanical strength and barrier qualities. When combined, these developments enhance postharvest safety and lessen the need for plastic packaging and artificial preservatives. Despite their enormous promise, a number of issues need to be resolved before they can be widely commercialized. These include issues with cost-effectiveness, production process scalability, customer acceptance of developing technology, and the safety and regulatory licensing of nanomaterials. Interdisciplinary cooperation between food scientists, material engineers, legislators, and industry stakeholders will be necessary to address these problems.

Future studies should concentrate on the creation of economical and environmentally friendly formulations, the incorporation of intelligent technologies like sensors and data-driven monitoring systems, and the creation of precise legal frameworks to guarantee uniformity and safety. Aligning these technologies with global environmental goals will need a focus on sustainability, especially via the utilization of renewable resources and biodegradable materials.

In conclusion, edible coatings and nano-packaging technologies have great potential as cutting-edge ways to extend fruit shelf life and guarantee postharvest safety. These technologies have the potential to greatly lower postharvest losses, enhance food security, and support a more resilient and sustainable agricultural system with continuing research and ethical use.

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