Review Article

Edible Coatings: A Novel Approach to Extending the Shelf Life of Fruits and Vegetables

ABSTRACT

The rapid deterioration of fruits and vegetables during pre- and post-harvest conditions leads to significant post-harvest losses, affecting both quality and shelf life. Edible coatings have emerged as an effective solution to mitigate these issues, providing a protective layer that can be safely consumed as part of the food. Recently, there has been growing interest in using herbal extracts such as lemongrass, oregano, Aloe vera, Tulsi, mint, neem, cinnamon, and clove for edible coatings due to their beneficial properties. These herbal-based coatings have been shown to prevent water loss, control the ripening process and respiration rate, delay oxidative browning, and reduce microbial growth in various fruits and vegetables, including grapes, papaya, oranges, cucumbers, tomatoes, apples, and mangoes.Research indicates that these herbal edible coatings can extend the storage time of fresh produce to 15-35 days at low temperatures, compared to the 8-10 days for uncoated produce. The use of herbal extracts in edible coatings is a promising alternative to post-harvest chemical treatments, offering an innovative approach for commercial application.Edible coatings not only extend the post-harvest life of fresh produce but also improve food appearance and safety due to their environmentally friendly nature. They can be derived from animal or vegetable sources and may consist of proteins, lipids, polysaccharides, resins, or combinations thereof. Acting as barriers to moisture and gases, these coatings reduce food deterioration and enhance safety, often incorporating antimicrobial compounds.The advantages of edible coatings include reduced packaging waste, extended shelf life, and protection from environmental effects while maintaining the transfer of oxygen, carbon dioxide, moisture, aroma, and taste. Given the high market demand for nutritious fruits and vegetables and their perishable nature, edible coatings present an effective method to address post-harvest challenges, benefiting both consumers and the environment. This review discusses the components, benefits, and application techniques of edible coatings, focusing on their potential to enhance the shelf life and quality of fresh produce.

Keywords: *oxidative browning, herbal, polysaccharides, shelf life, nutritious, ripening process and respiration rate*

1. INTRODUCTION

Edible coatings are an innovative and eco-friendly solution designed to improve the appearance and safety of food products. These coatings, which can be derived from both animal and vegetable sources, include materials such as proteins, lipids, polysaccharides and resins, either used alone or in various combinations [1]. The primary function of edible coatings is to act as a barrier against moisture and gases during processing, handling, and storage, thereby reducing food deterioration and enhancing safety. Additionally, edible coatings can incorporate antimicrobial compounds to further protect food from spoilage and contamination [2].One of the significant advantages of using edible coatings is their ability to extend the shelf life of fresh and minimally processed products. This is achieved by maintaining the transfer of oxygen, carbon dioxide, moisture, aroma, and taste compounds within the food system. By carrying functional ingredients such as antioxidants, nutrients, and flavours, edible coatings enhance food stability, quality, functionality, and safety [3]. Commonly, fruits and vegetables are coated by dipping, brushing, or spraying with edible materials to create a semi-permeable membrane on the surface. This membrane helps suppress respiration rates, control moisture loss, and provide other protective functions.

The issue of post-harvest losses, particularly in fruits and vegetables, is a major concern, especially in agriculture-based economies. These losses, often reaching up to 50% in developing countries, are primarily due to the perishable nature of horticultural crops, which contain high moisture content and are biologically active [4]. They undergo processes such as transpiration, respiration, and ripening, leading to quality deterioration. Improper storage, handling, and transportation exacerbate these losses, highlighting the need for effective post-harvest management strategies.During peak harvest seasons, the surplus of horticultural crops often leads to a slump in market prices and careless handling due to inadequate storage and transport facilities. This situation calls for better linkage between production and marketing, especially for perishable items like fruits and vegetables.

Without appropriate technologies for storage, packaging, transport, and handling, significant amounts of produce are wasted [5].

The consumption of fresh fruits and vegetables is on the rise due to their health benefits. Organizations like the USDA, WHO, and FAO recommend increasing the intake of these foods to reduce the risk of many diseases [6]. However, the challenge lies in preserving the quality of fresh produce post-harvest. Traditional packaging methods, although effective in preservation, pose environmental problems related to disposal and recycling. Edible coatings offer a sustainable alternative by not only extending shelf life but also being safe to consume as part of the product [7].Recent advancements in edible coatings involve incorporating various edible herbs and antimicrobial compounds to preserve fresh produce. These coatings help prevent firmness and moisture loss, control maturation and respiratory rates, and reduce oxidative browning and microbial growth. For example, tomatoes, cucumbers, and cherries have shown extended shelf life and improved quality when treated with edible coatings. These coatings, therefore, play a vital role in reducing physiological disorders and maintaining the sensory qualities of fruits and vegetables [8].

Different types of biopolymers are used to develop edible coatings, including polysaccharides, proteins, and lipids. Fat-based coatings are particularly effective in reducing water transfer, while polysaccharide-based coatings have lower gas permeability and protein-based coatings offer better mechanical properties [9]. Additional components such as resins, solvents, and plasticizers are used to achieve desired characteristics. For instance, plasticizers provide flexibility, solvents enhance tensile strength, and resins limit water vapour permeability.The effectiveness of edible coatings can vary depending on the fruit variety and the coating materials used. From a commercial perspective, coatings help preserve the quality of commodities, meet market requirements, and optimize production and packaging costs. Edible coatings regulate the migration of substances like oxygen, carbon dioxide, flavourings, lipids, moisture, and other dissolved compounds, leading to reduced respiration rates and minimized weight loss [10].

Moreover, edible coatings have the potential to serve as carriers for antimicrobial agents, significantly reducing diseases and microbial load in fruits. For example, peptide-based edible coatings have shown promise in controlling microbial growth. By fortifying nutrients and acting as carriers for natural preservatives like antioxidants and antimicrobial agents, edible coatings offer additional health benefits.Edible coatings represent a multifaceted approach to food preservation, particularly for perishable horticultural crops [1-2, 11]. They not only extend the shelf life and maintain the quality of fresh produce but also offer environmental benefits by reducing the need for traditional packaging materials. As the demand for fresh fruits and vegetables continues to grow, edible coatings will play an increasingly important role in ensuring food safety, reducing post-harvest losses, and enhancing the overall quality and nutritional value of food products [12].

2. EDIBLE FILMS AND COATINGS – MATERIAL TYPES

Edible coatings and films are crafted from various biomolecules, each offering unique properties that contribute to the preservation and quality enhancement of food products. These biomolecules can be categorized into five primary types: polysaccharides, proteins, lipids, composite materials, and agro-industrial waste (**Figure 1**). Understanding the characteristics and applications of each material type is crucial for optimizing the functionality and effectiveness of edible coatings.

2.1 Polysaccharides

Polysaccharides, derived from a diverse range of sources including plants, seaweed, insects, animals, and agro-industrial wastes, are widely used in the formulation of edible coatings and films [13]. These materials are particularly valued for their excellent gas barrier properties, which help to regulate the exchange of gases like oxygen and carbon dioxide. This regulation is vital in slowing down the respiration rates of fresh produce, thereby extending its shelf life. However, polysaccharides are inherently hydrophilic, which means they do not naturally provide a strong barrier against moisture. This limitation can lead to challenges in maintaining the moisture content of certain food products, making it necessary to combine polysaccharides with other materials to enhance their moisture barrier properties.

Despite their moisture barrier limitations, polysaccharides are extensively used due to their biodegradability, non-toxicity, and ability to form films and coatings that can be safely consumed [14]. They are also capable of being modified or blended with other substances to improve their functional properties. For instance, combining polysaccharides with hydrophobic materials can create a more balanced coating that provides both gas and moisture barrier capabilities. This versatility makes polysaccharides a foundational component in the development of sustainable and effective edible coatings.

2.1.1 Starch and Its Derivatives

Starch, a natural polysaccharide, is commonly used as a food hydrocolloid due to its high functionality and low cost. Starch films are transparent, odourless, tasteless, and colourless, offering low permeability to oxygen. This makes starch an excellent choice for food coatings, particularly for fruits and vegetables with high respiration rates. Dextrin, a derivative of starch with a smaller molecular size, is used in coating formation [15]. It provides better resistance to water vapour compared to starch coatings, enhancing its utility in maintaining food quality. Another starch derivative, pullulan, is an extracellular polysaccharide that is both edible and biodegradable. Pullulan films share similar properties with starch films—being colourless, odourless, and tasteless—while offering superior oxygen barrier properties. These films have been effectively applied to preserve fruits like strawberries and kiwi, demonstrating their practical benefits in extending the shelf life of produce.

2.1.2 Cellulose and Its Derivatives

Cellulose, the primary structural component of plant cell walls, is another valuable material for edible coatings. Cellulose derivatives, such as carboxymethyl cellulose (CMC), methyl cellulose (MC), hydroxypropyl cellulose (HPC), and hydroxypropyl methyl cellulose (HPMC), are known for their excellent film-forming properties, though their high cost can limit large-scale application [16]. These water-soluble polysaccharides are non-ionic and compatible with surfactants, making them versatile in food applications. CMC, in particular, is widely used for its ability to form edible coatings that provide barriers to oxygen, oil, and moisture transfer. Such coatings maintain the firmness and crispness of fruits like apples, peaches, and carrots, preventing flavour loss and reducing oxygen uptake without increasing internal carbon dioxide levels [8]. This helps in preserving the sensory and nutritional quality of coated produce.

2.1.3 Seaweed Extracts

Seaweed extracts, particularly alginates and carrageenan, offer valuable properties for edible coatings. Alginates, derived from brown seaweed (Phaeophyceae), are known for their film-forming abilities, transparency, and water solubility [17]. While they have high permeability to water vapour, their low permeability to oils and fats makes them ideal for specific food applications. Calcium alginate coatings enhance the quality of fruits and vegetables by reducing shrinkage, oxidative rancidity, moisture migration, and oil absorption, thereby improving appearance and color. Carrageenan, extracted from red seaweeds like *Chrondrus crispus*, is a complex polysaccharide mixture. Carrageenan-based coatings are effective in reducing moisture loss and oxidation, as seen in apple slices and grapefruits [18]. These coatings also inhibit microbial growth, further extending the shelf life of the produce.

2.1.4 Chitosan

Chitosan, a deacetylate form of chitin, is a naturally occurring cationic biopolymer found in the shells of crabs and shrimp, as well as in the skeletal substances of invertebrates and the cell walls of fungi and insects [19]. Chitosan is highly regarded for its excellent film-forming properties, antimicrobial activity, and compatibility with other substances such as minerals, vitamins, and antimicrobial agents. Chitosan-based coatings are particularly effective for fresh produce, as they delay ripening, decrease respiration rates, and retard weight loss, color wilting, and fungal infections. These properties make chitosan an ideal material for extending the shelf life and maintaining the quality of fruits and vegetables like cucumbers and tomatoes [20].

2.2 Proteins

Proteins used in edible coatings and films come from both plant and animal origins, providing a versatile range of options for food preservation. Plant-derived proteins such as soy protein, corn zein, and wheat gluten are commonly used, alongside animal-sourced proteins like casein, whey, albumin, keratin, and collagen [21]. Proteins offer suitable barrier properties against oxygen, carbon dioxide, and lipids, especially at low relative humidity levels. This makes them particularly effective in reducing oxidative reactions and lipid rancidity in food products, thereby preserving freshness and extending shelf life.

The functionality of protein-based coatings is largely influenced by their film-forming ability and their mechanical properties, which can be tailored through various processing techniques. These coatings are often used in combination with other materials to enhance their properties. For example, proteins can be blended with polysaccharides or lipids to create composite coatings that leverage the strengths of each component. This blending not only improves the barrier properties but also enhances the mechanical strength and flexibility of the coatings, making them more suitable for a wider range of applications.

2.2.1 Casein and Whey Protein

Casein, a major milk protein, exists in the form of micelles that include all casein species. Each micelle contains approximately 104 peptides, with a molecular weight around 105 kDa [22]. Its amphipathic nature, containing both hydrophilic and hydrophobic ends, makes casein ideal for creating emulsions. The most common derivative, caseinate, dissolves easily in water, enhancing its usability in edible coatings. The open secondary structure of casein simplifies the formation of these coatings. Casein-based edible coatings are advantageous due to their ease of application and effectiveness in extending the shelf life of food products. These coatings provide excellent barriers against oxygen and moisture, helping to preserve the quality and freshness of various fruits and vegetables.

2.2.2 Zein

Zein is a protein derived from maize, specifically extracted from corn gluten flour. It is water-immiscible but dissolves in aqueous alcohol and glycol esters. Zein is known for its superior film and coating formation capabilities, as well as its adhesive and binding properties. Coatings made from corn-zein protein are particularly effective in preventing color changes, maintaining firmness, reducing weight loss, and extending the shelf life of fruits and vegetables [23]. Zein offers exceptional barrier properties against oxygen and water vapour, significantly outperforming many other edible coatings. This high barrier property ensures that zein-coated produce remains fresh and protected from environmental factors that could lead to spoilage.

2.3 Lipids

Lipids are highly effective materials for edible coatings due to their hydrophobic nature, which makes them excellent barriers against moisture loss. This property is crucial for maintaining the moisture content and freshness of food products, particularly fresh produce that tends to lose water rapidly. By reducing moisture loss, lipid-based coatings help to extend the shelf life of fruits and vegetables and maintain their quality during storage and transportation.

In addition to their moisture barrier properties, lipid-based coatings also reduce the respiration rate of fresh produce, further contributing to extended shelf life. The hydrophobic nature of lipids can be leveraged in combination with other materials to create composite coatings that provide a balanced barrier against both moisture and gas exchange [11, 24]. This versatility and effectiveness make lipid-based coatings a valuable tool in the preservation of perishable food products.

2.3.1 Combination of Lipids and Polysaccharides/Proteins

Combining lipids with polysaccharides or proteins in coating materials significantly improves their barrier properties. This blend leverages the strengths of each component, resulting in coatings that offer superior protection against moisture, oxygen, and other environmental factors. Here are some of the most common lipid-based coating materials:

2.3.2 Waxes

Waxes are widely used in edible coatings due to their excellent water barrier properties. They create a hydrophobic layer on the surface of fruits and vegetables, preventing moisture loss and extending shelf life. Commonly used waxes include beeswax, carnauba wax, and paraffin wax. These waxes are applied as thin coatings, effectively sealing in the natural moisture of the produce and protecting it from external humidity and microbial contamination.

2.3.3 Lacs

Lacs are resinous secretions from insects like *Kerria lacca*. They are used in food coatings for their film-forming properties and ability to enhance the glossiness and appearance of coated products. Lac-based coatings provide a protective barrier that reduces water vapour transmission and oxygen permeability [25]. This makes them particularly useful for maintaining the quality and extending the shelf life of fruits and vegetables.

2.3.4 Fatty Acids and Alcohols

Fatty acids and alcohols, such as stearic acid and cetyl alcohol, are incorporated into edible coatings to improve their moisture barrier properties. These compounds create a hydrophobic layer that minimizes water loss and prevents spoilage. They are often combined with polysaccharides or proteins to enhance the overall effectiveness of the coating, providing a balance of flexibility, durability, and barrier performance.

2.3.5 Acetylated Glycerides

Acetylated glycerides are modified lipids that offer improved film-forming and barrier properties compared to their non-acetylated counterparts. These glycerides are used in edible coatings to create a strong barrier against moisture and gases, thereby preserving the freshness and quality of food products. They are particularly effective in applications where enhanced flexibility and resistance to cracking are required.

2.3.6 Cocoa-Based Materials

Cocoa-based materials are gaining popularity in edible coatings due to their natural origin and desirable properties. These materials form a hydrophobic barrier that protects against moisture loss and oxidative spoilage. Cocoa-based coatings are also valued for their sensory attributes, adding a pleasant flavour and aroma to the coated products. This makes them an attractive option for high-value fruits and vegetables, as well as confectionery items.

By integrating lipids with polysaccharides or proteins, these coatings harness the complementary strengths of each material. The resulting composite coatings not only provide superior barrier properties but also improve the mechanical strength and flexibility of the films. This combination approach is instrumental in developing advanced edible coatings that can effectively preserve the quality, safety, and shelf life of fresh produce and other perishable food items.

2.4 Composite Materials

Composite coatings are formed by blending one or more types of materials to create a bilayer or multilayer coating. This approach combines the beneficial properties of different materials to produce a superior quality film. For example, a composite coating might include a polysaccharide layer for its gas barrier properties, combined with a lipid layer for moisture resistance [26]. The resulting composite can be either homogenous or heterogeneous, depending on the specific application requirements and the desired properties of the final coating.

The primary advantage of composite coatings is their ability to offer improved mechanical and barrier properties compared to single-material coatings. By strategically combining materials, composite coatings can address the limitations of individual components and provide a more comprehensive solution for food preservation. This makes them particularly useful in applications where both moisture and gas barriers are needed, or where enhanced mechanical strength is required to protect the integrity of the food product during handling and storage.

2.5 Agro-Industrial Waste

Utilizing agro-industrial waste for the production of edible coatings is an innovative and sustainable approach that leverages the antioxidant and nutrient-rich properties of by-products such as peels, pomace, and seed fractions of fruits [27]. These waste residues often contain higher levels of beneficial compounds compared to the whole food, making them valuable resources for developing biopolymers. The extraction of biopolymers from agro-industrial waste is not only economical but also environmentally friendly, as it reduces waste and requires less energy for processing.

The use of agro-industrial waste in edible coatings has been the subject of recent studies and patent filings, highlighting its potential in the food industry. These biopolymers can be used to create coatings that enhance the nutritional profile of food products while also providing effective barrier properties. This approach aligns with the principles of circular economy and sustainability, offering a practical solution to food preservation that minimizes waste and maximizes the use of natural resources [28].

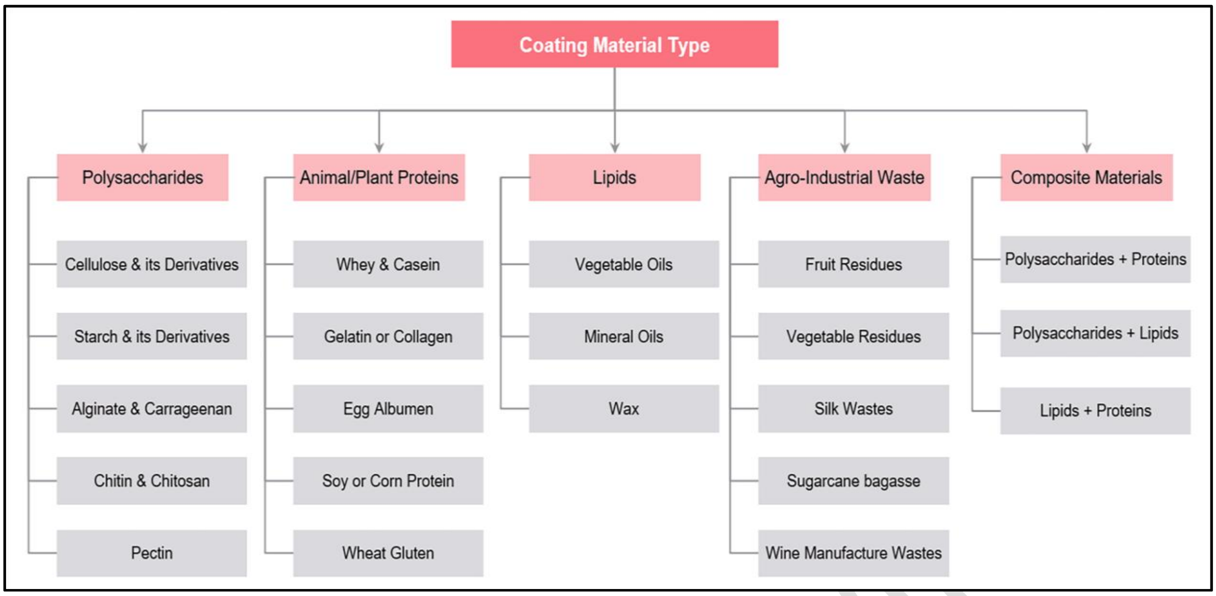

Figure 1: Various material types of edible films or coatings

3. KEY FUNCTIONALITIES OF EDIBLE FILMS AND COATINGS

Edible films and coatings play a crucial role in the preservation and enhancement of fruits and vegetables by acting as protective barriers and providing a controlled atmosphere around the produce [54]. These functionalities are essential for maintaining the quality, safety, and longevity of fresh produce during transportation, handling, and storage. Below, we discuss the major functionalities of edible films and coatings in detail:

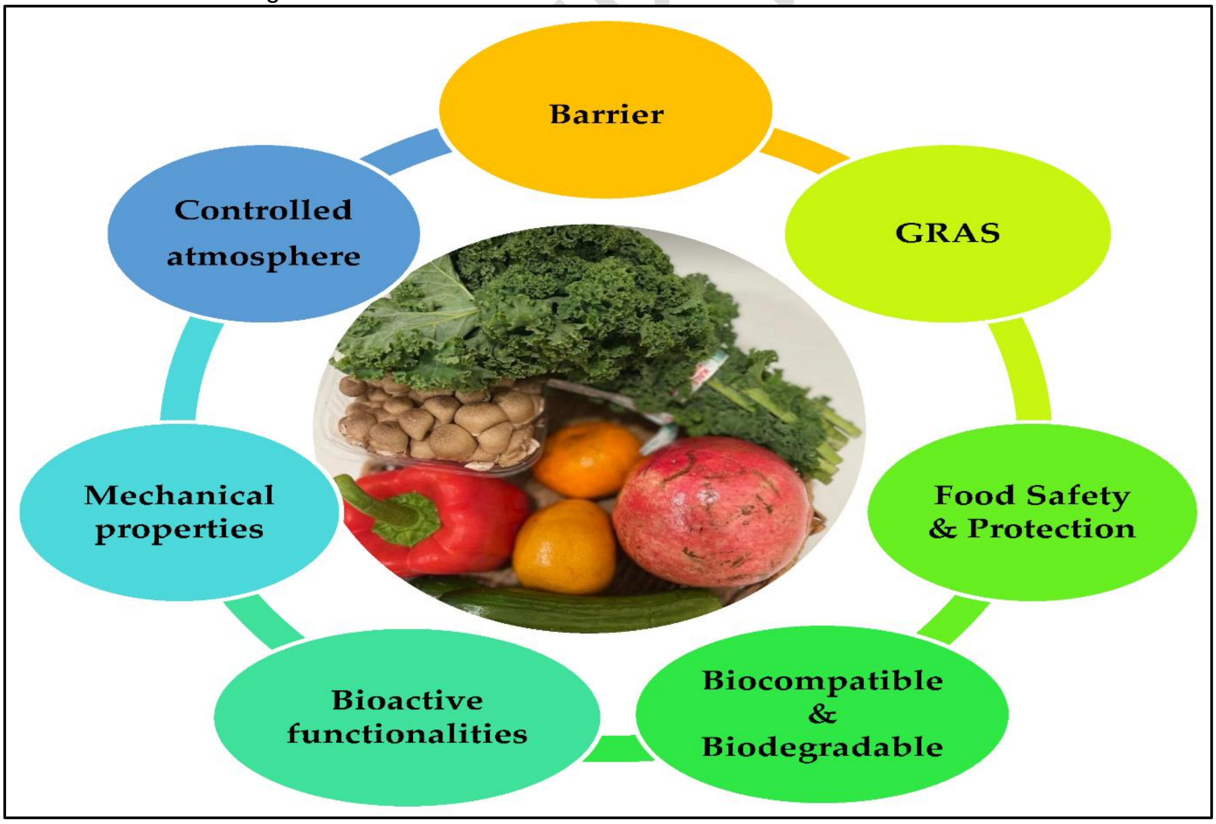

Figure 2: Major functionalities of edible films or coatings in fruit and vegetable preservation [28]

3.1 Protection from Transport, Handling, Mechanical Damages, and UV Radiation

Edible films and coatings serve as a physical shield that protects fruits and vegetables from damage caused during transportation and handling. They provide a layer of protection that helps to mitigate mechanical impacts and abrasions, ensuring that the produce reaches consumers in optimal condition[29]. Additionally, these coatings offer protection against UV radiation, which can degrade the quality and nutritional value of the produce. By filtering harmful UV rays, edible coatings help maintain the integrity and appearance of fruits and vegetables [53].

3.2 Barrier Properties

Edible coatings offer multiple barrier properties that are essential for preserving the freshness and quality of produce. One of the critical functions of edible coatings is to minimize water vapour transmission. By preventing excessive moisture loss, these coatings help maintain the hydration levels of the produce, reducing the risk of dehydration and shrinkage. Additionally, edible coatings control the levels of oxygen and carbon dioxide that pass through the protective layer [48]. This regulation is vital in slowing down the respiration process, thereby prolonging the shelf life of the produce. By maintaining optimal gas exchange, the coatings help prevent spoilage and extend freshness. Furthermore, these coatings act as barriers against volatile organic compounds (VOCs), protecting the produce from organic vapours such as aromas, solvents, additives, and pigments [49]. This helps in preserving the natural aroma and flavour of the fruits and vegetables, ensuring that they remain appealing to consumers.

Moreover, edible coatings can be enhanced with functional additives such as antimicrobial agents, antioxidants, and nutrients to provide additional protection and health benefits. These additives can help in inhibiting the growth of pathogenic microorganisms, thereby reducing the risk of foodborne illnesses. Antioxidants incorporated into the coatings can prevent oxidative damage, preserving the color and nutritional quality of the produce [50]. Additionally, the application of edible coatings is versatile and can be tailored to different types of produce, whether fruits, vegetables, or even prepared foods, providing a customizable solution to meet various preservation needs. This multifunctionality makes edible coatings a promising technology in the quest to reduce food waste and ensure the availability of fresh, high-quality produce for longer periods.

3.3 Prolongation of Shelf Life

One of the primary benefits of using edible films and coatings is their ability to extend the shelf life of fresh produce. By providing a controlled atmosphere and protective barrier, these coatings slow down the processes of respiration, ripening, and microbial growth [30]. This prolongation of shelf life not only reduces food waste but also ensures that consumers receive fresh and high-quality produce for a longer period.

3.4 Bioactivity

Edible coatings exhibit bioactive properties, including antimicrobial and antifungal activities. These properties help in inhibiting the growth of harmful microorganisms on the surface of the produce, thereby enhancing food safety [31]. Additionally, some edible coatings are formulated to act as carriers for probiotics, contributing to the health benefits of the produce.

3.5 Biodegradability

Edible films and coatings are biodegradable, making them an environmentally friendly alternative to traditional plastic packaging [51]. They break down naturally without leaving harmful residues, reducing the environmental impact of food packaging waste.

3.6 Structural Integrity

The structural integrity of edible coatings is designed to withstand various environmental conditions. These coatings melt above 40°C without decomposition, are water-resistant, easily emulsifiable, and non-sticky or non-tacky [32]. They also facilitate efficient drying, ensuring that the coating process does not compromise the quality of the produce.

3.7 Maintenance of Food Quality

Edible coatings are formulated to have minimal influence on the texture, flavour, or color of the produce. This ensures that the natural sensory qualities of the fruits and vegetables are preserved, providing consumers with a product that is as close to its fresh state as possible [52].

3.8 Formulated from Economical, Relatively Abundant, Consumer-Safety GRAS Materials

The materials used to create edible coatings are generally recognized as safe (GRAS) by regulatory authorities. These materials are economical and relatively abundant, making them a viable option for widespread use in the food industry. Their safety and availability ensure that edible coatings can be adopted without significant cost or health concerns.In conclusion, the key functionalities of edible films and coatings highlight their importance in the modern food industry [33]. By providing protection, extending shelf life, exhibiting bioactivity, and maintaining food quality, these coatings offer a sustainable and effective solution for preserving the freshness and safety of fruits and vegetables.

4. HERBAL EXTRACTS USED IN EDIBLE COATINGS

Recently, the incorporation of herbal extracts into edible coatings has gained significant attention due to their antimicrobial, antioxidant, and therapeutic properties. These extracts not only enhance the shelf-life of fruits and vegetables but also act as nutraceuticals, providing additional health benefits. Here are some commonly used herbal extracts in edible coatings:

4.1 Aloe Vera

Aloe vera is widely used in edible coatings due to its medicinal properties and effectiveness in extending the shelf-life of fruits and vegetables. The plant contains two types of gel: yellow latex (exudate) and clear gel (mucilage), which are rich in glycoproteins, polysaccharides, salicylic acids, phenolic compounds, lignins, amino acids, vitamins, saponins, and enzymes [34]. These components contribute to Aloe vera's antifungal, antibacterial, and anti-inflammatory properties. Aloe vera gel-based coatings form good moisture and gas barriers, improving the texture of fruits and vegetables by suppressing respiration, reducing microbial growth, and retaining volatile flavor components. Studies have shown that Aloe vera gel can extend the shelf-life of grapes by 40 days and prevent softening, oxidative browning, and microbial contamination in fruits like apples, bananas, cherries, and papayas .

4.2 Neem (*Azadirachta indica*)

Neem is known for its excellent antimicrobial properties and has been used in edible coatings to enhance the shelf-life of fruits and vegetables. Neem contains active components such as azadirachtin, nimbidin, and nimoid, which act as antimicrobial agents [35]. Studies have demonstrated neem extract's effectiveness against pathogenic microorganisms like *Salmonella, Staphylococcus, E. coli,* and *Vibrio*. Neem oil and extract are used in biodegradable edible coatings to extend the storage life of produce. For example, neem extract has been reported to extend the storage life of apples for up to 45 days [36].

4.3 Tulsi (*Ocimum sanctum*)

Tulsi, also known as the "Queen of Herbs," is highly valued for its therapeutic properties. It contains various beneficial compounds, including linalool, eugenol, carvacrol, camphor, methyl cinnamate, and β-caryophyllene [37]. These constituents provide antibacterial, antifungal, antiviral, antioxidative, and insecticidal properties. Tulsi extract and oil have been used to enhance the shelf-life of fruits and vegetables, maintaining their quality and extending their storage period. The use of Tulsi in coatings not only preserves produce but also offers additional health benefits due to its rich bioactive profile [38].

4.4 Cinnamon (*Cinnamomum cassia*)

Cinnamon is a well-known spice with strong antimicrobial and antioxidative properties, making it an effective natural preservative. The main components of cinnamon, such as cinnamaldehyde, eugenol, camphor, and caryophyllene oxide, inhibit the growth of bacteria and fungi [39]. Cinnamon has been evaluated as an antimicrobial agent in fresh-cut apple slices and other produce. For instance, the application of cinnamon bark ethanol extract and cinnamic aldehyde significantly reduced bacterial counts on fresh-cut apples, extending their storage life. Additionally, cinnamic acid and carvacrol treatments have been shown to reduce microbial spoilage in kiwifruit and fresh-cut melon [40].

5. HEALTH EFFECTS OF EDIBLE FILMS AND COATINGS

Edible films and coatings, as primary packaging materials, must adhere to strict regulations to ensure they do not transfer harmful substances to food. According to Regulation No. 1935/2004, food contact materials must be designed to prevent the migration of hazardous compounds into food products, thus safeguarding consumer health [41]. This regulation underscores the need for developing safe and non-toxic alternatives to conventional chemical and synthetic materials, which can pose significant health risks. Edible films and coatings were created to address these concerns, offering a safer means of food preservation and packaging.One of the significant health benefits of edible coatings is their ability to preserve the nutritional and sensory qualities of food. They can help retain antioxidants, phenolics, and pigments in food for extended periods, which are crucial for maintaining the health benefits and visual appeal of fruits and vegetables [42]. These compounds play an essential role in protecting cells from oxidative stress and may reduce the risk of chronic diseases. The inclusion of bioactive compounds, such as probiotics, through techniques like microencapsulation further enhances the health benefits of edible coatings. Foods coated with probiotics can be classified as functional foods, providing additional health benefits beyond basic nutrition [43]. For instance, probiotics are known to support gut health, boost the immune system, and may even contribute to mental well-being.

Certain materials used in edible coatings, such as waxes and paraffins, are widely recognized as safe for coating fruits and vegetables. These substances have been used historically and are generally regarded as safe (GRAS) due to their non-toxic nature [44]. Similarly, cellulose monomers and starch-based biopolymer monomers are considered harmless and do not pose health risks. These materials are biodegradable and do not introduce harmful residues into the food chain, making them environmentally friendly and safe for human consumption.However, the safety of some newer materials used in edible coatings, like nanocellulose, requires careful evaluation. Studies have shown that nanocellulose is non-toxic at concentrations of 0–50 µg/mL in human endothelial cells, although higher concentrations can induce physiological changes [45]. This indicates a need for stringent control and regulation of nanomaterials in food applications to prevent potential health risks. Additionally, there have been reports of adverse reactions to certain protein-based coatings, such as those made from collagen, which can cause discoloration, skin necrosis, granuloma formation, blindness, and foreign body reactions in some clinical settings [28, 46-47]. These findings highlight the necessity for thorough and ongoing research to fully understand the health implications of all materials used in edible coatings.

6. CONCLUSION

The utilization of edible films and coatings represents a significant advancement in food preservation technology, offering a sustainable and health-conscious alternative to traditional chemical preservatives and synthetic packaging. This review highlights the diverse range of materials used in the formulation of these coatings, including polysaccharides, proteins, lipids, and composite materials, each contributing unique properties that enhance the functionality of the coatings. Herbal extracts like Aloe vera, neem, Tulsi, and cinnamon, integrated into these coatings, provide additional benefits such as antimicrobial and anti-oxidative properties, further extending the shelf-life and quality of fresh produce.Polysaccharides, sourced from plants, seaweed, and agro-industrial waste, offer excellent gas barrier properties, while proteins from both plant and animal origins provide substantial barriers to oxygen, carbon dioxide, and lipids. Lipid-based coatings, with their superior moisture barrier properties, complement these materials by reducing respiration rates and moisture loss. Composite coatings, blending various materials, leverage the strengths of each component to enhance mechanical and barrier properties.Health effects of edible coatings are crucial, as they must comply with food safety regulations, ensuring they do not transfer harmful compounds to food. Biopolymers from natural sources, including cellulose and starch derivatives, are generally recognized as safe (GRAS). The addition of bioactive compounds, such as probiotics, can transform these coatings into functional foods, providing direct health benefits.Overall, edible films and coatings, enriched with natural extracts, present a multifunctional solution that not only preserves the quality and extends the shelf-life of fruits and vegetables but also offers added health benefits. This innovative approach aligns with the growing consumer demand for safer, more natural food preservation methods and supports the broader movement towards sustainability in food packaging.The incorporation of herbal extracts such as Aloe vera, neem, Tulsi, and cinnamon into edible coatings provides multiple benefits, including antimicrobial activity, antioxidative effects, and improved shelf-life of fruits and vegetables. These natural extracts enhance the quality and safety of fresh produce while offering additional health benefits, making them an attractive alternative to synthetic preservatives in the food industry.

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