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*Review*

# Edible Innovation: Exploring Advances in Active Packaging, Natural Additives, and Consumer Perception

Surabhi Pandey [1], Dipendra Kumar Mahato [2,*], Akansha Gupta [2], Anurag Singh [1], Madhu Kamle [3], Monika Singh [4] and Pradeep Kumar [4,5,*]

[1] Department of Food Technology, Harcourt Butler Technical University, Kanpur 208002, India
[2] CASS Food Research Centre, School of Exercise and Nutrition Sciences, Deakin University, Burwood, VIC 3125, Australia
[3] Department of Biochemistry, University of Lucknow, Lucknow 226007, India
[4] Department of Botany, University of Lucknow, Lucknow 226007, India
[5] Department of Food Biosciences & Technology, Korea University, Seoul 02841, Republic of Korea
* Correspondence: kumar.dipendra2@gmail.com (D.K.M.); pkbiotech@gmail.com (P.K.)

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**Abstract:** In the pursuit of sustainable and health-conscious food systems, edible innovation has emerged as a transformative frontier. This article explores the evolving landscape of edible packaging technologies, the integration of natural additives with functional benefits, and how consumer perception shapes the adoption of these novel approaches. Active packaging, such as chitosan-based films embedded with essential oils or silver nanoparticles, has demonstrated potential in extending shelf life and enhancing microbial safety. Natural additives, including rosemary extract, curcumin, and green tea polyphenols, are increasingly used for their antioxidant, antimicrobial, and health-promoting properties while supporting clean-label demands. Yet, consumer perception influenced by factors like sensory appeal, labeling, health consciousness, and environmental awareness remains a critical determinant of success. For instance, studies have shown that consumers are more likely to accept edible films if they are transparent, tasteless, and marketed as environmentally friendly. By examining recent scientific advances and market responses, this article provides a concise yet insightful overview of the edible innovation movement and its implications for the future of food.

**Keywords:** edible packaging; natural additives; functional compounds; consumer perception; food preservation

## 1. Introduction

The modern food industry is at the intersection of innovation and sustainability, striving to meet growing consumer demands for safe, minimally processed, and environmentally friendly products. A central challenge remains the perishable nature of food, which is prone to spoilage due to microbial activity, oxidation, enzymatic reactions, and physical damage. Traditional preservation methods, such as refrigeration, thermal processing, drying, and chemical additives, are widely used to extend shelf life, but they often compromise the nutritional and sensory quality of food or pose environmental and health concerns [1]. As a result, there is a critical need for novel strategies that ensure food preservation while aligning with current trends in health consciousness, environmental stewardship, and technological advancement.

This need has led to the emergence of edible innovation. This transformative approach integrates food science, material engineering, and biotechnology to develop consumable, functional, and sustainable alternatives to traditional packaging and preservation techniques [2]. At the forefront of this innovation are edible coatings and films, which represent a significant leap in food packaging technology. These are thin, consumable layers made from edible materials that are applied directly to the surface of food products to act as barriers against moisture, gases, and contaminants. By offering protection while being safe for consumption, edible coatings epitomize the principles of edible innovation: sustainability, functionality, and consumer-friendly design [3]. Edible coatings and films serve as multifunctional tools in food preservation. Not only do they mitigate spoilage and extend shelf life, but they can also enhance food safety, appearance, and nutritional value. Their biodegradability and edibility reduce reliance on synthetic plastic packaging, addressing mounting concerns about environmental pollution. Additionally, these coatings can be vehicles for bioactive compounds, including antimicrobial agents, antioxidants, colorants, and nutraceuticals, thus transforming the coating from a passive barrier into an active preservation system [4]. This aligns directly with the goals of edible innovation to go beyond traditional methods and create smart, sustainable, and health-promoting food systems. The effectiveness of edible coatings lies in their composition and structure. They are primarily based on biopolymers such as polysaccharides (e.g., starch, cellulose derivatives, alginate, pectin, and chitosan), proteins (e.g., casein, gelatin, soy, and whey proteins), and lipids (e.g., waxes and oils). These biopolymers can be used alone or in synergistic combinations to tailor the coating's barrier, mechanical, and functional properties. For instance, while polysaccharides offer good oxygen barrier properties, their poor moisture resistance can be improved by lipid incorporation [5]. The addition of plasticizers further enhances flexibility and film integrity, allowing these materials to meet the diverse demands of food products.

The application scope of these innovations is vast. In fruits and vegetables, edible coatings can reduce respiration and delay ripening; in dairy, they offer microbial protection and oxidative stability; in meat and seafood, they help retain moisture, color, and texture. These contributions are pivotal not only for extending shelf life but also for reducing food waste, another key objective of edible innovation [6]. Despite the growing interest and demonstrated potential, the widespread adoption of edible coatings faces several challenges, including scalability, production cost, standardization, regulatory approval, and consumer perception. However, ongoing research and interdisciplinary collaboration are steadily addressing these hurdles, bringing edible innovations closer to mainstream commercial use. This review provides a comprehensive exploration of edible coatings with their material composition, mechanisms of action, functional attributes, and diverse applications across food categories.

## 2. Overview of Edible Packaging

Although often perceived as a recent innovation, edible packaging has deep historical roots dating back several centuries. One of the earliest documented uses was in 12th-century China, where citrus fruits like oranges and lemons were coated with wax to reduce moisture loss during transport and storage, a preservation technique known as "larding" [7]. In 15th-century Japan, edible films called Yuba were created by boiling soy milk and drying the resulting protein-rich film, a practice that continues in traditional culinary use [8]. By the 16th century, larding techniques had become common in England for preserving fruits, vegetables, meats, and fish, functioning similarly to modern waxing by minimizing dehydration. The 19$^{th}$ century saw notable advancements, including the first gelatin film patent in the United States, which was intended to preserve meat products. Around the same time, sucrose and sugar derivatives began to be used as protective edible coatings on nuts to inhibit oxidative rancidity by limiting gas exchange [9,10]. In the 1930s, the commercial use of wax and lipid-based coatings gained momentum, especially for fruits and vegetables, to support respiration and maintain moisture during distribution. These coatings also enhanced the visual appeal of produce by providing a glossy finish [11]. While these traditional methods laid the foundation for edible packaging, the modern scientific interest in this technology began in the mid-20th century, primarily to address food preservation and extend shelf life. The 1980s and 1990s marked a significant period of research and development, driven by increasing concerns over environmental pollution caused by plastic waste. Innovations during this time led to more sophisticated edible films incorporating bioactive compounds such as antioxidants, antimicrobials, and, more recently, nanomaterials [12]. Despite a lull in development during the early 21st century due to the dominance of low-cost synthetic plastics, growing consumer demand for eco-friendly and sustainable packaging solutions has reignited interest in edible packaging. With advancements in food material science and a global push for environmental responsibility, edible packaging is now rapidly evolving into a commercially viable and environmentally conscious alternative. Table 1 represents a comparative overview of edible packaging in relation to conventional and biodegradable packaging based on key functional and environmental attributes.

**Table 1.** Comparison of edible packaging with conventional and biodegradable packaging [13].

| Parameter | Conventional Packaging | Biodegradable Packaging | Edible Packaging |
|---|---|---|---|
| Material origin | Petroleum-based | Renewable or petroleum-based | Renewable and food-grade |
| Environmental impact | High (non-biodegradable) | Moderate to low (biodegradable) | Minimal (fully edible and compostable) |
| Functionality | High mechanical and barrier properties | Improved over time, varies by material | Varies; improving with research |
| Edibility | Non-edible | Non-edible (though degradable) | Fully edible |
| Safety concerns | Migration of chemicals | Biocompatibility issues in some cases | Requires stringent food safety validation |
| Market adoption | Widely used | Growing | Niche but expanding |

Edible packaging is an innovative and sustainable approach that involves the use of materials capable of serving as both packaging and consumable components. Unlike conventional packaging materials that are typically discarded after use, edible packaging is formulated using food-grade ingredients, making it safe for human consumption [4]. These materials are derived primarily from natural biopolymers such as proteins (e.g., casein, whey, gelatin), polysaccharides (e.g., starch, cellulose, alginate), lipids (e.g., waxes, oils), or combinations of these components to form composite matrices [14]. The primary objective of edible packaging is to create a protective barrier around food that can maintain or enhance its quality, extend shelf life, and reduce the need for synthetic packaging materials [15]. Edible packaging systems are generally categorized into two main forms: edible films and edible coatings. Edible films are thin, pre-formed layers that are typically wrapped around food items or inserted between layers of food components. These films serve as effective barriers against moisture migration, oxygen infiltration, and microbial contamination, making them especially useful in layered food products or individually packaged servings [16]. On the other hand, edible coatings are applied directly onto the surface of food items in liquid form through dipping, spraying, or brushing, and then solidified by air-drying or cooling. These coatings form a continuous, conforming layer that helps prevent desiccation, oxidative deterioration, and microbial spoilage while sometimes also delivering added functionalities such as color enhancement, flavor retention, or nutrient fortification [4,17]. Both forms of edible packaging not only contribute to reducing plastic waste but also offer an additional layer of food functionality and safety.

## 3. Materials Used in Edible Packaging

Edible packaging materials are derived primarily from renewable, biodegradable, and digestible resources. These materials are generally safe, non-toxic, and suitable for direct consumption. They are categorized into four major groups: polysaccharides, proteins, lipids, and composite films, each offering distinct physicochemical and functional properties. The choice of material depends on the food product, desired functionality, and the method of application. Table 2 provides a structured comparison of edible packaging materials, including polysaccharides, proteins, lipids, composites, and bio-nanocomposites, highlighting their sources, advantages, and limitations.

**Table 2.** Comparative Summary of Edible Packaging Materials, highlighting their advantages and limitations.

| Material | Source | Advantages | Limitations | Reference |
|---|---|---|---|---|
| Polysaccharide Material | | | | |
| Cellulose & Derivatives (MC, HPMC, CMC, HPC, Cellulose acetate) | Plants | Excellent $O_2$ barrier; strong mechanical strength; transparent films; GRAS status; stable and safe | Poor moisture barrier (hydrophilic); requires plasticizers for flexibility | [18] |
| Chitosan | Crustacean shells, insects, fungi | Antimicrobial & antioxidant; good film-forming; selective gas permeability; biodegradable | Sensitive to moisture; variable quality depending on the degree of deacetylation; solubility issues at neutral pH | [19] |
| Starch (amylose–amylopectin) | Cereals, tubers | Abundant, low-cost, biodegradable; good oxygen barrier; edible and safe | Brittle without plasticizer; high water sensitivity; weak mechanical strength | [20] |
| Alginate (sodium, calcium salts) | Brown seaweed | Strong gel-forming ability with $Ca^{2+}$; clear films; biodegradable, GRAS | Poor moisture barrier; mechanical strength depends on cross-linking; sensitive to humidity | [21] |
| Protein Material | | | | |
| Casein | Milk | Transparent, elastic films; very low oxygen permeability; good carrier for bioactives | Poor moisture resistance; limited heat tolerance unless modified | [22] |
| Whey Protein Isolate (WPI) | Cheese whey | Excellent mechanical strength & gas barrier; good emulsification; reduces oxidation | Sensitive to moisture; may require plasticizers; costlier than starch/polysaccharides | [23] |
| Gelatin | Hydrolyzed collagen (animal skin, bones) | Good film-former; flexible; thermo-reversible gel; edible and clear | Highly moisture sensitive; limited thermal stability; dissolves in warm water | [24] |
| Collagen | Animal connective tissues | Improves moisture retention in meat; good adhesion | Limited film strength; sensitive to heat; animal-based (religious/ethical concerns) | [25] |
| Zein | Maize | Hydrophobic; good grease and gas barrier; smooth, shiny films | Brittle without plasticizers; relatively expensive; limited water resistance | [26] |
| Lipid Material | | | | |
| Natural Waxes (carnauba, beeswax, candelilla, rice bran wax) | Plants, animals | Excellent moisture barrier; hydrophobic; inhibits surface dehydration | Poor gas barrier; can impart a waxy appearance; low flexibility | [27] |
| Synthetic Waxes (paraffin, petroleum wax) | Petroleum | Strong moisture barrier; low cost; effective for fruits | Non-biodegradable; petroleum origin; not fully edible | [11] |
| Acetylated Monoglycerides | Plant/animal fats | Good hydrophobicity; improves composite film moisture resistance | Poor mechanical strength alone; not suitable as standalone film | [28] |
| Essential Oils & Fatty Acids | Plant extracts | Natural antimicrobial & antioxidant properties; improves shelf life | High volatility; strong flavor/aroma may affect sensory quality | [29] |
| Composite Type | | | | |
| Protein–Polysaccharide Composites | e.g., WPI + chitosan, casein + starch | Balanced mechanical & barrier properties; synergistic performance | More complex processing; compatibility issues between polymers | [30] |
| Polysaccharide–Lipid Composites | e.g., Starch + wax, Alginate + lipids | High moisture resistance; improved stability | Phase separation risk; may require emulsifiers | [31] |
| Protein–Lipid Composites | e.g., Zein + waxes | Better flexibility + moisture barrier; improved toughness | Processing complexity; cost increases | [11] |
| Ternary Composites | e.g., HPMC + chitosan + essential oils | Antimicrobial, antioxidant, and structural enhancement; multi-functional | Stability issues; potential aroma migration; higher cost | [32] |
| Bio-Nanocomposites | Biopolymer + nanoparticles (e.g., nano-clay) | Excellent mechanical & barrier strength; smart packaging potential | Regulatory concerns; safety evaluation needed; expensive | [33] |

### *3.1. Polysaccharide-Based Materials*

Polysaccharides are the most abundant natural macromolecules, composed of long polymeric carbohydrate chains [34]. Their sources include plants (e.g., starch, cellulose, and pectin), animals (e.g., chitosan), microbes (e.g., xanthan gum, pullulan), and marine organisms (e.g., alginate). These films are typically colorless, tasteless, and oil-free, offering excellent oxygen and carbon dioxide barrier properties, particularly under low to medium humidity conditions, making them ideal for extending the shelf life of fresh produce [35]. However, their hydrophilic nature leads to poor moisture barrier properties.

- Cellulose Films: Cellulose is a naturally occurring linear homopolysaccharide composed of glucose monomers linked by β1-4 glycosidic bonds. Known for its abundance and renewability, it possesses desirable attributes including low density, high tensile strength, chemical stability, and excellent film-forming ability. Moreover, it is non-toxic, biodegradable, biocompatible, and economically viable [8]. Extracted from plant materials, cellulose and its derivatives—such as methylcellulose and hydroxypropyl methylcellulose—are widely used due to their notable oxygen barrier capacity and mechanical strength, despite their limited water solubility. Common cellulose derivatives utilized in edible food packaging include methylcellulose, carboxymethylcellulose, hydroxypropyl methylcellulose, hydroxypropyl cellulose, and cellulose acetate. Notably, the U.S. FDA has classified cellulose acetate as GRAS (Generally Recognized as Safe), thereby supporting its incorporation in the packaging of bakery goods and fresh produce [36].
- Chitosan Films: Chitosan is a polysaccharide obtained through the deacetylation of chitin, which is primarily sourced from the shells of crustaceans, insects, and fungi. It is recognized for its environmental compatibility, being biodegradable, biocompatible, and non-toxic [37]. Chitosan exhibits excellent film-forming ability, mechanical integrity, and selective gas permeability, particularly to oxygen and carbon dioxide [36]. Additionally, it has inherent antimicrobial and antioxidant characteristics [3,38] These properties make chitosan-based coatings suitable for a variety of fresh produce, including apples, pears, strawberries, cucumbers, bell peppers, peaches, and plums.
- Starch Films: Starch, composed of amylose and amylopectin, is a polysaccharide known for its capacity to form films, mainly due to the linear structure of amylose. Native starch granules are insoluble in cold water; upon heating, their crystalline structure breaks down, allowing water to interact with hydroxyl groups, leading to partial solubilization and gelatinization—a necessary step for creating a uniform film-forming solution [39]. Despite its ability to form films, native starch suffers from low elongation and brittleness due to the amorphous regions formed by amylose, resulting in subpar mechanical performance. These limitations, however, can be overcome by incorporating plasticizers, which enhance the flexibility and extensibility of starch-based films [40].
- Alginate Films: Alginate is a naturally occurring, edible heteropolysaccharide derived from brown seaweed (Phaeophyceae), where it exists as the sodium, calcium, or magnesium salt of alginic acid [41]. Its molecular structure, rich in guluronic (G) and mannuronic (M) acid residues, contributes to its unique gelling ability through interchain associations, especially in the presence of divalent cations such as calcium. Alginate is biodegradable, biocompatible, hydrophilic, non-toxic, and chemically stable [42]. It is also recognized as GRAS by the FDA and is capable of forming clear, cohesive films with desirable mechanical and gelling characteristics, particularly when cross-linked to enhance water resistance and durability.

### *3.2. Protein-Based Materials*

Proteins offer strong mechanical and gas barrier properties, with low oxygen permeability and good oil and aroma barriers. They are either fibrous or globular and can be sourced from both plants and animals.

- Milk Proteins: Proteins obtained from milk are valued for their transparency, flexibility, and neutral taste, making them ideal candidates for edible film formation [43]. These proteins can also act as carriers for functional additives such as antioxidants, antimicrobials, and colorants, enhancing the sensory and preservation qualities of the packaged food. Casein, one of the primary milk proteins, produces highly transparent films with favorable elasticity, firmness, and moderate surface hydrophobicity. Additionally, casein films exhibit low oxygen permeability and good thermal stability, though their water resistance can be enhanced through the incorporation of lipids [44]. Whey protein isolate (WPI), a by-product of cheese production, is widely utilized for its excellent film-forming, mechanical, and barrier properties. Its availability and ability to form gels, emulsions, and foams have led to its growing application in food packaging. Whey-based films or coatings help reduce microbial contamination and oxidative spoilage, thereby preserving food quality and extending shelf life [45]. Moreover, WPI films are effective in limiting water vapor condensation in fruit and vegetable packaging, thus minimizing microbial growth [23].

- Collagen and Gelatin Films: Collagen, a structural protein derived from animal by-products such as skin, tendons, bones, and connective tissues, is commonly used to form edible coatings for meat products. These coatings enhance the visual appeal of the meat while reducing moisture loss [46]. Gelatin, obtained by hydrolyzing collagen, is a water-soluble, nearly tasteless protein with a pale-yellow appearance [37]. It is widely applied in the food industry for purposes such as gelling, thickening, emulsifying, and stabilizing, particularly in bakery, dairy, beverage, and confectionery products.
- Zein Films: Zein, a prolamin protein found in maize, is insoluble in water but dissolves in ethanol concentrations between 60–90% and in alkaline environments with pH values above eleven [47]. This protein exhibits thermoplastic behaviour along with notable hydrophobicity, and it also possesses antioxidant and antimicrobial qualities [48]. Zein-based films are known for their smooth texture, thermal resistance, and selective permeability to gases like oxygen and carbon dioxide, as well as oils. Due to these characteristics, zein has gained popularity for its film-forming ability. However, zein films tend to be brittle and therefore benefit from the inclusion of plasticizers or blending with other polymers to improve their flexibility and usability [3].

### *3.3. Lipid-Based Materials*

Lipids are hydrophobic compounds naturally derived from sources such as plants, animals, and insects. In edible packaging applications, commonly used lipid materials include natural waxes, acetylated monoglycerides, and resins. On their own, lipids are unable to form continuous and stable films; hence, they are typically incorporated into composite film structures to enhance functionality. One of the primary advantages of lipid components in edible coatings is their ability to serve as effective moisture barriers. Among them, wax-based coatings exhibit superior resistance to water vapor transmission compared to other lipid-containing or non-lipid films. These lipid substances can be applied individually or in combination with other film-forming agents to improve the overall protective performance of the coating.

- Natural and Synthetic Waxes: Waxes are compounds consisting of long-chain fatty acids esterified with long-chain alcohols, resulting in molecules with relatively high molecular weights. Found in both plant and animal sources, waxes naturally serve as protective barriers on tissues. Their hydrophobic nature significantly reduces moisture transmission, making them valuable components in edible packaging systems [49]. Both naturally derived and synthetic waxes are used either individually or in combination with other materials to enhance the barrier properties of food coatings. Common natural waxes such as carnauba wax, candelilla wax, beeswax, and rice bran wax are frequently applied to fresh produce to inhibit fungal growth and extend shelf life. Synthetic variants like paraffin wax and petroleum wax also serve similar purposes in food preservation [3].
- Essential Oils and Fatty Acids: Essential oils are known for their strong antimicrobial and antioxidant effects [50], which make them suitable for use in food packaging to delay spoilage and oxidative degradation. These natural compounds can effectively reduce lipid oxidation and help extend the shelf life of various food products. In particular, chitosan-based films infused with essential oils or fatty acids have shown great potential for application in meat preservation due to their antimicrobial activity [51].

### *3.4. Composite Films*

Composite edible films are formulated by combining different biopolymers such as proteins, polysaccharides, and lipids to synergistically enhance their functional properties while compensating for the individual shortcomings of each material. This integrative approach allows for the customization of packaging characteristics, including enhanced mechanical strength, moisture resistance, and bioactive functionality. Based on the number of biopolymers used, composites are generally categorized as binary (involving two components) or ternary (involving three) [52]. These blends can include combinations like protein–protein, carbohydrate–carbohydrate, or protein–carbohydrate matrices. A notable example includes the use of hydroxypropyl methylcellulose (HPMC) in conjunction with chitosan and bergamot essential oil, which demonstrated improved preservation efficiency in grapes compared to individual biopolymer films. Furthermore, the integration of nanomaterials into these composites has significantly strengthened their mechanical and barrier attributes. Such bio-nanocomposites are being actively explored for use in advanced packaging formats, including active and smart packaging applications [53]. While edible packaging offers clear sustainability and innovation benefits, challenges remain in terms of water sensitivity, mechanical strength, and regulatory hurdles. Nonetheless, its unique combination of functionality and eco-friendliness positions it as a compelling solution in the future of food packaging.

## 4. Advances in Active Edible Packaging

Active packaging represents a transformative shift from traditional inert packaging systems to dynamic packaging strategies that interact with food products and their surrounding environment to maintain or extend shelf life, improve safety, and preserve sensory quality [54,55]. In the context of edible packaging, the concept of activeness is implemented by incorporating functional bioactive substances directly into the edible matrix. These substances may include antimicrobial agents, antioxidants, oxygen scavengers, moisture regulators, or even flavor enhancers [56]. Unlike traditional packaging, which serves only as a physical barrier, active edible packaging is designed to respond to changes in the food environment, such as microbial growth or oxidative reactions. This response may occur through the controlled release of bioactives into the food matrix or surface contact activity, thereby minimizing the need for synthetic additives directly added to the food product [57]. The synergistic benefit of being both active and edible makes this packaging concept particularly suitable for ready-to-eat, fresh, and minimally processed food systems.

### *4.1. Functional Components: Antimicrobial, Antioxidant, and Moisture-Control Agents*

The integration of bioactive functional components into edible packaging systems marks a significant advancement in the field of active food packaging. These components, namely antimicrobial, antioxidant, and moisture-control agents, are incorporated into edible films and coatings to enhance food safety, extend shelf-life, and maintain product quality [58]. The application of edible coatings, typically formulated from biopolymers such as polysaccharides, proteins, and lipids, serves as an effective strategy to deliver these functional agents directly to the food surface. These coatings form a thin, consumable barrier over food items, capable of acting as a protective interface while contributing to improved sensory and functional attributes [59].

#### 4.1.1. Antimicrobial Agents

Microbial contamination is one of the leading causes of food spoilage and foodborne illnesses, making the incorporation of antimicrobial functionality a vital aspect of edible packaging. By embedding antimicrobial agents into biopolymer matrices, the outer surface of food products can be effectively safeguarded against microbial colonization and growth, thereby significantly lowering the risk of spoilage and food poisoning [60,61]. A wide array of natural antimicrobial agents is utilized in edible packaging due to their safety and efficacy. Essential oils such as thymol, carvacrol, and cinnamaldehyde, which are derived from aromatic plants, possess strong, broad-spectrum antimicrobial activity against both Gram-positive and Gram-negative bacteria [62]. These oils disrupt bacterial cell membranes and interfere with cellular respiration, effectively inhibiting microbial activity. Organic acids like lactic acid and sorbic acid act by lowering the surface pH of the food, thereby creating unfavourable conditions for microbial proliferation and compromising microbial membrane integrity. Bacteriocins such as nisin and pediocin, produced by certain lactic acid bacteria, are ribosomally synthesized peptides that are particularly effective against gram-positive pathogens like *Listeria monocytogenes* and *Staphylococcus aureus* by forming pores in the bacterial membrane, ultimately causing cell lysis [63]. Enzymes like lysozyme target the peptidoglycan layer of bacterial cell walls, leading to effective lysis of bacterial cells. The application of these agents into protein- or polysaccharide-based films allows for controlled and localized antimicrobial action [64]. This can occur through the gradual migration of the active compounds into the food matrix or through direct interaction at the interface between the food and the packaging. A notable example is the incorporation of *Aloe vera* gel, renowned for its antifungal properties, into corn starch matrices. When used in combination with glycerol as a plasticizer, this natural film significantly inhibited the growth of *Fusarium oxysporum* and effectively reduced decay in cherry tomatoes [65]. Such formulations present a non-toxic and consumer-friendly alternative to synthetic preservatives, resonating with the growing demand for clean-label and sustainable food packaging solutions.

#### 4.1.2. Antioxidant Agents

Lipid oxidation is a primary factor contributing to the deterioration of fatty foods, leading to undesirable changes such as rancidity, off-flavors, color degradation, and nutrient loss. To mitigate these effects and preserve the sensory and nutritional quality of food products, the incorporation of antioxidants into edible packaging has become increasingly important [66,67]. While synthetic antioxidants like butylated hydroxytoluene (BHT) and butylated hydroxyanisole (BHA) have traditionally been employed in food packaging, growing health concerns related to their potential toxicity, particularly due to their migration into food, have driven a shift toward natural alternatives [68]. Natural antioxidant agents commonly used in edible packaging include phenolic compounds, plant extracts, and vitamins [69–71]. Phenolic compounds, such as flavonoids, tannins, and phenolic acids, are abundant in fruits, vegetables, and herbs, and are renowned for their strong radical-scavenging abilities, metal-chelating properties, and capacity to quench singlet oxygen. These compounds function by stabilizing lipid radicals and interrupting the chain reactions responsible for lipid peroxidation [72]. Similarly, plant extracts like rosemary, green tea, and grape seed are rich in polyphenols and have shown substantial antioxidant efficacy in various food systems [73]. Vitamins, particularly ascorbic acid (vitamin C) and tocopherols (vitamin E), not only help protect food from oxidative degradation but also enhance its nutritional profile. When integrated into edible films or coatings, these natural antioxidants offer targeted protection by neutralizing free radicals at the food surface. This is particularly beneficial for oxidation-sensitive products such as meat, nuts, and oils. Beyond their preservative functions, these bioactive compounds also impart health-promoting properties, including anti-inflammatory, antihypertensive, and anti-aging effects. As a result, the inclusion of antioxidants in edible packaging aligns with the broader goal of developing functional packaging solutions that ensure food safety while promoting consumer wellness [74]. Figure 1 illustrates the architecture and functional mechanisms of multilayer active packaging systems, including raw materials, multilayer bioactive film structure (barrier, active, and control layers), controlled release strategies for active compounds, and the co-extrusion fabrication process.

#### 4.1.3. Moisture-Control Agents

Controlling moisture migration is a crucial aspect of food packaging, as water activity directly influences microbial stability, textural integrity, and the overall sensory quality of food products [75]. Edible packaging materials are designed to either function as barriers to water vapor or to absorb excess surface moisture, depending on the specific requirements of the food item and the storage environment [76]. Effective moisture control helps in preserving the freshness, extending shelf life, and enhancing consumer satisfaction [77]. Various agents are incorporated into edible packaging to regulate moisture. Hydrophobic substances such as beeswax, carnauba wax, and shellac are lipid-based materials that form water-repellent barriers, significantly reducing moisture permeability [78]. These agents are particularly useful in preventing desiccation or sogginess in moisture-sensitive items like confections and dried fruits. On the other hand, hydrophilic polymers such as starch and cellulose derivatives possess excellent water-absorbing properties, making them suitable for managing excess humidity in high-moisture foods like fresh fruits and vegetables [79]. An advanced approach involves the use of multilayer films that integrate both hydrophilic and hydrophobic components. These composite films offer dual moisture control by effectively balancing water absorption and vapor resistance, making them especially advantageous for packaging complex food matrices that undergo variable moisture interactions [80]. By employing such targeted moisture-regulating strategies, edible packaging can significantly reduce water-related spoilage, inhibit microbial growth, and maintain the desired texture, preserving crispness in baked products or retaining juiciness in fresh produce. Table 3 provides a summary of edible packaging systems integrated with functional agents such as antimicrobials, antioxidants, and nutraceuticals to enhance food quality and shelf life.

**Table 3.** Edible packaging incorporated with functional agents.

| Edible Packaging Material | Functional Agent Used | Food Product | Observation | References |
|---|---|---|---|---|
| Film (Chitosan-Thymol Nanoparticles) | Chitosan thymol nanoparticles | Blueberries, tomato cherries | Stronger antimicrobial action than thymol alone | [81] |
| Chitosan Film | Tea tree, rosemary, pomegranate, resveratrol, and propolis extracts | Minimally processed broccoli | Slowed psychrotrophic and mesophilic growth; improved sensory qualities | [82] |
| Whey Protein Isolate Film | Oregano oil | Fresh beef cuts | Extended shelf life | [23] |
| Gelatin-Based Nanocomposite Film | Chitosan nanofiber and ZnO nanoparticles | Chicken fillet, cheese | Reduced microbial growth and enhanced sensory attributes | [83] |
| Polylactic Acid (PLA) Film | Sorbic acid and *Ficus spiralis* algae | Megrim fish | Better preservation and quality of refrigerated fish | [84] |
| Chitosan Film | Nanoemulsion of cumin oil | Refrigerated beef loins | Prolonged shelf life and enhanced antioxidant activity | [34] |
| Gelatin & Carboxymethyl Cellulose Film | Chitin nanofiber & Ajowan oil | Raw beef | Controlled pathogenic growth and improved sensory quality | [85] |
| Pectin Edible Coating | Oregano essential oil & resveratrol | Pork loins | Increased shelf life, preserved sensory quality | [86] |
| Chitosan Film | Musk lime extract | Squids | Inhibited gram-negative bacteria | [87] |
| Sodium Caseinate Coating | Ginger essential oil | Chicken breast fillet | Significant antibacterial effect | [88] |
| Chitosan + Cellulose Nanoparticles | Propolis extract | Minced beef | Delayed microbial growth | [89] |
| Sago Starch Film | Cinnamon oil & nano-$TiO_2$ | Pistachios | Inhibited spoilage microbes; improved mechanical strength | [90] |
| Gelatin-Carrageenan Composite | Curcumin, gallic acid, quercetin (polyphenols) | Chicken meat | Shelf life extended to 17 days | [91] |
| Whey Protein & Oleic Acid Film | Activated lysozyme | Smoked salmon | Decreased bacterial load after opening | [92] |
| Whey Protein Concentrate Film | Lytic bacteriophage cocktail | Meat | Pathogen reduced to an undetectable level | [93] |
| Chitosan-Based Coating | Bacteriophage vB_EcoMH2W | Tomatoes | 3-log reduction in bacterial count | [94] |

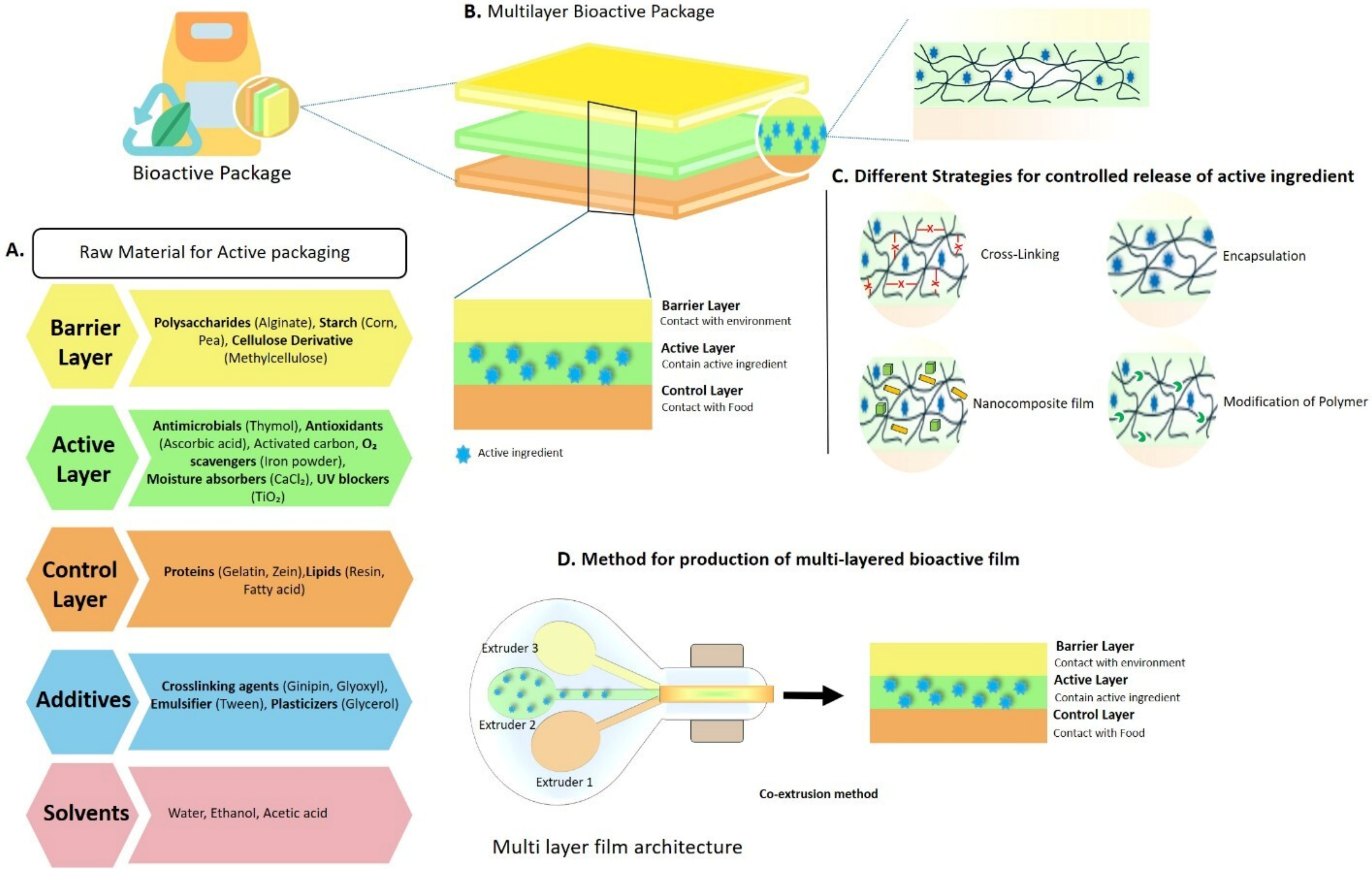


**Figure 1.** Multi-layer film architecture and mechanisms of active packaging. (**A**) Raw materials used in active packaging; (**B**) Multilayer bioactive package showing barrier, active, and control layers; (**C**) Strategies for controlled release of active ingredients; and (**D**) Co-extrusion process for producing multilayer bioactive films.

## 5. Emerging Technologies and Materials

The field of edible packaging has undergone significant innovation in recent years, driven by growing environmental concerns, consumer demand for clean-label and sustainable products, and the need for enhanced food safety and quality. Unlike conventional packaging materials, edible films and coatings offer the unique advantage of being consumable, biodegradable, and often functional. Several recent advancements have significantly improved the functionality, stability, and applicability of these systems.5.1. Integration of Bioactive Compounds

One of the most promising trends in edible packaging involves the incorporation of bioactive agents such as essential oils, phenolic compounds, enzymes, flavonoids, plant extracts, and vitamins [95]. These functional components enable edible films and coatings to go beyond passive protection, providing active preservation mechanisms that significantly improve food stability, quality, and safety. Their incorporation imparts antimicrobial, antioxidant, antifungal, and anti-browning properties, thereby enhancing food shelf life and reducing reliance on synthetic preservatives [96]. A wide range of essential oils, particularly those derived from thyme, oregano, rosemary, clove, and cinnamon, have demonstrated strong antimicrobial activity due to their high content of bioactive terpenes and phenolics, which can disrupt bacterial cell membranes and inhibit the growth of foodborne pathogens [97]. Incorporating these oils into edible matrices enables controlled release at the food surface, where microbial activity is typically highest. Similarly, polyphenol-rich plant extracts such as green tea, pomegranate peel, and grape seed have attracted attention for their potent antioxidant capacity. These compounds can effectively inhibit lipid oxidation in fatty foods, delay enzymatic browning in fresh-cut fruits, and maintain sensory quality during storage [98]. Their natural origin, biodegradability, and compatibility with diverse biopolymers make them especially suitable for clean-label packaging strategies. Natural antioxidants, including ascorbic acid (vitamin C) and tocopherols (vitamin E) are also widely incorporated into edible films and coatings to prevent oxidative degradation [74]. These molecules scavenge free radicals and stabilize lipids, which is particularly beneficial in oxidation-prone products such as meat, dairy, nuts, and ready-to-eat snacks [99]. Enzyme-based additives, such as lysozyme or lactoperoxidase, further enhance antimicrobial effects by catalyzing reactions that inhibit microbial activity on the food surface.

### *5.1. Nanoencapsulation and Controlled Release Systems*

A major challenge in the incorporation of bioactive compounds into edible packaging is their inherent instability and the tendency for uncontrolled release during storage or application. Many of these actives, such as essential oils, vitamins, phenolics, and enzymes, are highly sensitive to environmental factors like heat, light, oxygen, and pH fluctuations, which can significantly reduce their functional effectiveness [100]. To overcome these limitations, recent advancements have increasingly focused on nanoencapsulation, nanoemulsions, and other nanocarrier-based delivery systems. These technologies create protective barriers around sensitive compounds, shielding them from degradation while enabling sustained, controlled, and targeted release at the food surface [101]. For example, encapsulating bioactives such as eugenol or curcumin within chitosan nanoparticles not only enhances their physicochemical stability but also prolongs their antimicrobial and antioxidant action by modulating their diffusion from the film matrix. This controlled release is particularly beneficial for high-moisture foods where microbial activity tends to accelerate [102]. Likewise, nanoemulsions formed using lipid-based carriers have proven highly effective in improving the solubility and dispersion of hydrophobic bioactive compounds within hydrophilic matrices like starch, pectin, or alginate films [103]. Enhanced dispersion ensures a more uniform microstructure, improved mechanical integrity, and stronger interactions between the active components and the food surface. Figure 2 illustrates the nanostructures employed in nano-packaging and their formation pathways, highlighting nanocapsules, nanospheres, shell- and core-crosslinked nanogels, nanofibers, and common nanoencapsulation techniques such as casting, spraying, and immersion.

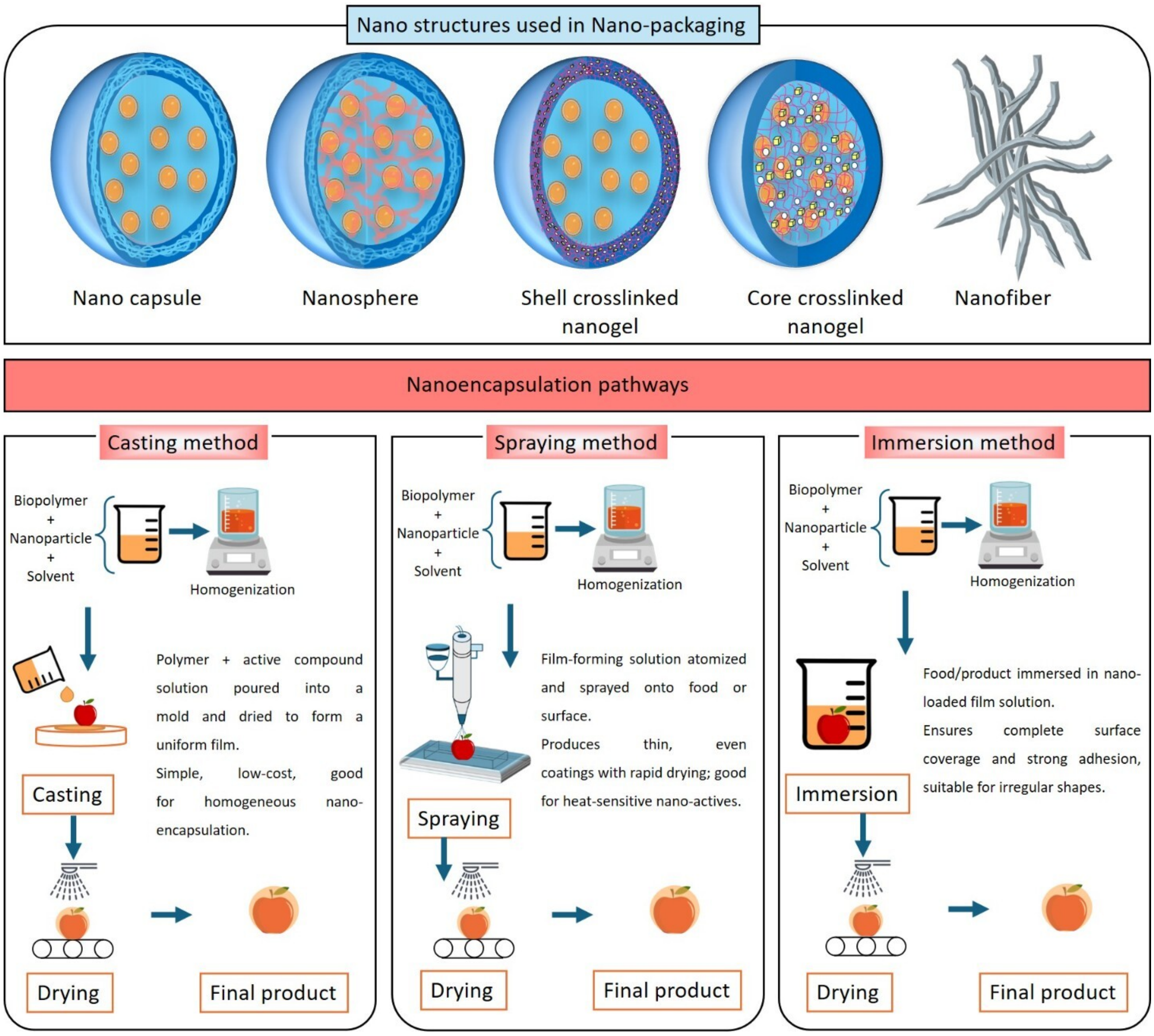


**Figure 2.** Nanostructures used in nano-packaging and their formation pathways, including nanocapsules, nanospheres, shell and core cross-linked nanogels, nanofibers, and common nano-encapsulation methods such as casting, spraying, and immersion.

### *5.2. Development of Smart and Intelligent Packaging Systems*

A significant leap in edible packaging is the emergence of smart or intelligent packaging systems, which are designed to monitor food quality, freshness, and environmental conditions in real time [104]. Unlike conventional edible films that function solely as protective barriers, smart packaging incorporates indicators, sensors, or responsive pigments that interact with biochemical or physicochemical changes occurring within the food matrix or its surrounding environment [105]. These integrated components provide immediate, visible feedback to consumers and supply-chain stakeholders, thereby improving transparency and decision-making regarding food safety. One widely studied approach involves the incorporation of natural, pH-sensitive dyes such as anthocyanins derived from red cabbage, purple sweet potato, and other pigment-rich plant sources [106]. These compounds undergo distinct and reversible colour changes when exposed to variations in pH, gas composition, or temperature parameters closely associated with microbial spoilage and quality deterioration [107]. For instance, as meat or fish begins to spoil and release volatile nitrogenous compounds, anthocyanin-containing films shift from purplish-red to greenish-blue, allowing consumers to instantly gauge freshness without opening the package [108]. Smart edible films have been successfully applied to highly perishable foods such as meat, fish, dairy, and minimally processed produce, where spoilage progression is rapid and often difficult to detect visually. Their use can help reduce food waste by preventing premature disposal, improve supply-chain safety by signalling temperature abuse or contamination events, and build consumer trust through real-time spoilage indication [109].

### *5.3. Multi-Layered and Composite Edible Films*

To overcome the inherent limitations of single-component edible films, such as weak mechanical strength in polysaccharides, poor water resistance in proteins, or brittleness in lipids, recent technological advancements have emphasized the development of multilayered and composite edible packaging systems. These systems strategically combine two or more biopolymers, including polysaccharides (e.g., starch, alginate), proteins (e.g., gelatin, casein), and lipids (e.g., beeswax, shellac), to create structures in which each layer contributes distinct functional benefits [110]. Through this synergistic arrangement, composite films achieve improved barrier, mechanical, and physicochemical properties that cannot be accomplished by single-material films alone. A common design strategy involves constructing a hydrophilic polysaccharide–protein inner layer that provides film integrity, tensile strength, and oxygen barrier capacity, coupled with an outer lipid layer that imparts hydrophobicity and significantly improves moisture resistance [111]. Such multilayer architectures allow the packaging to simultaneously restrict oxygen diffusion and limit water vapour transmission, two critical factors influencing the oxidation, dehydration, and microbial stability of foods [112]. Beyond structural enhancements, these layered films also enable targeted incorporation of bioactive compounds by embedding antimicrobials, antioxidants, or nutraceuticals into specific layers to achieve controlled release and maximize functional efficacy [113]. The practical application of these composite films has expanded across diverse food categories. For instance, multilayer coatings have been successfully utilized on fresh-cut fruits to minimize browning and moisture loss, on bakery items to delay staling, and on cheeses to inhibit mold growth while preserving texture and flavour. They are also increasingly employed in ready-to-eat and minimally processed meals, where improved barrier properties are crucial for extending shelf life and maintaining sensory quality [114].

## 6. Natural Additives in Edible Packaging

Natural additives have garnered considerable attention as effective alternatives to synthetic preservatives in edible packaging systems. These compounds not only offer health-safe preservation but also enhance the multifunctionality of films and coatings by imparting antimicrobial, antioxidant, and sensory-improving properties. The increasing consumer demand for clean-label, sustainable, and eco-friendly products aligns well with the incorporation of these bioactive components into edible packaging. Natural antimicrobials and antioxidants (NAMAs), derived from plants, animals, and microorganisms, present a vast array of compounds that can help improve food safety, prolong shelf life, and reduce chemical additive dependence [115].

### *6.1. Role of Natural Additives in Food Preservation*

Natural additives significantly contribute to extending the shelf life of perishable foods by mitigating spoilage factors such as microbial growth, oxidative damage, enzymatic degradation, and moisture imbalance. When integrated into edible films and coatings, these additives can offer multiple functional benefits [116]. They provide direct antimicrobial action against pathogens such as *Listeria monocytogenes*, *E. coli*, *Salmonella* spp., and various spoilage organisms, as demonstrated using nanoemulsions containing essential oil from cumin [117]. In addition to their antimicrobial properties, these additives exhibit antioxidant activity by scavenging reactive oxygen species (ROS) and preventing lipid peroxidation, which helps maintain the sensory quality of food. They also play a role in regulating moisture transfer, thereby protecting products from dehydration or becoming soggy. Furthermore, they can offer additional protective functions, including UV shielding, anti-browning effects, and enzyme inhibition, enhancing the overall stability and appeal of food products. These functionalities are particularly valuable in fresh produce, seafood, dairy, and ready-to-eat food applications, where synthetic preservatives are increasingly avoided by health-conscious consumers.

### *6.2. Plant-Derived Additives: Essential Oils and Extracts*

Plant-based compounds, particularly essential oils (EOs) and polyphenol-rich extracts, are widely used due to their potent antimicrobial and antioxidant effects. Essential oils and extracts from spices such as oregano, thyme, clove, rosemary, and cinnamon are rich in terpenes, phenolics, and aldehydes [118,119].These volatile and lipophilic compounds disrupt microbial membranes, interfere with cellular processes, and inhibit oxidative reactions [120]. Edible films made with starch, gelatin, or chitosan matrices have successfully incorporated EOs, improving food safety in fruits, cheeses, meats, and bakery items. Despite their effectiveness, direct use of EOs in food is limited by volatility, strong aroma, poor water solubility, and susceptibility to oxidation [121]. To address these issues, encapsulation techniques such as nano-encapsulation, spray drying, and polymer entrapment are employed. For example, grape seed extract and carvacrol microcapsules in chitosan films showed antimicrobial activity against *Pseudomonas* spp. and *Staphylococcus aureus* [122]. Similarly, clove essential oil integrated into millet starch films effectively inhibited a wide spectrum of bacteria and fungi [123]. Additionally, functional edible coatings with Ginkgo biloba or anthocyanin-rich extracts serve as color-based freshness indicators while improving shelf life [121].

### *6.3. Animal-Derived Additives: Chitosan, Proteins, and Enzymes*

Animal-derived bioactive components also exhibit significant preservation capabilities. Chitosan, a polycationic polysaccharide derived from crustacean shells, is especially noteworthy for its inherent antimicrobial activity against bacteria, yeasts, and molds. Its action is attributed to the disruption of microbial cell membranes and the chelation of essential nutrients. Besides being a strong antimicrobial agent, chitosan provides excellent film-forming capabilities [124]. Proteins such as whey protein, gelatin, and casein serve as both structural materials and bioactive carriers. Whey protein-derived peptides exhibit antimicrobial effects, and their incorporation with titanium dioxide nanotubes has shown promising results against *Listeria*, *Salmonella*, and *E. coli* in meat storage [125]. Enzymes like lactoperoxidase and lysozyme, and glycoproteins like lactoferrin, also demonstrate bactericidal properties through mechanisms like iron sequestration and cell wall disruption [126]. For instance, lactoferrin-coated cellulose films were effective against *E. coli* and *Staphylococcus aureus*, while lysozyme-containing composites inhibited multiple spoilage organisms in sausages [127]. 6.4. Microorganism-Derived Additives: Bacteriocins and Bacteriophages

Bacteriocins, antimicrobial peptides produced by *Lactobacillus* and *Bacillus* species, are increasingly utilized in edible packaging [128]. Nisin, a well-known GRAS-certified bacteriocin, has shown effectiveness against *Salmonella* and *Vibrio* species in seafood applications. A study investigated the antifungal potential of *Lactobacillus plantarum* when applied to grapes along with edible coatings. The researchers evaluated different coating formulations, both with and without the incorporation of *L. plantarum*, using pregelatinized potato starch and sodium caseinate as base materials. Among the tested combinations, the formulation containing *L. plantarum* with potato starch demonstrated significant antifungal activity against *Botrytis cinerea*, suggesting its potential in enhancing the preservation of fruits and vegetables through bioprotective mechanisms [129]. Bacteriophages, viruses that infect bacteria, are another innovative class of additives. Encapsulation of phages in films ensures targeted pathogen elimination while maintaining phage stability [130]. Studies have demonstrated significant log reductions in *Listeria* and *Salmonella* when films incorporated specific phages into biopolymer matrices like alginate and caseinate. Phage-loaded films thus offer a targeted and environmentally safe approach to microbial control [131]. Table 4 highlights the various applications of natural additives in edible packaging, emphasizing their roles in improving mechanical properties, extending shelf life, and providing antimicrobial or antioxidant functionality.

**Table 4.** Applications of natural additives in edible packaging.

| Material | Food Product | Antimicrobial/Preservation Properties | Reference |
|---|---|---|---|
| Tapioca starch | Fresh-cut cauliflower | Reduced weight loss; improved moisture retention | [132] |
| Chitosan + *Artemisia annua* EO liposomes | Cherry tomatoes | Effective against *E. coli* O157:H7 | [133] |
| Aloe vera gel + glycerol in corn starch matrix | Cherry tomatoes | Inhibited *Fusarium oxysporum* growth | [65] |
| Cactus mucilage–agar blend | Tomatoes | Antifungal and moisture barrier properties | [134] |
| Chitosan–cinnamon EO film | Strawberries | Reduced *Botrytis cinerea* and extended shelf life | [135] ) |
| Pullulan film + oregano EO | Fresh-cut carrots | Inhibited microbial growth; retained carotenoid content | [136] |
| Chitosan-coated nisin-silica liposomes | Cheddar cheese | Controlled release of nisin; reduced *L. monocytogenes* | [133] |
| Whey protein isolate + rosemary extract | Cheese slices | Prevented surface mold and oxidation | [137] |
| Gelatin + green tea extract | Paneer | Reduced microbial spoilage and oxidative changes | [138] |
| Zein film + nisin | Soft cheese | Prolonged microbial safety | [139] |
| Chitosan + natamycin | Yogurt | Prevented fungal growth | [140] |
| Chitosan–gelatin + grape seed extract | Fresh pork | Reduced microbial load and lipid oxidation | [141] |
| Whey protein isolate + oregano EO nanoemulsion | Chicken meat | Suppressed Listeria monocytogenes growth | [142] |

## 7. Safety Considerations

Ensuring the safety of emerging food technologies requires a comprehensive understanding of ingredient interactions, consumer exposure pathways, and potential long-term health or environmental effects. Many studies across food processing and packaging emphasise the need for risk assessments that consider dose, bioavailability, and real-world consumption patterns. These foundational safety principles become even more critical when applied to nanotechnology-based systems. Despite rapid advancements, the safety profile of nanomaterials remains inadequately understood. Most cited studies highlight potential hazards such as allergenicity, heavy-metal release, oxidative stress, and genotoxicity, but many rely on *in vitro* or small-animal models that may not accurately reflect real human exposure [143]. Moreover, nanoparticle behaviour in complex food matrices is not fully explored, limiting the translational relevance of the findings. A central concern relates to nanotoxicity, as many nanomaterials can interact with cellular components, disrupt metabolic pathways, or induce DNA damage [144]. While these studies offer valuable mechanistic insights, they often use high concentrations or pristine nanoparticles**,** which differ significantly from processed or encapsulated forms used in foods. Consequently, the actual dietary risk may be either over- or underestimated. Environmental implications are another emerging issue. Several studies report that nanoparticles may persist in soil and water systems, accumulate in plants, or affect microbial ecology. Yet, life-cycle assessments and long-term environmental monitoring are largely missing. This gap makes it difficult to evaluate trade-offs: although nanomaterials can reduce food waste by improving shelf life, their environmental footprint may offset these benefits if disposal pathways are not addressed [145]. Exposure assessments reviewed in the literature typically focus on dermal, respiratory, and digestive routes, but comprehensive human exposure databases are lacking [146]. Additionally, studies documenting immune disruption, organ accumulation, or oxidative stress seldom consider realistic exposure durations or mixed-nanoparticle scenarios that occur in real environments [147]. Regulatory discussions highlight the lack of global harmonization, with only a few nanomaterials approved for food-contact applications under EFSA or FDA guidelines. However, many cited regulations assume bulk and nanoforms behave similarly, which may not always be valid. Studies calling for stricter oversight often do not propose specific, validated analytical methods to measure nanoparticle migration or transformation in foods, indicating a methodological limitation [148].

## 8. Case Studies and Commercial Applications

Numerous experimental studies and commercial ventures underline the expanding significance of edible packaging in enhancing food preservation, safety, and sustainability. In research settings, chitosan-based coatings incorporated with essential oils like oregano or clove have been effectively used on fresh-cut apples and strawberries, where they not only suppressed microbial growth but also mitigated browning and preserved sensory quality [149]. Similarly, whey protein films fortified with natural antioxidants such as rosemary or green tea extracts have shown promise in extending the oxidative stability of refrigerated meat products [137]). Starch-based edible films infused with nisin, a natural antimicrobial peptide, have demonstrated successful reduction of surface bacterial contamination in sliced cheese and sausage without altering their taste profiles [150]. On the commercial front, companies across the globe have embraced edible packaging technologies with innovative products reaching the market. Apeel Sciences (Goleta, CA, USA), a notable player, has introduced Edipeel, a spray-on edible coating derived from plant oils and agricultural by-products. This colorless, tasteless, and odorless coating has been applied to a variety of fresh produce, such as avocados, citrus fruits, and cucumbers, significantly reducing water loss and oxidation while nearly doubling shelf life [151]. For instance, Ooho by Notpla (London, UK) is an edible bubble made from seaweed that encapsulates beverages and can be swallowed whole [152]. Lolistraw by Loliware (New York, NY, USA) features edible, biodegradable straws derived from seaweed-based compounds like alginate and agar [153]. Ello Jello by Evoware (Jakarta, Indonesia) offers nutritious seaweed-based edible cups and wrappers [154].

## 9. Consumer Perception and Acceptance

Consumer awareness regarding edible packaging remains in a nascent stage, with general familiarity being relatively low compared to other sustainable packaging innovations. While environmental concerns have driven interest in biodegradable and compostable packaging, the concept of ingestible packaging materials is still novel to many. Studies suggest that when informed, consumers often express positive attitudes toward edible packaging, especially when associated with natural ingredients, safety, and environmental friendliness [155]. However, skepticism persists regarding hygiene, taste, and the practical utility of such solutions in daily life.

Consumer acceptance of edible packaging is influenced by a complex interplay of sensory, psychological, economic, and practical factors. One of the most immediate determinants is the sensory appeal of the material. Consumers tend to favor edible films and coatings that exhibit neutral or pleasant flavors, appropriate texture, and a visually appealing appearance. If the packaging is perceived as too chewy, sticky, or off-flavored, it may detract from the overall food experience and reduce acceptance [156]. Perceived safety and hygiene also weigh heavily on consumer decisions. There is often concern about how the packaging has been handled, whether it has been exposed to environmental contaminants, and if it remains safe to consume after storage and transportation. Unless these concerns are addressed through clear labelling, tamper-evident designs, or education, skepticism may persist [157]. Figure 3 presents the consumer acceptance framework, highlighting key predictors influencing perceptions and purchase intentions toward edible packaging and the adoption pathway from awareness to trial and final acceptance.

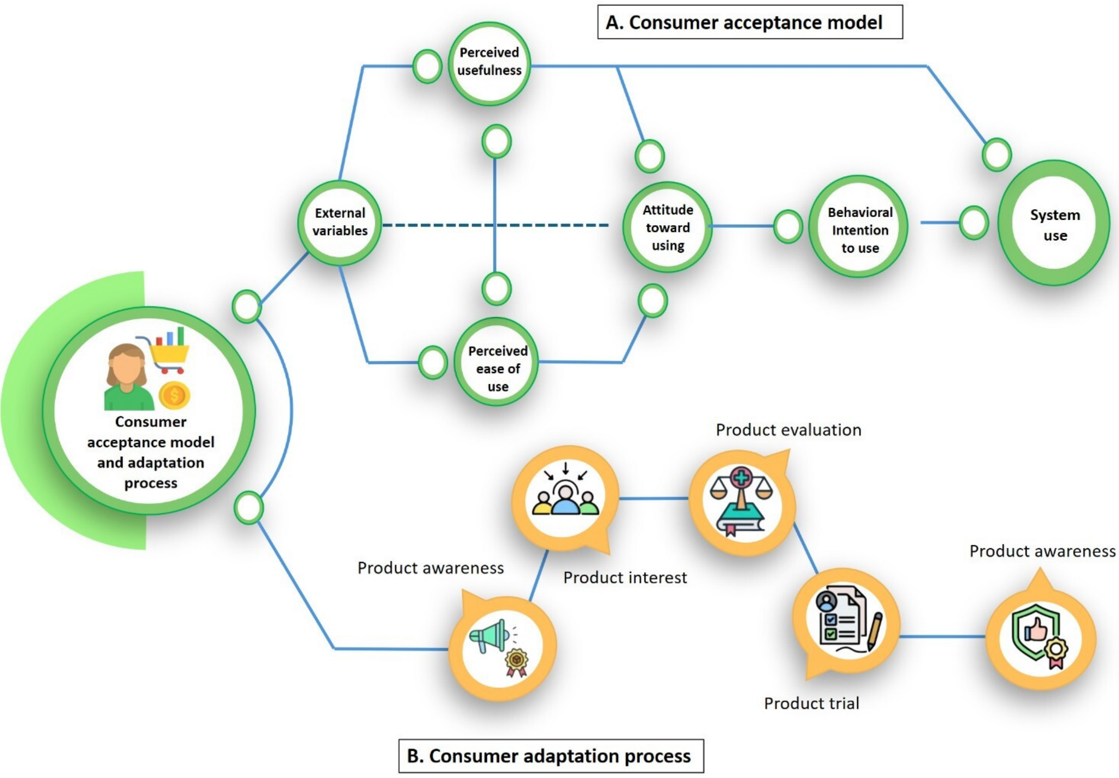


**Figure 3.** Consumer acceptance model. (**A**) Consumer acceptance model showing key predictors influencing perceptions and purchase intentions toward edible packaging; (**B**) Consumer adoption process illustrating the progression from awareness to trial and final adoption.

Economic considerations also play a key role; consumers are generally hesitant to adopt products with edible packaging if the cost is perceived as significantly higher than traditional alternatives, especially in low- and middle-income markets [158]). Furthermore, accessibility and availability influence adoption; if such products are not widely distributed or are inconvenient to use, their market potential remains limited. On the other hand, environmental consciousness among consumers has been steadily rising, and awareness of the ecological benefits of edible packaging, such as reducing plastic waste and lowering environmental footprints, can positively influence acceptance, particularly among sustainability-minded individuals [159]. Lastly, convenience is a major deciding factor. Edible packaging that seamlessly integrates into daily food routines, such as wraps, pouches, or coatings that enhance taste or do not require removal, tends to be more readily embraced [160]). Successful consumer adoption, therefore, hinges on a multidimensional strategy that balances sensory quality, safety, affordability, sustainability, and practicality.

Cultural context influences how edible packaging is perceived. In some regions, consuming packaging may align with traditional food practices (e.g., rice paper or banana leaf usage), while in others it may conflict with food norms or taboos. Psychological discomfort related to eating something usually considered non-edible can also create hesitation. Ethical considerations may also arise regarding the use of food-grade materials for packaging amid global food insecurity, prompting debate on resource allocation [3]). Recent consumer behavior studies indicate a growing willingness to adopt eco-friendly and health-conscious food technologies. Brands like Notpla (seaweed-based film) and Apeel (plant-based coatings) have helped normalize the concept of edible or disappearing packaging in the market [3,152]). Surveys also reveal higher acceptance among younger consumers, particularly Gen Z and Millennials, who value innovation, sustainability, and transparency. Nevertheless, actual market penetration remains limited and highly dependent on education, effective communication, and visible benefits.

## 10. Regulatory and Environmental Perspectives

Edible packaging is subject to diverse regulatory frameworks worldwide, typically falling under general food contact material legislation. In the United States, the Food and Drug Administration (FDA) requires that all edible packaging components meet the criteria of being Generally Recognized as Safe (GRAS). In contrast, the European Food Safety Authority (EFSA) enforces more rigorous evaluations, including toxicological assessments and migration testing, to ensure safety [46]. Key regulatory concerns include ingredient safety and purity, proper labeling of functional claims such as antioxidant or antimicrobial properties, allergen disclosure, and the microbial safety and shelf-life of the packaging material itself. A significant challenge lies in the lack of harmonized global standards, which hampers international commercialization and trade of edible packaging products. A coordinated effort to standardize regulations could streamline innovation and facilitate market expansion [53].

Edible packaging offers notable environmental advantages by potentially reducing plastic pollution, lowering greenhouse gas emissions, and supporting circular economy initiatives. Life Cycle Assessment (LCA) analyses generally indicate that biopolymer-based edible films have a smaller carbon footprint than conventional petroleum-derived plastics, particularly when derived from food processing byproducts. Nevertheless, the overall environmental impact depends on several factors, including raw material sourcing, energy usage during production, and end-of-life disposal strategies. One of the most compelling benefits of edible packaging is the elimination of post-consumption waste, which can significantly alleviate landfill pressure and reduce marine pollution, contributing to a more sustainable packaging paradigm [161]).

## 11. Industrial and Economic Aspects

The transition toward sustainable food systems has intensified the need for alternatives to conventional petrochemical-based packaging. Edible packaging aligns with global zero-waste and circular bioeconomy goals by transforming food by-products into value-added materials. This approach not only reduces waste generation and environmental pollution but also avoids competition with food resources, while decreasing dependence on petroleum-derived plastics, currently accounting for nearly 99% of global plastic production and contributing to contamination across all trophic levels [162]). In this context, edible coatings and films provide viable solutions, particularly for fresh and minimally processed products, where they help maintain quality and extend shelf life. Their applicability to fruits, vegetables, and animal-source foods supports consumer demand for high-quality, chemical-free products with reduced spoilage. Despite their clear sustainability benefits, the industrial and economic landscape of edible packaging is shaped by several cost and production constraints. Biopolymer matrices and natural active additives remain relatively expensive, and additional formulation, encapsulation, and process-control steps increase overall manufacturing costs. Regulatory validation and compliance further add to cost structures. Compounding these issues, economies of scale are still limited; many producers operate as small or medium enterprises, restricting rapid upscaling. As a result, per-unit costs for edible packaging continues to exceed those of traditional plastics in most commercial applications [163], ), even though market analyses show steady growth driven by sustainability policies and environmentally conscious consumers [162]). Industrial scalability also faces technical barriers. Production relies on agricultural feedstocks and by-product streams that fluctuate seasonally, affecting consistency and availability. The transition from laboratory-scale casting to industrial-scale continuous extrusion or roll-to-roll coating must occur within narrow process windows, requiring significant capital investment. Additionally, European circular-economy initiatives highlight the urgency of reducing packaging waste, which reached 173 kg per capita in 2017, placing further pressure on industries to adopt recyclable or edible formats [164]). Supply-chain considerations extend across all stages of edible packaging development. Upstream, valorisation of side streams into film-forming polymers and active extracts requires investment in collection, stabilization, and biorefinery logistics. Midstream, edible films and coating formulations often have shorter shelf lives and require specialized storage, complicating inventory management and increasing distribution costs. Downstream, maintaining product performance under cold-chain variability, ensuring traceability, labelling natural additives, and educating consumers about the use, safety, and disposal of edible components all introduce additional coordination and compliance demands. These added costs and operational complexities must be balanced by clear benefits in reducing food spoilage, enhancing quality, and contributing to environmental sustainability.

## 12. Future Directions and Conclusions

Future development in edible packaging depends on a well-defined research roadmap supported by strong interdisciplinary collaboration. Although notable progress has been made, several key research gaps still limit practical, safe, and scalable applications. One major gap involves the creation of multifunctional composite materials that can simultaneously provide strong barrier properties, mechanical stability, good sensory quality, and biodegradability. Most current films excel in only one or two of these areas, so future work must prioritize hybrid formulations that combine polysaccharides, proteins, lipids, and functional fillers. This also requires standardized testing methods to compare film performance across studies. Another important gap concerns the stability and controlled release of active ingredients. Many bioactive compounds used in edible packaging are unstable or release too quickly, and although nanoencapsulation techniques show potential, issues related to scalability, safety, and real-world performance remain unresolved. Developing encapsulation systems suitable for continuous manufacturing and testing their release behaviour under realistic food conditions is essential. In addition, the integration of smart or intelligent features such as freshness indicators, biosensors, or pH-sensitive colourants remains mostly at the conceptual stage. Their long-term stability, consumer acceptance, and regulatory approval must be addressed through pilot-scale trials and stability studies across the supply chain.

Personalization and sensory optimization also require greater attention. While customizable films with added nutrients, flavours, or culturally tailored properties are promising, consumer expectations regarding flavour, texture, and mouthfeel often limit adoption. Advancing this area requires stronger collaboration between sensory scientists and material developers. Another key challenge is consumer perception. Misinformation and skepticism about the safety and hygiene of edible packaging continue to hinder commercial acceptance. Clear communication, transparent labelling, and educational efforts are needed to highlight benefits such as reduced waste and lower chemical additives. Moreover, industrial feasibility, cost, and scale-up remain major bottlenecks. Many current formulations do not align with continuous manufacturing processes, making them difficult to apply at a commercial scale. Research on process engineering—such as extrusion, roll-to-roll coating, and integration into existing packaging lines is crucial. Regulatory gaps also persist, as no unified standards exist specifically for edible packaging, especially for systems involving nanomaterials. Establishing harmonized safety guidelines, validated migration testing methods, and life-cycle assessment tools will be essential for accelerating regulatory approval and ensuring safe, consistent implementation.

## Author Contributions

D.K.M. and P.K.: Conceptualization and supervision; A.S., S.P. and A.G.: data curation, writing the original draft; A.G., M.K., M.S., D.K.M., and P.K.: reviewing and editing the manuscript. All authors have read and agreed to the published version of the manuscript.

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## Conflicts of Interest

The authors declare no conflict of interest.

## Use of AI and AI-Assisted Technologies

During the preparation of this manuscript, the authors used ChatGPT (Model 4o) to assist with language refinement, including rephrasing complex sentences, improving logical coherence, and clarifying the presentation of analyses. All AI-generated content was critically reviewed, edited, and approved by the authors, who assume full responsibility for the final manuscript.

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