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Review

Advanced Biopolymer-Based Active and Intelligent Packaging Systems for Food Preservation: A Critical Review

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Abstract

Balancing reliable food protection against the ecological damage caused by synthetic plastics is a major priority in food processing. Polysaccharide systems, chiefly chitosan, starch, and functionalized celluloses, serve as practical substitutes to prolong food shelf life using active and intelligent mechanisms. This review covers developments in biopolymer preservation technologies from 2010 to 2026. We examine the microbial disruption mechanisms and radical-scavenging pathways that slow lipid breakdown in meats, dairy, and fresh produce. Furthermore, we address controlled release profiles, moisture sensitivity, and the performance of natural colorimetric dyes used for freshness monitoring. Chitosan provides natural antimicrobial action, starch delivers an effective oxygen barrier when dry, and nanocellulose reinforces physical structure. Even so, practical adoption remains limited by water affinity, manufacturing expenses, and migration limits enforced by the European Food Safety Authority (EFSA) and the United States Food and Drug Administration (US FDA). Resolving these bottlenecks via crosslinking and the use of agricultural waste will be central to creating functional, commercial bio-packaging.

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Keywords
Biopolymers; active packaging; intelligent food packaging; food preservation; chitosan; thermoplastic starch; nanocellulose; shelf-life extension; antimicrobial films; freshness indicators

1. Introduction

Packaging is a major part of keeping food fresh and safe from spoilage. As the world evolves, so do our concerns about how to keep food fresh and safe using traditional methods while searching for better and more environmentally friendly ways to package our food (such as biodegradable materials). As a result, researchers have increasingly focused on creating biopolymer-based food packaging materials because they are more sustainable than traditional plastic-based Food Packaging Materials [1, 2]. Biopolymers such as Chitosan, Starch, and Cellulose are widely used in research because they are biodegradable, can produce films with excellent barrier and mechanical properties, and can support the development of active and intelligent Food Packaging Systems.

In addition to the active properties associated with biopolymer-based active food packaging systems through the addition of antimicrobial and antioxidant additives to the structure, intelligent sensory capabilities related to large-scale food quality monitoring and detection will be developed through microbial growth reduction, decreased oxidative process deterioration due to real-time monitoring of storage parameters, and higher temperature control. However, there are still some issues with biopolymer-based active food packaging that include reduced mechanical strength of the final product, higher moisture sensitivity, and increased manufacturing costs; thus, restricting the industry scalability of biopolymer-based active food packaging systems [3, 4].

Modern food systems face a unique challenge: balancing the need to meet today's demands for food safety while minimising environmental impacts. The Green Hazard Analysis Critical Control Point (Green HACCP) approach focuses on creating a safe and sustainable food supply chain by combining traditional food safety management with new sustainable principles to create safer products and more environmentally sound production processes. Biopolymer-based packaging is one example of this approach, combining innovative product development with sustainable supply chain practices [5, 6].

While previous reviews have independently summarized the film-forming characteristics of biopolymers or general active packaging concepts, comprehensive frameworks bridging active preservation mechanisms with real-time intelligent monitoring and rigorous comparative benchmarking remain scarce. The explicit novelty of this review lies in three interrelated contributions:

- **Tri-polymer comparative benchmarking:** A systematic performance matrix directly contrasting chitosan, thermoplastic starch, and cellulose derivatives under matching experimental storage parameters and real food matrices (fresh produce, meats, seafood, and dairy).
- **Integrative active-intelligent interplay:** A critical evaluation of multifunctional matrices that simultaneously deliver targeted bioactivity (antimicrobial/antioxidant sustained release) and real-time freshness sensing (colorimetric pH/volatile amine indicators).

- **Translational and regulatory roadmap:** A cross-disciplinary bridge linking laboratory release kinetics with industrial scalability barriers, specifically detailing capital expenditure (CAPEX) for specialized compounding infrastructure, Green HACCP principles, and international food contact compliance (EFSA and US FDA standards).

2. Methodology

This review adopts a systematic and integrative literature review design, adhering to the updated PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. It synthesizes empirical findings and technological developments concerning biopolymer-based active and intelligent food packaging systems, with a particular emphasis on chitosan, starch, and cellulose matrices.

2.1 Data Sources and Search Strategy

Primary literature was identified through comprehensive searches across four core indexed scientific databases: ScienceDirect (Elsevier), Scopus, SpringerLink, and PubMed, supplemented by Google Scholar for extended coverage. Search queries were structured around Boolean operators (AND, OR) and exact phrase querying across three conceptual pillars:

Search 1 (Active Preservation): “biopolymer” AND “active packaging” AND “food preservation”.

Search 2 (Intelligent Systems): “biopolymer-based” AND “intelligent packaging” AND “food”.

Search 3 (Polymer-Specific Formulations): (“chitosan” OR “starch” OR “cellulose”) AND (“active packaging” OR “intelligent packaging”) AND (“food preservation” OR “food packaging”).

The search was restricted to peer-reviewed original research articles and critical review papers published in English between 2010 and 2026. Reference lists of seminal reviews and landmark experimental studies were additionally screened using snowballing to ensure complete coverage.

2.2 Inclusion and Screening

Following the PRISMA 2020 flow framework, we systematically screened retrieved records in two sequential phases. Initial inclusion required articles to directly study natural polysaccharide matrices (chitosan, starch, or cellulose derivatives) for active functions (antimicrobial, antioxidant, moisture or headspace control) or real-time diagnostic sensing. Retained papers needed to validate preservation outcomes using genuine perishable foods (meats, fish, dairy, produce) or regulated food simulants, restricted to peer-reviewed English publications. Conversely, we excluded studies limited to petroleum polymers without bio-additives, medical formulations (such as tissue engineering), and gray literature lacking complete methodological details.

Initial database querying returned 35,106 records. Removing duplicate entries across platforms eliminated 6,842 files, leaving 28,264 titles and abstracts for inspection. Screening against topical criteria removed 27,918 irrelevant items. Of the 346 full-text articles assessed, 293 were discarded due to missing control data, incomplete migration kinetics, or unclear processing parameters. Ultimately, 53 experimental benchmark studies met every criterion for qualitative comparison (Figure 1).

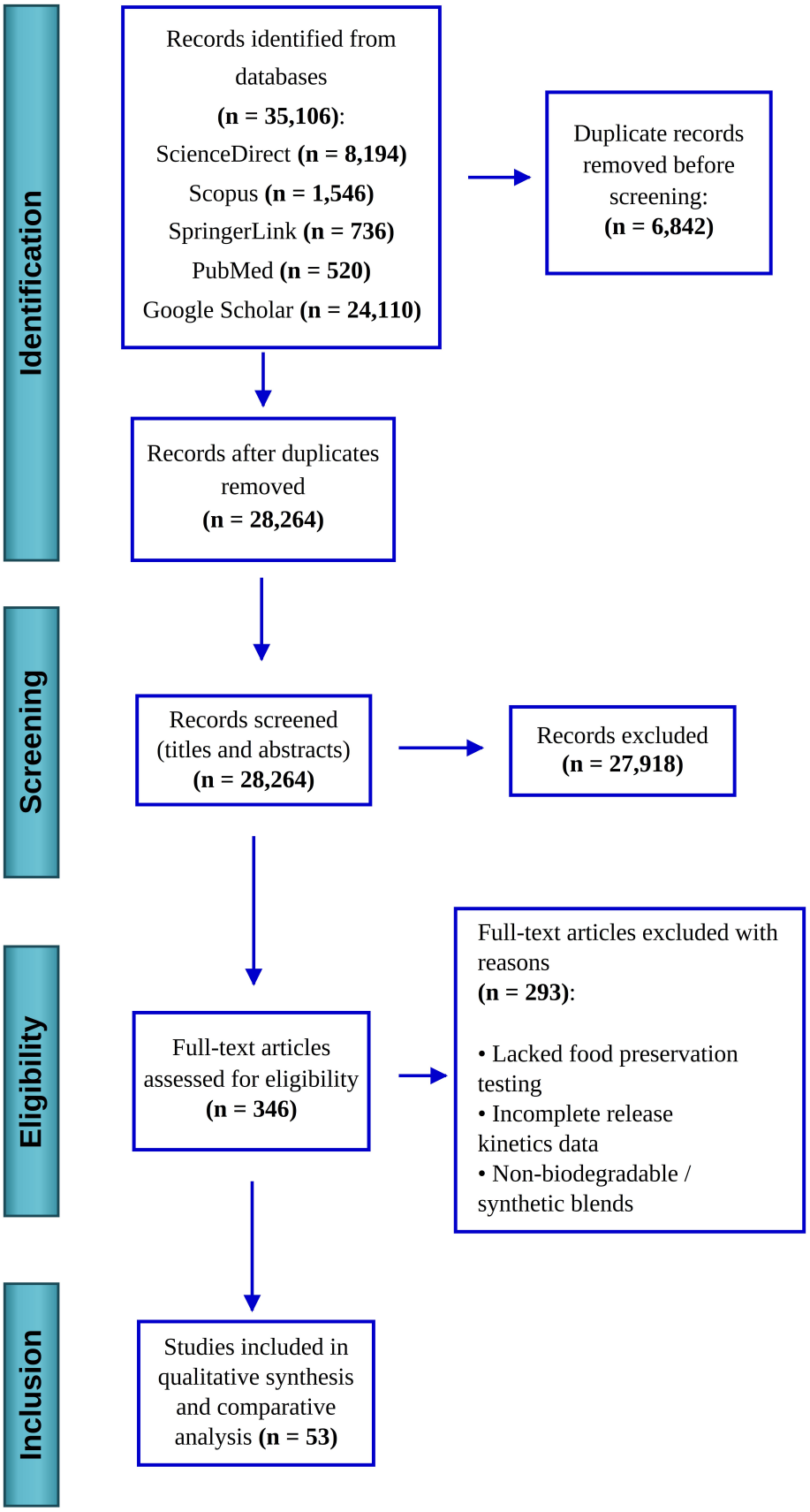


Figure 1 PRISMA 2020 flow diagram of the literature search and study selection process, from record identification to the inclusion of 53 studies in the qualitative synthesis and comparative analysis [7].

2.3 Analysis and Comparative Data Synthesis

We analyzed the retained publications through qualitative and comparative content analysis. Extracted datasets were systematically categorized according to: (i) biopolymer matrix type and nanofiller/crosslinker integration; (ii) incorporated active agents or intelligent sensing mechanisms; (iii) target food matrices and storage conditions; and (iv) functional performance (antimicrobial efficacy, radical scavenging capacity, barrier changes, and migration kinetics).

We mapped these variables into a benchmark matrix to identify technical trade-offs between mechanical strength and barrier functionality across polymer systems.

2.4 Time Frame for the Literature Review

Database queries focused on research published between 2010 and 2026 to evaluate recent advancements in nano-reinforcements and colorimetric indicators, with primary emphasis placed on work from 2018 to 2026. Earlier literature dating back to 1998 was referenced solely via manual citation tracking to establish baseline properties and standard polymer definitions.

2.5 Method of Analyzing and Organizing Selected Articles

The articles that were included in this literature review were analyzed critically and were grouped according to:

The type of biopolymer that was used (e.g., chitosan, starch, or cellulose, blends and composites). The function that the biopolymer provided (e.g., antimicrobial, antioxidant, moisture/gas control). The methods used to incorporate active agents into the biodegradable packaging materials. The particular types of food that were packaged with the biopolymer-based materials (e.g., fruits and vegetables, meat and meat products, dairy, seafood).

2.6 Benefits, Challenges, and Limitations of Intelligent Sensor-Based Packaging Applications

The information was qualitatively synthesized to show trends, technological improvements, enhancements to biopolymer systems used in packaging products, and gaps in research. A comparative method was employed when appropriate for discussing the different biopolymers and active packaging systems.

2.7 Limitations of the Methods

The findings reported in this review are based on published work; however, even with the best attempt to limit variability in experimental conditions (film formulation, food matrix, storage conditions, and method of testing/handling the samples), each of these variables may impact results from all of the reviewed studies so much that they are difficult to compare. Nevertheless, these large-scale datasets provide an excellent overview of what types of studies are currently being conducted and the challenges facing scientists in the packaging field today.

3. Biopolymers Used in Food Packaging

3.1 Chitosan

Chitosan, a polysaccharide derived from crustacean shells, can be produced by deacetylating chitin (Figure 2) [8, 9]. Chitosan has many potential uses across a variety of industries, including food, agriculture, and medicine, owing to its being non-toxic, antimicrobial, biodegradable and from a renewable resource [10, 11]. The films and other coatings made with chitosan have been widely studied. The films produced from chitosan are normally made using the casting technique, where the chitosan is dissolved in an appropriate solvent, with the plasticizer and the active compound and the nanofiller being combined at the same time with the chitosan solution. The antibacterial property observed with chitosan is due to the presence of positively charged amino groups (NH_3^+) in the C-2 position in the glucose monomers that comprise chitosan [12].



Figure 2 Experimental extraction of chitosan from crustacean shells: preparation of the raw material, demineralization, deproteinization, and deacetylation [13].

The film-forming capacity of chitosan is governed by its degree of deacetylation (DDA) and molecular weight, which dictate both tensile resistance and chain flexibility in casting processes [8, 9, 12]. Under acidic dissolution, protonated amine residues enable strong polycationic interactions with bacterial cell walls, inducing localized membrane lysis and intracellular electrolyte leakage [10, 11]. However, neat chitosan films inherently exhibit elevated water vapor permeability and moisture sensitivity due to abundant hydrophilic functional groups, necessitating chemical crosslinking (e.g., using genipin or glutaraldehyde) or the integration of lipid fractions to enhance hydrophobic barrier properties in humid food environments [12].

3.2 Starch-Based Biopolymers

Because of their general transparency, biodegradability, and good barrier properties against oxygen and carbon dioxide at low to moderate relative humidity [14], research into forming films from native starch has become more common. The main factor behind native starch's good barrier properties against oxygen and carbon dioxide is the large number of hydrogen bonds that form 3D networks within the polysaccharide polymer. While there are many positives associated with packaging films made from native starch, such as its mechanical strength and longevity, problems do exist with native starch films in that they tend to be quite brittle. The mechanisms that contribute to the limited performance of native films could be linked to their brittleness and other characteristics that can be defined as being related to brittleness when intact but can also be affected by exposure to direct light over extended periods or under other deteriorating conditions, e.g., humidity [15].

To address many of the previously described limitations of Native Starch films, researchers commonly produce starch packaging films using glycerol (plasticizers) and/or other polyols to increase flexibility and tensile elongation [16]. In general, plasticizing increases the ductility of the starch film while also increasing the free volume of the starch film and therefore increasing the hydrophilicity of the starch film, resulting in increased water vapor permeability (WVP) and decreased tensile strength of the starch film [16]. Other more recent methods, such as TEMPO-mediated oxidation (a chemical modification), have shown promise for increasing the flexibility of Starch by improving chain mobility without the addition of glycerol, thereby enabling the starch film to have sufficient flexibility and barrier properties [17].

Research also found that barrier coatings and nanofillers significantly reduce the water vapour permeability of biodegradable films. Dong et al. [18] demonstrated that incorporating 10wt% MXene nanoplatelets into starch-based films reduced water vapor permeability (WVP) by 92.9% compared with unmodified starch films.

Additionally, crosslinking poly(vinyl alcohol) (PVA)/montmorillonite nanoclay hydrogels has resulted in a reduction of the WVTR of paper products by about 90%. Several other studies supported similar benefits from using two-dimensional transition metal carbides/nitrides (MXenes) as a filler or coating, providing excellent improvements in moisture barrier properties; however, the overall performance of MXene-based systems depends upon the specific characteristics of the polymer matrix, the amount of filler, and the processing conditions used. In addition, starch composition also has a large effect on the mechanical properties of starch-based films. Tensile strength positively correlates with starch amylose content, peaking around 40% amylose; beyond 40%, increased amylopectin reduces elongation at break [19, 20].

Mung bean starch has a much greater elongation property (33% amylose) than cassava starch (26% amylose). The tensile strength of quinoa, lentil, and pumpkin starch films ranges from 8.98 to 13.85 MPa with elongation-breaking values between 3.35 and 4.44%. Adding fructose may improve the mechanical properties of standard starches such as corn and cassava; however, tensile strengths remain below synthetic polymers.

3.3 Cellulose and Its Derivatives

Cellulose and its derivatives are some of the most abundant of all biopolymers in nature and have become increasingly popular within the food packaging area because cellulose is biodegradable, inexpensive, has good mechanical properties, and is widely used [21]. The hierarchical structure of cellulose enables high tensile strength (when dry), high mechanical integrity (driven by its linear homopolysaccharide chain structure and extensive inter- and intramolecular hydrogen bonding), and low density, making it a sustainable packaging material. Additionally, cellulose is sourced from renewable materials and is therefore a favourable material that aligns with the current trend of reducing plastic waste generated within food packaging systems [21].

Cellulose does have some drawbacks regarding its native form, as it cannot dissolve in water or in most solvents; cellulose is sensitive to humidity. In addition, cellulose has poor resistance to microbial degradation [22]. To address some of these issues, cellulose can be chemically modified through hydroxyl substitution to produce various cellulose-based products such as carboxymethyl cellulose (CMC), hydroxypropyl methyl cellulose (HPMC), hydroxyethyl cellulose and cellulose nanofiber/crystals that are soluble, processable, and function better than regular cellulose (cellulose derivatives), making them easier to produce and use for food packaging materials. The performance of cellulose when used to make food packaging is notably improved over traditional food packaging films and composites containing cellulose because of the ability of cellulose materials to act as an oxygen barrier and have acceptable mechanical characteristics. The use of cellulose nanomaterials in polymer matrices has proven to enhance the mechanical properties (strength) of film, including reducing gas permeability and improving thermal properties [23, 24].

Additionally, cellulose and its derivatives are efficient materials for use as active packaging materials to carry active agents (i.e., antimicrobial and antioxidant), which have allowed for the development of active packaging materials that can extend the shelf life of food products [22]. The use of cellulose-based packaging materials has been demonstrated to positively influence the preservation of fruit and vegetables through reducing moisture loss, delaying microbial growth, and maintaining product quality during storage.

However, challenges related to moisture sensitivity and limited water vapor barrier performance still restrict broader commercial deployment [22]. Therefore, ongoing research focuses on blending cellulose with other biopolymers, incorporating nanofillers, and growing multilayer systems to ameliorate overall packaging performance.

4. Active Packaging Systems

4.1 Antimicrobial Active Packaging

Microbial contamination is a major cause of food spoilage and foodborne illness and is especially concerning for highly perishable fresh products, including seafood, meats, dairy products, and fresh vegetables. With the increase in the number of microorganisms that have developed resistance to standard antimicrobial treatments, the food industry has been looking to other methods for maintaining safe food products. One of these methods is active antimicrobial packaging, which is a beneficial way to inhibit the growth of microorganisms at the interface between a food product and its package and thus extend the shelf life of the product as well as maintain the quality of the food. Antimicrobial agents can kill or lyze microorganisms through different mechanisms. These

mechanisms include disrupting or denaturing proteins in microorganisms, altering cell membrane structure and permeability, inhibiting cell wall synthesis, preventing nucleic acid replication and transcription, and inhibiting vital metabolic pathways [25]. The success of these mechanisms relies on the kind of antimicrobial compound as well as the microorganism that gets targeted.

In antimicrobial packaging systems, the polymer matrices may have their active agents introduced either from natural or synthetic sources. The merging of antimicrobial agents with biopolymers and producing them as films or coatings is a viable option for controlling microbial contamination of the food product inside the pack. Antimicrobial agents, from a practical point of view should be released in a controlled manner to ensure effectiveness while avoiding excessive concentrations that could negatively affect sensory attributes or raise toxicological concerns [25].

Antimicrobial packaging systems can be divided into migrating and non-migrating systems. In migrating systems, antimicrobial agents are released over time from the packaging material to the food surface or surrounding air. Non-migrating systems, by contrast, rely on antimicrobial agents fixed in the packaging material to come into direct contact with the food surface, limiting diffusion while retaining antimicrobial action. Both types of systems have different benefits depending on the food product and storage conditions.

Embedding antimicrobial agents in packaging materials has been found to significantly improve microbial safety, prolong shelf life, and maintain food quality, especially for very perishable foods [26, 27]. Nevertheless, the incorporation of antimicrobial compounds may also affect key packaging features, such as mechanical strength, barrier properties, and material stability. Hence, the selection of antimicrobial agents must be done carefully, and either connection must be optimized in order to strike an effective balance between antimicrobial efficiency and packaging functionality [27].

4.2 Antioxidant Active Packaging

One of the main reasons food spoils is through oxidative reactions. This is especially true for foods that are high in lipids, such as meats and meat-based products [28, 29]. Lipid oxidation alters how food tastes, looks, and feels, and its nutrient content, negatively affecting how long a food lasts and reducing the likelihood that a consumer will purchase it. To combat this problem, antioxidant active packaging has been developed as a viable means to lower oxidation rates in food while being stored. There are two primary types of antioxidant active packaging systems:

Antioxidant Emitters - emitters are antioxidant agents that add antioxidant substances to either the food itself or to the surrounding environment to reduce the rate of oxidative reactions.

The second approach relies on antioxidant scavengers that remove or neutralize undesirable compounds such as oxygen, free radicals, or other pro-oxidant species present in the food matrix or headspace [29, 30]. Both systems aim to reduce oxidative stress and preserve food quality, although their effectiveness depends on the type of antioxidant used and the characteristics of the packaged food.

Historically, because of good mechanical performance, as well as the low cost of producing synthetic polymers, these materials have found extensive use in the food packaging industry [31]. However, because of their non-biodegradable nature and limited capacity to be recycled, synthetic polymers pose large environmental issues due to air and water pollution. Therefore, in recent years, there has been an increasing amount of interest in using biodegradable polymeric materials instead

of synthetic polymers (biopolymers) to produce antioxidant active packaging systems, which provide a sustainable solution for packaging while also allowing the use of natural antioxidant compounds.

One of the most promising applications of antioxidant active packaging is found in the meat industry, where oxidation is a major factor limiting product shelf life. Antioxidant films and coatings have been investigated to reduce lipid oxidation and maintain the quality of meat and meat products during storage. Although research in this area is still limited, recent studies indicate growing interest in the application of antioxidant packaging systems for meat preservation. Nevertheless, variability in experimental conditions, such as the type of antioxidant, film formulation, application method, and food matrix, makes it difficult to directly compare results across studies, highlighting the need for further research in this field [30].

4.3 Moisture and Gas Control Systems

Managing moisture and gas levels within the packaging of food products is integral to sustaining food quality and prolonging their shelf life. Water vapor and gases like oxygen and carbon dioxide greatly determine microbial growth, chemical changes, and various physiological activities in food. As a result, moisture and gas control mechanisms have been introduced as key elements of active food packaging [31].

Oxygen has the highest potential for damaging food items among many different types of gases because of its strong oxidizing properties. When oxygen is available, it will promote a large variety of harmful reactions, including the oxidation of mucous membranes resulting in rancid flavors, loss of pigment/vitamin stability, increase of aerobic microorganisms, and a host of other problems [31, 32]. To combat this issue, oxygen-scavenging devices are used extensively to lower oxygen concentration in food packaging. As a result, food spoilage reactions are hindered, and food remains stable. A decrease in oxygen concentration results in a decrease in respiration rates for fruits and vegetables, resulting in a direct correlation with the shelf life of that product [32, 33].

Oxygen scavengers form one of the most commercially successful active packaging technologies. Generally, these packaging systems operate through sachets or built- in components holding the reactive medium, such as powder iron or ascorbic acid. Oxygen scavengers that are iron-based are very efficient, but their application might be constrained because of the metal detector interference during the packaging process [34].

5. Incorporation of Active Agents into Biopolymer Matrices

One of the most important techniques for creating active food packaging systems is the incorporation of antimicrobial agents into biopolymer matrices [35]. Composite materials typically combine a natural or synthetic active agent with a biopolymer to enhance functional qualities and prolong the shelf life of food. Compared to conventional passive packaging materials, these biopolymer-based composites have a substantially longer shelf life because they can be antimicrobial, antioxidant, moisture-regulating, and odor-regulating [28, 30-33].

In essence, surface coating and modification techniques involve applying coatings of some sort to food or packaging surfaces to allow the active layer to come into direct contact with the food [26, 27]. Encapsulation techniques is growing in popularity as a means of safeguarding sensitive bioactive substances and regulating their release over time, maintaining the compounds' efficacy

while minimising any adverse effects on sensory qualities. In active packaging based on biopolymers, the release of active agents is crucial.

An ideal release rate consistently provides sufficient antioxidant or antimicrobial activity throughout storage without excessive migration that could compromise food safety or quality [36, 37]. Despite their effectiveness and proven performance, the stability of the active ingredients, the polymer, and their compatibility, as well as the potential for scaling up industrial production, remain key concerns that need to be resolved [36, 37]. Therefore, the development of incorporation techniques and the enhancement of these systems' commercial potential should be the main areas of future research.

6. Applications of Biopolymer-Based Active Packaging in Food Preservation

6.1 Fruits and Vegetables

Microbial growth, oxidation, moisture loss, and physiological respiration processes make fruits and vegetables extremely vulnerable to spoiling. To enhance the preservation of fresh produce, biopolymer-based active packaging that incorporates natural bioactive compounds has been extensively studied in recent years. Fruit by-products, like seeds and peel extracts, are abundant in antibacterial and antioxidant compounds and are increasingly popular as natural additives in active packaging systems [38].

These bioactive substances have been demonstrated to dramatically improve food preservation when added to biopolymer films by preventing oxidative degradation and microbial growth. Citrus peel extracts, for instance, have shown enhanced antimicrobial and antioxidant activity when added to starch-based films, extending the shelf life and preserving the quality of fruits and vegetables. Using fruit by-products in packaging materials not only improves preservation effectiveness but also adds value to food-industry waste, making food packaging systems more sustainable [38, 39].

6.2 Meat and Meat Products

The shelf life and safety of meat and meat products are restricted by their heightened susceptibility to oxidative spoilage and microbial contamination [40, 41]. Active packaging systems based on biopolymers, particularly those derived from cellulose and chitosan, have demonstrated encouraging outcomes in tackling these issues. When compared to single-component films, composite films that combine cellulose and chitosan frequently show increased antimicrobial activity and mechanical strength. In these systems, cellulose helps to improve structural stability, while chitosan is essential for preventing bacterial growth.

Numerous studies have concluded that chitosan-based films and coatings are useful for inhibiting microbial proliferation and delaying the degradation of meat products. Chitosan has a direct influence on food surfaces through mediated effects and can therefore prevent meat products from spoiling and prolong their storage life. Test protocols used to validate the effectiveness of particular products are microbiological, sensory, and physicochemical; all three methods are applicable for preserving and extending the lifespan of food items [41].

6.3 Aquatic and Seafood Products

Seafood items, including finfish, crustaceans, and cephalopods, represent exceptionally perishable food matrices driven by rapid enzymatic autolysis, high moisture activity, and microbial proliferation predominantly caused by psychrotrophic Pseudomonas species and Shewanella putrefaciens. The accumulation of total volatile basic nitrogen (TVB-N), trimethylamine (TMA), and thiobarbituric acid reactive substances (TBARS) drives rapid sensory decline and protein spoilage. The application of active biopolymer packaging—particularly polycationic chitosan coatings enriched with natural essential oils (e.g., oregano, thyme, or cinnamon) or polyphenolic plant extracts—effectively retards psychrotrophic bacterial growth and diminishes nucleotide breakdown. Concurrently, nanocellulose-reinforced chitosan matrices demonstrate superior barrier integrity against lipid oxidation in fatty fish fillets (such as salmon and mackerel), significantly delaying post-mortem degradation without leaving synthetic chemical residues.

6.4 Dairy Products

Dairy commodities, particularly hard and semi-hard cheeses, butter, and fermented derivatives, are primarily susceptible to superficial fungal contamination (Penicillium and Aspergillus species), surface dehydration, and photo-oxidative rancidity induced by ambient light exposure. The integration of natural bio-preservatives—such as nisin, natamycin, lysozyme, and green tea polyphenols—into thermoplastic starch (TPS) or cellulose ether films (e.g., CMC, HPMC) creates an effective contact-active antimicrobial barrier at the food interface. This active entrapment suppresses fungal sporulation on sliced cheese surfaces while preserving natural moisture equilibrium. Moreover, the intrinsic oxygen-barrier properties of dense polysaccharide matrices combined with light-barrier nanofillers limit lipid auto-oxidation and photo-induced off-flavor generation, providing a clean-label alternative to conventional paraffin wax and multi-layer plastic packaging.

6.5 Multifunctional and Intelligent Applications

In addition to their antimicrobial and antioxidant functions, biopolymer-based packaging materials can be designed to incorporate intelligent features. For instance, chitosan films can include indicators such as pH or freshness sensors that enable real-time monitoring of food quality. These multifunctional systems combine active and intelligent packaging concepts, providing both preservation and quality monitoring functions. Such applications are particularly valuable for perishable products such as meat, seafood, and dairy, where rapid quality changes can occur during storage and distribution.

6.5.1 Intelligent Food Packaging Mechanisms

Intelligent food packaging technology represents an advancement in smart active food packaging, incorporating sensory elements, indication technologies, and data transmission. In the context of smart packaging technology based on biopolymers, chitosan, starch, and cellulose can be used in combination with pH-sensitive dyes, gas indicators, and biosensors to display dynamic and real-time trends of food freshness and overall quality in real-time. It has the ability to detect shifts in terms of microbial growth rates, pH levels, gas production, and oxidation levels in packaged products. In

this way, it makes supply chain decision-making smarter by improving safety, reducing waste, and increasing sustainability [42].

To translate these concepts into practical packaging systems, three main indicator technologies are predominantly integrated into biopolymer matrices:

Colorimetric pH and Spoilage Freshness Indicators.

Natural pigments—principally anthocyanins (derived from red cabbage, black carrot, or berries) and curcumin—are immobilized within hydrophilic biopolymer networks like chitosan or carboxymethyl cellulose (CMC). During protein degradation in meat and seafood, accumulating total volatile basic nitrogen (TVB-N), such as ammonia and dimethylamine, alters the local microenvironment pH, triggering visible and reversible color changes that consumers can detect visually without opening the package.

Headspace Gas and Leakage Indicators.

Biopolymer films can host redox-sensitive dyes (e.g., methylene blue with reducing sugars or titanium dioxide) to monitor gas composition within modified atmosphere packaging (MAP). Unintended oxygen ingress caused by seal breaches or package micro-cracks prompts rapid oxidation of the indicator, alerting distributors to premature loss of product safety.

Time-Temperature Integrators (TTIs).

Enzymatic or chemical TTIs integrated into polysaccharide films monitor cumulative thermal exposure along the cold chain, tracking quality loss in chilled items such as fresh poultry, fish, and dairy.

6.5.2 Biosensors and Biotechnology Interfacing

In biotechnological terms, incorporating bio-based sensors into biopolymer matrices offers huge prospects for smart food monitoring. Among biopolymers, chitosan seems one of the most suitable for sensor realization because it naturally possesses film-forming ability, biocompatibility, and responsiveness to environmental changes. Biosensors incorporated into packaging materials can detect microbial metabolites, volatile compounds, or biochemical markers associated with food spoilage. For example, immobilizing specific enzymes (such as xanthine oxidase or glucose oxidase) directly onto functionalized chitosan or cellulose matrices enables the precise quantification of post-mortem degradation by-products (such as hypoxanthine) in meat and fish tissue. Such intelligent systems enable continuous food quality monitoring without destructive sampling, supporting safer, more effective preservation throughout distribution.

7. Advantages, Limitations, and Challenges

Due to growing concerns about pollution from chemical pollutants and the continued use of polymer products that create massive amounts of waste, there has been an increase in demand for biodegradable, recyclable, and environmentally-friendly materials to package goods [43]. Materials derived from renewable sources (biopolymers) add to the classification of being biodegradable and environmentally-friendly, thus helping to combat our impact on the environment. Many polymer materials incorporate active additives (such as active ingredients including but not limited to antimicrobial and antioxidant materials) that allow these types of packaging systems to preserve

food. Additionally, biopolymer-based packaging allows consumers to control bacterial growth, slow oxidative processes in food, or, in some cases, offer "intelligent" indicators to monitor the condition of packaged products [35].

The shelf life of food can be significantly improved by the use of biopolymers as packaging materials in conjunction with active agents and/or sensing components. There are many different types of biopolymers such as starch, chitosan, protein, and cellulose, each providing a unique solution for producing packaging materials that will meet specific food needs through varying mechanical, barrier, and functional properties [44-46]. While there are many positive aspects of using biopolymers to produce packaging materials, there are still many limitations and challenges. Compared to standard plastics used in the manufacture of packaging materials, there are many film and/or sheet-type biopolymer-based films that have lower strength, fewer moisture-resistant properties, and lower barrier properties than their standard plastic counterparts. Most often, these limitations must be improved through blends of biopolymer(s) or chemistries, the addition of nanofillers, or the creation of a multi-layer structure. The addition of active agents may also negatively affect film stability, sensory properties, or compatibility between the biopolymer-based film and active agent when added to the film unless they are properly engineered [47].

From an industrial perspective, challenges related to production cost, scalability, and process standardization continue to restrict the widespread commercialization of biopolymer-based active packaging. Regulatory issues and consumer acceptance also play an important role, particularly when active compounds migrate into food products. Consequently, continued research and technological development are necessary to overcome these limitations and enable the large-scale adoption of biopolymer-based active packaging systems [48].

8. Mass Transfer and Release Kinetics of Active Compounds

The preservative utility of biopolymer active packaging hinges not merely on the intrinsic potency of embedded additives, but upon their continuous mass transport dynamics into the food matrix or internal headspace. Active release kinetics—governed by molecular diffusion, solvent relaxation, and matrix swelling—must maintain interfacial agent concentrations strictly above the minimum inhibitory concentration (MIC) while adhering to established food contact safety thresholds [49].

In biopolymeric systems, active agent release is primarily described by Fickian or non-Fickian (anomalous) transport principles, dictated by the macromolecular architecture of the matrix, the penetrant's molecular weight, and thermodynamic partitioning at the film-food interface. Hydrophilic matrices such as uncrosslinked chitosan and thermoplastic starch undergo rapid plasticization and macromolecular chain relaxation under high relative humidity (RH) or in direct contact with aqueous foods, resulting in a pronounced initial burst release [49, 50].

While an initial burst provides rapid pathogen inactivation during the vulnerable lag phase of microbial growth, uncontrolled diffusion depletes the bioactive reservoir prematurely, preventing sustained preservation during prolonged distribution. To maintain continuous therapeutic efficacy, mass transport must be modulated through structural engineering of the biopolymer network. Incorporating chemical crosslinkers, forming hydrophobic polyelectrolyte complexes, or integrating inorganic nanofillers (such as montmorillonite, zinc oxide, or cellulose nanocrystals) increases matrix tortuosity and reduces polymer free volume, shifting mass transfer from rapid swelling-dominated erosion to sustained, diffusion-limited release profiles.

Encapsulation within micro- or nanocarriers (e.g., nanoliposomes, cyclodextrin inclusion complexes, and polymeric nanocapsules) represents a robust strategy to stabilize volatile essential oils against thermal degradation during processing while enabling on-demand, stimuli-responsive release triggered by shifts in environmental pH, enzymatic activity, or moisture [51].

Furthermore, specific intermolecular interactions between the bioactive compound and the host polymer network significantly influence release kinetics. Strong physical bonding—such as hydrogen bonding, hydrophobic interactions, and electrostatic attraction between protonated amino groups of chitosan ($-NH_3^+$) and negatively charged functional groups of phenolics—promotes active agent retention and mitigates uncontrolled leaching. Controlling mass flux is essential to ensure migration remains safely below Specific Migration Limits (SML) and prevents off-flavor sensory contamination in packaged foods [50, 51].

As an alternative to migrating configurations, non-migrating (immobilized/contact-active) packaging systems offer surface-bound bioactivity via covalent tethering without sustained mass transfer into the food matrix. However, establishing standardized predictive kinetic models remains technically challenging because real foods differ from idealized liquid simulants (e.g., 10% ethanol, 3% acetic acid, or isooctane) in structural heterogeneity, water activity, and fat content. Future industrial translation requires multi-component finite element modeling validated under dynamic, non-isothermal supply chain conditions [51].

9. Food Safety, Legal Aspects, and Durability

9.1 Food Safety Aspects

Food safety is a critical aspect when developing active and intelligent packaging systems made using biopolymers, as they have the potential to affect the food's safety; the biopolymers themselves are generally regarded as safe owing to being of natural origin and biodegradable, and the biopolymers (chitosan, starch, and cellulose) are generally regarded as safe because they do not have any adverse effects on the food or on their own inherent qualities. Despite the general safety associated with the use of biopolymers, there are safety concerns associated with the addition of active ingredients that enhance a food's performance [48].

There are changes taking place in food safety management systems to include both microorganism hazards and environmental impacts. The Green HACCP Design extends the traditional HACCP system to include sustainability elements within the hazard analysis and controls. This design not only enhances food safety, but it also reduces environmental burdens. The combination of sustainable, biodegradable, and active packaging will result in the enhancement of both food safety and the food product environmental footprint.

Controlled release of antimicrobial and antioxidant elements or agents from the materials that comprise the packaging system can prevent bacterial or mould growth on the food products being packaged. Toxicological safety must also be ensured to avoid negatively affecting the sensory characteristics of food, such as taste, odour, or appearance [48, 49].

Because active ingredients can migrate excessively or uncontrollably from packaging materials into food, regulatory migration limits could be exceeded. Bioactive compounds found in Nature are generally viewed as a safer alternative to synthetic food additives; however, high-dose exposure can result in only temporary adverse effects, particularly when interacting with certain food types or food formulations. The second major aspect of food safety focuses on microbial resistance

development over time as a result of repeated exposures to sublethal levels of antimicrobial substances placed into the packaging material.

Due to this, food packaging manufacturing must incorporate precision control over the release kinetics and contact mechanisms to provide adequate antimicrobial action against microbes while not selecting for adaptive resistance. In addition, intelligent packaging components (e.g., indicators and sensors) must be designed so that they do not come into direct or indirect contact with food until the safety of the indicators/sensors has been established [49].

The use of inks, dyes, or electronics in intelligent packaging requires a systematic evaluation process to create a reasonable assurance that they will not cause chemical contamination of food during storage and handling.

9.2 Regulatory Framework and Food Contact Compliance

One of the major hurdles to large-scale commercialisation of bio-polymer-based active packaging supplies is the regulatory approval of active packaging materials. Active packaging materials used in food contact applications are fully regulated by strict regulatory agencies worldwide, including the European Food Safety Authority (EFSA) and the United States Food and Drug Administration (FDA) [46-52]. Consequently, active food contact packaging materials must have their material composition, migration properties, toxicological evaluations, and intended use conditions thoroughly assessed in order to obtain regulatory approval. Active packaging systems are additionally subject to even greater regulatory scrutiny due to their intended release of agents into either the food product or its surrounding environment.

For instance, active packaging materials must provide evidence that all compounds released into food products or their environment by the packaging are legally allowed to be in contact with food, and must not exceed established specific migration limits determined by the relevant authority. Testing for Food Contact (i.e., food packaging) will usually require extensive laboratory testing against Standards under assumed worst-case storage conditions, which can result in longer times for development and increased costs [46]. The main regulatory issue regarding the assessment of complex composite systems, such as multilayer films or nanocomposites, is how to conduct risk assessments for case-by-case assessments [53].

The interaction of biopolymers, nanofillers, and active agents adds complexity to risk assessments and therefore often requires individual regulatory approval for each type of biopolymer packaging. The lack of harmonised global regulations can further slow innovation and market uptake.

9.3 Durability and Functional Stability

Durability is a key performance attribute of biopolymeric packaging because it has to retain it's 'structural' and 'functional' characteristics from the point of manufacture through to the end of active or useful product life (i.e., processing, storage, transport, shelf life) [52]. Biopolymers usually have lower mechanical strengths and are more sensitive to moisture than conventional plastics, which may exhibit deformation and/or cracking, and loss of barrier under humid conditions. Adding an agent to an existing material can also affect the durability of the material by changing how the polymers are structured or speeding up the degradation process. Some active substances, such as

plasticizers and some natural extracts, can provide increased flexibility and improved tensile strength but can also reduce the long-term stability of the material.

Additionally, any intelligent device used in packaging may create weak points unless it is satisfactorily incorporated into the packaging design [52]. Research has shown that these approaches, polymer blending/multi-layered packaging, chemical modification, and nanofilling, can improve durability while maintaining biodegradability. However, the application of these techniques must be optimally conducted to avoid degradation and/or increased environmental impact of the packaging material [47].

Research on long-term durability under actual service conditions is not yet well documented compared with many laboratory studies performing short-term evaluations. Therefore, future research should focus on aging studies, real-food tests, and validation testing at the industrial level to more accurately evaluate the functional stability of these materials over time.

9.4 Harmonization with EFSA and FDA Specific Migration Limits (SML)

The deployment of active and intelligent biopolymer packaging requires strict compliance with international food contact material (FCM) regulations, notably EU Regulation (EC) No 450/2009 (active and intelligent materials) and US FDA 21 CFR § 175-178. The primary regulatory hurdle is the unintended migration of active constituents—including essential oil volatiles, phenolic derivatives, and synthesized nanoparticles (e.g., nano-ZnO or nanocellulose)—into adjacent food-contact layers. Under European Food Safety Authority (EFSA) mandates, non-authorized substances must adhere to an absolute specific migration limit (SML) below 0.01 mg/kg in food matrices [46, 52]. For nano-reinforced biopolymers, safety evaluations require toxicological profiling and direct characterization of nano-migrants to exclude cellular accumulation and cytotoxicity prior to regulatory approval [37].

9.5 Integration of Green HACCP in Biopolymer Processing

To bridge the gap between laboratory formulation and industrial-scale manufacturing, conventional Hazard Analysis Critical Control Point (HACCP) frameworks must expand into "Green HACCP" protocols. In biopolymer active film production (via twin-screw extrusion or solution casting), Green HACCP identifies critical control points (CCPs) across three production stages [5, 6]:

- **Raw Material Pre-processing:** Quantitative monitoring of purity and chemical residues in agro-industrial by-product extractions (e.g., crustacean chitin or agricultural starch).
- **Thermal and Mechanical Processing:** Optimization of extruder barrel temperatures and shear rates to prevent the thermal volatilization or degradation of embedded bioactives (essential oils, natural anthocyanins).
- **Controlled Release and Migration Verification:** Establishing continuous batch-testing CCPs to ensure active release kinetics remain within therapeutic antimicrobial thresholds while complying with global chemical migration thresholds.

In order to successfully transfer biopolymer-based active packaging from the laboratory to the marketplace, it is critical to ensure food safety and regulatory compliance while maintaining durability.

There has been considerable progress made thus far, but developing commercial applications will require a multidisciplinary approach that combines knowledge from multiple disciplines, including material science, toxicology, regulatory science, and food engineering. Ongoing

partnerships among researchers, industry participants, and regulators will be integral to developing packaging systems that are both sustainable and safe/secure/available to consumers.

10. Future Trends and Perspectives

The incorporation of biopolymers to create active packaging has the potential to make significant shifts in how we view the value of by-products from food processors. Many by-products from agriculture and food processors, including fruit peels, seeds, fruit processing pomace, and shells, contain antimicrobial and antioxidant compounds that can add value by incorporating bioactive compounds into biopolymer-based food packaging systems. Not only does this provide a sustainable solution for improving the shelf life and providing greater stability of food or ingredients, but the approach also creates a closed-loop solution to food waste by providing a high-value use for low-value by-products. By adding the bioactive compounds in biopolymers into an active packaging application, consumers may also be more likely to accept the use of these natural-derived active agents than synthetic agents.

Future research in the area of active packaging from biopolymer sources is expected to focus on achieving effective and efficient extraction methods, as well as improving the stability and controlled release of the identified bioactive compounds from food waste within the biopolymer matrix. In addition, future research will evaluate the effectiveness of food waste bioactives in various packaging systems. There will be an emphasis on the use of intelligent applications/digital technologies as a potential future development of biopolymer-based active packaging systems. Smart sensors/degradable materials as well as data collection and smart indicators, will allow for the continued monitoring of food quality as it is stored and transported [53].

These intelligent packaging systems may be further connected to digital platforms or Internet of Things (IoT) technologies, allowing data collection, analysis, and predictive decision-making. Such advancements align with the concept of intelligent systems for sustainable development, offering innovative solutions to reduce food waste, improve supply chain efficiency, and enhance consumer trust.

11. Overall Discussion

As the demand for sustainable packaging in the food industry continues to escalate, biopolymer active and intelligent packaging systems provide viable alternatives to existing plastic packaging made from petroleum. This research has extensively documented the promising properties of biopolymers such as chitosan, starch, and cellulose for enhancing food shelf life while reducing environmental impacts. Biopolymers are biodegradable, renewable, and functionally versatile materials; therefore, they are particularly desirable materials in today's market where consumers desire both safety and sustainability. Chitosan is a biopolymer with inherent antimicrobial properties; therefore, it can serve as both a structural material and an active agent.

This property significantly minimizes the need for added synthetic ingredients to produce clean-label packaging concepts. The film of starch is cheap and plentiful but needs to be modified or blended to reduce the brittleness and moisture sensitivity inherent in starch films. Cellulose and its derivatives have excellent mechanical strength and gas barrier properties. However, cellulose and its derivatives have a high affinity for moisture, which limits their capability when exposed to humidity. Active agents, such as naturally occurring antimicrobial and antioxidant compounds, have

improved the functional performance of biopolymer films as shown in a number of studies. These biopolymer-based systems have been shown to inhibit microbial growth and prevent the oxidative degradation of food, the two main reasons for food spoilage. However, the success of these biopolymer-based systems will depend on the compatibility of the biopolymer matrix (film) with the active compound and the release characteristics during storage. Recent developments in smart packaging systems show that integrating physiological sensors and/or indicators with intelligent materials into biopolymer matrices is possible. The ability of intelligent packaging systems to provide real-time data and feedback on the quality of food (e.g., freshness) and environmental conditions during storage will help create much smarter and safer food supply chains. Still, these types of systems are primarily experimental and need to be further optimized for practical use as an industrial application.

11.1 Comparative Critical Analysis and Data Synthesis

The comparison of the reviewed studies showed marked performance differences between the major biopolymer categories. Each biopolymer category demonstrated both its own set of advantages and its own set of disadvantages. One of the main advantages that have been observed in chitosan films as compared with films made from starches or cellulose-based polymers is that chitosan is more effective at inhibiting microbial growth due to the presence of positively charged amino functional groups, which exert some degree of disruption to the integrity of microbial cell membranes. Although the mechanical flexibility of chitosan films may be limited, chitosan films typically show greater manufacturing costs, therefore reducing their chances of commercialization.

Starch-based packaging materials also have great film-forming properties and low oxygen barrier under dry conditions, yet still exhibit poor vapor barrier with high moisture vapor permeability. While many studies have used plasticizers, incorporating nanofillers or chemically modifying the matrix can improve plasticity and barrier performance, but these changes can also reduce mechanical strength or increase moisture sensitivity, demonstrating a direct trade-off between functionality/performance and structural integrity/compatibility. Compared with starch-based films, nanocellulose-reinforced cellulose systems show superior mechanical and gas-barrier properties; overall, composite materials generally offer greater strength and dimensional stability than starch. While they have limited antimicrobial properties, external bioactive agents are required for their use in food contact applications due to concerns regarding migration, sensory effects, and regulatory issues.

A literature synthesis shows that no single biopolymer currently meets all functional requirements for food packaging materials.

A structured synthesis benchmarked across target food matrices, operational storage conditions, functional preservation mechanisms, and associated performance trade-offs is systematically consolidated in Table 1.

Table 1 Comparative Performance Matrix of Biopolymer Packaging Systems Across Experimental Conditions and Food Applications [54-56].

Biopolymer Matrix	Active/Intelligent Agent Incorporated	Target Food Matrix	Storage Conditions	Preservation Mechanism & Key Performance	Major Limitations & Trade-offs
Chitosan (Native/ Blends)	• Thyme/Cinnamon Essential Oils • Grape seed extract • Anthocyanins (Intelligent)	Fresh beef, chicken fillets, cold-water shrimp	4°C, 85% RH (Refrigerated storage)	• Inherent polycationic membrane disruption (NH_3^+ groups) • Extended microbial lag phase against L. monocytogenes & E. coli • TBARS reduced by >45% • Real-time colorimetric pH/TVB-N spoilage sensing	• High moisture sensitivity in humid environments • Rapid initial burst release of volatile oils • Higher raw material production cost
Thermoplastic Starch (TPS)	• Green tea polyphenols • Nanoclay/MXenes • Curcumin extract	Strawberries, table grapes, fresh bakery	20-25°C, 50-65% RH (Ambient to mild cool)	• High oxygen barrier under low-to-moderate RH due to dense hydrogen bonding • Significant reduction in fruit weight loss and respiration rate • Nanoclay addition reduced WVP by up to ~90%	• High brittleness requiring polyol plasticizers (which increase WVP) • Structural retrogradation over prolonged storage • Low moisture resistance
Cellulose & Derivatives (CMC, HPMC, CNCs)	• Nisin/Lysozyme • Metal oxide NPs (ZnO, TiO_2) • Clove extract	Fresh-cut fruits, sliced cheeses, processed meats	4-10°C, controlled modified atmosphere	• Superior tensile strength and dimensional stability • Excellent gas barrier in dry states • Nanocellulose reinforcement enhances tortuous path, retarding vapor and gas diffusion	• Native cellulose insolubility requires chemical functionalization • Slower release kinetics in hydrophilic derivatives • Risk of active agent aggregation at high nanofiller loadings

Note: CNCs = Cellulose Nanocrystals; CMC = Carboxymethyl Cellulose; HPMC = Hydroxypropyl Methyl Cellulose; WVP = Water Vapor Permeability; TBARS = Thiobarbituric Acid Reactive Substances; TVB-N = Total Volatile Basic Nitrogen.

Therefore, the most successful systems will usually be composite or multilayered, combining the properties of different biopolymers with additive functionality. Examples include using blends of chitosan and starch or cellulose-based composites that are supplemented with naturally derived extracts, which produce synergistic effects on the materials through enhancement of antimicrobial properties, mechanical strength, and barrier properties. The variability of experimental methodologies used within each study, as well as differences in food matrices and storage conditions between them, significantly limits the ability to compare results across studies on a direct basis, despite the evidence of each study's utility from laboratory-scale evaluations.

The lack of a uniform way to present research findings makes it difficult to use those findings in an industry setting. Additionally, most of the studies have only studied short-term storage experiments, and therefore they have not studied long-term stability and scalability or economic feasibility. Overall, comparative studies show that future advancements in biopolymer packaging will depend on combining material design with controlled release, as well as establishing standard methods to evaluate materials once they reach the market. The most significant challenge facing this field is bridging the gap between academic work and its use in the business community.

12. Conclusion

Biopolymer-based active and intelligent packaging systems represent a promising and sustainable approach to addressing the growing challenges of food preservation and environmental pollution. By combining biodegradable materials such as chitosan, starch, and cellulose with active functionalities, these packaging systems move beyond the traditional passive role of packaging and actively contribute to improving food safety, quality, and shelf life. Incorporating antimicrobial, antioxidant, and moisture- and gas-controlling systems demonstrates the significant potential of biopolymers to replace conventional petroleum-based plastics in many food packaging applications.

Despite the considerable progress achieved in recent years, several challenges continue to limit the large-scale adoption of biopolymer-based active packaging. Mechanical performance, moisture sensitivity, cost, and industrial scalability remain critical and require further optimization. In addition, the effective and controlled release of active compounds, as well as regulatory and consumer acceptance aspects, must be carefully addressed to ensure safe and practical implementation.

The future of biopolymer-based active packaging will require innovative multi-disciplinary systems that support net-zero emissions, functional performance capabilities, and the economic feasibility of the materials at the same time. One of the greatest opportunities for the food industry is using by-products as sustainable sources of natural bioactive compounds to create more functional packaging while still adhering to circular-economy principles. Continued interdisciplinary research and developments in materials science and processing technology will be required for commercially viable solutions to evolve from the laboratory to products on store shelves. Biopolymer-based active packaging will support the transition toward a sustainable and resilient food system.

Author Contributions

MZ and BEB conceptualized the manuscript. BE drafted the initial version. MZ and BEB subsequently revised, developed, and validated the manuscript.

Competing Interests

The authors have declared that no competing interests exist.

AI-Assisted Technologies Statement

Artificial intelligence (AI) tools were used solely for basic grammar correction and language refinement in the preparation of this manuscript. Specifically, ChatGPT was employed to improve the readability and linguistic clarity of the English text. All scientific content, data interpretation, and conclusions were developed independently by the authors. The authors have thoroughly reviewed and edited the AI-assisted text to ensure its accuracy and accept full responsibility for the content of the manuscript.

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