



Shelf Life Extension of Marine Food by the Use of Biopolymer-Based Edible Coatings

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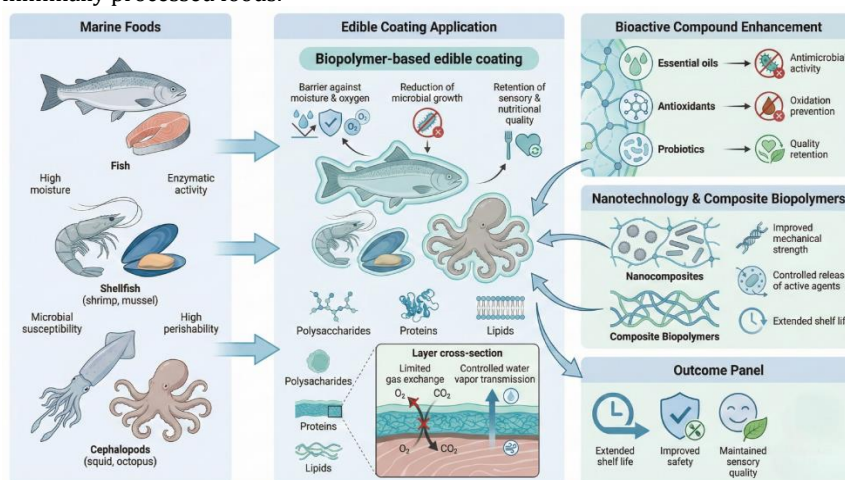
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ABSTRACT

Marine foods including fish, shellfish, and cephalopods, represent nutrient-dense commodities, vital for global food security and human health. However, their high moisture content, enzymatic activity, and susceptibility to microbial contamination make them highly perishable, resulting in substantial postharvest losses. Conventional preservation methods, such as freezing, vacuum packaging, and modified atmosphere storage, offer limited protection and may compromise on product quality. In recent years, biopolymer-based edible coatings have emerged as a sustainable and effective strategy to enhance the shelf life of foods. Derived from natural sources such as polysaccharides, proteins, and lipids, these coatings create a thin, edible barrier that regulates moisture & oxygen transfer, and microbial growth while maintaining sensory and nutritional properties. Moreover, addition of bioactive compounds, including essential oils, antioxidants, and probiotics, further improves functional performance. Additionally, recent advances in nanotechnology and composite biopolymers have enhanced mechanical strength, controlled release of active agents, and broadened industrial applications of edible coatings. Nevertheless, edible coatings represent a promising alternative to synthetic packaging, aligning with sustainability goals and consumer demand for safe, minimally processed foods.



INTRODUCTION

Consumption of animal source foods (ASFs) has decreased than plant-based food due to its impact on health and environment. Among the diversity of nutrients like carps aquaculture, bivalve and small pelagic fisheries have lower environmental influence to express their nutrients richness. However, in comparison with beef, prawns, pork, pangasius catfish and crustaceans show great nutrients

abundance due to environmental impact (Koehn et al., 2022). Global food security comprises with seafood which include plants and animals in freshwater and marine, there are about 59.6 million population rest on aquaculture and fisheries to fulfill their nutrients need and livelihoods. About 3.2 billion People get 20% animal protein from fish (Stetkiewicz et al., 2022). Seafood is richest source of omega 3 fatty acids, good quality protein, minerals and

essential vitamins to prevent from different chronic disorders and promote health. Due to unhygienic conditions and poor handling of seafood has resulted in serious problems to human health. There is need to improve detecting and monitoring system to check and control microbial metabolites like parasites, viruses and bacteria which are basic reason to spread foodborne illnesses (Taylor et al., 2025). There are different kind of marine organisms discovered which are best source of food and provide benefits to pharmaceutical industries. Over half of the world's biota make up of marine ecosystem and contains excessive amount of bioactive components (including sponges, mollusks, echinoderms, and crustaceans) (such as bacteria, cyanobacteria, and action-bacteria), algae (both macro-algae and microalgae), invertebrates), and, most importantly, fish. These organisms possess with unique biological functions and complex molecules with extreme living environment.

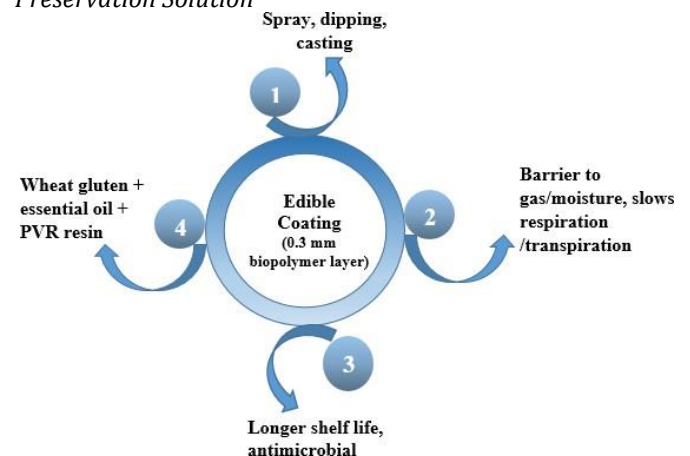
Moreover, various polysaccharides, carotenoids, saponins and peptides are present in marine biomolecules e.g. in poly-unsaturated fatty acids. They are beneficial in functional and nutraceutical products. In food industries these are become auspicious due to different properties like antimicrobial, anticoagulant, anticancer, antidiabetic, antioxidant, anti-inflammatory, anti-thrombotic, cardio protective impact and anti-proliferative (Senadheera et al., 2023). In developing countries where sustainable practices are imperative in global fishery and fish export industries (Phang et al., 2023). These circumstances demand for a serious shift towards liable resource management and environmental preservation (Elahi et al., 2024).

Edible coatings are deliberated biodegradable as they can substitute plastic packaging and diminish food waste by extending the shelf life of food yields. These coatings can decrease the product interaction with environment. For this purpose, edible packing play important role to retain qualities, freshness and prolong shelf life of Food. These coatings generate a defensive barrier, decreasing moisture loss, lipid oxidation, and microbial progression. Coating's effectiveness depends on various factors like storing conditions and low temperature (Freezing and refrigeration), it will slow down biochemical reactions and increase food quality (Kurek et al., 2024). Moreover, mechanical properties of coatings are improved with the addition of hydrogels which can change adhesive factors and strength (Tkaczewska et al., 2023). Coatings are hydrophobic in nature because they cannot break its water portion coherent polymer matrix during freezing. Lipids, proteins and carbohydrates are parameters which make the composition of coatings; these factors entirely depend on product nature. These parameters have strong impact on hygienic properties, protection and organoleptic properties of product. Antioxidants can increase coatings abilities by preventing oxidation and neutralize free radicals (Kurek et al., 2024). Endogenous enzymes activity and microbe's contamination can change fish quality during storage by protein degradation and lipid oxidation (Nie et al., 2022).

Freshness of seafood can quickly deteriorate and cause spoilage which is hazardous to health if not store properly. Different innovative packaging and preservation

techniques are used to overcome this problem. 50% life of seafood can increase by using modern technologies like active packing, Modified Atmosphere packaging (MAP), vacuum packaging and High-Pressure Processing (HPP). There are few factors like storage temperature; type of product can affect the efficiency of these technologies (Siddiqui et al., 2024). As fish is richest source of nutrients but is highly susceptible to spoilage. Naturally preserve and minimally processed fish which are label as clean fish are most preferred by consumers. Metabolites can affect spoilage of fish and fishery products (Rathod et al., 2022). Specific Spoilage Organisms (SSOs) have greater impact on aquatic products to spoil them. Spoilage mechanism can be determined by microbial interaction and microbiome composition (Dong et al., 2022). Lipid oxidation starts from slaughter to preservation and storage. The oxidation of lipids in muscle foods is a spectacle widely considered in the scientific community, recognized as one of the essential elements affecting their quality, safety, and human health (Dragoev, 2024). Perishability of fish meat depends on naturally occurring microbiota, composition and enzymes activity. The food trade intentions to deliver healthy, harmless, and high-grade products to the marketplace (Kunová et al., 2021). Seafood demand is increasing day by day as it is expected to increase 56% by 2050. As seafood contain high moisture level so it can easily microorganisms and biochemical reactions can speed up, to retain its freshness high preservation and processing techniques should apply (Lisboa et al., 2024). Worldwide marine fish yields have stretch to a plateau over the last decade, and efforts to proliferation aquaculture tend to face restrictions in terms of water resources and contagion problems. 50% fish is discarding as waste during harvesting. Fish capturing techniques should be improved to utilize, preserve and process of seafood. Processing of fish into attractive and innovative products can reduce its loss. Processing effectiveness of fish can be improved by using the combination of modern and conventional processing methods (Samarajeewa, 2024). According to the demand of consumer to avail less quality damage products, there are various non-thermal techniques are used like fluorescence spectroscopy, pulsed electric field (PEF) and high-pressure processing (HPP).

Figure 1
Schematic Overview of Edible Coatings as a Novel Preservation Solution



Objectives

- Evaluate the efficiency of biopolymer-based edible coatings in prolonging the shelf life of marine foods.
- Classify significant biopolymers (polysaccharides, proteins, lipids) used in edible coatings.
- Examine conservancy mechanisms such as anti-microbial, anti-oxidant, and barrier properties.
- Consider coating performance across changed marine products (fish, shellfish, cephalopods).
- Identify existing challenges, including sensory changes, regulatory issues, and scalability.
- Highlight ecological benefits and future developments like nanotechnology and smart coatings.

PRINCIPLES OF EDIBLE COATINGS AND BIOPOLYMERS

Definition and Functionality

There is a major difference between coating and filming of products. Filming is a coating process in which coating material prepared separately and then applied on food product while in coating product dip in coating material and is ready to eat. Composition of coating material is really affect to its regulation process on product. Coating process also used as a preservation method, it's not only extend the shelf life of product but also make it attractive, improve its texture, and present as a new product. It can also stop the migration of oxygen, moisture, colorants and other components to the product and environment and increase its life span. To increase the strength and function of films it should be thin without any defect (Kumar et al., 2022; Petkoska et al., 2021). Edible and bio-based food packaging material is made from eatable biopolymers and food-grade additives. These bio-polymers can be proteins, polysaccharides (carbohydrates and gums) or lipids. Plasticizers and other additives are joined with the biopolymers to change the physical factors or functionality of films. Biopolymers are branched particles prepared of covalently involved monomeric units resulting from natural renewable resources, micro-organisms, or artificial bio-degradable sources. Emerging biopolymer films aims to provide an alternate to packaging materials made from non-renewable fossil fuels (Roy et al., 2024).

Barrier properties and Role in carrier of antioxidants, antimicrobials

Degradation of perishable foods because of fungal contamination and lipid per-oxidation are the most susceptible concern to food industry (Chaudhari et al., 2023). To enhance packaging sustainability a natural biopolymer known as cellulose can be used it will increase thermal, mechanical and barrier properties. It also has a drawback that it is hydrophilic in nature. For active packaging and coating nano-cellulose are used which are biodegradable. While it's natural properties, such as hydrophilicity, need enhancement for wider use. By addition of composites such as tannin, lignin and stearic acid, nano-cellulose can be improved to accomplish better hydrophobicity, mechanical power, thermal resistance, and anti-oxidant activity. By improving its property nano-cellulose can be used in multiple industries like chemical, biomedical, food and cosmetic industry (de Lima et al., 2025). The use of biopolymer-based food packing holds substantial potential to bring into line with sustainability

goals and improving food safety by posing a recyclable, bio-degradable, and safer substitute to traditional artificial polymers. Though, these biopolymer-derived films often show reduced barrier and mechanical attributes, potentially regulating their commercial feasibility. Necessary barrier properties, such as humidity and oxygen resistance, are acute for preserving and sustaining the excellence of packaged food products (Shah et al., 2024). To overcome these restrains essential oils are important in this era due to their antioxidant and antifungal properties. Many essential oil based inventions have been in practice but their industrial-scale application is still narrow, because of its poor solubility, exposure towards oxidation, and aroma outcome on treated foods. In this case, active food packaging using biopolymers could be deliberated as promising approach. The biopolymers can boost the stability and effectiveness of essential oils (Eos) through orderly release, thus reduces the deterioration of foods triggered by fungal pathogens and oxidation without cooperating with their sensory properties (Chaudhari et al., 2023).

In food preservation industry edible coatings are considered as great revolution. Prepared from natural biopolymers for example proteins, polysaccharides, and lipids, these coatings form a thin, edible layer on food outsides. This barrier lessens moisture loss, protects in contradiction of oxidative damage, and edges microbial growth, thereby lengthening shelf life while stabilizing food quality. These coatings act as beneficial for human health when natural additives like anti-oxidants and essential oils are used. These coatings can influence shelf life of meat, bakery and dairy products by retaining their nutrition and sensory due to respiration and moisture control (Petkoska et al., 2021; Kaur et al., 2022). When we compare modified atmosphere packaging with new emerging technologies like bio-nano-composites, composite material and nano emulsion, these techniques will improve mechanical, compatibility and barrier properties of coatings. Although tasks remain in cost, consumer approval, and regulation, edible coatings represent a important stride towards sustainable food systems and reduced dependency on artificial packaging (Karnwal et al., 2025). Current research has concentrated on using plant-based polysaccharides, proteins, and lipids to generate functional films and coatings with desired properties. Addition of bioactive compounds and antimicrobial mediators as well as employing nano technological methodologies has upgraded the functional properties of plant-based materials, prolonging their shelf life and maintaining food quality (Gupta et al., 2024).

Biopolymer Categories

Edible coatings and films (ECFs) are gradually significant in bio based packaging because they have a chief role in improving the organo-leptic features of the food products and diminishing the spread of microorganisms. These are formed from proteins, polysaccharides, lipids, plasticizers, emulsifiers, and dynamic substances. Nanocomposite films are also commencement to be established and supportive networks of biological polymers (Wibowo et al., 2024). Antioxidant, flavoring, and coloring complexes can be engaged to improve the quality, wellbeing, and

stability of packaged foods. Gelatin rich fruit and vegetable-based ECFs structures have the potential to produce decomposable films. Root plants like cassava, potato, and sweet potato have been active to generate edible films and coatings. Achira flour, amylum, yam, ulluco, and water chestnut have all been deliberated as new film-forming ingredients. The physical possessions of biopolymers are effected by the features, biochemical confirmation, compatibility, relative moisture level, temperature, water resistance, and application processes of the constituents (Matloob et al., 2023; Pillai et al., 2024). Polymers which are eatable such as polysaccharides, proteins, and lipids are biodegradable and bio-compatible materials apply as a thin layer to the surface of food or inside the package. They increase food quality by extending its shelf-life and avoiding the decline phenomena caused by oxidation, humidity, and microbial activity (Singh & Packirisamy, 2022). In order to advance the biopolymer presentation, antimicrobial agents and plasticizers are also involved in the formulation of the main complexes utilized for edible coating packages. Some plants can produce secondary natural compounds which can help to reduce growth of microbes. Biofilms efficiency can be increased by using these secondary natural compounds because they act as antifungal and antioxidant. Pathogens need oxygen for their proliferation, antioxidants and antimicrobials can protect product from oxidation and retard microbes' growth (Moeini et al., 2022; Vanaraj et al., 2024). Food waste increasing day by day and it's a great challenge for food industries. This can be overcome by the use of edible food coating. These coatings are comprised of solvents, fillers and binding agents. The key components of these coatings include food-grade binding agents, solvents, and fillers. The assimilation of polysaccharide, protein, lipids, bio-active and composite-based materials with edible coating medium aids to combat considerable postharvest loss of highly perishable commodities and raises the quality of minimally processed food (Yaashikaa et al., 2023).

Polysaccharides

Chitosan is the de-acetylated form of chitin observed as one of the most plentiful polymers and because of its properties, both chitosan alone or in mixture with bio-active constituents for the production of bio-degradable films and coatings is attaining attention in terms of applications in the food industry. To heighten the antimicrobial and antioxidant properties of chitosan, a massive variety of plant abstracts have been integrated to meet consumer demands for more environmental friendly and artificial preservative-free foods (Muñoz-Tebar et al., 2023). Polysaccharides derivative of fruits, roots, and traditional crops to create edible films and coatings (Gupta et al., 2024). Polysaccharides, ordinarily known as complex carbohydrates, are the richest carbohydrates in food. These macro-molecules include long chains formed by linking/coupling slighter sugar units, called mono-saccharides, linked by glycol-sidic bonds or associations. Polysaccharides display a substantial degree of heterogeneity. Sugar units show characteristic proper ties based on their construction, organization, and slight alterations of these replications. The huge majority and variety of food

polysaccharides are derived from plants, both global and aquatic (Bernaerts et al., 2019). Cellulose is the key component and macro-molecular polysaccharide of the plant cell wall, designed by linking D glucopyranose with a b-1,4 glycosidic bond. Cellulose is damp proof and biodegradable and compromises excellent film forming possessions. Carbox ymethyl cellulose (CMC) edible films and coatings are usually flexible, tasteless, transparent, and offer a reasonable obstacle to oxygen and moisture, and resistance to fat and oil (Panahirad et al., 2021). Minerals, bio-active compounds, and phenolics constituents present in the gel, which offer major potential for use in active film and coatings. In this regard, blending aloe vera gel with other biopolymers can improve the functions of coatings/flms (Maan et al., 2021).

Proteins

Proteins are macro-molecules make up of amino acids, commonly known as the building blocks of proteins. Indeed, proteins are polymers comprises of several amino acids connected by peptide bonds with each other. These complexes exist naturally in the form of spherical or fibrous proteins. Commonly, amino acids consist of carboxyl, R groups, and hydrogen (Wu et al., 2024). Proteins have good mechanical possessions associated to poly-saccharides and discrete structures with tremendous barrier properties for oils and aromas. Whey proteins, soy sequesters, and wheat proteins can be used as films and coatings (Panahirad et al., 2021). Numerous edible films and coatings consumption gluten, whey, casein, soy protein, and peanut protein for their developed. Since these constituents are formed from proteins and can cause allergic reactions, they are categorized as allergens. In order to avoid mix-up, the labels should clearly specify if certain allergenic ingredients are used in the construction of edible films and coatings (Carpena et al., 2021). Soy protein isolate (SPI) isolated from soybeans, and designated it as a bio-degradable circular protein with good oxygen and oil barrier properties and significant forming properties; offering films with horizontal and flexible consistencies. SPI coatings can be pragmatic to fruits and vegetables because of their high penetrability to water. It was experiential that the elongation at break (EB) and tensile power (TS) of SPI-derived films quickly increased with the accumulation of 2.5% of chitosan, while the superficial of the edible film was also smoother and thicker with fewer pores and crashes (Erdem et al., 2022). Whey protein isolate (WPI) is a cheese whey derived protein with good immersion and a high nutritional value. WPI-derived films and coatings are odourless and transparent, colourless, and offer oil and oxygen resistance (Seiwert et al., 2021). However, WPI is hydrophilic with a poor moisture barrier and necessitates plasticizers to overcome the brittleness of WPI-based films and coatings (Vanden Braber et al., 2021).

Lipids

Food lipids, or nutritional lipids/fatty acids, are frequently fats and oils in food; certainly, fats and oils are the solid and liquid arrangements of lipids. Chemical lipids are the polymers of fatty acids, contained of long chains and nonpolar hydrocarbons with a small polar oxygen district. Use of lipid constituents as an edible film could deliver

hydrophobicity, elasticity, and consistency in the film. In accumulation, the lipid edible coatings could serve as a remarkable barrier in contradiction of oxygen and moisture and thereby withstand the food quality for a extended period. These lipid edible films and coatings have

nutritious and functional properties as well. The lipid films include a hydrophobic barrier that improves the barrier function and reduces water vapour porousness (Milani et al., 2022).

Table 1

Biopolymer Matrices and Active Additives for Edible Coatings in Marine Foods

Biopolymers	Representative Polymers	Typical Active Additives	Functional Roles	Marine Applications & Outcomes	References
Polysaccharides	Chitosan, cellulose, alginate, carrageenan, starch derivatives	Clove oil, thyme oil, green-tea extract, pomegranate peel, grape seed extract	Strong oxygen barrier, moderate moisture control, antioxidant & antimicrobial when combined with essential oils	Fish fillets and shrimp: shelf-life extended 6-13 days; reduced microbial growth & lipid oxidation	Muñoz-Tebar et al., 2023; Alotaibi & Tahergorabi, 2018
Proteins	Whey protein isolate, soy protein isolate, fish/squid gelatin, casein	Nisin, rosemary extract, clove oil, tea polyphenols	Excellent mechanical strength; oil/aroma barrier; carrier for natural antimicrobials	Salmon fillet and golden pomfret coatings: delayed oxidation, maintained texture	Yun Xiong et al., 2021
Lipids/Lipid-Polymer Blends	Waxes, fatty acids, plant oils	Cinnamon oil nano-emulsion, oreganoil	Hydrophobic barrier against water vapor; improves elasticity	Composite films for fish and shellfish to reduce moisture loss and improve sensory quality	Supisara Jitpasutham et al., 2024
Composite & Nano-composites	Chitosan-gelatin blends, nano-cellulose, bio-nano-composites	Silver nanoparticles, nano-encapsulated Essential oils, probiotics	Enhanced mechanical and barrier properties; controlled release of bioactives	Squid ink or chitosan-gelatin coatings on cephalopods: 9-10 day shelf life, strong antimicrobial action	de Lima et al., 2025; Jin et al., 2024; Martínez et al., 2024

Formulation and Application Techniques

Dipping, Spraying

The dipping method is considered by its easiness and is the most generally used method. It encompasses three primary steps: (i) absorption and dwelling, in which the food is plunged in the coating solution and endorsed to dwell for a definite duration; (ii) confession, which includes the adherence of the coating explanation to the food surface; and (iii) solvent vanishing, which leaves a tinny coating on the food product's surface. Many features can affect the quality individualities of the coating formed through plunging, including the number of coating cycles, the quickness at which the food is reserved from the solution, and the duration of absorption. Also, constraints related to the coating solution, such as its density, viscosity, and surface tension, can affect the eminence of the coating (Leya et al., 2024). Moreover, the drying circumstances and substrate surface properties are important in formative the coating density and morphology. One of the main disadvantages of the dipping method is the rough coating, which can lead to areas of fruit breathing and surface destruction. Another restriction is the high volume of coating solution compulsory per unit mass of produce to achieve an optimum coating. The contact period with the coating solution is also essential, as prolonged contact can result in extreme moisture absorption, whereas an inadequate contact time can lead to irregular coating (Gedarawatte et al., 2021). The coating can also be functional in the form of foam, which can enable a uniform circulation over the food surface. The foam application technique can also ensure a constant coating thickness. With the help of the dipping method, it was described that an aloe vera coating combined with salicylic acid could sustain the phenolic content, firmness, and mass of oranges, while also providing antimicrobial properties (Fan et al., 2019). Also, a lotus leaf extract incorporated complex coating was found to be able to surge the shelf life, maintain the ascorbic acid content, and diminish the deterioration rate

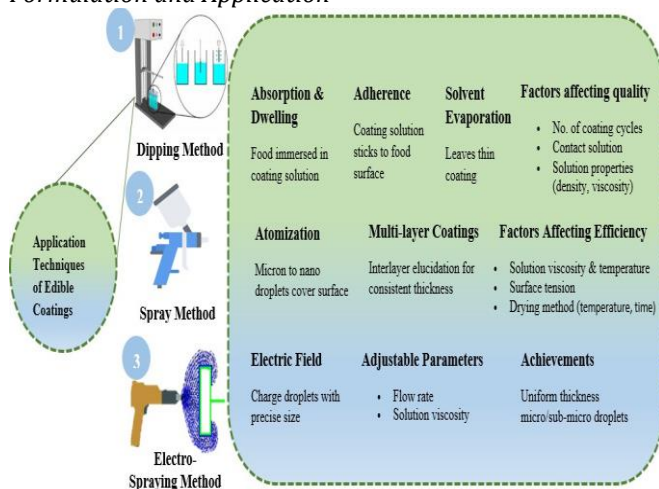
and malondialdehyde content of fresh Goji (*Lycium barbarum* L.) fruit (Prakash et al., 2020), although pineapples coated with sodium alginate and citral nano-emulsions displayed condensed microbiological growth, a lower respiration rate, and better colour retention (Priya et al., 2023). Atmozier is used to spray liquid coating in the form of layer in spray method. In this method size of particles range from micrometers to nanometers. These tiny droplets cover the most of food surface area when passed through this atomizer. Rheological propertied effected by spray method efficiency e.g. viscosity, temperature, surface tension. Multi layers of coatings can be used by spray methods, like inter layer elucidations, and forms a stable coating with consistent thickness. Then drying method is used on coated sample, its efficiency depends upon temperature, time and drying methods (Lara et al., 2020; Weng et al., 2025). Electro-spraying is a lately developed specialized procedure that uses a resilient electric field to yield charged precipitations with precise size control, demonstrating a cutting-edge method for accomplishing micro- and sub-micro droplets. These method authorizations the customization of the droplet provisions by changing the flow rate and solution viscosity, thereby proposing precise regulator over the coating thickness and uniformity. A xanthan gum based edible coating, along with citric acid and glycerol, was practical to fresh-cut lotus roots by spray coating, which exhibited a substantial reduction in the colour changes of coated lotus roots upon storage. Furthermore, it also inhibited enzymatic browning and the development of *Bacillus subtilis* (Lipin & Lipin, 2022).

Factors influencing coating efficiency: Hydroxypropyl methylcellulose solutions were used as coating and Fuji apples were coated by dipping and stored 4 days at room temperature, after which the core oxygen and carbon dioxide were dignified. Results showed that coating thickness different with viscosity, concentration, density, and challenging time of the bio-polymer clarification. Coating thickness narrates to the square root of thickness

and the inverse square root of draining time, which agrees with the theoretical method for flat plate dip coating in low-capillary-number Newtonian liquids. These results designate the possibility of monitoring coating thickness and internal gas conformation based on coating solution properties (Cisneros-Zevallos et al., 2023; Barringer & Sumonsiri, 2015). Edible films were established by using pre-gelatinized corn starch (PCS), comprising corn mint essential oil (CEO) and cellulose nano-crystals (CNC). The coating solution's pH and viscosity, as well as the thickness and roughness of the film, usually growth with an increase in CNC absorption. Conversely, this led to a decrease in the weight loss during heating, elongation, and tensile strength, as well as Young's modulus. The altered amount of CNC (%) did not have a substantial effect on the water solubility, hydrophobicity, color, water vapor penetrability, or surface micro-structure, as detected by atomic force microscopy. The accumulation of CNC to the film matrix condensed its mechanical strength but basically has low water vapor permeability and high surface hydrophobicity. Subsequently, the films manufactured in this study can be efficiently used as edible films in circumstances that demand strong resistance to water but do not need important mechanical strength (Wigati et al., 2025). Coatings made from safe, natural ingredients such as carboxymethylcellulose (CMC), nano cellulose fibre (NCF), nano chitosan (N-Ch), and fluctuating concentrations of green pomelo peel essential oil (GPO). Accumulation of GPO into coating/film expressively changed the pH, viscosity, and TSS values of the coating solutions while falling film weight loss. These findings emphasized the potential application of edible coating in drying method to shelter the nutrients of dried products (Van et al., 2025).

Figure 2

Process Flow and Influencing Factors in Edible Coating Formulation and Application



MECHANISMS OF SHELF LIFE EXTENSION

Microbial Control

Chitosan shows strong anti-microbial effects by distracting bacterial cell walls. Including silver nanoparticles and nano-encapsulated essential oils (turmeric, cinnamon, nettle, wormwood) into chitosan films empowers controlled issue and stronger inhibition against pathogens biofilm development. Nano emulsions and

encapsulation stabilize volatile oils, refining dispersion and antimicrobial persistence (Silva et al., 2018). Chitosan is the deacetylated procedure of chitin observed as one of the most plentiful polymers and due to its properties, both chitosan alone or in mixture with bioactive constituents for the assembly of biodegradable films and coatings is gaining attention in terms of applications in the food industry. To improve the antimicrobial and antioxidant properties of chitosan, an immense variety of plant extracts have been incorporated to meet customer difficulties for more environmental friendly and artificial preservative free foods (Muñoz-Tebar et al., 2023; López-Gómez et al., 2013). The edible films and coatings may decrease the distribution of bioactive composites with antimicrobial activity into the produce since the essential oils form part of the chemical structure of the film and interrelate with the polymer and the plasticizer. The release of the antimicrobial compounds from the edible films depends on different factors such as electrostatic connections between the antimicrobial agent and the polymer chains, osmosis, structural changes prompted, and environmental conditions (Nadira et al., 2022). Plants and other vegetal raw materials represent an un-limited source of novel phytochemicals compounds, which have potential use in the food industry and other applications. Conservatively, the raw extracts acquired from different parts of several plants, including the root, stem, flower, fruit, and twigs, are generally developed for prevention or disease treatments. Crude extracts acquired from plants comprise in their composition several phytochemicals including polyphenolic compounds (phenolic acid and flavonoids), alkaloids, and tannins, which can exert antibacterial capacity (Zhang et al., 2020; Mauriello, 2025).

Lipid Oxidation Inhibition

Antioxidants (plant extracts, essential oils, vitamins) surrounded in coatings scavenge free radicals, hinder peroxide formation, and delay rancidity in seafood. Aquafaba can be used either alone or combined with essential oil as a bioactive compound in edible films. The advanced Aquafaba lemon essential oil edible films have the potential to be used as active antioxidant packing in the food industry, especially for highly perishable food items (Aksun Tümerkan et al., 2023).

Moisture Retention and Gas Barrier Properties

Edible coatings have been recognized one of the best biologically harmless preservative coatings for different types of foods because of its film-forming properties, anti-microbial actions, bio-degradability and bio-chemical properties. In fruits and vegetables, oxygen and moisture are natural barrier of deterioration but edible coatings can reduce their effects on food. Edible packing reduces respiration rate and quality characteristics of fruits and vegetables so increase their shelf life. It has antifungal and antibacterial properties which act as a defensive barrier in contradiction of microbial impurity. The present review defines about the different edible coatings and their potential application for improving the postharvest life and quality of different types of fruits (Hazarika et al., 2023; Zhang Y et al., 2020). The stability of edible oils expressively influences their quality, safety, and shelf life.

While artificial antioxidants have conventionally been used, the growing consumer interest in food safety and sustainability has shifted focus towards natural substitutes. Plant-derived antioxidants offer an auspicious solution, increasing oxidative stability while meeting clean-label demands. Natural antioxidants from peels, seeds, spices, fruits, and vegetables efficiently decrease hydrolysis, polymerization, and secondary oxidation products (Yildiz et al., 2025).

Enzymatic Activity Reduction

Coatings help delay enzymatic breakdown by decreasing respiration and preventing enzymes like proteases and oxidases. Decline in volatile nitrogenous complexes is incidentally achieved via antimicrobial action and reduced enzymatic cell lysis. The edible chitosan coating treatment is an operational method for postponing the postharvest ripening procedure of sweet cherry, which is demonstrated by reduced color changes, firmness losses and respiration rate, as well as a positive consequence in sustaining higher applications of total phenolics and anthocyanins, and in deferring the growths of CAT (catalase), SOD (superoxide dismutase) and APX (ascorbate peroxidase) actions (Hu et al., 2022; Sharma et al., 2018). Active edible coating is a just developed auspicious food packaging method to lengthen shelf-life of agriculture products, through giving a semi permeable barrier to gases and water vapor, and decreasing enzymatic browning, water loss, and rate of respiration. Poly-saccharides such as chitosan, alginate, carrageenan, gellan, and starch have been described as safe natural biodegradable materials to formulate edible coatings. Numerous polysaccharide-based edible coatings have been used to effectively prolong the storage time of fruits and vegetables, such as melon, potato, carrot, cucumber, and lotus root. These coatings had significant influences on sustaining food quality such as enzymatic browning, loss of texture, and adverse odors and flavor development (Li et al., 2021).

BIOPOLYMER-BASED EDIBLE COATINGS IN DIFFERENT MARINE PRODUCTS

Fish Fillets

The status of pre-processed fresh fishery products such as fillets and skinned shrimps is developing in today's market due to their suitability for consequent processing and cooking. Though, fishery products are highly perishable because of the joint actions of biochemical reactions and microbial metabolism. Many methods have been proposed to address this problem. Among these methods, bio-based edible coating has been highlighted as a promising solution (Yu et al., 2019). Fish and crustaceans, are some of the most consumed foods globally and are highly prone to microbial contamination. Such products have been conserved using conventional treating techniques such as freezing, cold storage, modified atmospheric packaging (MAP), and vacuum packaging. Though, these procedures have been used since years and are not costly. One feasible option as an alternative supportable policy is the use of biopolymer-based films and coatings encumbered with active antimicrobial agents for the preservation of aquatic food products (Navarro-Segura et al., 2020). Nisin is the

most broadly used peptide for the growth of antimicrobial coatings, while eugenol, carvacrol, and cinnamaldehyde are among the best widespread essential oil compounds. Outcomes reveal that both peptides and essential oils, when applied in mixture within a coating system, prove vigorous antimicrobial activity, hindered lipid oxidation, and maintain the overall quality of the aquatic food system (Chakraborty et al., 2022). The active packaging of fish characterizes an economic alternate to conventional preservation knowledges (vacuum and modified atmosphere packaging) due to the less capital investment as compared to those. Besides being bio-degradable, edible films and coatings improve the microbiological stability of fish and decrease waste; moreover, retard lipid oxidation. For the past 10 years, research on the use of antimicrobial packaging materials for fresh fish applications has experienced significant advancement (Socaciu et al., 2018). Proteins, lipids polysaccharides and their combined mixture are basic biopolymers which can be used as bio-based coatings. Including natural preservatives, plus extracts with good antimicrobial and antioxidant properties, flavors, spices, and colorant to film and coatings, can develop the functionality of edible packing to prolong life of food products such as fish trials by controlling the active mechanisms discharge into the surface (Haghighi & Yazdanpanah, 2020). Edible coatings and films are very useful to retard the growth of microorganisms, decrease fish nutrients degradation rate and prevention of chemical metabolites, so it will increase the life of fish products from 6 to 13 days. Use of these preparations can reduce fish waste, a reduction of economic losses for fish traders and retailers (Socaciu et al., 2018). Coatings can reduce the loss of weight and colors. Fish without coatings and organo essential oils become softer than with coating and show high sensory acceptability by consumers (Vital et al., 2018). Fish qualities, preservation period and freshness can be increased by edible coatings and films. These coatings act as a barrier, decrease lipid oxidation, microorganism's growth and moisture loss. Its efficiency depends upon storage conditions like temperature (refrigeration, freezing) and also improves fish quality by reducing biochemical processes (Kurek et al., 2024).

Shellfish

There are many techniques which can be used to increase the quality of seafood products, like packing, preservatives, coatings and chemical additives. The use of edible coatings for seafood products is found to be more common by empowering the basic possessions for the expansion of this edible film (Koirala et al., 2023). Bioactive, edible and environment friendly packing is a best replacement of petroleum base packing. *Ulva lactuca* macroalgae powder (ULP) used as an active additive in crab (*Portunus segnis*) chitosan-based films for regular food packaging. The combination of ULP at different concentrations into the chitosan films considerably increased the opaqueness, while the moisture content and liquid solubility expressively declined. The films, studied by FTIR, exhibited good chemical collaboration between the chitosan and ULP, creating a stable complex film with excellent reliability

(Zaghib et al., 2025). The combined films were also considered by improved mechanical properties, which led to stronger and stretchier films. Developments in the barrier properties against UV-Vis light were determined because of the increased cloudiness and color due to the strong contact of polyphenols within the polymer matrix (Navarro-Segura et al., 2020). Chitosan and gelatin act as a preservative when used in combination and their bioavailability makes them fit for human consumption. These coatings show antioxidant and antimicrobial properties when used as active packaging films. It will retard microbial growth and oxidation (Rathod et al., 2023).

Cephalopods (squid, cuttlefish)

An ecological and domestic bi-functional silk procedure consuming a new biomaterial called squid ink, which is rich in protein, polysaccharides, melanin, and metal ions, was used. Squid ink coating could donate silk with “tremendous” UV protection, which was recognized to the presence of melanin constituents that can absorb ultraviolet radiation (Jin et al., 2024). Mixture of edible coating used; 0.25% squid ink and low temperature (4°C) for squid packing gives important benefits. The shelf life extension was up to 9-10 days. Squid coated with 0.25% squid ink showed low bacterial growth during 4°C storage. Between cephalopod discards, ink has revealed numerous valuable properties concerning human health, environmental conservation and food protection (Martínez et al., 2024). Enzymatic hydrolysis process is used to obtain squid gelatin, beneficial for chitosan-squid gelatin films. Outcomes showed that SGH effect different properties of product like color, antioxidant activity, antifungal property and mechanical strength like fungi *Aspergillus parasiticus* properties of chitosan films. Intermolecular bond become strong with the combination of chitosan and gelatin films, it will also improve in-vitro degradability and stiffness. It will also improve film properties. (Cuevas-Acuña et al., 2021).

Comparison with Uncoated Controls

Edible films/coatings combined with various active agents applied to fresh fish are able to prevent the microbial proliferation and lessening the rate of fish nutrient breakdown, thus preventing the development of chemical metabolites; a shelf-life increase from 6 to 13 days was attained for fish fillets, depending on the species on which the active packaging materials were applied. Use of these edible films lead to decrease the fish waste and also decrease loss for retailers and traders (Socaciu et al.,

2018). Water activity is high in cuttlefish and squid so they are very prone to degrade, they have protein rich muscles and lack protective scales. Chemical breakdown and microorganism’s activity can be slow down in refrigerator but cannot be stop. So edible coatings can be used in this case to increase life span. These coatings are partial permeable, reduce oxygen and moisture movement and improve antimicrobial and antioxidant properties of end product. Squid fish and cuttlefish show different challenges like their smooth, mucilaginous skin complicates adhesion non-uniform films tend to fleck off. Squid ink is a mutual coating ingredient, comprises melanin pigments that can deepen the product and discourage consumer approval if not properly canned. To diminish this, studies often develop purified, melanin-free ink removes to balance efficiency and presence (Karim et al., 2016; Carullo et al., 2023). Alternative well-cited preservation method uses chitosan and fish gelatin based coatings. While research has largely focused on fish like golden pomfret, the consequences transferal well to cephalopods. Ideal pomfret fillets glazed with chitosan combined with 7.2% fish gelatin at 4 °C reserved myofibril reliability up to 17 days, although uncoated controls had strictly ruined protein structure (e.g., myosin light chain) at the same time. Texture deterioration and antimicrobial activity can be improved by using these composite coatings (Feng et al., 2016). While chitosan–gelatin films may not constantly double shelf life, they steadily inhibit water loss, lipid oxidation, and microbial propagation in some studies dropping moisture loss by 30–40% over ~12-day storing periods (e.g., silver pomfret and tuna fillets with clove oil enrichments). Their functional enlargements include providing barriers to oxygen and water vapor, and leveraging chitosan’s clearly charged molecules to dislocate bacterial cell walls (Kumar et al., 2018; Mubarak, Othman, & Karim, 2019). Edible coatings expressed with squid ink or chitosan–gelatin combinations provide quantifiable, quantitative preservation benefits over uncoated cephalopods. Squid ink coatings formed a clear shelf-life proliferation (from ~5 to ~9 days at refrigerated temperatures), while chitosan gelatin systems preserved quality markers Myofibril integrity, moisture holding, microbial firmness even when precise “fresh days” were not comprehensive. Future research should improve surface treatments, develop adhesion, minimize sensory adjustments, and incorporate natural bioactive such as essential oils to promote optimize post-harvest feature.

Table 2
Marine Products, Applied Edible Coatings, and Shelf Life Extension

Marine Products	Biopolymer + Active Agents	Key Findings on Preservations	Shelf Life Extension	Notable Challenges	References
Fish Fillets	Proteins, polysaccharides, lipids; coatings with nisin, essential oils (eugenol, carvacrol, cinnamaldehyde), natural extracts	Strong antimicrobial & antioxidant activity; Reduces lipid oxidation, nutrient loss, weight loss, color change	Increased from ~6 days → ~12-13 days (species-dependent)	Efficiency depends on cold-chain; flavor impact of essential oils, film uniformity	Khorami et al., 2024
Shellfish (crab, shrimp)	Chitosan films + Ulva lactuca macroalgae powder (ULP); chitosan-gelatin blends	Improved mechanical strength, UV barrier, antimicrobial & antioxidant effects	Extended shelf life up to 12 days (vs ~6-7 days uncoated control)	Maintain transparency; optimize ULP content for acceptability	Karimkhani et al., 2025
Cephalopods (squid, cuttlefish)	Squid-ink (0.25%) coating; chitosan-gelatin composites	UV protection, antimicrobial action, reduces moisture loss, preserves texture	Squid-ink: ~5 → 9-10 days (4 °C); Chitosan–gelatin: quality retained up to ~17 days (in some fish models)	Adhesion on smooth/mucilaginous skin; dark pigment may affect appearance	Zaghib et al., 2025; Kamali et al., 2023

Fish Fillets (alginate / chitosan bilayer)	Alginate + chitosan (layer-by-layer active coating)	Good antimicrobial & antioxidative performance, better barrier properties	Extended shelf life (from ~6 → ~12+ days in trial)	Ensuring film integrity, adhesion, and uniform coverage	Salgado et al., 2023
Grey Mullet (fish steaks)	Nanochitosan + clove oil edible coating	Lower microbial counts, reduced oxidation (TBA, TVB-N), better texture & sensory stability	Up to ~24 days in refrigerated storage compared to control	Balancing essential oil concentration (avoid off-flavor), consistency in nanoformulation	Aref et al., 2022

Functional Additives in Biopolymer Coatings

From the last few decades, consumer preference has progressed by deciding for natural active agents over synthetic and chemical condiments due to concerns about food safety and quality (Zhong et al., 2018). The extracts and essential oils removed from plants, enzymes take out from animals, organic acids, and inorganic materials combined into wrapping can interrupt the cell membrane of several foodborne micro-organisms and extend the food product's shelf life (Kumar, Deshmukh, et al., 2024; Novais et al., 2022). Numerous natural compounds display antioxidant, antimicrobial, pH observing, ethylene scavenging, damp controlling, and moisture fascinating properties (Deshmukh and Gaikwad, 2022; Gaikwad et al., 2019; Kumar, Deshmukh et al., 2022; Sarangi et al., 2023; Sood et al., 2024). Frequent plants, microflora, and animals contain bioactive compounds. When essential oil or extract or enzymes consequent from these bio-resources are applied to edible films or coatings over the delicate food products, they can preserve these foodstuffs by hindering the growth of various kinds of foodborne microorganisms (Fadiji et al., 2023). The edible films and coatings also act as a transporter for antimicrobial agents, and these agents can travel through packaging over the superficial of food products (Chawla et al., 2021). Several edible packaging materials such as polysaccharides, proteins, lipids, and their compounds, these biopolymers generate a protective layer around perishable food products that acts as a defensive layer from moisture, gases, and adulterations (Zhao et al., 2021). Furthermost edible polymers have impartial organoleptic properties, such as flavor, aroma, and odor, which diminish unwanted sensory experiences when food is consumed with the edible packaging. Though, polymers like chitosan, whey protein, collagen, gelatin, soy protein, and lipid-based materials like fats and waxes may give bitter or spicy flavors that affect the sensory properties of edible packaging (Moeini et al., 2022). The escalating alarm about micro plastics and bio-accumulation has moved the trend of plastic packaging to sustainable substitutes containing of biopolymers (Ziani et al., 2023). Polysaccharides, proteins, and lipids are most regularly invoked as characteristic biopolymers due to their capability to be bio-compatible, recycle, environment friendly, and decomposable associated to non-renewable artificial polymers (Taherimehr et al., 2021; Umaraw et al., 2020). These biopolymers break down into natural constituents such as biomass, water, and carbon dioxide by microorganisms without donating to bio-accumulation like synthetic polymers (Moshood et al., 2022). Natural resources can extract these packing materials from animal, plant and seaweeds that's why product can be eat with its packaging. Films and coatings produced from food grade edible polymers are recognized as edible packaging, like

edible films and edible coatings (Yao et al., 2024; Zhang, Liu et al., 2023). These films are impartial and formed separately, deliberated direct food contact materials under the Food and Drug Administration (FDA) Title 21 Code for Federal Regulations (CFR) Part 184 and food interaction materials under EU Rule 1935/2004; future food products are packed, while the edible coatings are openly placed over the perishable food, considered as external treatment (CFR 2025; European Union 2004). Edible packing increase food flavor, nutritional properties, color, freshness and act s protective layer against deterioration, also save from spoilage during postharvest stages (Guimarães et al., 2018; Ribeiro et al., 2024). The edition of using edible films and coatings as main packaging is directed by extreme safety strategies regulated by the FDA by retaining generally recognized as safe (GRAS) constituents, European Food Safety Authority (EFSA), and the International Organization for Standardization (ISO) (Peerzada Gh et al., 2023). The FAO emphases on global food safety domination without specifying ethics like GRAS, backup policy frame works, and risk assessment procedures that impact regulatory atmospheres of sustainable packaging clarifications (Lacourt et al., 2024). Numerous food-grade agents are also assimilated into edible packaging, which exhibits active properties in edible films and coatings that deliver extra benefits (Han and Aristippos, 2005; Kumar et al., 2021).

Natural Antioxidants

Green tea extract: Polysaccharides e.g. chitosan (Ch), are extensively used for the improvement of a variety of food coatings. Chitosan is an efficient biopolymer attained through the deacetylation of chitin, displaying operative inhibition of bacterial, yeast and fungal progression. Natural antioxidants resultant from plants, fruits, animals or their by-products have been deliberate and combined into bio-based coatings as these foundations are rich in phenolic compounds with antioxidant capability (Umaraw et al., 2020). Green tea is a valued source of phenolic compounds, being described as a scavenger of free radicals that stimulates lipid oxidation in food systems, and its demonstrations in vitro inhibitory effects against food spoilage and pathogenic microorganisms (Munekata et al., 2020). In accumulation, essential oils from plants such as oregano essential oil (OO) and thyme essential oil (TO), which comprise thymol and carvacrol, indicate strong antioxidant and antibacterial properties against a wide range of food pathogens (Mirsharifi et al., 2023). One of the challenges of using essential oils as natural additives is how to daze the high abstraction cost and the impact of their aroma flavor on glazed food (Alexandre et al., 2021). To avoid this issue, an unknown substitute could be use of oil removed from flaxseed, whose gum has been efficiently used as a useful agent in edible coatings, maintaining the

sensory qualities and safety of food products. In accumulation, flaxseed oil (FO) presents antioxidant, anti-inflammatory and anti-cancer properties and has no strong odor (Rizvi et al., 2022). Tea polyphenols are mainly composed of flavonoids, where catechins represent to 80-90% of total flavonoids in tea leaves (*Camellia sinensis*). Epigallocatechin gallate (EGCG) is the chief catechin in tea leaves, representing 50-80% of total catechins and the utmost biologically active compound among other polyphenols create in tea (Yan et al., 2020). Addition of tea catechins in aquaculture exhibited positive results in growth performance, antibacterial, immune stimulant, antiviral, and antioxidant activities, among others (Li et al., 2022; Qian et al., 2021; Zhang et al., 2020; Zhang et al., 2021). Though, tea polyphenols have drawbacks, as they display low constancy in biological media; they are easily despoiled by physiologically appropriate temperature, oxygen deliberation, and metal ion content at alkaline and neutral pH as well (Jin et al., 2022a;). Consequently, oral management of tea polyphenols leads to low absorption and a short life. To overwhelmed these difficulties, nano encapsulation has become a policy to deliver these labile particles (Di Santo et al., 2021; Rambaran, 2020). Nano-technology has diverse applications in aquaculture, such as the distribution of nutraceutical molecules and vaccines, water sanitization, pathogen recognition, antimicrobial and antiviral activity, and protection of products (Fajardo et al., 2022; Shah and Mraz, 2020). Biopolymer nano carriers have extended significance for the distribution of active compounds due to their low toxicity and biodegradability. Zein is a protein used for encapsulation because it has less ability to absorb water (Jin et al., 2022b; Nunes et al., 2020; Zheng et al., 2022). Though, distributions of zein nanoparticles exhibit low colloidal firmness, an affinity toward accumulation, and precipitation at pH 5-7 (Yuan et al., 2022). Biopolymers can be used with zein to improve their stability and interaction between bioactive molecules and nano particles (Yuan et al., 2022). For this purpose alginate and chitosan can be used which evolved from marine environment (Carrasco-Sandoval et al., 2021; Jiang et al., 2021; Loureiro et al., 2022; Wu et al., 2023). These polymers have low in toxicity, biodegradable, and biocompatible (Abdel-Ghany and Salem, 2020; Lee and Mooney, 2012). Alginate and chitosan have been used distinctly or together for the explanation of encapsulation mediums for the delivery of bioactive substances in aquaculture development promoters and immune-stimulants (Abdel-Ghany and Salem, 2020).

Rosemary: Chitosan is used to develop rosemary essential oil and used it for active packing. These act as antibacterial and contain more phenolic contents to preserve food. Tea extracts can be used to obtain chitosan films, it will provide new techniques to formulate films with antioxidant properties. If rosemary essential oil is extracted at the concentration of 0.5, 1.0 and 1.5% it will increase the ability of phenolic contents and antibacterial activity of chitosan (Abdollahi et al., 2012a). Chitosan films efficiency can be improved by using rosemary essential oil. From natural plant extracts, rosemary and oregano extracts are rich source in phenolic constituents and effective when

combined into edible or indigestible films, while the several extraction techniques, the film matrix used to combine the antioxidants or the food itself somehow relocation of total phenolic from gelatin films developed with oregano or rosemary extracts and cold-smoked sardines from the start of storage. If oregano essential oil use as alone it did not show significant results than when enriched with rosemary essential oil. This shows that rosemary release antioxidant over period of time. Contrast of thiobarbituric acid reactive (TBAR) analyze results for oregano and rosemary enriched film-coated samples shown that rosemary extract dropped the oxidation rate more than Oregano, although rosemary had lower CPTs (Mohamed, 2018).

Clove oil: Clove oil, an essential oil from *Eugenia caryophyllata*, is deliberated as one of the best operational antimicrobial and antioxidant essential oils. Clove oil has been mixed into the edible coating and revealed to hinder a comprehensive spectrum of microorganisms, delay meat oxidation, and efficiently extend the shelf life of meat foodstuffs. Consequently, in the present study, gelatine was removed from salmon fish bone and used as an edible coating base comprising bioactive ingredients of chitosan, gallic acid and clove oil, to reserve additional salmon fillet during cold storing. Formerly, various packaging approaches have been described for salmon or salmon product shelf life delay, such as pork gelatine combining green and puerh tea extracts for coatings of salmon sushi, gulfwweed-based edible coatings of smoked salmon whey protein constructed green tea extract film wrapping of fresh salmon fish gelatine (unspecified source)-olive leaf extract film packaging of cold-smoked salmon, and conjoining of gelatine-chitosan-clove essential oil coating with high pressure treatment to extend fresh salmon meat shelf life To the best of our information, this is the first study to extract gelatine from salmon bone and relate it back to salmon fillet coating, which would deliver a novel approach in valorisation of fish dispensation by-products (Yun Xiong et al., 2021).

Essential Oils and Plant Extracts

In this review paper some biopolymers are used like carrageenan, CMC, chitosan, whey protein, starch agar, gelatin, alginate or their combination, some food additives like sorbitol, Tween and glycerol, there are also some active agents e.g. clove, thyme, lemon, oregano, grape seed extract, pomegranate peel extract, lysozyme, green tea extract, carvacrol, all of these can improve quality of edible films and coatings in fish products. Among these, chitosan is the most active biopolymer in terms of seafood conservation due to its resilient antimicrobial and antioxidant activities (Inanli et al., 2020). The properties of coating with rosemary extract (0.2%) and tea polyphenols (0.2%) joint with chitosan (1.5%) on lipid oxidation of yellow croaker (*P. crocea*) was considered. It was detected that the both PV and TBARS ethics of the uncoated and coated samples improved progressively during the whole storage period. While chitosan coating was well-organized in hindering the creation of PV and TBARS, existence of rosemary extracts condensed a greater effect associated to that enriched with tea polyphenols edible coatings have been advanced from

sweet potato starch and thyme essential oils (at 2, 4, and 6%) for coating shrimp, and physical properties (color and texture) of products were determined. The L value suggestively increased with the rise of EOs deliberation and diminished during the storage period. However, samples coated with EOs preserved a higher L value associated to the control at the end of the storage period (Alotaibi and Tahergorabi, 2018).

Cinnamon oil: Cinnamon oil is a plant based oil which is potentially added to chitosan films to increase coating efficiency. Cinnamon oil mainly comprises of cinnamaldehyde, which is an effective antimicrobial complex that interrelates with the bacterial cell surface, producing a) the retardation of enzymatic activities and cell wall biosynthesis, b) the escape of inner cell materials, and c) the distortion of bacterial morphology, that lead to cell death. Cinnam-aldehyde is also an antioxidant that can bind free radicals due to its aromatic ring and aldehyde group (Piyanan Chuesiang, 2021). Though, the hydrophobicity and vulnerability to oxidation of cinnam aldehyde bound the direct use of cinnamon oil in foods. One of the keys is to encapsulate cinnamon oil consuming a surfactant to improve its water dispersibility, letting the establishment of cinnamon oil nano-emulsion (CONE). Encapsulation of cinnamon oil in a nano-emulsion has been described to improve and continue its antibacterial activities in the aqueous phase. The motive is that the bioactive compounds in the form of fine oil precipitations in nano-emulsion are constant and have high inactive transport to cooperate toward bacterial cell membrane. Low energy emulsification procedures such as phase inversion temperature (PIT), phase inversion concentration (PIC), and spontaneous emulsification (SE) have been used for the nano-emulsion assembly (Supisara Jitpasutham et al., 2024).

Probiotics and Bioactive Peptides: The components which are used to enhance the shelf life of food and can be edible with food product known as edible packaging system. Biodegradable edible food compounds are known to prepare this edible packing system. In contrast with synthetic polymer packing these can be easily breakdown (Barbosa et al., 2021). Just because of the several downsides related with synthetic polymer packing; edible packaging has enlarged significant consideration in the scientific world and has drained the approval among the scientists and customers owing to its environmental friendly nature (Teixeira-Costa and Andrade, 2022). Usually, edible coating and film is an organizational medium that is designed by carbohydrates, lipids,

proteins, or a combination of other constituents. The key dissimilarity between edible film and coating is: edible film is a skinny layer that is prepared of edible constituents and this can be placed on or between the food ingredients; while the edible coating is a resolvable edible constituent and is designed as a coating on the surface of food (Lim et al., 2021). Edible coating and films support to prolong the shelf life of food products, such as fruits, vegetables, bakery foodstuffs, and slightly treated food foodstuffs. While edible films and coatings cannot entirely exchange the external packaging, yet, it may decrease the desired amount of outer packaging (Yuvaraj et al., 2021). The integrated concept of addition of probiotic with edible packing system will develop the shelf life of food, eco-friendly and delivers health benefits. (Vishnupriya Subramaniyan et al., 2023). In contrast to laboratory study examinations, the number of business claims of probiotic comprising edible films is suggestively slighter (Zoghi et al., 2020). Probiotics are frequently referred to as valuable microorganisms, and their assimilation into food products boosts consumers' immune function, cognitive reaction, and overall health. Additionally, probiotics are being suggested as an operative and ecological auxiliary for chemical-based stabilizers. This developing trend has gained the consideration of both the food business and scientific community, who are keenly working on generating advanced food products that comprise probiotics. To this end, investigators are discovering the procedure of edible packaging skills as carriers for probiotic entities, contribution a wide variety of applications. Edible packing approaches demonstration great promise in emerging food products that are safe for both consumers and the atmosphere. Characteristically, edible packaging depends on maintainable and decomposable materials that are functional as a coating or wrap around food items. In last few years, edible packing has been progressively used to prolong the shelf life of foodstuffs and improve their nutritional value (Subramanyan et al., 2023). The supreme blend of materials, expertise, and probiotic strains, food applicability, and reasonable price, are the hindrances to be engage in in order to reach a bigger industrial use. The preservation of a high probiotic cell thickness during the production of the probiotic edible film and after depletion remained a challenge. These should be the motivation of future study to apply health benefit towards consumers. Additionally, more research is required to regulate the health advantages of probiotic edible film.

Table 3
Functional Additives, Natural Antioxidants, and Probiotics in Food Preservation

Category	Component	Key Functions / Properties	Application / Notes
Natural Antioxidants	Rosemary Essential Oil	Sustained antioxidant release	Provides long-lasting protection against oxidation.
	Oregano & Thyme Essential Oils	Rich in phenolics, free-radical scavenging	Effective in neutralizing oxidative compounds.
	Green Tea Extract	Antioxidant, imparts a mild aroma	Adds functionality without strong off-flavors.
	Flaxseed Oil	Antioxidant, immune-stimulant	Offers dual health and preservation benefits.
Functional Additives	Cinnamon Oil (Cinnamaldehyde)	Antimicrobial, antioxidant release	Active against microbes while preventing oxidation.
	Clove Oil	Broad-spectrum antimicrobial, extends meat shelf-life	Particularly effective for preserving meat products.
	Pomegranate Peel, Grape Seed, Lemon Oil	Antioxidant	Utilizes by-products for value-added preservation.
	Combined EO Systems (e.g., Thyme+Rosemary+Tea Polyphenols)	Synergistic control of lipid oxidation	Enhanced efficacy through combination.

Probiotics & Bioactive Compounds	Lactobacillus / Bifidobacteria Strains	Improves gut health, boosts immunity	Live microbes added for direct consumer health benefits.
	Bioactive Peptides	Antioxidant & Antimicrobial functions	Protein fragments with dual protective functions.
	Nano-encapsulation (Zein, Chitosan, Alginate)	Protects heat- and pH-sensitive compounds (e.g., probiotics, oils)	Enhances stability and viability of sensitive ingredients.
	Edible Films/Coatings	Generally Recognized As Safe (GRAS), complies with EFSA & ISO standards	Safe, regulated delivery system for additives on food surfaces.

Regulatory and Safety Issues

In US edible coatings must have Generally Recognized As Safe GRAS status under FDA law. In the EU, they also fall in food additives or food contact materials, e.g. natural biopolymers like chitosan, gelatin, alginate, and collective additives (e.g., glycerol, essential oils) must come from appropriate GRAS or EU sanctioned lists (Kumar et al., 2023). Labling is another factor which can cause practical and legal complications e.g. coatings may have some allergens like soy protein, nut extract, fish gelatin which should be mentioned on labeling according to the rules and regulations of EU and FDA. Additionally, nano-enabled coatings increase concerns around nanoparticle movement and toxicity authorizing severe safety testing for every additive. Worldwide regulatory landscapes also change:

- In the U.S., it's necessary that coatings GRAS or FDA permitted food additives.
- In the EU, coatings may need Novel Food agreement and must follow Regulation (EC) 1333/2008 and associated with food-contact laws.

Other countries e.g., India, China, Australia execute variable labeling and allergen discovery requirements, especially when animal-derived or allergenic coating materials are used (Ali et al., 2025).

Scalability and Cost Considerations

Petrochemical plastics are much costly that biopolymers like pullulan, chitosan, alginate i.e. \$1.5–2/kg to 5–8× more per kilogram respectively. Their resource can be unpredictable e.g., seaweed collecting is focused in Asia, susceptible to weather and ailment. Maximum edible coatings are formed via solvent casting, which is less expensive i.e. 50–100 kg/hr and energy saving process ~\$0.50/kg, compared to plastic film extrusion 1,000–2,000 kg/hr at ~\$0.10/kg. Topping up have need of costly infrastructure advancements (\$2–5M per line) and harsh environmental controls like temperature 20–25 °C, moisture 40–60%. Laboratory aeration can take 48–72 hours inappropriate for marketable timelines. Edible coatings damage quicker than plastics 30–50% more sensitive to high temperature or moisture, requiring refrigerated logistics that increase cost by ~25–40%. Deceased packaging materials also pose register losses assessed ~12% volume loss in Europe due to perishability. Cost per square meter for edible coatings (~\$3.40/m²) far increase plastic wraps (\$0.42/m²), with extra expenses from bioactive additives like antimicrobials, plasticizers. Accomplishing cost correspondence requires operational effectiveness and economies of scale, which are presently missing (Radev & Kurshumov, 2024).

SUSTAINABILITY AND ENVIRONMENTAL IMPACT

Marine biopolymers have different benefits that's why these are used for edible coatings like these act as stabilizer, thickening agent, thicken emulsion, make

dispersions, gelling agents, prevent ice and sugar crystals, control additives and prevent degradation. The resilient commercial position that marine biopolymers have newly accomplished has attracted many marine researchers and consumers (Nair et al., 2023). There is a need to modify packaging material before the application of any packaging method e.g. a material description of the packing material like its mechanical and barrier possessions is compulsory to exhibit its applicability for particular applications. In order to produce ecological and value-added products, it may be worthwhile to value these ample and accessible bio wastes. Lobster industry, fisheries and fish canning waste are rich in collagen, gelatin, chitosan and chitin (Uranga et al., 2021). If products prepare from crustaceans and mollusks then shrimp and carbs shell used to make chitin, which is then converted into chitosan to broadened its use (Chakraborty et al., 2023). Wide research has been conducted on compounds based on polysaccharides derivative of seaweed, determined by their renewable and maintainable nature, mainly in industries such as food packing and medical such as tissue culturing and drug delivery. Seaweed byproducts such as alginate, carrageenan, and agar are generally developed in these applications due to their plentiful availability, biocompatibility, and gelling abilities. While seaweed shows notable film-forming characteristics, its mechanical strength and water-vapor-barrier properties are quite limited. Therefore, amendments are essential to expand and improve the properties of seaweed for these applications (Bukhari et al., 2023).

Biopolymer applications are dominant in many fields where maintainable and biodegradable solutions are required, and biopolymers have piqued the attention of many people. Biopolymers have well prospective in food applications (Hamed et al., 2022). Marine biopolymers, because of their distinctive properties and capability to relate with other food constituents, have conventionally played an important role in food processing. Chitosan and gelatin of 10% and 1%, correspondingly, were applied as spray coatings on vacuum packed beef to get how well they affected the shelf life of the produce for up to 21 days, and the consequences showed that the coatings expressively reduced the rate of lipid oxidation and retard the growth of lactic-acid bacteria (Roy et al., 2022). Natural pigments resulting from marine biopolymer sources have caught the attention of the food and beverage businesses due to their benefits and biological activities, such as possessing antibacterial, antioxidant, and sensory properties. In food packing and processing methods natural pigments act as functional bioactive constituent (Ozogul et al., 2021). Biopolymers produce long shelf life products with natural macro-molecules. These are environment friendly, act as modifiers, biocompatible in various processes. Biomacropolymers are not directly use in industries like packaging because of their inadequate mechanical and

physical properties. As a result, they are estimated to undergo certain changes or to develop new creative methodologies to yield value-added industrial level biopolymers (Zhang et al., 2023). Marine sources can be valorized to provide raw materials that are active in food packaging, decreasing the use of non-recyclable and non-biodegradable materials while observing sustainability strategies. Furthermore, active substances such as natural antioxidants and antimicrobials should be combined into food packing applications with biopolymers. Red algae is a major source of agar which is also a prospective biopolymer (Hamed et al., 2022). Agar films are a good substitute plastic base food packing. On the other hand plain agar films are brittle in nature and high in water permeability and is less stable to thermal. Agar films have extensive uses because of good refining properties e.g. integration with other biopolymers, hydrophobic components, antibacterial agents, assimilating plasticizers and nanomaterial reinforcement (Mostafavi et al., 2020). The influence of a bioactive film prepared of agar and comprising green tea extract and probiotic bacteria on hake fillets were assessed during 15 days of refrigerated storage. During the storage time, the agar-green tea-probiotic strain film affected a drop in H₂S-producing bacterium counts and overall viable bacteria. Trimethylamine nitrogen (TMA-N), pH and total volatile basic nitrogen (TVBN) are fish quality indicators. For 15 days, the overall viable counts, H₂S-producing bacteria, and TVB-N were less acceptable levels (Mohamed et al., 2020). Agar comprising alginate, collagen, silver nano particles, and grapefruit seed extract was revealed to be very translucent. The film had greater water holding capacity and an exceptional UV screening effect. Additionally, composite films revealed exceptional antibacterial action in contradiction of Gram-positive (*Listeria monocytogenes*) and Gram-negative (*Escherichia coli*) food-borne pathogenic microorganisms. The microbiological, physical, and chemical characteristics of flounder fillets coated with agar-clove essential oil films were deliberate during 15 days at 5 °C. During storing, flounder fillet had little total viable bases, a low pH, and hindered development of H₂S-producing bacteria (Zhao et al., 2021).

Comparison with Synthetic Packaging

An edible film is a thin foil used for packaging products. A coating is a layer applied directly to the surface of the product, and maintained until completely dry. Usually, the coatings are applied to perishable fruits and vegetables. For microbiological safety, they may contain organic acids, bacteriocins, or natural extracts (Jeevahan et al., 2020). A film with good properties must have some characteristics, such as (a) protecting the product it contains, (b) very good sensory qualities, barrier properties, or mechanical performance, (c) microbial stability and no toxins, (d) safe, and (e) easy to obtain, with low cost, and easy to handle and use. Moreover, due to its composition, development, and use, various beneficial substances, such as powders from natural products (Zibaei et al., 2021), essential oils dyes and flavorings, can be incorporated into the film-forming solutions. These substances can be consumed together with the packaging material and can improve the

characteristics of the final product (Massoud et al., 2021). Because the performance of these films cannot reach that of plastics, which are more resistant, especially in terms of mechanical and barrier properties, new techniques for obtaining biopolymeric materials have been developed. Layer-by-layer self-assembly is a common technique in interface science to produce biobased-films and a method widely used today for the development of natural materials, with properties similar to synthetic ones. The method involves alternating positively and negatively charged layers and thus high-performance smart materials can be obtained (Yong et al., 2021). The present study investigated the development and testing of new potential materials used for food packaging that requires solubilization before consumption. The idea of obtaining such films arose in response to authorities' concern about the intensive pollution of the environment due to conventional, oil-based packaging that is largely single-use and difficult to sort and recycle. The films were obtained from biopolymers, such as agar and alginate, being completely natural and edible (Szabo et al., 2020). The sample with the most suitable characteristics was obtained from agar, alginate, and glycerol in a ratio of 2:1:1. According to the tests performed, a higher amount of plasticizer in the composition was responsible for the improvement of the physical characteristics and solubility of the films. The results obtained indicate the possibility of using these foils as packaging material (Sharma et al., 2020). To improve their properties, they can be enriched by the addition of natural compounds in the form of powders, purees, extracts, or essential oils, or in combination with other biopolymers, when their use is intended for packaging other categories of food. Although biopolymer films can be a substitute for plastics, there are still some issues that need to be addressed. First, since biopolymers are natural substances, influenced by the growing environment, climatic conditions, and extraction methods, there is the possibility that the reproducibility of the method does not ensure the development of the same product with identical characteristics, unlike synthetic materials. At the moment, production costs are higher than those for plastics, but as the demand and need for these biomaterials increase, costs can be mitigated. Besides this, the obtaining technology is easy and does not involve qualified personnel or special equipment (Rehman et al., 2020). In most cases, the films and coatings act as a medium to preclude the passage of water, oxygen, and carbon dioxide. Even though the technological properties of marine biopolymer-based packaging have been reported, the efficacy is still lower and underdeveloped compared to synthetic and plastic polymer materials. Consequently, several researchers are making significant attempts to build high barrier and thermal properties food packaging systems from cheap, available, and renewable biopolymers, especially marine sources. To this aim, several propositions already have been made, and a recent upgrade has been brought with the application of active agents with potent antimicrobial and anti-oxidative properties that target to suppress the growth of microorganisms and to diminish the oxidation of lipids and pigments in food and the surroundings in a packaging arrangement (Asgher et al., 2020). The protection of food

quality and the assurance of microbiological safety are the two most crucial aspects of food packaging. Beyond making it possible to handle, transport, and store a variety of food commodities, packaging also shields food from physical, chemical, and microbiological harm, improving quality preservation and shelf life. Long-chain hydrophilic polymers derived from polysaccharides and proteins are examples of biopolymers. However, the preponderance of materials utilized in the packaging of food is polymeric polymers obtained from petroleum, also known as plastic (Rai et al., 2023). The biodegradability, recycling, biocompatibility, and reusability of plastic packaging are hampered. Polymeric materials separate the above from others for their advantages, such as flexibility and degradability, which allow the manufacturing of flexible pouches, bags, or stiff containers in a variety of shapes and sizes (Juikar & Warkar, 2023). As a result, they are widely employed to hold and preserve fresh food commodities. These plastic packaging results in a mass of waste, which has a severe effect on the ecosystem by contaminating soil, polluting the ocean, polluting the air, and killing animals all over the world. The entire human habitat has now been poisoned by discarded plastics (Oyervides-Muñoz et al., 2023). Nowadays, an upsurge is being noticed regarding the use of polymers made from renewable resources to create environmentally acceptable materials, using polysaccharides and proteins (such as starch, chitosan, and cellulose) which are directly obtained from biomass (including soy protein, caseinates, gluten, whey protein, and zein) (Grzebieniarsz et al., 2023). Polyhydroxyalkanoates (PHAs) and bacterial cellulose are examples of microorganisms that can create polymers naturally or through genetic modification. These bio based polymers are beneficial in three primary areas for use: as edible films for food, encapsulating/packaging of food, and as food-coating materials. Marine sources are becoming more popular and desirable as cutting-edge resources for producing biopolymers such as proteins and polysaccharides (Moradali et al., 2020). These biopolymers have been promoted as being useful in the formation of packaging materials for food commodities due to their biocompatibility, biodegradability, and nontoxic properties. When marine resources such as mollusks, crabs, and fish are developed industrially to create commercial products, marine biopolymers undergo a significant development. Muscle proteins, collagen, and gelatin are the three main categories of common marine proteins, whereas chitin, chitosan, alginate, agar, and carrageenan are examples of common marine polysaccharides. Then, using these proteins and polysaccharides, biodegradable films and coatings are created along with the necessary mechanical qualities to shield the food product inside from various spoiling factors. The ability of these packaging materials to decompose in the environment is their most significant quality and may also be the most anticipated (Mahmud et al., 2020).

Life Cycle Assessment (LCA) Perspectives

Life cycle assessment (LCA) is a well-established method used to quantify the environmental impacts of products and processes. Previous LCAs and environmental

assessments of biopolymers are largely limited to global warming potential and fossil fuel depletion impact categories which may favor biopolymers because of the inherent properties of plastics made from biogenic carbon, which is carbon that was recently captured from the atmosphere through the biological process of photosynthesis by plants, compared to fossil based plastics and may miss the potential environmental tradeoffs that can occur when shifting to agriculturally produced feed stocks. Life cycle assessment (LCA) is a methodological framework used to systematically evaluate the potential environmental performance of a product, and its lifecycle, spanning the stages of raw material acquisition, through to product use and end-of-life. To date, only a handful of LCAs have been carried out on biorefinery systems incorporating high-value algal products (Zhang et al., 2021; Zhang and Thomsen, 2021). Conducted an LCA, (accompanied by in-depth sensitivity and uncertainty analysis) evaluating the sustainability of a biorefinery coproducing single-cell oils (substitutes for oils in the exotic fats market), 2-phenylethanol (for use in perfumery) and a proteinous yeast extract (for animal feed). Primarily targeting the pharmaceuticals market, evaluated a series of biorefining schemes producing fucoxanthin, sodium alginate and phenolic compounds (antioxidants), from wild-harvested *Sargassum muticum* (Zhang et al., 2021). Recently performed an *ex ante* LCA assessing the environmental hotspots in two cascading biorefining systems valorising South African *Ecklonia maxima*, and producing laminarin, fucoidan and alginate. The evaluated product systems employed novel solvent-free 'sub-critical water' and 'hot water' methods for laminarin and fucoidan extraction. While the overall water footprint was halved compared to commercially produced alginate, the carbon footprints of the marine biorefining systems were found to be twice as high a direct consequence of the coal-dominated South African energy mix.

Future Prospects and Recommendations

Nanotechnology Integration: Nanotechnology has emerged as a pivotal advancement in enhancing edible coating efficiency. Incorporating nanoemulsions and nanoparticles enables controlled release of bioactive compounds such as antimicrobials, antioxidants, or essential oils. These nanocarriers ensure more uniform dispersion, higher surface contact, and prolonged activity over storage periods (Tabassum et al., 2023). For instance, chitosan-based edible films embedded with silver nanoparticles or nano-encapsulated clove oil have shown superior antimicrobial activity against *Listeria* and *Salmonella* in fish fillets, without affecting sensory properties when properly dosed (Cheng et al., 2024). Similarly, curcumin-loaded nanoemulsions integrated into gelatin coatings provided sustained antioxidant activity and preserved color in mackerel fillets (Ghosh et al., 2020). Despite promising lab-scale outcomes, regulatory concerns persist regarding nanoparticle migration, long-term toxicity, and environmental effects, necessitating further toxicological evaluation and harmonized labeling policies (EFSA, 2021).

Smart and Intelligent Coatings: Intelligent edible coatings incorporating pH-responsive indicators or

spoilage sensors can offer real-time monitoring of fish freshness. These coatings typically include natural dyes like anthocyanins, curcumin, or betalains, which change color in response to shifts in pH caused by spoilage-related compounds like ammonia and TVBN (Marappan et al., 2025). For example, gelatin-based films integrated with red cabbage extract turned from purple to green as pH increased, accurately correlating with microbial load in shrimp samples (Ren et al., 2023). These smart coatings not only enhance consumer confidence but can also reduce food waste by providing visual cues about product safety. However, challenges remain in stabilizing colorants over time, avoiding dye migration into the food matrix, and standardizing indicator thresholds across various seafood types.

Combination Technologies: Combining edible coatings with traditional preservation techniques like refrigeration and modified atmosphere packaging (MAP) offers synergistic effects. For example, gelatin coatings enriched with essential oils, when used alongside MAP (CO₂-rich environments), extended the shelf life of salmon fillets by up to 14 days, delaying microbial growth and lipid oxidation (Lou & Chen, 2023). Likewise Coating + MAP systems effectively reduce oxygen exposure, control moisture, and suppress spoilage bacteria, outperforming either method alone (reference). These multi-hurdle approaches are particularly valuable for cold-chain distribution of foods (reference).

RESEARCH GAPS AND SUGGESTED STUDIES

While significant progress has been made, several research gaps need urgent attention:

1. Toxicological Studies of Nanomaterials: Most nanomaterial-based coatings lack comprehensive long-term safety data under real storage and consumption conditions.
2. Scalability Trials: Few studies test coatings at pilot or industrial scale, limiting commercial adoption.

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3. Sensory Preservation Validation: Despite technical successes, more studies should correlate functional performance with consumer sensory acceptability across different marine species.
4. Standardization of Smart Indicators: Further research is needed to standardize response ranges, stability, and non-interference of visual indicators under practical storage conditions.
5. Life Cycle Assessment (LCA): Environmental footprint comparisons with plastic and bioplastic packaging are still limited and should be expanded to guide policy and industry practices.

CONCLUSION

Biopolymer-based edible coatings represent a promising and eco-friendly strategy to enhance the preservation of marine foods by reducing microbial growth, lipid oxidation, enzymatic activity, and moisture loss. Derived from natural polysaccharides, proteins, and lipids, these coatings not only act as protective barriers but also serve as carriers for bioactive compounds such as essential oils, antioxidants, and probiotics, thereby extending shelf life while maintaining sensory and nutritional qualities. Recent advances in nanotechnology and composite formulations have further strengthened their mechanical and functional properties, demonstrating significant potential in industrial applications. Despite these advantages, challenges remain in terms of coating adhesion, sensory impacts, cost-effectiveness, and large-scale production feasibility. Addressing regulatory requirements, consumer acceptance, and optimization of formulation techniques will be critical for their successful commercialization. Overall, edible coatings align with sustainability goals by reducing food waste and dependency on synthetic packaging, offering a valuable pathway toward safer, healthier, and more sustainable seafood preservation.

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