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Review

Marine-Derived Edible Biopolymer Coatings for Seafood Preservation: Structure–Property–Interface Relationships

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Highlights

What are the main findings?

- Marine biopolymer coatings link structure, properties, interfaces, and preservation performance.
- Polymer rheology, wettability, adhesion, and bioactive release influence coating effectiveness.
- Collagen, gelatin, chitosan, alginate, and carrageenan offer distinct preservation functions.

What are the implications of the main findings?

- Integrated design can guide the development of more effective seafood coatings.
- Standardization, scalability, safety, and regulatory compliance are key challenges.
- Marine biopolymers offer opportunities for circular and sustainable seafood preservation.

Abstract

Marine-derived edible biopolymer coatings are increasingly investigated for seafood preservation, yet their reported performance remains difficult to compare because polymer characteristics, coating formation, interfacial behavior, and preservation outcomes are frequently evaluated independently. This critical narrative review synthesizes literature published primarily from January 2016 to June 2026, while retaining earlier foundational studies when mechanistically relevant. Collagen, gelatin, chitosan, alginate, carrageenan, and emerging marine-derived materials are examined through a structure–property–interface–performance framework that distinguishes evidence from isolated polymers, preformed films, model substrates, and coatings applied directly to seafood. The available evidence shows that polymer identity and dry-film properties alone do not reliably predict coating performance on moist seafood surfaces. Molecular characteristics, solution rheology, wettability, spreading, adhesion, hydration stability, coating continuity, and active-compound retention and release jointly determine preservation efficacy. Direct seafood studies demonstrate meaningful shelf-life extensions in selected systems, but remain highly heterogeneous and frequently lack

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quantitative characterization of coating thickness, adhesion, interfacial stability, and release behavior. Evidence is concentrated mainly in refrigerated fish and crustaceans, whereas mollusks, cephalopods, processed aquatic products, frozen systems, and pilot-scale applications remain underrepresented. Future progress requires standardized molecular and formulation reporting, direct quantitative characterization of the coating–seafood interface, integrated microbiological, oxidative, physicochemical, and sensory validation, and demonstration of safety, scalability, economic feasibility, and environmental benefit.

Keywords: chitosan; alginate; collagen; carrageenan; seafood quality; coating rheology; wettability; controlled release

1. Introduction

Seafood plays an important role in global food and nutritional security because it provides highly digestible proteins, long-chain omega-3 polyunsaturated fatty acids, essential amino acids, vitamins, minerals, and other health-promoting compounds [1,2]. Global fisheries and aquaculture production reached a record 235 million tonnes in 2024, including 195 million tonnes of aquatic animals, highlighting the growing contribution of aquatic foods to global food security, nutrition, and livelihoods [1]. Nevertheless, the nutritional, sensory, and commercial value of seafood is limited by its rapid postharvest deterioration.

The intrinsic composition and postmortem metabolism of seafood promote rapid autolytic, oxidative, microbiological, and structural deterioration. These interconnected processes progressively impair texture, color, flavor, nutritional quality, technological functionality, and consumer acceptance, resulting in a relatively short shelf life and substantial losses throughout seafood supply chains [3,4].

Refrigeration, icing, freezing, vacuum packaging, modified-atmosphere packaging, and chemical preservatives remain essential for controlling seafood deterioration. However, these technologies may require considerable energy, provide incomplete protection against surface oxidation or microbial growth, depend on petroleum-derived packaging materials, or conflict with the increasing demand for minimally processed foods preserved using naturally derived ingredients. These limitations have stimulated interest in edible coatings applied directly to seafood surfaces by dipping, spraying, brushing, casting, or sequential multilayer deposition [5,6].

Unlike preformed films, edible coatings develop their functional structure directly on moist, irregular, chemically heterogeneous, and biologically active food surfaces. Their effectiveness therefore depends not only on the chemical composition of the polymer matrix but also on coating-solution rheology, surface tension, wettability, spreading, adhesion, coating pickup, drying kinetics, thickness, continuity, morphology, and stability during refrigerated storage. Properly designed coatings can regulate oxygen, moisture, and solute transfer while acting as localized carriers of antioxidants, antimicrobials, and other functional compounds. Through these complementary barrier and active mechanisms, coatings may delay oxidation, microbial proliferation, dehydration, discoloration, texture deterioration, and sensory rejection [7,8].

Marine-derived biopolymers, particularly collagen, gelatin, chitosan, alginate, and carrageenan, are attractive coating matrices because of their film-forming capacity, biodegradability, biocompatibility, generally low toxicity, and compatibility with diverse active agents. Their recovery from fish skins, scales, bones, cartilage, crustacean shells, seaweeds, and other marine-processing residues also supports biomass valorization and circular bioeconomy strategies [9–12]. Nevertheless, these materials are not functionally equivalent.

Molecular weight, functional-group distribution, charge density, chain conformation, crystallinity, gelation behavior, and crosslinking density determine solution rheology, network formation, mechanical integrity, permeability, interfacial adhesion, compatibility with active compounds, and release kinetics.

Protein-based coatings generally provide favorable oxygen-barrier properties under low-humidity conditions, but their hydrophilic nature makes them sensitive to water absorption, swelling, and mechanical weakening. Marine polysaccharides exhibit distinctive ionic and gelation mechanisms, although they also commonly show limited resistance to water vapor transfer under conditions of high humidity. Chitosan additionally possesses intrinsic antimicrobial activity, whereas alginate and carrageenan form hydrogel networks suitable for encapsulation and controlled release. Because these matrices differ in their structural and functional attributes, product-specific formulation and modification are often required to balance adhesion, flexibility, moisture resistance, active-compound stability, and release behavior [13,14].

Recent advances have transformed marine-derived coatings from passive protective layers into active delivery platforms for essential oils, phenolic extracts, antioxidant peptides, bacteriocins, enzymes, probiotics, nanoparticles, and other functional agents. Nanoemulsions, polymeric nanoparticles, and nanoencapsulation systems may improve the dispersion, stability, retention, and sustained activity of these compounds during storage [13,14]. However, active-agent incorporation may also modify polymer organization, solution viscosity, wettability, coating morphology, mechanical behavior, permeability, adhesion, color, aroma, and release kinetics. Preservation performance should therefore be interpreted according to coating integrity and the sustained interfacial availability of the active compound rather than solely to its intrinsic antioxidant or antimicrobial activity.

Several reviews have established the potential of edible films and coatings for food and seafood preservation by summarizing coating materials, active ingredients, application methods, and their effects on microbial growth, oxidation, physicochemical quality, sensory acceptance, and shelf-life extension [15]. Other contributions have examined marine biopolymers mainly as renewable materials for biodegradable food packaging, emphasizing their sources, extraction, film-forming properties, active functionality, and safety considerations [9,11,16]. More recent reviews have focused on individual polymers, particular active compounds, nanostructured systems, or selected preservation applications [13,17,18].

Recent reviews have provided valuable perspectives on marine biopolymers, edible films and coatings, active packaging systems, and their application to seafood preservation. However, important methodological and mechanistic disconnects remain among molecular characterization, coating-solution behavior, interfacial phenomena, and preservation performance. In particular, material properties are frequently discussed independently from the conditions under which coatings are deposited and function on moist, heterogeneous seafood surfaces.

Accordingly, the contribution of the present review lies not in the simultaneous coverage of these topics, but in critically examining the mechanistic sequence by which source-dependent molecular characteristics influence coating formation and, ultimately, preservation performance. Particular attention is given to the relationships among polymer molecular characteristics, solution rheology and deposition behavior, wettability, spreading, adhesion, hydration and stability at the coating–seafood interface, active-compound retention and release, and measurable oxidative, microbiological, physicochemical, sensory, and shelf-life outcomes.

A further objective is to distinguish the level of experimental evidence supporting these relationships. Evidence obtained from preformed films, model substrates, and coatings applied directly to seafood is therefore considered separately when their transferability

differs. This distinction is particularly relevant because properties measured in dry films or under simplified conditions cannot necessarily be extrapolated to hydrated coatings formed in situ on chemically and structurally heterogeneous seafood surfaces. Through this evidence-based structure–property–interface–performance approach, the review aims to identify both experimentally supported relationships and mechanistic hypotheses that still require direct validation in seafood systems.

This review critically examines marine-derived edible biopolymer coatings for seafood preservation through an integrated structure–property–interface–performance framework. It connects the molecular organization and functional characteristics of collagen, gelatin, chitosan, alginate, carrageenan, and emerging marine-derived materials with solution rheology, deposition behavior, interfacial adhesion, mechanical and barrier properties, active-compound retention and release, and preservation outcomes in aquatic foods. Emerging developments in intelligent and stimuli-responsive coatings, nanostructured delivery platforms, industrial scale-up, safety, regulation, by-product valorization, and circular bioeconomy are also evaluated. Through this integrated approach, the review identifies the material, processing, interfacial, and active-release parameters that should be characterized and optimized to support reproducible formulation, meaningful comparison among studies, and the commercial translation of marine-derived edible coatings.

2. Review Scope and Literature Search

Search Strategy

This critical narrative review was developed from a targeted literature search intended to identify representative and mechanistically relevant evidence on marine-derived edible biopolymer coatings for seafood preservation. Web of Science Core Collection, Scopus, PubMed, and ScienceDirect were used as the main bibliographic sources, whereas Google Scholar was used as a complementary search engine to identify additional relevant publications and cited references. The literature search focused primarily on peer-reviewed publications available from January 2016 to June 2026. Earlier studies were retained when they provided foundational information on seafood deterioration, polymer chemistry, molecular structure, gelation mechanisms, coating formation, mass transfer, interfacial phenomena, analytical methods, or established theoretical concepts that had not been adequately replaced by more recent evidence. Accordingly, the 2016–2026 interval represents the primary search window rather than an absolute exclusion criterion.

Literature searches used combinations of terms related to marine-derived biopolymers, edible coatings, and aquatic foods, including “marine biopolymer”, “marine-derived biopolymer”, collagen, gelatin, chitosan, alginate, carrageenan, agar, fucoidan, ulvan, laminarin, “seaweed polysaccharide”, “marine exopolysaccharide”, “edible coating”, “active coating”, “multilayer coating”, seafood, fish, shellfish, crustacean, and mollusk. Additional targeted terms related to molecular weight, functional groups, crosslinking, rheology, deposition, wettability, spreading, adhesion, drying, swelling, mechanical and barrier properties, encapsulation, controlled release, antioxidants, and antimicrobials were used according to the specific topic being examined. Because the review was designed as a critical narrative synthesis rather than a systematic review, the search strategy was intended to support mechanistic interpretation and critical comparison of the literature rather than to generate an exhaustive PRISMA-based inventory of all available publications.

Publications were selected according to their relevance to one or more of the main thematic areas addressed in this review: (i) source, extraction, composition, or molecular characterization of marine-derived biopolymers; (ii) formulation and rheological behavior of coating solutions; (iii) coating deposition, wettability, spreading, adhesion, drying, or stability on food surfaces; (iv) mechanical, barrier, encapsulation, or release properties relevant to edible coatings; (v)

incorporation of antioxidant, antimicrobial, or other functional compounds; and (vi) preservation performance in fish, crustaceans, mollusks, or processed seafood products. Studies focused exclusively on terrestrial polymers or on preformed packaging materials with no clear relevance to marine-derived coating systems, interfacial behavior, mass transfer, or active-compound delivery were generally not included in the core discussion.

Studies focused exclusively on terrestrial polymers were excluded unless the material was blended with, compared with, or used to modify a marine-derived coating matrix. For the comparative assessment of seafood-preservation performance, studies were required to involve direct application of a coating to a seafood product and to provide sufficient information on formulation, application conditions, storage conditions, experimental controls, and quantitative preservation outcomes to permit meaningful interpretation. Incomplete reporting of secondary coating-characterization variables, such as molecular specifications, coating thickness, adhesion, interfacial properties, or release kinetics, did not automatically exclude an otherwise relevant direct seafood-application study. Instead, these deficiencies were retained as evidence limitations; such studies were interpreted cautiously and were not used to support broad comparative claims regarding the superiority of individual polymers or formulations. Studies based exclusively on preformed films, food simulants, model substrates, or in vitro assays were retained only when they provided mechanistic information relevant to the structure–property–interface analysis and were not used as direct evidence of seafood-preservation performance.

Literature screening and selection were conducted according to the stated scope, thematic relevance, and conceptual framework of this critical narrative review. Because the review was not designed as a systematic review, formal duplicate independent screening, inter-reviewer adjudication, a PRISMA-based record flow, and formal risk-of-bias assessment were not performed. Database-specific search strings, exact search execution dates, and record-level screening counts were not prospectively archived and were therefore not retrospectively reconstructed. For mechanistic interpretation, evidence from preformed films, model substrates, food simulants, and in vitro studies was considered when directly relevant to coating formation, structure–property relationships, interfacial behavior, or active-compound release. However, when discussing seafood-preservation efficacy, greater interpretive weight was given to studies in which coatings were applied directly to seafood and that provided sufficient information on formulation, application conditions, storage conditions, experimental controls, and preservation outcomes.

Relevant information was organized according to polymer source and molecular characteristics, formulation composition, active compounds, deposition method, seafood substrate, storage conditions, material properties, interfacial behavior, release characteristics, preservation indicators, sensory effects, and reported shelf-life extension. The evidence was critically synthesized using the structure–property–interface–performance framework proposed in this review, linking polymer molecular characteristics and formulation conditions with solution rheology, coating formation, interfacial stability, mechanical and barrier properties, active-compound retention and release, and seafood-preservation outcomes. Because of substantial heterogeneity in biopolymer origin, molecular specifications, formulation, application method, seafood species, storage conditions, and analytical endpoints, the evidence was synthesized narratively rather than through meta-analysis.

3. Seafood Deterioration as a Basis for Functional Coating Design

Seafood deterioration results from the interaction of postmortem metabolism, enzymatic autolysis, lipid and protein oxidation, moisture migration, and microbial proliferation. These processes are favored by high water activity, near-neutral pH, endogenous enzymes, abundant non-protein nitrogen compounds, and oxidation-prone polyunsaturated fatty

acids [3,19]. Each deterioration pathway imposes specific requirements on coating design. Oxidative reactions require continuous matrices with low oxygen permeability and effective antioxidant delivery, whereas moisture loss requires controlled water transfer without promoting surface condensation. Microbial control depends on adequate wettability, spreading, adhesion, and sustained antimicrobial concentrations at the coating–seafood interface. Coatings must also remain continuous and stable despite swelling, exudation, and structural changes during refrigerated storage [20].

Coating performance should therefore be interpreted as the combined result of the deterioration mechanism, polymer structure, deposition behavior, interfacial stability, mass transfer, and active-compound release. The following subsections examine the principal biochemical, oxidative, and microbiological processes that determine the functional requirements of marine-derived edible coatings.

3.1. Postmortem Changes and Their Implications for Coating Design

After harvest, postmortem metabolism, ATP depletion, rigor development, proteolysis, and membrane disruption progressively alter seafood texture, water-holding capacity, surface exudation, and susceptibility to oxidation and microbial deterioration [3,21–24]. These postmortem changes are particularly relevant to edible-coating design because they modify the physical and chemical characteristics of the substrate on which the coating must spread, adhere, and remain continuous during storage.

Edible coatings cannot prevent ATP depletion, rigor mortis, or endogenous proteolysis. Instead, they limit secondary deterioration by regulating oxygen and moisture transfer and delivering antioxidant or antimicrobial agents at the seafood surface. However, postmortem contraction, softening, exudation, and changes in surface composition may alter wettability, adhesion, thickness, and coating continuity. Effective systems must therefore tolerate these interfacial changes without cracking, swelling, delamination, or premature active-compound loss.

3.2. Lipid and Protein Oxidation: Antioxidant and Barrier Requirements

Oxidative deterioration is particularly relevant in seafood rich in long-chain polyunsaturated fatty acids and can affect flavor, color, texture, nutritional quality, and sensory acceptability [22,25]. Lipid and protein oxidation are interconnected and are promoted by oxygen exposure, light, temperature fluctuations, pro-oxidant metals, and structural disruption during processing and storage [25–29]. From a coating-design perspective, these reactions create two principal requirements: maintaining a continuous barrier that limits oxygen transfer, and providing antioxidant activity at the seafood surface.

Marine-derived coatings can address these requirements through complementary passive and active mechanisms. Polymer-network organization, thickness, continuity, hydration, and oxygen permeability influence barrier performance, whereas incorporated phenolics, carotenoids, peptides, essential oils, and other antioxidants may provide radical-scavenging or metal-chelating activity [19,30,31]. Preservation efficacy therefore depends not only on antioxidant capacity but also on coating integrity, polymer–bioactive interactions, retention, and release kinetics. Excessive crosslinking may restrict active-compound diffusion, whereas excessive hydration or weak matrix interactions may accelerate release and premature depletion.

3.3. Microbial Spoilage and Antimicrobial Interfacial Requirements

Microbial deterioration of seafood depends on product composition, initial microbiota, processing history, temperature, oxygen availability, and packaging atmosphere [4,32–36]. Consequently, the microbial target of an active coating is product- and storage-specific rather than universal. From a coating-design perspective, antimicrobial performance

depends not only on the intrinsic activity of the polymer or incorporated compound but also on its ability to reach and remain active at the seafood surface.

Wettability, spreading, adhesion, coating continuity, surface exudation, and active-compound release determine whether inhibitory concentrations can be maintained uniformly across the product [37,38]. Poor coverage, delamination, or disruption by surface moisture may create unprotected regions despite strong antimicrobial activity measured in vitro. Marine-derived coatings may deliver chitosan, peptides, bacteriocins, essential oils, phenolic compounds, nanoemulsions, or other antimicrobial agents, but their effectiveness depends on compatibility, retention, diffusion, sustained release, sensory acceptance, and microbiological safety [39–42]. Antimicrobial coating design should therefore integrate microbial target, interfacial coverage, coating stability, and active-compound availability rather than relying solely on inhibition measured in model systems.

Depending on the active compound and target microorganism, antimicrobial effects may involve membrane disruption, altered membrane permeability, chelation of essential ions, and interference with cellular metabolism [31,39,40,42]. Chitosan additionally interacts electrostatically with negatively charged microbial surfaces, although its activity depends on molecular weight, degree of deacetylation, protonation, ionic strength, and food composition.

Effective antimicrobial systems must balance compatibility, retention, diffusion, and release. Excessively strong polymer–bioactive interactions may restrict antimicrobial availability, whereas weak interactions may cause burst release, sensory changes, and premature depletion. Consequently, antimicrobial coating design requires the simultaneous optimization of surface coverage, adhesion, moisture stability, structural continuity, sustained release, safety, and sensory acceptability [41,42]. The biochemical and microbiological deterioration pathways and the corresponding intervention points for active coatings are summarized in Figure 1.

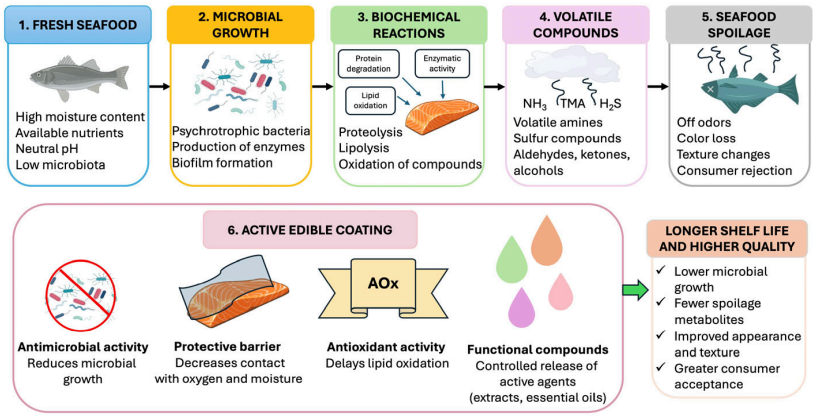


Figure 1. Biochemical and microbiological mechanisms driving seafood spoilage and their implications for active edible coatings. This figure was created with BioRender.com.

3.4. Quality and Shelf-Life Indicators for Evaluating Coating Performance

Coating efficacy should be evaluated using complementary product-level endpoints selected according to the intended preservation function. Depending on the targeted deterioration mechanism, relevant measurements may include oxidative indices, microbial counts, volatile nitrogen compounds, moisture or weight loss, color, texture, freshness indicators, and sensory acceptability [3,26,43–47]. No individual indicator should be interpreted as sufficient evidence of coating performance or shelf-life extension.

Preservation indicators should be interpreted together with coating-specific properties. Antioxidant systems should relate oxygen permeability, coating thickness and continuity,

active-compound retention, and release to oxidative changes in the seafood. Moisture-control systems should connect water-vapor transfer, swelling, and coating stability with drip loss, weight loss, and texture, whereas antimicrobial systems should integrate surface coverage, adhesion, release kinetics, microbial counts, and sensory shelf life. This integrated assessment is necessary to determine whether preservation results primarily from passive barrier effects, interfacial stability, active-compound delivery, or their combined action. Rapid non-destructive technologies may complement these measurements, but their usefulness requires validation across seafood species, processing conditions, and realistic storage systems [48–50].

4. Marine-Derived Biopolymers as Coating Matrices

The performance of marine-derived biopolymers as coating matrices is governed by functional-group distribution, molecular weight, chain conformation, crystallinity, charge density, and intermolecular interactions. These molecular characteristics determine solution rheology, network formation, mechanical integrity, permeability, interfacial adhesion, and active-compound retention and release [7].

Marine coating matrices can be broadly classified as protein- or polysaccharide-based. Collagen and gelatin form networks mainly through hydrogen bonding, electrostatic interactions, and hydrophobic associations. Chitosan, alginate, and carrageenan exhibit distinctive ionic and gelation mechanisms associated with their amino, carboxyl, and sulfate groups. Chitosan also possesses intrinsic antimicrobial activity, whereas alginate and carrageenan form hydrogel networks suitable for encapsulation and controlled release [14,16].

Selection of the coating matrix should be product-specific and based on its molecular characteristics, processing history, formulation requirements, and behavior at the seafood interface. Emerging materials, including myofibrillar proteins, bioactive peptides, fucoidan, ulvan, laminarin, agar, and marine microbial exopolysaccharides, further expand the structural and functional options available for seafood-coating development [18,20]. However, their technological performance and suitability for direct application to seafood require further characterization and validation.

4.1. Protein-Based Marine Biopolymers

Marine proteins are suitable edible-coating matrices because their amino acid side chains establish hydrogen bonds, electrostatic interactions, hydrophobic associations, and, under appropriate conditions, covalent crosslinks. These interactions govern solution rheology, network formation, mechanical and barrier properties, adhesion, and compatibility with active compounds [7,13]. Collagen and gelatin are mainly recovered from fish skins, scales, bones, fins, cartilage, and swim bladders, supporting the valorization of seafood-processing by-products [10,12]. Both matrices can incorporate antioxidants, antimicrobials, peptides, enzymes, essential oils, and nanoparticles, thereby combining passive barrier protection with active preservation [15,51].

Their performance depends on amino acid composition, molecular-weight distribution, chain conformation, surface charge, and polymer–polymer or polymer–bioactive interactions. Polar and ionizable residues promote hydration and interactions with seafood surfaces, whereas hydrophobic residues contribute to chain association and compatibility with lipid-soluble compounds. Chain rearrangement during drying determines coating continuity, porosity, thickness, and mechanical integrity, while the hydrophilic character of these matrices may limit their stability on moist seafood surfaces. Collagen retains an ordered triple-helical structure capable of forming relatively cohesive fibrillar networks, whereas gelatin consists of more flexible and disordered chains produced through collagen denaturation and hydrolysis. These structural differences determine their solubility,

processing behavior, spreading, gelation, thermal stability, interfacial performance, and capacity to retain and release active compounds.

4.1.1. Marine Collagen

Marine collagen is recovered mainly from fish skins, scales, bones, fins, cartilage, swim bladders, and other connective-tissue by-products, providing a value-added use for seafood-processing residues [10,12]. Structurally, collagen consists of three α-polypeptide chains arranged in a triple helix stabilized primarily by interchain hydrogen bonds. Its repetitive Gly-X-Y sequence permits close chain packing, whereas proline and hydroxyproline contribute to conformational and thermal stability [52]. Preservation of the triple-helical structure and subsequent fibrillar assembly influence solubility, viscosity, network cohesion, and coating-forming behavior. Marine collagen is highly source-dependent. Species, habitat temperature, anatomical tissue, age, and extraction conditions affect amino acid composition, molecular-weight distribution, natural crosslinking, solubility, and denaturation temperature. Collagen from cold-water fish generally contains less hydroxyproline and exhibits lower thermal stability than that obtained from warm-water species. Although type I collagen predominates in fish skins, scales, and bones, differences in molecular integrity and fibrillar organization can substantially modify functionality [53–55].

Acid- and pepsin-assisted extraction are the most common recovery methods. Pepsin partially removes telopeptide regions involved in intermolecular crosslinking, generally increasing solubility and extraction yield while preserving most of the triple-helical domain. Ultrasound- and enzyme-assisted approaches may improve extraction efficiency and reduce processing time, although processing severity can affect molecular integrity and molecular-weight distribution [56,57].

During coating formation, collagen chains associate through hydrogen bonding, electrostatic interactions, hydrophobic associations, and fibrillar assembly. Its ordered structure can provide cohesive networks, but may limit solubility, spreading, and adaptation to irregular seafood surfaces. Collagen can also carry phenolics, carotenoids, essential oils, antimicrobial peptides, and nanoparticles, although compatibility depends on polymer integrity and polymer–bioactive interactions [15]. The principal limitations of marine collagen are source-dependent variability, relatively low thermal stability, moisture and enzymatic sensitivity, and insufficient standardization. These molecular and technological characteristics are summarized in Figure 2.

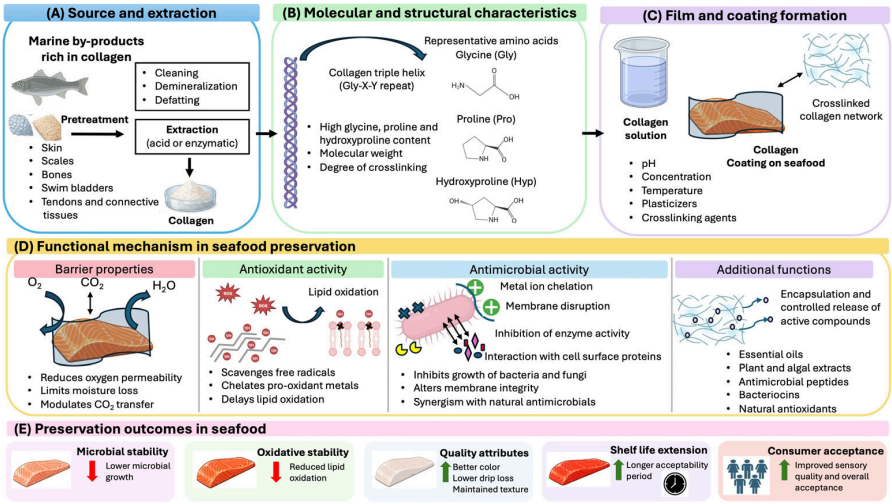


Figure 2. Molecular structure, coating-forming behavior, and structure–property relationships of marine collagen in active coatings for seafood preservation. This figure was created with BioRender.com.

4.1.2. Marine Gelatin

Marine gelatin is obtained through the partial hydrolysis and thermal denaturation of collagen recovered mainly from fish skins, bones, scales, and other collagen-rich by-products. Its production contributes to seafood-residue valorization and provides an alternative to mammalian gelatin under certain religious, cultural, and animal-health considerations [10,13]. Collagen denaturation disrupts the triple helix and produces a heterogeneous mixture of α-chains and higher-molecular-weight β- and γ-chain aggregates. This disordered and flexible molecular organization generally provides greater solubility, chain mobility, spreading, and processability than native collagen [54,55]. During drying or cooling, gelatin chains partially reassociate through hydrogen bonding, hydrophobic interactions, electrostatic forces, and chain entanglement, forming continuous coating networks.

Gelatin characteristics vary with species, habitat temperature, anatomical source, pretreatment, extraction temperature, pH, and molecular-weight distribution. Production commonly involves acid or alkaline pretreatment followed by controlled thermal extraction. These conditions influence extraction yield, viscosity, bloom strength, gelation and melting temperatures, and coating-forming behavior [54,58]. Gelatin from cold-water fish generally exhibits lower gel strength and thermal stability than gelatin obtained from warm-water species or mammalian sources.

The mobility of gelatin chains facilitates solution preparation and adaptation to irregular seafood surfaces. However, coating formation depends on polymer concentration, temperature, pH, ionic strength, viscosity, surface tension, deposition method, and drying conditions. These variables influence coating pickup, spreading, continuity, and adhesion. The hydrophilic amino acid composition of gelatin also promotes moisture absorption and structural changes under the high-humidity conditions typical of refrigerated seafood. Gelatin matrices can incorporate phenolic extracts, essential oils, antioxidant peptides, antimicrobials, enzymes, probiotics, nanoparticles, and nanoemulsions [15,17,51]. Nevertheless, poorly compatible or inadequately dispersed compounds may alter solution behavior, coating morphology, transparency, color, aroma, and sensory acceptance.

The principal limitations of marine gelatin include source- and process-dependent variability, comparatively low gel strength and thermal stability, and insufficient standardization.

4.2. Marine Polysaccharide-Based Coating Matrices

Marine polysaccharides are obtained mainly from crustacean-processing residues, macroalgae, and marine microorganisms. Their availability, biodegradability, gel-forming capacity, and compatibility with active compounds make them relevant matrices for edible-coating development and marine-biomass valorization [10,11,20]. Their functionality is determined by monosaccharide composition, glycosidic linkages, molecular weight, branching, charge density, and the distribution of amino, carboxyl, sulfate, and hydroxyl groups. These characteristics regulate solubility, chain conformation, solution viscosity, ionic interactions, network formation, and affinity for seafood components and incorporated bioactives [59].

Chitosan, alginate, and carrageenan exhibit distinct molecular and gelation behaviors. Chitosan is a cationic copolymer whose protonatable amino groups provide acidic solubility, electrostatic reactivity, and intrinsic antimicrobial activity. Alginate is an anionic copolymer composed of mannuronic- and guluronic-acid residues and forms networks through divalent-cation-mediated crosslinking. Carrageenans are sulfated galactans whose conformation and gelation depend on sulfate distribution, 3,6-anhydrogalactose content, temperature, and counterion composition [14,16,59].

These charged polymers can also form polyelectrolyte complexes and multilayer structures through interactions between oppositely charged functional groups. Their behavior nevertheless varies with molecular characteristics, purity, extraction conditions, pH, ionic strength, and polymer concentration. Consequently, polysaccharides of the same nominal type may exhibit substantially different processability and coating-forming performance.

Fucoidan, ulvan, agar, laminarin, and marine microbial exopolysaccharides provide additional structural or biological functionality. However, most remain less standardized than chitosan, alginate, and carrageenan because their composition varies with biological source, season, extraction, and purification [12,20]. The following subsections examine the molecular characteristics, distinctive coating behavior, and principal limitations of the main marine polysaccharide matrices.

4.2.1. Chitosan

Chitosan is the most extensively investigated marine polysaccharide for edible coatings because it combines coating-forming capacity, biodegradability, biocompatibility, electrostatic reactivity, and intrinsic antimicrobial activity. It is produced through the partial deacetylation of chitin, mainly recovered from crustacean-processing residues, thereby supporting seafood by-product valorization [10,60]. Structurally, chitosan is a linear copolymer of β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine. Its functionality depends primarily on molecular weight, degree and pattern of deacetylation, purity, concentration, and formulation pH. Under acidic conditions, protonation of amino groups gives the polymer a positive charge and promotes interactions with microbial surfaces, proteins, anionic polysaccharides, seafood components, and incorporated bioactives [60,61].

The degree of deacetylation regulates the proportion of available amino groups and generally influences solubility, charge density, and antimicrobial potential. Molecular weight affects solution viscosity, chain entanglement, processability, network cohesion, and molecular mobility. High-molecular-weight chitosan commonly produces more viscous solutions and cohesive networks, whereas lower-molecular-weight fractions may exhibit greater solubility and biological activity [62]. Meaningful comparison among studies therefore requires reporting molecular weight, degree of deacetylation, concentration, solvent, pH, and viscosity.

The antimicrobial action of chitosan is mainly attributed to electrostatic interactions between protonated amino groups and negatively charged microbial-cell surfaces, which may increase membrane permeability and promote intracellular leakage. Additional mechanisms include chelation of essential metals, interference with nutrient transport, formation of polymeric layers around cells, and, particularly for low-molecular-weight fractions, interactions with intracellular components [60]. Its effectiveness varies with polymer characteristics, microbial species, pH, ionic strength, and food composition, and may decrease near neutral pH or in salt- and protein-rich seafood matrices. Chitosan readily interacts with phenolic extracts, essential oils, peptides, bacteriocins, enzymes, nanoparticles, and nanoemulsions through its amino and hydroxyl groups [15,51]. These interactions can enhance active functionality but may also modify solution behavior, coating formation, bioactive availability, and sensory properties.

The principal limitations of chitosan include restricted solubility near neutral pH, variable antimicrobial efficacy in complex food matrices, moisture sensitivity, and considerable variability in molecular specifications. The main structural and antimicrobial characteristics of chitosan are summarized in Figure 3.

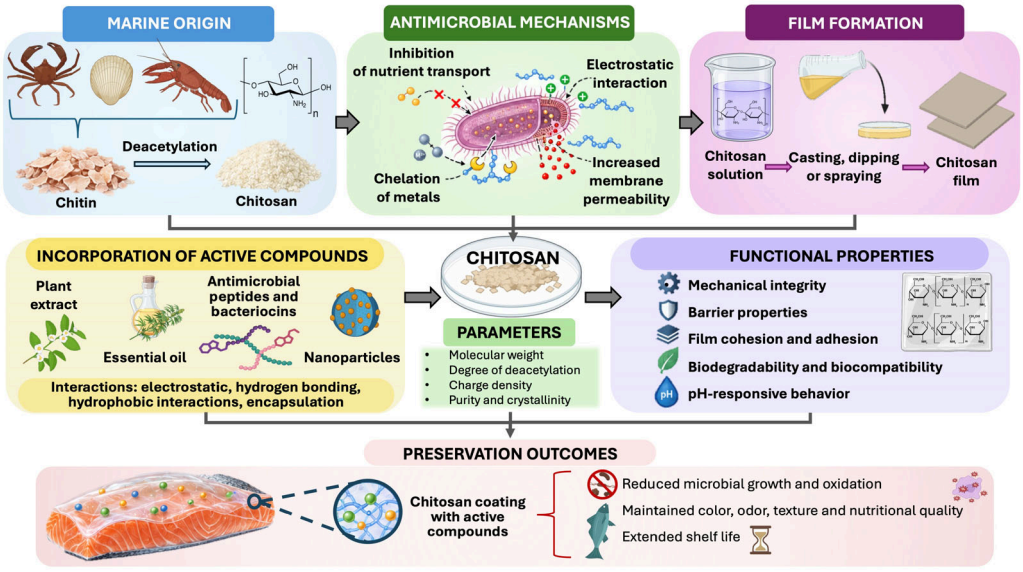


Figure 3. Molecular structure, coating-forming behavior, and antimicrobial mechanisms of chitosan-based active coatings for seafood preservation. This figure was created with BioRender.com.

4.2.2. Alginate

Alginate is an anionic, biodegradable, and biocompatible polysaccharide obtained mainly from brown macroalgae. Its capacity to form hydrogels under mild conditions makes it a widely investigated matrix for edible-coating and bioactive-delivery applications. Structurally, alginate is a linear copolymer of β-D-mannuronic acid (M) and α-L-guluronic acid (G), arranged in M-, G-, and alternating MG-blocks. Molecular weight, M/G ratio, and block distribution determine solution viscosity and gel characteristics. G-rich alginates generally produce stronger and more rigid networks, whereas M-rich materials form softer and more elastic structures [63,64].

Alginate gelation occurs primarily through ionic crosslinking with divalent cations, particularly Ca^{2+}. According to the egg-box model, calcium ions coordinate carboxyl groups from adjacent G-blocks, forming junction zones that stabilize the network [65]. Gel development depends on alginate and calcium concentrations, molecular characteristics, exposure time, and crosslinking method. Insufficient ionic association produces weak coatings, whereas excessive crosslinking may increase rigidity and limit adaptation to irregular seafood surfaces. Although alginate has little intrinsic antimicrobial activity, its hydrogel network can incorporate essential oils, polyphenols, peptides, bacteriocins, enzymes, probiotics, nanoemulsions, and other active agents [11]. Their retention and availability are influenced by matrix composition, M/G ratio, hydration, and crosslinking density.

Alginate–chitosan multilayers are particularly relevant because electrostatic interactions between alginate carboxyl groups and protonated chitosan amino groups can improve network cohesion and combine alginate gelation with chitosan antimicrobial functionality [15,16]. Their formation depends on polymer concentration, deposition sequence, charge density, pH, ionic strength, and layer thickness. The principal limitations of alginate include source-dependent variability, hydration- and ion-dependent network stability, limited intrinsic antimicrobial activity, and insufficient reporting of molecular specifications. These structural and gelation characteristics are summarized in Figure 4.

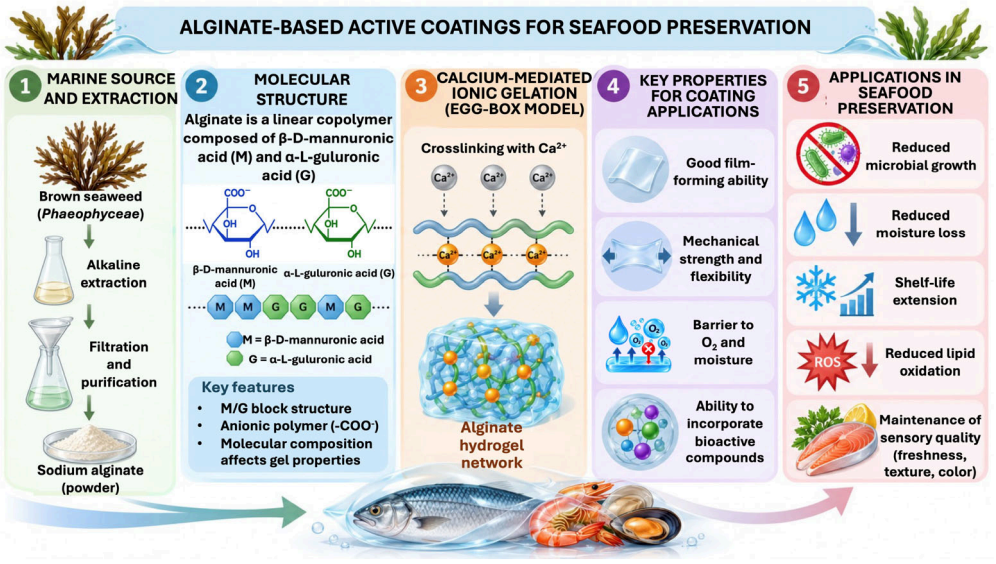


Figure 4. Molecular structure, calcium-mediated gelation, and distinctive characteristics of alginate-based active coatings for seafood preservation. This figure was created with BioRender.com.

4.2.3. Carrageenan

Carrageenan comprises a family of sulfated galactans extracted from red macroalgae. Its functionality depends on molecular weight, sulfate distribution, 3,6-anhydrogalactose content, chain conformation, and counterion composition, which determine solubility, rheological behavior, gelation, and network organization [66–68]. Its backbone consists of alternating β-(1→3)-D-galactose and α-(1→4)-D-galactose residues. Variations in sulfation and 3,6-anhydrogalactose content generate the principal κ-, ι-, and λ-carrageenan types. κ-Carrageenan contains one sulfate group per repeating disaccharide and forms strong, relatively rigid gels, particularly in the presence of K^+. ι-Carrageenan contains two sulfate groups and produces softer, more elastic Ca^{2+}-associated networks. In contrast, λ-carrageenan contains three sulfate groups, lacks 3,6-anhydrogalactose, and functions mainly as a thickener rather than as a gel-forming polymer [67].

Gelation involves a temperature-dependent coil-to-helix transition followed by counterion-mediated helix aggregation. Carrageenan type, polymer concentration, ionic composition, and cooling conditions therefore determine network rigidity, elasticity, porosity, and stability [66,69]. Insufficient ionic association produces weak networks, whereas excessive aggregation may increase brittleness and reduce adaptation to irregular seafood surfaces.

Carrageenan can incorporate antioxidants, essential oils, plant extracts, antimicrobial peptides, bacteriocins, nanoemulsions, and nanoparticles [14]. However, its highly hydrophilic and charged structure promotes moisture absorption and swelling, while its limited intrinsic antimicrobial activity commonly requires combination with active compounds or complementary polymers.

The principal limitations of carrageenan include dependence on counterion composition and processing temperature, variability among commercial types, and insufficient molecular characterization.

4.2.4. Emerging Marine Polysaccharides: Fucoidan, Ulvan, Agar, and Laminarin

Fucoidan, ulvan, agar, and laminarin are emerging marine polysaccharides whose distinctive monosaccharide composition, sulfation, branching, gelation behavior, and biological activity can provide additional functionality to edible coatings. Except for agar,

their limited independent coating-forming capacity generally favors their use as functional components in composite matrices rather than as primary structural polymers [20,70].

Fucoidan is a sulfated polysaccharide obtained mainly from brown seaweeds, including Fucus, Undaria, Laminaria, and Sargassum species. It consists predominantly of α-(1→3)- and α-(1→4)-linked L-fucose residues, although its composition varies considerably among sources. Molecular weight, branching, and sulfate content and distribution determine its physicochemical and biological properties [71,72]. Its antioxidant and antimicrobial activities support its incorporation into chitosan-, alginate-, carrageenan-, and gelatin-based coatings, but its comparatively weak structural performance limits its use as the principal matrix [12,20].

Ulvan is a sulfated heteropolysaccharide extracted from green seaweeds of the genus Ulva. It contains rhamnose, uronic acids, xylose, and sulfate groups that promote hydrogen bonding, ionic interactions, and hydrogel formation [73–75]. Ulvan may provide antioxidant, antimicrobial, and prebiotic functionality, although its composition varies with species, season, extraction, and purification, limiting reproducibility and industrial standardization [74,75].

Agar, obtained mainly from *Gelidium* and *Gracilaria*, consists primarily of agarose and agaropectin. Agarose forms thermoreversible networks through helix formation and aggregation [76]. Agar-based films can provide transparent and structurally stable matrices, while their physical and mechanical properties are strongly influenced by polymer and plasticizer concentration [76,77]. Because agar has limited intrinsic antimicrobial activity, it is frequently combined with chitosan, proteins, natural extracts, essential oils, or nanoparticles to develop active coatings.

Laminarin is a relatively low-molecular-weight β-(1→3)-glucan with occasional β-(1→6) branches, obtained mainly from brown algae such as *Laminaria* and *Saccharina* species [78]. Its limited gel-forming capacity restricts its structural role, but its antioxidant, antimicrobial, immunostimulatory, and prebiotic properties support its use as a functional additive [20,79].

These polysaccharides are therefore better considered complementary functional components than direct replacements for chitosan, alginate, or carrageenan. Their broader application requires standardized extraction, molecular characterization, compositional reproducibility, safety assessment, scalable production, and validation in coatings applied directly to seafood [11,12]. Across established marine-derived coating biopolymers, meaningful comparison requires systematic reporting of polymer-specific molecular descriptors together with formulation and processing variables. These include molecular weight, purity, and rheological behavior, as well as imino-acid composition and thermal stability for collagen and gelatin, degree of deacetylation and protonation conditions for chitosan, M/G ratio and block distribution for alginate, and sulfate content, 3,6-anhydrogalactose content, and counterion composition for carrageenan. These characteristics should be related to coating formation, interfacial behavior, active-compound release, and preservation performance under direct seafood-application conditions. The principal structural and functional characteristics of established and emerging marine-derived biopolymers are compared in Table 1.

Table 1. Comparative molecular characteristics, distinctive functions, coating potential, and principal limitations of marine-derived biopolymers used in seafood preservation.

Marine Biopolymer	Key Structural and Network Determinants	Distinctive Coating Contribution	Representative Quantitative Evidence	Main Limitations and Key Variables	Representative References
Marine collagen	Triple-helical integrity, molecular-weight distribution, imino-acid content, and fibrillar organization. Networks form through fibrillar assembly, hydrogen bonding, electrostatic interactions, and hydrophobic associations.	Cohesive networks with favorable mechanical integrity and oxygen-barrier performance under low-humidity conditions.	Reported denaturation temperatures are approximately 10–19.4 °C for cold-water fish collagen and 26.1–36.5 °C for warm-water fish collagen.	Limited thermal, moisture, and enzymatic stability; strong source dependence. Key variables include molecular weight, imino-acid composition, denaturation temperature, triple-helix integrity, and rheology.	[11,51,52,55,56,58,80,81]
Marine gelatin	Amino-acid composition, molecular-weight distribution, chain mobility, and reassociation during cooling or drying.	High processability, flexibility, surface spreading, and favorable oxygen-barrier performance under low-humidity conditions.	No directly comparable quantitative range was identified across the studies considered; values are strongly dependent on source and extraction conditions.	Moisture sensitivity, comparatively low thermal stability, and batch variability. Key variables include molecular weight, bloom strength, viscosity, gelation/melting temperatures, and rheology.	[13,15,51,54,58]
Chitosan	Molecular weight, degree and pattern of deacetylation, amino-group density, purity, and pH-dependent protonation.	Coating formation, surface adhesion, oxygen-barrier properties, intrinsic antimicrobial activity, and compatibility with bioactives.	Chitosans with 90%–99% deacetylation showed MIC values from approximately 0.03% to >0.1%; in one study, 99% deacetylation and 17.9 mPa·s viscosity provided the highest overall antibacterial effectiveness. Critical molecular-weight ranges of approximately 4–10 kDa have also been reported in datasets showing strong antimicrobial relationships.	Limited solubility near neutral pH, moisture sensitivity, and matrix-dependent antimicrobial performance.	[9,16,51,60–62,82,83]
Alginate	Molecular weight, M/G ratio, block distribution, carboxyl-group availability, and crosslinking density.	Mild Ca^{2+}-mediated gelation; useful for encapsulation, multilayers, and controlled release.	Reported alginates commonly contain approximately 30%–70% guluronic acid residues. Higher G-content/lower M/G ratios generally produce stronger and more rigid Ca^{2+}-crosslinked networks.	Moisture and ionic sensitivity, limited intrinsic antimicrobial activity, and crosslinking-dependent swelling or brittleness.	[11,51,63–65,84]
Carrageenan	Carrageenan type, molecular weight, sulfate distribution, 3,6-anhydrogalactose content, chain conformation, and counterion composition.	κ-Carrageenan forms strong gels; ι-carrageenan softer elastic networks; λ-carrageenan mainly provides thickening.	κ-carrageenan: approximately 25%–30% sulfate and 28%–35% 3,6-anhydrogalactose; ι-carrageenan: approximately 28%–30% sulfate and 25%–30% 3,6-anhydrogalactose; λ-carrageenan: approximately 32%–39% sulfate and essentially lacks 3,6-anhydrogalactose.	Moisture sensitivity, low intrinsic antimicrobial activity, and strong dependence on ions and temperature.	[66–69,85]

Table 1. *Cont.*

Marine Biopolymer	Key Structural and Network Determinants	Distinctive Coating Contribution	Representative Quantitative Evidence	Main Limitations and Key Variables	Representative References
Fucoidan	Molecular weight, branching, monosaccharide composition, and sulfate content/distribution.	Mainly antioxidant and antimicrobial functionality in composite matrices.	No broadly comparable quantitative range was identified because composition varies markedly with species, season, extraction, and purification.	Limited independent structural capacity and high source-dependent variability.	[20,71,72]
Ulvan	Sulfated rhamnose, uronic acids, xylose, branching, and charge density.	Antioxidant, antimicrobial, prebiotic, and complementary hydrogel functionality.	Quantitative structure–property relationships remain insufficiently standardized for direct comparison.	Variable composition and limited standardization.	[73–75]
Agar	Agarose/agaropectin ratio, molecular weight, polymer concentration, and thermal history.	Transparent, networks suitable as primary or composite coating matrices.	Reported functional values are highly formulation- and source-dependent; no single representative range was synthesized in this review.	Moisture sensitivity, brittleness, and limited intrinsic antimicrobial activity.	[11,76,77]
Laminarin	Low-molecular-weight β-(1→3)-glucan with occasional β-(1→6) branches.	Mainly antioxidant, antimicrobial, immunostimulatory, and prebiotic functionality as an additive.	Quantitative coating-specific structure–property data remain limited.	Limited independent coating-forming capacity and variable composition.	[20,78,79]

Note: Quantitative values represent selected structure–property relationships reported in the cited literature and should not be interpreted as universal specifications for seafood coatings. Many values were obtained from isolated polymers, gels, preformed films, or in vitro systems rather than coatings applied directly to seafood. Direct quantitative coating-level evidence remains limited for several marine-derived biopolymers.

5. Structure–Property Relationships Governing Marine-Derived Coating Performance

Marine-derived coating performance results from the interaction among polymer architecture, formulation, processing conditions, network organization, and behavior at the seafood surface. These factors determine coating formation, mechanical and barrier properties, interfacial stability, and active-compound retention and release. The following subsections integrate these relationships to support the rational design of product-specific coating systems.

5.1. Molecular Architecture and Coating Formation

Despite their different biological origins and chemical compositions, marine biopolymers follow common structure–property principles. Molecular weight, functional-group distribution, chain conformation, flexibility, crystallinity, and intermolecular interactions govern solution behavior, network formation, coating integrity, permeability, and active-compound mobility [9,57].

Coating formation involves polymer-chain organization during solvent evaporation, cooling, or ionic gelation. Collagen and gelatin form networks mainly through hydrogen bonding, hydrophobic associations, and chain entanglement; chitosan additionally develops electrostatic interactions; alginate undergoes divalent-cation-mediated crosslinking; and carrageenan forms helices followed by counterion-dependent aggregation [59,64]. These mechanisms generate networks with different degrees of cohesion, porosity, flexibility, and stability.

Functional-group availability is central to these interactions. Hydroxyl groups promote hydration and hydrogen bonding, protonatable amino groups contribute to electrostatic interactions and adhesion, carboxyl groups enable ionic crosslinking, and sulfate groups regulate hydration and ion-mediated association [60,64,66]. Their abundance and accessibility determine water affinity, polymer compatibility, crosslinking efficiency, and interactions with active compounds.

Quantitative evidence demonstrates that the effect of molecular architecture on coating-related functionality cannot be described by polymer identity alone. For chitosan, antimicrobial activity depends simultaneously on molecular weight, degree of deacetylation, solution viscosity, pH, and the target microorganism. Jung et al. [82] examined acid-soluble chitosans with degrees of deacetylation of 90 and 99% and different viscosities and reported minimum inhibitory concentrations ranging from 0.03% to above 0.1% against Gram-positive and Gram-negative bacteria. Among the materials evaluated, chitosan with 99% deacetylation and a viscosity of 17.9 mPa s showed the highest overall antibacterial effectiveness [82]. More recently, a quantitative analysis of 29 datasets reported a nonlinear relationship between chitosan molecular weight and antimicrobial activity, with critical molecular weights commonly ranging from approximately 4 to 10 kDa in datasets showing the strongest statistical fits [83]. These findings indicate that molecular weight and deacetylation should be reported together rather than interpreted as independent predictors of antimicrobial performance.

Alginate provides another clear example of composition-dependent functionality. Reported alginates commonly contain approximately 30%–70% guluronic acid residues, and the relative abundance and distribution of mannuronic and guluronic blocks strongly affect calcium-mediated network formation. G-rich alginates, corresponding to lower M/G ratios, generally form stronger and more rigid calcium-crosslinked networks, whereas M-rich alginates produce softer and more elastic gels. Molecular weight and G-block distribution also contribute to gel strength, indicating that M/G ratio alone is insufficient to predict mechanical performance [63,64,84]. These differences are directly relevant to

coating integrity because excessive rigidity may promote brittleness, whereas highly M-rich networks may provide greater flexibility but lower resistance to deformation.

Carrageenan functionality is similarly governed by sulfate substitution, 3,6-anhydrogalactose content, and counterion composition. κ-Carrageenan generally contains approximately 25%–30% sulfate groups and 28%–35% 3,6-anhydrogalactose, whereas ι-carrageenan contains approximately 28%–30% sulfate and 25%–30% 3,6-anhydrogalactose. λ-Carrageenan has a higher sulfate content, approximately 32%–39%, and lacks 3,6-anhydrogalactose, which contributes to its predominantly thickening rather than gel-forming behavior. Increasing sulfate substitution generally increases electrostatic repulsion and is associated with reduced gel strength. Counterion identity is also critical: K+ preferentially promotes κ-carrageenan gelation, whereas Ca2+ strongly promotes ι-carrageenan gelation. In mixed κ/ι systems, combinations of K+ and Ca2+ can increase network stiffness and modify gel homogeneity [66,69,85].

For marine collagen, thermal stability is strongly associated with amino acid composition, particularly the abundance of the imino acids proline and hydroxyproline, which stabilize the triple-helical structure. Studies comparing marine teleost collagens have demonstrated greater triple-helix stability in species with higher proline and hydroxyproline contents [80]. Consistent with this relationship, reported denaturation temperatures for collagen from cold-water fish are commonly approximately 10–19.4 °C, whereas values of approximately 26.1–36.5 °C have been reported for warm-water fish collagen. These differences are important for coating processing because collagen sources with lower thermal stability may undergo structural disruption at temperatures tolerated by collagen obtained from warm-water species [81].

These quantitative relationships should nevertheless be interpreted according to the experimental system from which they were obtained. Many molecular structure–property relationships have been established using isolated polymers, hydrogels, preformed films, or in vitro antimicrobial assays rather than coatings formed directly on seafood. Therefore, the reported ranges provide mechanistic guidance for formulation design but should not be interpreted as universal performance thresholds for seafood coatings. Direct validation under realistic conditions of surface hydration, ionic strength, temperature, and refrigerated storage remains necessary.

Coating formation also depends on polymer concentration, viscosity, pH, ionic strength, deposition method, drying conditions, and seafood-surface characteristics. These variables regulate spreading, drainage, coating pickup, thickness, uniformity, porosity, and adhesion. Therefore, coating performance cannot be inferred from polymer chemistry or from properties measured in preformed films alone. Rational formulation must combine sufficient network cohesion with flexibility, interfacial stability, controlled permeability, and the molecular mobility required for sustained active-compound release [7,15,41,59].

For thermoreversible coating matrices such as gelatin, carrageenan, and agar, processing and application temperatures should be established according to the specific polymer source, concentration, ionic environment, formulation, viscosity, and gelation or melting behavior rather than inferred solely from polymer identity. When relatively warm coating solutions are applied to raw seafood, the temperature and exposure time at the product surface should also be considered to avoid unintended thermal effects. Likewise, gelation or melting properties alone should not be interpreted as evidence of coating stability during cold-chain temperature abuse without direct experimental validation under relevant storage conditions.

5.2. Wettability, Spreading, and Adhesion at the Coating–Seafood Interface

The effectiveness of an edible coating depends not only on its bulk properties but also on its ability to wet, spread over, and remain attached to the seafood surface. These

interfacial phenomena determine coating coverage, thickness, uniformity, continuity, and resistance to delamination during storage. They are particularly relevant for seafood because muscle surfaces are moist, chemically heterogeneous, topographically irregular, and dynamically modified by postmortem exudation.

Wettability is commonly evaluated through the contact angle (θ) formed between a coating droplet and the food surface. Lower contact angles generally indicate greater affinity of the liquid for the substrate and improved wetting, although the interpretation depends on surface roughness, chemical heterogeneity, liquid absorption, and the time elapsed after droplet deposition. For an ideal smooth and chemically homogeneous surface, the interfacial balance can be described by Young's equation:

$$\gamma SV = \gamma SL + \gamma LV \cos \theta$$

where γSV, γSL, and γLV represent the solid–vapor, solid–liquid, and liquid–vapor interfacial tensions, respectively. The work of adhesion can be estimated using the Young-Dupré relationship:

$$Wa = \gamma LV \ (1 + \cos \theta)$$

where Wa represents the work of adhesion.
whereas the work of cohesion of the coating liquid can be approximated as:

$$Wc = 2\gamma LV$$

where Wc is the work of cohesion.

The spreading coefficient can consequently be expressed as:

$$Ws = Wa - Wc$$

where Ws is the spreading coefficient.
or, under the assumptions of Young's equation:

$$Ws = \gamma LV \ (\cos \theta - 1)$$

Complete spontaneous spreading corresponds theoretically to $Ws \geq 0$, whereas negative values indicate partial wetting. For edible coating systems, values approaching zero indicate progressively more favorable spreading, although the optimal value must also consider drainage, coating pickup, viscosity, and final coating thickness [37,38,86].

Direct measurements on fish demonstrate the practical importance of these relationships. Alcântara et al. [37] reported a surface tension of 63.80 mN m^{-1} for Nile tilapia (Oreochromis niloticus) fillets, including polar and dispersive components of 49.98 and 13.82 mN m^{-1}, respectively. For chitosan and fish-gelatin coating formulations, the best experimental spreading coefficients were −13.565 and −10.762 mN m^{-1}, respectively. Increasing chitosan concentration increased the adhesion coefficient but reduced spreading, whereas glycerol modified these relationships differently depending on the polymer matrix [37]. These results demonstrate that increasing polymer concentration does not necessarily improve interfacial coverage, because greater viscosity and cohesive interactions may oppose spreading.

A similar relationship has been reported for chitosan coatings applied to *Scomberomorus brasiliensis*. Vale et al. [38] characterized the fish surface as having a surface tension of approximately 62.03 mN m^{-1} and evaluated formulations containing 1.5%–2.5% chitosan and 0.30%–0.60% glycerol. A formulation containing 2.0% chitosan and 0.60% glycerol produced a spreading coefficient close to zero relative to the other formulations, approx-

imately -11.72 ± 4.56 mN m^{-1}, and was subsequently selected for preservation trials. This provides an example in which interfacial characterization was used directly as a formulation-selection criterion rather than being treated only as a descriptive material property [38].

Surface free energy, however, should not be interpreted as a fixed property of seafood. Fish muscle, skin, crustacean surfaces, and processed seafood differ in protein, lipid, water, salt, mucus, and connective-tissue composition. Surface roughness further modifies the apparent contact angle by altering the effective solid–liquid contact area. During refrigerated storage, drip and exudate containing water, soluble proteins, salts, and low-molecular-weight compounds can form a transient interfacial layer that changes surface polarity, dilutes the coating, modifies local viscosity and ionic strength, and weakens polymer–substrate interactions. Consequently, contact angle and adhesion measured immediately after coating application may not fully represent interfacial stability during storage.

These considerations support evaluating interfacial performance using complementary measurements rather than contact angle alone. Whenever feasible, seafood-coating studies should report surface tension or surface free energy, initial and time-dependent contact angle, spreading and adhesion coefficients, coating pickup, final thickness, surface roughness or morphology, and evidence of coating continuity after storage. Such measurements would permit a more direct connection between coating formulation, interfacial behavior, and preservation efficacy.

These interfacial relationships are schematically integrated in Figure 5 (Step 4), which places wettability, contact angle, spreading, adhesion, coating pickup and thickness, surface morphology, hydration stability, and active-compound retention and release as quantitative validation parameters linking coating formulation with seafood-preservation performance.

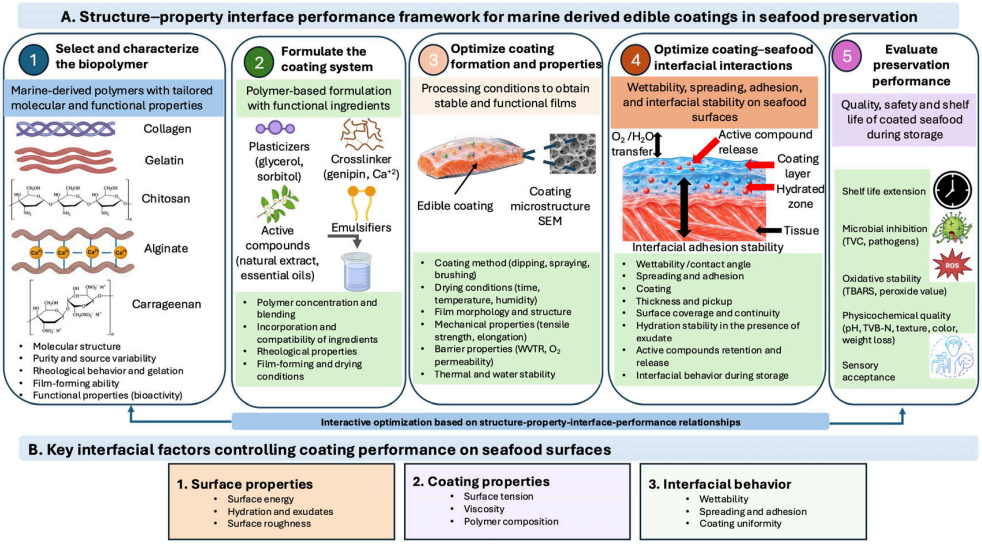


Figure 5. Structure–property–interface–performance framework for marine-derived edible coatings in seafood preservation. (**A**) Stepwise framework for coating development and validation. (**B**) Conceptual representation of the main factors governing coating–seafood interfacial behavior and performance. This figure was created with BioRender.com.

5.3. Barrier Properties and Mass Transfer

Marine-derived coatings act as semipermeable interfaces that regulate oxygen, water vapor, solute, and volatile-compound transfer between seafood and its environment. Complete impermeability is neither feasible nor desirable; coatings should instead limit detrimental transport while maintaining conditions compatible with product quality. Bar-

rier behavior depends on network organization, crystallinity, free volume, intermolecular interactions, thickness, continuity, and water affinity [7,8].

Evidence for the oxygen-barrier performance of collagen, gelatin, chitosan, alginate, and carrageenan is derived predominantly from preformed-film studies conducted under controlled relative-humidity conditions. Because conditioning and test relative humidity vary among preformed-film studies and are not consistently reported under directly comparable conditions, missing RH values were not reconstructed retrospectively, and film-derived oxygen-barrier values were not used as cross-study quantitative benchmarks. Instead, these data are interpreted as condition-specific mechanistic evidence, and oxygen-barrier values should not be compared or extrapolated without considering the corresponding RH and hydration state. Accordingly, film-derived barrier data are treated here as condition-specific mechanistic evidence rather than as quantitative benchmarks for the near-saturated interfacial environment of refrigerated seafood. In these systems, hydrogen bonding, chain entanglement, and ionic crosslinking can create tortuous pathways that restrict oxygen transport. However, oxygen-barrier values obtained from dry or moderately hydrated films should be interpreted as material-level evidence rather than as direct measurements of hydrated coatings formed in situ on seafood. At the surface of refrigerated seafood, high water activity and local relative humidity promote water sorption, plasticization, swelling, and increased polymer-chain mobility, which may substantially reduce oxygen-barrier performance [9,56,62,64]. Consequently, barrier properties measured in preformed films should not be directly extrapolated to coating performance on seafood without considering hydration state, coating continuity, thickness, interfacial stability, and the actual storage environment.

Importantly, reduced oxygen transfer should not be interpreted as evidence of improved microbiological safety. If a coating, particularly in combination with the surrounding packaging system, substantially restricts oxygen availability, the resulting environment may alter the competitive microbiota and requires product-specific safety assessment. In refrigerated seafood, reduced-oxygen conditions are of particular concern because nonproteolytic *Clostridium botulinum* may grow and produce toxin at refrigeration temperatures under permissive conditions. Therefore, oxygen-barrier performance should be interpreted together with storage temperature, pH, water activity, salt concentration, packaging atmosphere, intended shelf life, and, when relevant, pathogen-specific challenge testing.

Water-vapor control is more difficult because hydroxyl, amino, carboxyl, and sulfate groups promote moisture sorption and swelling. Moderate hydration may improve flexibility, adhesion, and active-compound mobility, whereas excessive water uptake reduces strength, increases permeability, and destabilizes the coating–seafood interface. This limitation is particularly relevant during refrigerated storage of moist seafood [52,87].

Blending, crosslinking, lipid incorporation, multilayer assembly, and nanocomposite reinforcement can improve barrier performance. Hydrophobic phases reduce water affinity, protein–polysaccharide blends combine complementary properties, and well-dispersed nanofillers increase diffusion-path tortuosity. Electrostatic complexation between oppositely charged polymers, including chitosan and alginate, can generate denser polyelectrolyte networks or multilayer structures [7,15,60,64,88].

Mass transfer also controls the release of antioxidants, essential oils, antimicrobial peptides, bacteriocins, and other active agents. Diffusion depends on network porosity, crosslinking density, polymer–solute affinity, hydration, thickness, and storage conditions. Excessively compact networks may restrict release, whereas highly porous or hydrated coatings may cause rapid migration and premature depletion. Effective design therefore requires balancing oxygen resistance, moisture regulation, structural stability, and sustained active-compound delivery.

5.4. Mechanical Performance and Structural Stability

Mechanical integrity is required to maintain coating continuity during application, handling, transportation, and refrigerated storage. Insufficient strength, flexibility, or adhesion can cause cracking, delamination, and defects that impair barrier performance and accelerate active-compound loss. Stability therefore depends on balancing tensile resistance, deformability, toughness, and interfacial adhesion rather than maximizing rigidity [6,59,89].

Mechanical performance is commonly evaluated through tensile strength, Young's modulus, elongation at break, puncture resistance, and toughness [90]. Ordered networks generally exhibit greater strength and stiffness, whereas plasticized or hydrated matrices are more flexible but less resistant. Excessively rigid coatings may fracture, while highly flexible systems may lack sufficient cohesion to remain continuous [91].

These properties reflect polymer structure. Collagen derives strength and dimensional stability from its triple helix, whereas gelatin generally exhibits greater elongation but lower stiffness because of its more mobile denatured chains [52,55,58]. Chitosan forms compact networks that may require plasticization to reduce brittleness [60,61]. G-rich alginate produces relatively rigid calcium-crosslinked gels, whereas M-rich alginate forms softer networks; similarly, κ-carrageenan is generally stronger and more brittle than ι-carrageenan [64–67].

From a mechanical perspective, excessive water uptake disrupts polymer interactions and reduces strength, modulus, cohesion, and adhesion. Maintaining coating integrity on high-water-activity seafood therefore remains a major challenge for hydrophilic matrices [8]. Mechanical modification should balance strength and extensibility because excessive crosslinking or filler loading can increase stiffness, reduce flexibility, and restrict bioactive diffusion. Poorly compatible essential oils or plant extracts may also weaken network cohesion by disrupting polymer interactions [59].

Adhesion is equally important because a mechanically resistant coating provides limited protection if it does not wet, cover, and remain attached to the seafood surface. Effective design should therefore balance strength, flexibility, hydration resistance, adhesion, and sufficient molecular mobility for controlled active-compound release [15].

5.5. Controlled Release of Bioactive Compounds

Marine-derived coatings can deliver antioxidants, antimicrobials, peptides, essential oils, enzymes, probiotics, and other functional compounds directly to the seafood surface. Controlled release may maintain effective interfacial concentrations during refrigerated storage, reduce premature depletion, and limit the amount of additive required [9].

Release kinetics depend on coating thickness, network porosity, free volume, chain mobility, hydration, crosslinking density, and polymer–bioactive affinity. Compact or highly crosslinked networks generally slow diffusion, whereas porous or strongly hydrated matrices accelerate migration [41,87]. Excessively slow release may prevent effective concentrations from being reached, while rapid migration can cause premature depletion or sensory alterations. Release behavior should therefore be matched to the targeted deterioration mechanism and storage period. Diffusion-controlled release can be described using mathematical models such as the Higuchi model, provided that its underlying assumptions are appropriately considered [92].

Bioactive retention is governed by hydrogen bonding, electrostatic interactions, hydrophobic associations, and van der Waals forces. Chitosan amino groups interact with anionic compounds, while ionic junction zones in alginate and carrageenan regulate network mesh size and diffusion. Collagen and gelatin can interact with phenolics, peptides,

essential oils, vitamins, and natural pigments through their polar and hydrophobic domains [56,59].

Release also depends on the molecular size, charge, solubility, volatility, and stability of the active compound. Hydrophilic molecules generally diffuse readily through hydrated matrices, whereas hydrophobic or volatile compounds may undergo phase separation or rapid loss. Nanoemulsions, liposomes, cyclodextrin inclusion complexes, lipid nanoparticles, and biopolymeric nanocarriers can improve dispersion, protect sensitive compounds, and prolong their activity [8].

Temperature, relative humidity, pH, ionic strength, and seafood water activity further modify coating hydration and diffusion. Multilayer, nanocomposite, and stimuli-responsive systems may provide greater release control while improving mechanical and barrier stability [59,91]. Loading efficiency, retention, migration, and release kinetics should therefore be quantified under realistic seafood-storage conditions rather than inferred solely from in vitro or food-simulant studies.

5.6. Design Strategies for Multifunctional Marine-Derived Coatings

High-performance marine-derived coatings require coordinated selection of the polymer matrix, formulation components, processing conditions, and preservation target. Multifunctional design should balance mechanical integrity, adhesion, gas and moisture regulation, bioactive stability, and controlled release rather than maximize one property. Because no biopolymer satisfies all technological requirements, blending is used to combine complementary functions. Gelatin–chitosan, alginate–chitosan, collagen–alginate, gelatin–carrageenan, and chitosan–fucoidan systems may integrate oxygen-barrier capacity, antimicrobial activity, ionic gelation, and structural stability [9,58,64]. Hydrogen bonding, electrostatic complexation, and chain entanglement can strengthen these networks, whereas unsuitable polymer ratios, pH, charge density, or ionic strength may cause phase separation [8].

Crosslinking and plasticization provide complementary control of network properties. Calcium and potassium ions stabilize alginate and κ-carrageenan, respectively, while transglutaminase, genipin, tannic acid, and citric acid may improve strength, thermal stability, and water resistance [9,64]. Plasticizers such as glycerol and sorbitol generally increase chain mobility and flexibility, whereas excessive concentrations may reduce mechanical strength and increase water-vapor permeability; plasticizer type and concentration should therefore be optimized [91,93].

Nanostructured reinforcement may improve mechanical and barrier properties by increasing network cohesion and diffusion-path tortuosity. Nanocellulose, chitin nanofibers, nanoclays, graphene oxide, and silica can reinforce the matrix, whereas nanoemulsions and nanocarriers improve the dispersion, protection, and release of poorly soluble or volatile bioactives. Excessive loading, however, may cause aggregation, brittleness, opacity, and safety concerns [59].

Multilayer coatings can separate complementary functions. Hydrophilic layers may promote adhesion and oxygen resistance, hydrophobic layers may limit moisture transfer, and intermediate layers may store active compounds. Layer-by-layer assembly permits control of thickness and release sequence, although repeated deposition complicates scale-up [8].

Formulation priorities should be determined from the dominant deterioration mechanisms of the specific seafood product rather than from broad product categories alone. Lipid-rich seafood may require greater emphasis on oxidative protection and sustained antioxidant delivery, whereas products in which microbial spoilage predominates may benefit from stronger antimicrobial and interfacial control. Crustacean products may additionally require consideration of melanosis, dehydration, oxidation, and microbial deterioration. These priorities

should therefore be established according to product composition, processing history, storage conditions, packaging atmosphere, intended shelf life, and sensory constraints.

5.7. Structure–Property Relationships and Their Impact on Seafood Quality Preservation

The technological relevance of marine-derived coatings should ultimately be demonstrated through measurable improvements in seafood quality and shelf life. This section therefore connects the material and interfacial properties discussed above with oxidative, microbial, physicochemical, and sensory preservation outcomes [9,51].

Oxidative protection requires both restricted oxygen transfer and sustained antioxidant availability, particularly in seafood rich in eicosapentaenoic and docosahexaenoic acids [2]. Dense networks formed through hydrogen bonding, chain entanglement, or ionic crosslinking may delay peroxide and thiobarbituric acid-reactive substance formation, while chitosan amino groups, sulfated polysaccharides, and incorporated antioxidants provide additional chelating or radical-scavenging effects [9,58]. These mechanisms may also reduce protein oxidation and its effects on water-holding capacity and texture. However, excessive crosslinking can restrict antioxidant diffusion, whereas excessive hydration may accelerate release and weaken coating integrity.

Microbial control also depends on polymer structure, active-compound release, and interfacial coverage. Chitosan activity varies with molecular weight, degree of deacetylation, charge density, concentration, pH, ionic strength, microbial species, and food-matrix conditions [61]. When chitosan is solubilized using organic acids, antimicrobial studies should include an appropriate acid-only or solvent control whenever possible, because the solvent system itself may contribute to microbial inhibition and could otherwise confound attribution of the observed effect to chitosan. Coating-solution pH and, when relevant, changes in seafood surface pH after application should also be reported to facilitate mechanistic interpretation. In active coatings, antimicrobial efficacy further depends on the dispersion, retention, and sustained availability of essential oils, phenolics, peptides, bacteriocins, or nanoparticles. Cracks, pores, poor adhesion, and delamination may create unprotected regions despite strong in vitro antimicrobial activity.

Hydration-induced loss of coating continuity and adhesion may increase drip formation, weight loss, and textural deterioration during seafood storage. These effects should be evaluated under the high-humidity conditions characteristic of refrigerated seafood.

Preservation efficacy should be assessed using indicators aligned with the intended coating function, including oxidation indices, microbial counts, volatile nitrogen compounds, moisture and weight losses, color, texture, active-compound release, and sensory acceptability. Improved mechanical or barrier properties alone are insufficient if the coating produces undesirable opacity, flavor, aroma, appearance, or mouthfeel. The most effective systems therefore maintain barrier protection, adhesion, flexibility, moisture stability, bioactive availability, and sensory compatibility throughout storage.

6. Bioactive Compounds Incorporated into Marine-Derived Coatings

Marine-derived biopolymers provide structural matrices and, in some cases, intrinsic antioxidant or antimicrobial activity. However, these functions are generally insufficient to control the simultaneous oxidative and microbial deterioration of seafood. Incorporating bioactive compounds can therefore produce multifunctional coatings that target several spoilage pathways during refrigerated storage [9,13].

Successful incorporation requires compatibility between the bioactive compound and the coating matrix to ensure adequate dispersion, retention, stability, and release at the seafood surface. Although the matrix may protect sensitive compounds, bioactive addition can modify solution rheology, wettability, permeability, mechanical integrity, and sensory

properties [11,59]. Formulation should therefore prevent phase separation, antagonistic interactions, excessive migration, and unacceptable changes in product quality.

6.1. Natural Antioxidants

Natural antioxidants delay lipid and protein oxidation through radical scavenging, electron or hydrogen donation, metal chelation, singlet-oxygen quenching, and interruption of oxidative chain reactions [94]. Their effectiveness depends on concentration, stability, matrix compatibility, processing retention, and release at the seafood surface rather than solely on in vitro antioxidant capacity.

Plant phenolics, including phenolic acids, flavonoids, tannins, catechins, and anthocyanins, stabilize radicals and chelate transition metals. Extracts from green tea, grape seeds, rosemary, oregano, and pomegranate peels have reduced lipid-oxidation products in marine-biopolymer coatings. Because composition varies with source, maturity, extraction, and storage, chemical characterization and dose standardization are essential. Excessive concentrations may disrupt polymer organization, alter color, and reduce flexibility.

Essential oils containing thymol, carvacrol, eugenol, or cinnamaldehyde provide antioxidant and antimicrobial activity, but low water solubility, volatility, instability, and intense sensory properties complicate incorporation into hydrophilic matrices. Nanoemulsification, encapsulation, and cyclodextrin complexes may improve dispersion and sustained release, although sensory acceptance must be confirmed in coated seafood.

Marine antioxidants, including phlorotannins, astaxanthin, fucoxanthin, and peptides obtained through the hydrolysis of marine proteins, may provide antioxidant protection through radical scavenging, metal chelation, and singlet oxygen quenching. They may also enhance the light barrier properties of coatings while contributing to the valorization of marine biomass [2].

Functional performance is governed by molecular size, charge, solubility, hydrophobicity, matrix affinity, and release behavior. Combining phenolics, carotenoids, peptides, and essential-oil constituents may provide complementary protection while modifying UV-barrier, mechanical, and permeability properties. However, excessive loading may weaken the polymer network or impair color, aroma, and flavor. Component selection should therefore balance antioxidant effectiveness, coating stability, release kinetics, and sensory acceptance under realistic storage conditions.

6.2. Antimicrobial Compounds

Microbial spoilage is a major limitation to refrigerated seafood shelf life. Specific spoilage organisms, including *Pseudomonas* spp., *Shewanella putrefaciens*, *Photobacterium phosphoreum*, and lactic acid bacteria, generate volatile bases, trimethylamine, off-odors, and textural defects. Incorporating antimicrobials into marine-derived coatings provides localized protection at the seafood surface, where microbial adhesion and proliferation begin [4].

Efficacy depends on antimicrobial activity, stability, distribution, and release. Strong polymer–compound interactions may improve retention but restrict diffusion, whereas rapid migration can cause intense initial inhibition followed by premature depletion. Effective coatings must therefore sustain inhibitory interfacial concentrations without compromising structural or sensory quality.

Chitosan combines coating formation with intrinsic antimicrobial activity. Its protonated amino groups interact with negatively charged microbial surfaces, increasing membrane permeability and disrupting ion and nutrient transport. Activity varies with molecular weight, degree of deacetylation, concentration, pH, ionic strength, microbial species, and seafood composition [61,62].

Essential oils, plant extracts, antimicrobial peptides, and bacteriocins can broaden the inhibitory spectrum. Thymol, carvacrol, and eugenol mainly disrupt membranes, whereas bacteriocins such as nisin form pores in susceptible cells [39,40,95,96]. Although polymer matrices may improve stability and release control, efficacy can be limited by food-component interactions, poor diffusion, volatility, narrow target spectra, or sensory effects [95].

Multicomponent coatings may combine membrane disruption, metabolic inhibition, quorum-sensing interference, and suppression of adhesion or biofilm formation, but are not necessarily synergistic and may alter coating rheology, permeability, mechanical stability, flavor, or aroma.

Microbiological validation should distinguish between spoilage control and food-safety assessment. Studies addressing spoilage should use microorganisms relevant to the specific seafood product and storage conditions, whereas claims involving pathogen control require appropriately designed challenge studies, suitable controls, and safety-relevant endpoints. Reductions in spoilage microorganisms or extension of shelf life should not be interpreted as evidence of pathogen control or microbiological safety. Microbial counts should be interpreted together with spoilage metabolites, coating continuity and adhesion, active-compound release, and sensory acceptability to distinguish sustained preservation from transient in vitro inhibition.

6.3. Emerging Marine Bioactives and Nanotechnology-Based Delivery Systems

Marine organisms provide bioactive compounds that can complement plant-derived additives in active coatings. Examples include brown-algal phlorotannins, astaxanthin, fucoxanthin, marine-protein-derived peptides, and chitosan-derived chitooligosaccharides. Their antioxidant and antimicrobial activities depend on molecular weight, composition, charge, solubility, degree of sulfation or polymerization, and matrix compatibility [2].

Many marine bioactives are sensitive to oxidation, light, temperature, volatilization, and food-component interactions. Direct incorporation into hydrophilic matrices may also cause poor dispersion, phase separation, rapid migration, degradation, or sensory changes. Nanoemulsions and related nanoencapsulation approaches can improve the dispersion of hydrophobic or volatile essential-oil constituents, protect them during processing, and enhance their antimicrobial effectiveness [96].

Encapsulation may sustain antioxidant or antimicrobial concentrations and reduce burst release. Nanostructured carriers can also reinforce polymer networks and increase diffusion-path tortuosity, thereby modifying mechanical and barrier properties. These effects depend on particle size, surface chemistry, concentration, distribution, and polymer–carrier interactions. Poor dispersion or excessive loading may instead cause aggregation, opacity, brittleness, increased permeability, or uncontrolled release.

Preservation efficacy should not be inferred solely from encapsulation efficiency or in vitro activity. Particle stability, bioactive retention, migration and release, coating integrity, preservation indicators, sensory quality, and food-contact safety should be evaluated under realistic seafood-storage conditions. Marine bioactives and nanostructured carriers are therefore promising when activity, matrix compatibility, controlled release, sensory effects, and safety are considered jointly.

6.4. Representative Applications and Preservation Outcomes in Seafood

The technological relevance of marine-derived biopolymer coatings must ultimately be demonstrated through their performance when applied directly to seafood products. Direct seafood-application studies have evaluated collagen-, gelatin-, chitosan-, alginate-, carrageenan-, and composite-based coatings, but the evidence represented in the current

literature is concentrated primarily in fish and crustaceans under refrigerated storage. Comparatively fewer studies address mollusks, cephalopods, surimi and other processed aquatic products, frozen systems, or pilot-scale conditions. These systems differ considerably in polymer characteristics, formulation, active-compound concentration, deposition method, drying conditions, seafood species, storage temperature, analytical endpoints, and criteria used to define shelf life. Representative studies and their principal preservation outcomes are summarized in Table 2.

Table 2. Representative applications, preservation outcomes, and main reporting and validation gaps of marine-derived biopolymer coatings in seafood.

Seafood Product and Category	Coating System	Storage Conditions	Main Preservation Outcomes	Main Reporting or Validation Gap	Reference
Fresh salmon fillets (refrigerated seafood)	Collagen (4%, *w*/*v*) with lysozyme (0.1%–0.7%, *w*/*v*)	4 ± 1 °C for 15 days	Reduced microbial growth, TVB-N, and weight loss. The 0.5% lysozyme treatment provided the best overall quality balance, whereas 0.7% more strongly reduced TVB-N and bacterial growth but adversely affected sensory acceptability.	High lysozyme levels may impair sensory quality; coating thickness and lysozyme release were not evaluated.	[97]
White shrimp (*Litopenaeus vannamei*) (refrigerated seafood)	Gelatin–chitosan composite coating	Refrigerated storage for 14 days	Reduced total and psychrotrophic bacterial counts by >3 log cycles at the end of storage, delayed TVB-N formation, lipid oxidation, and weight loss, and maintained sensory quality up to 13 days compared with 7 days for the uncoated control (≈6-day shelf-life extension).	Polymer characteristics, thickness, adhesion, and barrier properties were insufficiently reported.	[98]
Grass carp (*Ctenopharyngodon idellus*) fillets (refrigerated seafood)	Fish gelatin with curcumin/β-cyclodextrin emulsion	4 °C	Reduced microbial growth, lipid oxidation, TVB-N, protein degradation, and weight loss while maintaining color and sensory quality.	Curcumin release, adhesion, and coating uniformity were not quantified.	[99]
Rainbow trout (*Oncorhynchus mykiss*) fillets (refrigerated seafood)	Carrageenan with lemon essential oil (1%, *w*/*v*)	4 ± 1 °C for 15 days	Delayed microbial growth and lipid oxidation; TVB-N remained <25 mg N/100 g at day 15, below the acceptability limit used in the study.	Only one oil concentration was tested; release, volatility, and aroma transfer require evaluation.	[100]
Rainbow trout fillets (refrigerated seafood)	Sodium alginate with resveratrol (0.1%–0.2%)	4 °C for 15 days	Reduced TVB-N, TBARS, and microbial counts and maintained better sensory quality.	Alginate structure, coating thickness, resveratrol retention, and release were not fully characterized.	[101]
Ready-to-eat fresh salmon (ready-to-eat product)	Sodium alginate with bacteriocin EFL4 (0.64 µg/mL)	4 °C for 8 days	Reduced viable counts, TVB-N, and K-value and maintained sensory quality.	Bacteriocin release and distribution were not determined; broader safety evaluation is required.	[102]
White shrimp (refrigerated seafood)	Microalgal exopolysaccharide with *Gracilaria gracilis* extract (0.5%–1.5%, *w*/*v*)	4 ± 1 °C for 8 days	Reduced TVB-N, TMA-N, oxidation, polyphenol-oxidase activity, and microbial growth while preserving texture and sensory quality.	Polymer composition, molecular weight, rheology, adhesion, and bioactive release require standardization.	[103]
Smooth-hound shark (*Mustelus mustelus*) fillets (refrigerated seafood)	Fish-skin gelatin with *Moringa oleifera* leaf extract	Refrigerated storage for 6 days	Reduced weight loss (~26%) and malondialdehyde (~70%) vs. uncoated control; delayed microbial and sensory deterioration.	Short storage period; thickness, adhesion, permeability, and active-compound release were not evaluated.	[104]

Table 2. *Cont.*

Seafood Product and Category	Coating System	Storage Conditions	Main Preservation Outcomes	Main Reporting or Validation Gap	Reference
Rainbow trout fillets (refrigerated seafood)	Chitosan nanoparticles (2%) with walnut green-husk extract (1.5 or 3%)	4 °C for 6 days	The 3% extract treatment produced the lowest microbial counts, TVB-N, peroxide value, and TBARS and maintained sensory quality.	Short validation period; nanoparticle migration, safety, and scale-up require evaluation.	[105]
Cazon fish (*Mustelus lunulatus*) fillets (iced seafood)	Muicle (*Justicia spicigera*) extract-chitosan coating	Ice storage for 18 days	Muicle, chitosan, and combined coatings retarded physicochemical and microbiological deterioration, including increases in TVB-N, pH, and microbial load relative to the control.	Sensory acceptability and applied-coating interfacial properties were not evaluated; interpretation of TVB-N in elasmobranchs remains species-dependent.	[106]
Rainbow trout fillets (refrigerated seafood)	Alginate–chitosan layer-by-layer coating containing fucoidan (0.5 or 1%, w/v) from *Sargassum angustifolium*	4 ± 1 °C for 16 days	Fucoidan-containing LbL coatings reduced microbial growth, TVB-N, TBARS, and weight loss and maintained sensory quality. Shelf life increased from 6 to 16 days; TVB-N remained 13.44–14.28 mg N/100 g at day 16 versus 32.20 mg N/100 g in the control.	Applied-layer thickness and adhesion were not quantitatively characterized; validation was limited to one fish species and laboratory-scale storage.	[107]
Ready-to-eat baked fish product (ready-to-eat product)	Chitosan (1%, *w*/*v*), alginate (1%, *w*/*v*), or chitosan–alginate bilayer coating	4 °C for 21 days and 14 °C for 7 days	Chitosan most effectively reduced aerobic microbial growth and water loss. Estimated shelf life increased from 7 to 21 days at 4 °C and from 2 to 7 days under temperature abuse at 14 °C.	Microbiological safety was assessed mainly through total aerobic counts rather than pathogen-challenge testing; validation was restricted to one RTE formulation.	[108]
Rainbow trout fillets (refrigerated seafood)	κ-Carrageenan coating with dill essential oil combined with oxygen-absorber packaging	Refrigerated storage for 20 days	Reduced microbial growth, TVN, lipid and protein oxidation, and organoleptic deterioration. Estimated shelf life was 4 days for control/KCA, 16 days for KCA + DEO, and ≥20 days for KCA + DEO + OA.	The combined hurdle design makes the independent contribution of the coating and oxygen absorber difficult to separate; interfacial properties and active-compound release were not directly quantified.	[109]
Black tiger shrimp (*Penaeus monodon*) (refrigerated seafood)	Alginate-based nanoparticle coating containing longkong pericarp extract (0.5%–1.5%)	4 °C for 14 days	The 1.5% extract formulation provided the strongest preservation effect, reducing physicochemical deterioration, polyphenol-oxidase activity, lipid and protein oxidation, and microbial growth during refrigeration.	Coating pickup, applied-layer thickness, adhesion, and bioactive release/migration were not quantified; scale-up and food-contact implications of the nanoparticle system require further validation.	[110]
Pacific white shrimp (*Litopenaeus vannamei*) (refrigerated seafood)	Sodium alginate–chitosan coating (1%/1%) containing cell-free supernatant of *Streptococcus thermophilus* FUA329	4 °C for 15 days	Suppressed total viable counts and increases in pH, TVB-N, and TBARS; reduced water loss and improved texture and sensory characteristics relative to the control.	The active composition of the cell-free supernatant is complex and was not fully resolved; release behavior and coating–surface interfacial properties require further characterization.	[111]

Table 2. *Cont.*

Seafood Product and Category	Coating System	Storage Conditions	Main Preservation Outcomes	Main Reporting or Validation Gap	Reference
Quick-frozen fish balls (processed/frozen aquatic product)	Chitosan ice coating (1.5%)	Repeated freeze–thaw cycles (up to seven cycles)	Reduced frost formation and thawing loss and better preserved water-holding capacity, texture, color, and microstructure by limiting ice-crystal growth and recrystallization during repeated freeze–thaw cycles.	Emphasis was primarily on physicochemical and structural quality; microbiological shelf-life validation and formal sensory acceptance were limited.	[112]
White-leg shrimp (iced seafood)	Chitosan coating containing nanoliposomes loaded with licorice-root hydroethanolic extract (1%)	Ice storage for 20 days	Licorice extract reduced browning, TBA, and FFA; chitosan-coated extract produced the lowest TVN, microbial counts, and discoloration. The nanoliposome–chitosan system also maintained acceptable peroxide value, WHC, and cooking loss.	The multicomponent coating/encapsulation system complicates attribution of individual effects; release kinetics and coating–seafood interfacial properties were not established.	[113]
Squid (*Illex argentinus*) muscle (cephalopod)	Fish gelatin (4%, *w*/*v*) with tea tree essential oil	4 °C for 12 days	The combined coating maintained WHC, texture, sensory quality, and flavor, slowed TVB-N accumulation, and altered spoilage microbial communities. Preservation remained effective through 12 days compared with faster deterioration of the untreated samples.	The mechanisms underlying microbial-community shifts were not functionally validated, and interactions between coating components and microbial communities were not systematically established.	[114]
Freshly shucked oysters (mollusk)	Fish gelatin from tilapia, grass carp, or sea bass with UV-C-irradiated gallic acid	0 °C for 8 days	Preserved color, sensory quality, and muscle structure; reduced lipid oxidation, microbial growth, TVB-N, and biogenic-amine formation. Shelf life was extended by approximately 4 days.	Short laboratory-scale validation; applied coating thickness, adhesion, active release, and pilot-scale performance require further assessment.	[115]

Note: Quantitative outcomes are reported relative to the corresponding controls when available. TVB-N acceptability limits are species- and study-dependent and should not be interpreted as universal rejection thresholds. Abbreviations: EFL4, bacteriocin produced by *Enterococcus faecalis* L04; TBARS, thiobarbituric acid-reactive substances; TMA-N, trimethylamine nitrogen; TVB-N, total volatile basic nitrogen.

For frozen seafood, conventional water glazing remains an established industrial reference for limiting surface dehydration and oxidative deterioration. Accordingly, studies proposing edible biopolymer coatings for frozen seafood should ideally include a conventional water-glazed treatment as a benchmark rather than relying solely on an uncoated control. Such comparisons are necessary to determine whether a novel coating provides a meaningful technological advantage over current commercial practice in terms of dehydration, oxidation, coating retention, sensory quality, processing feasibility, and economic performance.

An important distinction should be made between conventional refrigerated seafood and ready-to-eat (RTE) aquatic products because coating performance must be interpreted according to product form, processing history, microbiological status, and intended use. In conventional refrigerated seafood, coating efficacy is primarily evaluated in terms of delaying spoilage, oxidation, moisture loss, texture deterioration, and sensory rejection during storage. In RTE products, however, the coated product is intended for consumption without a subsequent microbial inactivation step. Therefore, post-processing contamination, microbiological safety, initial microbial status, compatibility with previous processing operations, maintenance of sensory acceptability, and product-specific shelf-life criteria require particular attention. Consequently, preservation responses observed in raw or

minimally processed refrigerated seafood should not be directly extrapolated to RTE products without product-specific validation.

Table 2 is intended as a critical selection of representative direct seafood-application studies rather than as a chronological or exhaustive inventory of all publications identified during the literature search. Consequently, the publication years represented in the table do not reproduce the full temporal distribution of the literature considered in this review. As summarized in Table 2, direct seafood validation remains heterogeneous and is dominated by laboratory-scale studies of conventional refrigerated seafood, whereas evidence specifically addressing ready-to-eat aquatic products remains comparatively limited. This distinction is important because preservation endpoints, microbiological concerns, processing history, and rejection criteria may differ substantially between these product categories. Several representative studies evaluate relatively short storage periods, commonly between 6 and 15 days, and direct comparison among systems is limited by differences in seafood matrix, initial product quality, formulation composition, active-agent concentration, application method, storage conditions, analytical endpoints, and criteria used to define shelf life. Consequently, the available evidence supports the preservation potential of marine-derived coatings but does not yet allow broad conclusions regarding the superiority of a particular polymer or formulation across seafood products.

To improve reproducibility and comparability, future seafood-coating studies should report, at minimum: (i) polymer source, molecular characteristics, purity, and concentration; (ii) complete coating formulation, including plasticizers, crosslinkers, and active compounds; (iii) solution properties such as pH, viscosity, and, when relevant, surface tension; (iv) application method, coating pickup, thickness, drying conditions, and coating uniformity; (v) interfacial properties including wettability, adhesion, surface coverage, and stability during storage; (vi) active-compound loading, retention, and release when active agents are incorporated; (vii) seafood species, product form, initial quality, control treatment, and relevant initial microbial or physicochemical characteristics; (viii) storage temperature, atmosphere, duration, and sampling intervals; and (ix) complementary microbiological, oxidative, physicochemical, and sensory measurements together with an explicit criterion for shelf-life determination. Pilot-scale validation and comparison with conventional preservation practices should also be encouraged when commercial translation is proposed.

The presence of freshwater fish in Table 2 reflects the scope of this review, which focuses on marine-derived coating materials and their application to aquatic foods rather than exclusively on marine-origin seafood species. Nevertheless, preservation responses observed in freshwater fish should not be assumed to be directly transferable to marine fish, crustaceans, mollusks, or processed aquatic products because composition, surface properties, deterioration pathways, and storage requirements differ among product categories. Direct validation remains particularly limited for mollusks, cephalopods, surimi and other processed products, frozen seafood, and pilot-scale applications.

For studies in which the biological source of the coating polymer was not explicitly reported, the material is identified by polymer type only, and a marine origin is not inferred solely from the polymer name.

A recurrent limitation is incomplete characterization of the coating as actually applied to the seafood surface. As highlighted in Table 2, coating thickness, coating pickup, wettability, adhesion, surface coverage, structural continuity, and active-compound retention or release are frequently not reported. In addition, shelf-life extension is sometimes inferred from selected microbiological or physicochemical indicators without simultaneously establishing sensory acceptability or an explicit product-specific rejection criterion. These omissions make it difficult to determine whether improved preservation results from the

intrinsic functionality of the polymer or active compound, from improved surface coverage and interfacial stability, or from differences in experimental design.

The structure–property–interface–performance relationships and validation requirements discussed throughout this review are integrated into the stepwise decision framework shown in Figure 5. The framework is intended to guide progression from definition of the seafood-preservation problem to polymer selection, coating formulation, direct interfacial validation, and demonstration of preservation and translation performance. At each stage, insufficient performance should lead to reformulation or reassessment before progression to the subsequent stage.

7. Emerging Technologies and Industrial Translation

Marine-derived coatings can limit oxidative and microbial deterioration, regulate mass transfer, and deliver active compounds during seafood storage. However, most systems remain at the laboratory scale because of raw-material variability, limited process standardization, application complexity, production costs, regulatory uncertainty, and insufficient validation under industrial processing, distribution, and storage conditions.

Future coating systems may incorporate freshness indicators, biosensors, and connected monitoring technologies, provided that these approaches demonstrate clear improvements in seafood quality assessment, preservation performance, scalability, and consumer acceptance. Nevertheless, increased technological complexity must provide demonstrable improvements in preservation, scalability, economic feasibility, and consumer acceptance.

Industrial translation requires reproducible raw materials, scalable deposition methods, safety and regulatory compliance, economic viability, and verified environmental performance. Marine by-product valorization may support circular bioeconomy strategies, provided that extraction efficiency, supply consistency, material functionality, and life-cycle benefits are adequately demonstrated.

7.1. Smart and Intelligent Marine-Derived Edible Coatings

Smart and intelligent marine-derived coatings extend conventional preservation by detecting or communicating changes in seafood freshness and storage conditions. Unlike active coatings, which directly delay deterioration through barrier, antioxidant, or antimicrobial effects, intelligent systems contain sensing components responsive to physicochemical, microbial, or environmental changes. Their integration may therefore combine product protection with real-time quality monitoring during storage and distribution [116,117].

pH-responsive colorimetric systems are particularly relevant because seafood spoilage generates alkaline metabolites such as ammonia, dimethylamine, trimethylamine, and other volatile bases. Natural pigments, including anthocyanins, curcumin, shikonin, and betalains, undergo visible pH-dependent color changes and can be incorporated into collagen, gelatin, chitosan, alginate, or carrageenan-based matrices. Some also provide antioxidant activity, allowing freshness indication and active preservation within the same coating [118].

Indicator response depends on the sensing compound, polymer matrix, seafood surface, and storage environment. Hydration, transparency, gas permeability, pigment–polymer affinity, and volatile-metabolite diffusion influence sensitivity, response time, color stability, and reversibility. Color changes should therefore be calibrated against microbial counts, volatile-base concentrations, sensory rejection limits, and other product-specific freshness indicators.

Biosensors, time–temperature indicators, radio-frequency identification systems, and wireless devices may complement edible coatings by monitoring microbial deterioration, temperature abuse, cold-chain history, and traceability [117]. Commercial application

nevertheless remains limited by pigment instability, environmental sensitivity, batch variability, calibration, scalability, food-contact safety, and regulation. Future research should prioritize stabilized sensing compounds, standardized thresholds, smartphone-assisted color analysis, and multifunctional coatings that provide monitoring and preservation without compromising integrity, edibility, or sensory acceptance [118].

7.2. Circular Bioeconomy and Sustainable Valorization of Marine Resources

The circular bioeconomy provides a framework for converting seafood-processing residues into renewable coating materials and functional ingredients rather than treating them as waste. Depending on species and processing method, seafood-processing by-products such as skins, scales, bones, fins, shells, viscera, and heads may account for up to approximately 70% of the total processed biomass [10,119].

Marine-derived coatings support this strategy by transforming fish connective tissues, crustacean shells, and seaweed biomass into coating-forming polymers and active ingredients. Their use may create added value, reduce disposal, and provide renewable alternatives to conventional food-contact materials [10,11,119]. However, sustainability should not be inferred solely from marine origin, renewability, biodegradability, or edibility. Extraction yield, energy and water consumption, chemical use, transportation, processing efficiency, and end-of-life behavior must also be considered.

Quantitative environmental assessments demonstrate that marine origin alone does not guarantee a lower environmental burden. For chitosan produced from shrimp-shell residues, a comparative environmental assessment of different chitin extraction and chitosan-conversion routes reported greenhouse-gas footprints ranging from approximately 184 to 1891 g CO_2-eq per g of chitosan, depending on the processing pathway. Electricity consumption was identified as a major environmental hotspot, while acid production, NaOH use, water consumption, and other processing inputs also contributed substantially to specific impact categories [120]. These results illustrate that the environmental performance of chitosan depends strongly on extraction chemistry, deacetylation conditions, energy source, and process efficiency rather than solely on the valorization of a seafood by-product.

Similar considerations apply to seaweed-derived polymers. Life-cycle assessments of seaweed biorefineries have identified fuel consumption and biomass drying as important environmental hotspots, whereas the environmental performance of alginate extraction is strongly affected by extraction yield [121]. More recent work comparing alginate-extraction protocols has likewise shown that extraction conditions can substantially alter water and energy requirements, chemical consumption, greenhouse-gas emissions, and the molecular characteristics of the recovered polymer [122]. Thus, extraction efficiency and polymer functionality should be evaluated together with environmental performance when proposing marine biopolymers as sustainable coating materials.

Marine biorefineries can improve resource efficiency by enabling the sequential recovery of multiple product streams from the same biomass and reducing residual waste; however, their economic feasibility remains dependent on process configuration, recovery yields, energy requirements, and production scale [123].

The potential environmental benefit of an edible coating should also account for the seafood losses that may be avoided through shelf-life extension. This aspect is especially relevant because the environmental burden associated with producing, refrigerating, transporting, and distributing seafood may be considerably greater than the mass of coating applied to the product. However, an environmental benefit should not be assumed solely from a reported increase in storage time. Life-cycle assessment should compare the additional burdens generated by biopolymer extraction, coating manufacture, active ingredients,

application, drying, refrigeration, and end-of-life management with the avoided impacts associated with reduced seafood loss. Such analyses should use experimentally demonstrated shelf-life extension and realistic waste-reduction scenarios rather than theoretical assumptions.

Commercial implementation is also influenced by seasonal and species-dependent raw-material availability, geographical distance between seafood-processing facilities and biopolymer-production sites, transportation requirements, extraction yield, chemical recovery, wastewater treatment, production scale, and consistency of polymer properties. Previous life-cycle studies of chitosan have shown that environmental profiles can differ substantially among supply chains because of differences in raw materials, chemical inputs, energy sources, processing locations, and transportation patterns. Therefore, laboratory-scale extraction efficiency cannot be extrapolated directly to industrial sustainability. Techno-economic analysis should accompany environmental assessment and include raw-material collection and stabilization, energy, water, chemicals, waste treatment, equipment, labor, transportation, coating manufacture, and application costs. At present, the limited availability of directly comparable industrial-scale economic and life-cycle data prevents general conclusions regarding the environmental or economic superiority of marine-derived coatings over conventional preservation systems.

7.3. Industrial Translation, Safety, and Regulatory Challenges

Despite extensive laboratory research, commercial adoption of marine-derived edible coatings remains limited by raw-material variability, production costs, scale-up difficulties, regulatory requirements, and insufficient standardization [55,61,70,124]. Many studies demonstrate preservation under controlled conditions without assessing throughput, coating uniformity, drying, storage stability, or compatibility with seafood-processing lines.

Marine-biopolymer composition and functionality vary with species, season, anatomical source, extraction, and purification. Industrial production therefore requires standardized specifications for molecular weight, degree of deacetylation or sulfation, amino acid composition, purity, rheology, and microbiological quality, supported by reproducible extraction and quality-control procedures [55,61,70,124].

Scale-up requires rapid and uniform application by dipping, spraying, or continuous deposition. Viscosity, drainage, adhesion, thickness, drying time, and resistance to surface moisture must remain consistent at higher production volumes. Multilayer systems, prolonged drying, precise temperature control, and costly encapsulation or crosslinking may limit industrial feasibility.

Safety assessment of edible coatings requires particular attention because the coating is intended to remain on the food and may be consumed together with the seafood product. Consequently, safety evaluation should consider the complete formulation rather than only the regulatory status of the individual biopolymer. Relevant factors include polymer purity, residual proteins, extraction reagents and solvents, crosslinkers, plasticizers, active compounds, degradation products, contaminants, and the expected level of dietary exposure. Marine-derived materials recovered from processing by-products should also be evaluated for microbiological quality and source-dependent contaminants, including heavy metals and other residues that may be concentrated during extraction or purification.

For seaweed-derived polymers, contaminant assessment should explicitly consider arsenic, cadmium, lead, mercury, and iodine because their concentrations can vary substantially among species, harvesting areas, and processing conditions. The European Commission has specifically identified arsenic, cadmium, iodine, lead, and mercury as relevant contaminants for monitoring in seaweeds and seaweed-based products. Consequently, extraction and purification procedures should be validated for their ability to

control these contaminants rather than assuming that polymer isolation alone ensures their removal [125].

Allergenicity is particularly relevant for marine-derived coatings. Collagen and gelatin obtained from fish may contain proteinaceous components derived from a recognized allergenic source, while chitosan obtained from crustacean shells requires adequate purification and assessment of residual proteins. In the United States, fish and Crustacean shellfish are classified as major food allergens, and ingredients containing proteins derived from these sources may require appropriate allergen declaration. Therefore, the biological origin, degree of purification, residual protein content, and applicable labeling requirements should be considered when marine-derived biopolymers are incorporated into edible coatings [126].

Regulatory status must also be evaluated for the specific ingredient, intended use, concentration, and jurisdiction rather than inferred from the general classification of a polymer as natural or edible. In the United States, ingredients may be permitted through food-additive regulations or may have a Generally Recognized as Safe status for specified uses. For example, carrageenan is regulated for food use under 21 CFR 172.620, but authorization of an individual ingredient does not automatically establish the safety or regulatory acceptability of a complete multicomponent edible-coating formulation [127].

In the European Union, regulatory assessment similarly depends on the identity and intended use of the ingredient. Novel ingredients or materials produced through new processes may fall within the scope of Regulation (EU) 2015/2283 on novel foods, and authorized novel foods are subject to specific conditions of use, specifications, and labeling requirements. Carrageenan requires particularly careful interpretation because its safety has been the subject of continuing scientific discussion. In its re-evaluation of food-grade carrageenan (E 407) and processed Eucheuma seaweed (E 407a), EFSA reported no concern regarding genotoxicity or carcinogenicity based on the available data, but identified uncertainties related to chemical characterization, exposure assessment, and biological and toxicological evidence and therefore considered the existing group acceptable daily intake of 75 mg/kg body weight per day to be temporary pending improvement of the database. Importantly, food-grade carrageenan should not be conflated with poligeenan (degraded carrageenan), a substantially lower-molecular-weight material that is not authorized as a food additive. These distinctions illustrate why regulatory status, molecular specifications, processing history, and intended use should be considered together when evaluating carrageenan-containing edible coatings [128,129].

Nanostructured delivery systems require additional consideration because nanoscale materials may exhibit physicochemical and biological behavior that differs from their conventional forms. Particle size and distribution, aggregation, dissolution, gastrointestinal fate, potential migration or release from the coating, exposure, and toxicological effects should therefore be characterized [130]. In the European Union, intentionally produced engineered nanomaterials used in food are subject to specific regulatory and risk-assessment considerations, including provisions under the Novel Food framework [131].

Labeling and consumer acceptance are also integral to commercial translation. Because edible coatings may contain marine proteins, crustacean-derived materials, essential oils, plant extracts, nanoparticles, or other active ingredients, labeling should accurately communicate ingredients and allergenic sources according to the applicable jurisdiction. Sensory effects, perceived naturalness, willingness to consume coated seafood, and transparency regarding active or nanostructured ingredients should be evaluated together with preservation performance. In addition, the biological source and processing route of marine biopolymers may affect suitability for religious or cultural markets. Halal and kosher compliance should therefore be verified through the relevant certification requirements

when products are intended for these markets, particularly when coatings contain ingredients of animal origin or processing aids whose source may not be evident from the final formulation.

Commercial translation requires effective, reproducible, affordable, and scalable coatings compatible with industrial operations. Green extraction, process integration, and scalable manufacturing strategies may improve resource efficiency and facilitate more consistent industrial implementation [123,124]. Pilot-scale validation, realistic shelf-life studies, techno-economic assessment, and collaboration among researchers, processors, manufacturers, and regulatory authorities remain essential.

8. Conclusions

Marine-derived biopolymers provide chemically and functionally diverse matrices for seafood coatings, but the evidence reviewed here demonstrates that preservation performance cannot be predicted from polymer identity alone. Coating effectiveness emerges from the combined influence of molecular characteristics, formulation and rheology, deposition conditions, interfacial behavior, hydration, coating continuity, and active-compound retention and release. Consequently, properties measured in isolated polymers or dry preformed films should not be directly extrapolated to hydrated coatings formed on seafood surfaces.

The available direct seafood evidence supports the potential of collagen-, gelatin-, chitosan-, alginate-, carrageenan-, and composite-based systems to delay microbial, oxidative, physicochemical, and sensory deterioration. However, comparison among formulations remains limited by substantial heterogeneity in seafood matrices, polymer specifications, coating composition, application conditions, storage protocols, and criteria used to define shelf life. Direct validation is also disproportionately concentrated in refrigerated fish and crustaceans, with considerably less evidence for mollusks, cephalopods, processed aquatic products, frozen systems, and pilot-scale applications.

A central conclusion of this review is therefore that reliable evaluation of marine-derived edible coatings requires quantitative linkage among polymer structure, coating-solution properties, behavior at the hydrated coating–seafood interface, and product-level preservation outcomes. Standardized characterization, appropriate controls, explicit shelf-life criteria, and direct assessment of coating thickness, wettability, adhesion, hydration stability, and active-compound release are essential for improving reproducibility and causal interpretation. Commercial translation will additionally require preservation efficacy to be demonstrated together with sensory acceptance, safety, regulatory compliance, scalability, economic feasibility, and environmental performance.

9. Future Perspectives

Future research should move from predominantly descriptive formulation studies toward hypothesis-driven validation of the structure–property–interface–performance relationships identified in this review. Particular priority should be given to determining which molecular and rheological variables most reliably predict coating formation and stability on moist seafood surfaces, and whether interfacial properties measured directly on seafood provide stronger predictors of preservation performance than properties obtained from isolated films or model substrates.

A second priority is to establish quantitative relationships between active-compound retention and release and the kinetics of specific deterioration processes. Rather than maximizing initial antioxidant or antimicrobial loading, future studies should determine whether matching release profiles to microbial growth, oxidation, or other product-specific deterioration pathways provides more effective and sustained preservation.

Seafood validation should also be expanded beyond short-term refrigerated studies on individual fish species. Greater attention is required for mollusks, cephalopods, crustaceans, processed aquatic products, frozen systems, and pilot-scale conditions. Studies should use the minimum reporting and validation parameters proposed in Section 6.4 so that coating performance can be compared across formulations, seafood matrices, and laboratories.

Finally, commercial translation should integrate preservation efficacy with safety, regulatory compliance, sensory acceptance, processing scalability, techno-economic feasibility, and life-cycle performance. Future studies should demonstrate not only that a coating extends shelf life, but also that the resulting reduction in seafood loss justifies the additional material, processing, environmental, and economic burdens associated with coating production and application.

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Abbreviations

The following abbreviations are used in this manuscript:

ADP	Adenosine diphosphate
AMP	Adenosine monophosphate
ATP	Adenosine triphosphate
EFL4	Bacteriocin produced by Enterococcus faecalis L04
EFSA	European Food Safety Authority
FAO	Food and Agriculture Organization of the United Nations
Hx	Hypoxanthine
HxR	Inosine (hypoxanthine riboside)
IMP	Inosine monophosphate
TBARS	Thiobarbituric acid-reactive substances
TMA-N	Trimethylamine nitrogen
TVB-N	Total volatile basic nitrogen
UV	Ultraviolet
w/*v*	Weight per volume

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