



Sustainable Marine Macroalgal Polysaccharide Films and Coatings: Toward Active and Intelligent Food Packaging System

Sweta Sinha*

Department of Chemistry, Amity University Jharkhand, Ranchi, Jharkhand, India-834001

*Corresponding author (sweta.sinha2203@gmail.com)

Abstract

Marine macroalgal polysaccharides have emerged as sustainable biopolymers with immense potential for developing active and intelligent food packaging systems. Derived from abundant and renewable seaweed biomass, polysaccharides such as alginate, agar, carrageenan, laminarin, ulvan and fucoidan exhibit excellent film-forming ability, biodegradability, and non-toxicity. Their intrinsic antioxidant and antimicrobial properties make them ideal for packaging materials that not only protect food but also enhance shelf life and quality. This review (2020-2025) comprehensively examines the extraction techniques, structural diversity and functionalities of marine polysaccharide, highlighting their suitability for edible films, coatings, and biodegradable bioplastics. Recent advancements in polymer blending, nanocomposite formation, and cross-linking strategies are discussed, which significantly improve mechanical strength, thermal stability, and barrier properties. Additionally, the integration of natural bioactive compounds enables real-time monitoring of food freshness, transforming conventional packaging into active and intelligent systems. Although challenges such as moisture sensitivity, moderate mechanical strength, and production scalability remain, marine macroalgal polysaccharides represent a promising and sustainable alternative to conventional plastics. By supporting circular economy principles and sustainable packaging initiatives, these biopolymers present innovative solutions to mitigate plastic pollution, reduce food waste, and promote environmental responsibility. This review highlights their potential to catalyze a paradigm shift in the food packaging sector, advancing high-performance, safe, and eco-friendly applications.

Article information:

Received: 18 March 2025

Accepted: 14 November 2025

Available online: 28 November 2025

Keywords:

Marine macroalgae

Polysaccharide

Edible films

Antimicrobial

Food Safety

Active and Intelligent packaging

© 2025

Indonesian Food Technologists

All rights reserved.

This is an open access article
under the CC BY-NC-ND
license.

doi: 10.17728/jaft.26242

Introduction

The pervasive accumulation of plastic waste represents a critical environmental and public health challenge, with annual marine plastic input exceeding 8 million tons. Conventional petroleum-based packaging not only persists in ecosystems but also introduces microplastics into the food chain, with studies detecting these particles in over 80% of commercial seafood and 90 % of edible salt brands, leading to an estimated human ingestion of 50,000-100,000 microplastic particles annually (Kuttykattil et al., 2023; Sinha et al., 2024; Lakshmayya et al., 2024). This crisis has catalyzed the search for sustainable alternatives, positioning biodegradable biopolymers from renewable resources at the lead of packaging innovation due to their compostability, reduced carbon footprint, and compatibility with a circular economy (Akinsemolu et al., 2024; Sinha, 2023, 2024).

Marine macroalgae (seaweed) have emerged as a particularly promising source, evidenced by a about

150% of rise in global research output over the last ten years, and a market forecast to exceed USD 1.5 billion by 2030 (Ross et al., 2023; Eger et al., 2022). This momentum is fundamentally driven by an inherent sustainability profile featuring rapid growth, high biomass yield, and minimal requirements for freshwater and land. Seaweed polysaccharides, primarily agar, alginate, carrageenan possess intrinsic functional properties, including exceptional film-forming capacity, selective gas barrier characteristics, and versatile gelation. These biopolymers also exhibit inherent bioactive functions, such as: sulfated polysaccharides like carrageenan demonstrate antimicrobial efficacy against pathogens such as *E. coli* and *S. aureus* (Kumar et al., 2025), while alginates show significant free-radical scavenging capacity (Krishnan et al., 2024; Cabral et al., 2021). These attributes make them ideal for developing active packaging systems.

This review critically assesses the latest advancements (2020-2025) in packaging materials

derived from marine macroalgal polysaccharides. It explores their structural characteristics, functional performance, and cutting-edge applications in active and intelligent food packaging, while also addressing prevailing limitations and commercialization challenges to facilitate the transition toward high-performance, circular packaging solutions that mitigate microplastic pollution and enhance food safety.

Marine Macroalgae: A Sustainable Resource for Biopolymers

Marine macroalgae also called seaweeds, are a diverse group of aquatic organisms vital to marine ecosystems, contributing approximately half of the planet's primary productivity (Pessarrodona et al., 2022). Taxonomically classified into red (Rhodophyta), brown (Ochrophyta/Phaeophyta), and green (Chlorophyta) algae based on pigmentation (Kajla et al., 2024). Historical records confirm the ancient use of algal derivatives, like carrageenan utilized as a food additive since from the 15th century and the discovery of agar in Japan (Mouritsen et al., 2024). Global seaweed cultivation increased by 1.4% in 2020, reaching over half a million tons, reflecting rising demand for algae-derived products across food, pharmaceuticals, cosmetics, and biofuel sectors (Peng et al., 2020). A key advantage of seaweed cultivation is its profound environmental benefit. It acts as a powerful carbon sink, sequestering an estimated 1-8 tons of CO₂ per hectare annually, contributing to global carbon mitigation efforts (Saravanan et al., 2023), while also aiding in nutrient bioremediation from aquatic systems (Kolandasamy et al., 2025). However, sustainable growth faces challenges, including habitat degradation, invasive species, and market volatility, necessitating interdisciplinary collaboration and supportive policies (Nakhate & van der Meer, 2024).

Each algal group synthesizes distinct, valuable polysaccharides. Red algae (e.g., *Gracilaria*, *Gelidium*) are primary sources of agar and carrageenan, sulfated galactans with bioactive properties, including prebiotic and immunomodulatory effects (Chumsook et al., 2023). Brown algae (e.g., *Laminaria*, *Fucus*) produce alginate, fucoidan, and laminarin, while green algae (e.g., *Ulva*, *Cladophora*) are rich in ulvan, an acidic sulfated polysaccharide (Hoque & Sultana, 2024; Elkaliny et al., 2024).

These diverse seaweed-derived polysaccharides have attracted significant interest for developing eco-friendly packaging materials due to their bioactive properties and functional versatility (Chumsook et al., 2023). A primary advantage of macroalgae derivatives is their inherent biodegradability; these biopolymers can be decomposed by microorganisms into simpler organic compounds and helps to mitigate plastic pollution. These polymers are inherently Bioactive and biodegradable, breaking down into organic compounds, which helps mitigate plastic pollution (Elkaliny et al., 2024). Their production aligns with biorefinery concepts, maximizing resource use by deriving multiple products from a single feedstock, and requires minimal land, often integrating with wastewater treatment for enhanced resource efficiency (Cotas et al., 2023).

Major Macroalgae in Food packaging

The transition to sustainable packaging increasingly incorporates macroalgae-derived polysaccharides such as alginate, carrageenan, agar, ulvan, fucoidan, and laminarin. Sourced from diverse species (Table 1), these biopolymers are typically isolated from harvested biomass through chemical, enzymatic, or mechanical treatments, with a growing shift toward greener extraction technologies (Otero et al., 2023).

Their biocompatibility, non-toxicity, and superior film-forming ability make them suitable for food, pharmaceutical, and cosmetic applications. In packaging, their functionality extends beyond basic containment. Active packaging systems utilize these polymers to interact with the food environment, releasing natural antimicrobials or antioxidants and regulating moisture, gas levels to prolong shelf life (Roopa et al., 2023). Furthermore, their adaptability enables integration into intelligent systems featuring freshness indicators, pH sensors, and contamination detectors. This dual role; replacing conventional plastics while adding value through enhanced protection and monitoring establishes seaweed polysaccharides as a key resource for next-generation, sustainable food preservation technologies. Major seaweed-derived polysaccharides employed in film and coating formulations are as follows:

Agar

Agar is an algae-derived biopolymer composed of alternating α (1-4) 3,6-anhydro L-galactose and β (1-3) D-galactose units, with sulphate content typically below 6% (w/w). It contains two major fractions, agarose, a neutral galactose polymer responsible for strong gel formation, and agarpectin, an anionic component enriched in sulphate and carboxyl groups (Ojanguren et al., 2021). Agar films are physiologically inert and can be modified with bioactive compounds or plasticizers to improve elasticity or flexibility (Guo et al., 2021). Agar exhibits low hygroscopicity, meaning it does not readily absorb bulk liquid water; however, its highly hydrophilic polymer matrix provides a pathway for water vapor molecules to diffuse, resulting in high water vapor permeability (WVP). This WVP is typically quantified using the standard ASTM E96 cup method (Sinha, 2024). Reported tensile strength values for pure agar films range from 20-60 MPa, which is comparable to alginate but lower than the 40-110 MPa range of chitosan films, indicating a clear need for reinforcement to compete with conventional materials (Lo Faro et al., 2023; Jayakody et al., 2022).

Industrial agar production involves sequential steps of seaweed separation, filtration, decanting, drying, and extraction. Alkali pretreatment enhances gelation by converting L-galactose-6-sulfate to 3,6-anhydro-L-galactose, a transformation critical for achieving high gel strength (Oliveira et al., 2024). Pretreatment is species-specific, *Gracilaria* sp. undergoes alkali treatment to remove pigments and improve yield, while *Gelidium* sp. is treated with acidified water followed by hot water extraction, filtration, freeze-thaw cycles, and dehydration (Ottolina et al., 2025; Vinagre et al., 2025). Traditional autoclaving at high pressure and temperature remains a common method,

effectively disrupting cell walls to yield clear, high-purity agar (Manning & Gol, 2021).

Carrageenan

Carrageenan, a sulfated polysaccharide extracted from red algae, is composed of alternating α -1,3 and β -1,4 linked D-galactose units, with its 15–40% ester sulfate content defining its κ , ι , and λ types. Its solubility is governed by ionic strength, temperature, pH, and cation concentration. Although sulfate and hydroxyl groups enhance hydrophilicity, which often compromises the mechanical integrity and water resistance of pure carrageenan films (Pereira et al., 2017). These films typically exhibit a tensile strength of 20–50 MPa, which is substantially lower than conventional packaging materials like polylactic acid (PLA) (50–70 MPa) and chitosan (40–110 MPa), emphasizing the necessity for reinforcement (Asadzadeh et al., 2023).

Enhancement strategies often involve blending with hydrophobic polymers or incorporating fillers to improve strength and moisture barrier performance. The gel strength and film integrity are directly correlated with a high 3,6-anhydro-D-galactose content and low sulfation, properties typically enhanced through alkali treatment. However, conventional extraction based on this method involving alkali treatment, washing, boiling, alcohol precipitation, and drying confines from low yield and high water consumption, escalating wastewater management costs. While more sustainable techniques like microwave-assisted, ultrasound-assisted, and enzymatic extraction offer improved efficiency and reduced environmental impact, their large-scale implementation is currently limited by high operational costs and the need for further process optimization.

Ulvan

Ulvan, also known as sea lettuce polysaccharide, is a water-soluble sulphated heteropolysaccharide obtained from green algae cell walls. Its structure comprises α and β (1,4)-linked monosaccharides, including sulphated rhamnose, xylose, glucuronic acid, and iduronic acid. The polymer features repeating disaccharide sequences, predominantly aldobiuronic acid, accompanied by minor *ulvan* biose units (Salehi et al., 2019). *Ulvan* possesses unique sugar components that distinguish it from other algal polysaccharides. Notable characteristics include exceptional metal-ion binding capacity, low viscosity, and aqueous gel-forming capability, with molecular weights spanning 1.5×10^5 to 2×10^6 Da (Istiqlaal et al., 2025). *Ulvan* rich algae provide higher yields and polysaccharide concentrations than terrestrial crops while demonstrating excellent film-forming characteristics. The cellulose fraction in *Ulva* species offers potential as filler or reinforcement material in bioplastic manufacturing. Its advantageous physicochemical properties enable thermos reversible gel formation, attributed to its polyanionic nature and presence of diverse functional groups, including hydrophilic moieties and hydrophobic groups (Istiqlaal et al., 2025). Multiple extraction techniques can isolate *ulvan*, including acid and enzymatic extraction, hot water extraction with precipitation, chemical cross-linking, Soxhlet extraction, carboxymethylation with solvent

casting, ultrasonics, microwave-assisted extraction, and autoclaving. Evidence shows that hot acidic and ultrasonic treatments are highly efficient for extraction (Istiqlaal et al., 2025). Among these, the ultrasonic enzyme-assisted method proves superior, achieving the highest yield and significantly boosting antioxidant activity through vibrational cavitation processing (Istiqlaal et al., 2025; Chen et al., 2021).

Alginates

Alginates are linear polysaccharides composed of alternating β (1 $\rightarrow$ 4) linked D-mannuronic acid (M) and α (1 $\rightarrow$ 4) linked L-guluronic acid (G) units. Variations in M/G ratio depend on species, growth season, and environmental conditions, which significantly influence gel strength, flexibility, and thermal stability (Abka-Khajouei et al., 2022). These hydrophilic polymers possess good biocompatibility and are widely recognized as safe for food contact applications, as supported by the U.S. Food and Drug Administration (FDA) (Hurtado et al., 2022). Alginates exhibit excellent thickening, stabilizing, and gelling abilities but suffer from high water sensitivity, limiting their direct use in packaging. Upon interaction with divalent cations such as Ca^{2+} , alginates undergo ionotropic gelation to form thermos irreversible, water insoluble gels. Low M/G ratio alginates form strong, brittle gels with excellent thermal resistance, while high M/G ratio alginates demonstrate greater elasticity (Abka-Khajouei et al., 2022). A significant challenge for these biopolymers is their high water affinity, which, despite strong film formation and biodegradability, causes swelling and loss of mechanical integrity under humidity. Consequently, a key strategy involves blending them with hydrophobic agents or nanofillers to improve moisture resistance (Zhou et al., 2024).

Extraction processes commonly use alkaline conditions at 60–100°C, though milder industrial protocols (25°C) help preserve polymer molecular weight. Emerging green technologies, including enzyme-assisted, microwave-assisted, and ultrasound-assisted extraction have demonstrated enhanced yields, reduced impurities, and lower energy consumption, facilitating cleaner and more sustainable production routes (Nesic et al., 2023). In terms of mechanical properties, pure alginate films exhibit tensile strength values in the range of 30–70 MPa and elongation at break of 5–20%, depending on plasticizer content and degree of crosslinking. These values compare favourably with chitosan films (40–60 MPa, 5–15% elongation) and fall slightly below those of PLA films (50–150 MPa, 2–10% elongation) (Eslami et al., 2023). The functional properties of seaweed biopolymers can be optimized through strategic reinforcement. Incorporating fillers like nanocellulose, starch, or polyvinyl alcohol addresses brittleness by enhancing tensile strength and flexibility. Concurrently, the moisture and oxygen barrier performance of alginate films is reinforced through methods like ionic cross-linking or hydrophobic additives. These modifications enable the development of advanced, biodegradable active packaging systems capable of controlled atmosphere management and the integration of functional compounds, such as antimicrobial and antioxidant agents. (Lavrič et al., 2021).

Fucoidan

Fucoidan represents a complex, heterogeneous anionic sulphated polysaccharide with a backbone of α -L-fucopyranose residues connected through (1 $\rightarrow$ 3) and (1 $\rightarrow$ 4) bonds (Kurera et al., 2024). The structural complexity of fucoidan arises from its branched architecture and the presence of various sulfate ester groups, which contribute to its unique functional properties. The sulfate content typically ranges from 20% to 40% depending on the algal source, extraction method, and environmental conditions during seaweed growth. The enzyme-assisted extraction of polysaccharides from the brown alga *Ecklonia radiata* (Charoensiddhi, et al., 2020), utilizing a series of commercially available enzyme mixtures under varying pH conditions. While enzyme treatments minimally affected yield, they influenced extracted polysaccharide molecular weight. High buffer salt concentrations adversely impacted extraction efficiency (Quitério et al., 2022). The molecular weight of fucoidan varies considerably, ranging from 10 kDa to 100 kDa, depending on the extraction conditions and algal species.

Conventional *fucoidan* extraction involves acid hydrolysis at elevated temperatures, typically between 70 and 90 °C, followed by precipitation and purification steps (Quitério et al., 2022). However, harsh extraction conditions can lead to polymer degradation and loss of sulphate groups. Alternative extraction methods, including enzyme-assisted, ultrasound-assisted, and microwave-assisted techniques, have been developed to preserve structural integrity and bioactivity. Fucoidan exhibits remarkable film-forming properties and can be processed into transparent, flexible films with good mechanical strength. Its inherent antimicrobial, antioxidant, and antiviral activities make it particularly attractive for active packaging systems (Iqbal et al., 2024). Bioplastic production from algae depends heavily on extracted polysaccharide types, as all algal species contain substantial quantities of these biomaterials. Polysaccharide content ranges from 4% to 68% in Chlorophyta, 63% to 76% in Rhodophyta, and 66% to 70% in Phaeophyta. These percentages fluctuate based on species identity and seasonal variations, influencing final product unit costs (Kumar et al., 2021). Additionally, bioplastics can be produced from algal processing waste, reducing raw material requirements while minimizing solid waste generation.

Laminarin

Laminarin serves as the primary glucose storage polysaccharide in brown algae, comprising glucose monomers linked through β -1,3-glucosidic bonds with partial β -1,6-glucosidic branching (Ota et al., 2023). The degree of branching typically ranges from 3% to 6%, which influences the polymer's solubility, viscosity, and functional properties. Laminarin exists in two main forms: G-laminarin, which terminates with a glucose residue, and M-laminarin, which contains a mannitol residue at the reducing end. As a β -glucan family member, laminarin exhibits high solubility in aqueous and organic solvents, enabling enzymatic breakdown into glucose monomers or oligosaccharide structures by enzymes

present in soil and marine environments. This characteristic contributes importantly to reducing microplastic pollution (Mardhekar et al., 2025). The biodegradability of laminarin is enhanced by its structural features, as β -1,3-glucosidic linkages are readily recognized and cleaved by microbial enzymes in various environmental conditions.

Laminarin molecular weight approximates 5 kDa, though variations occur with polymerization degree. Brown algae may contain up to 35% laminarin under dry conditions. Multiple factors contribute to yield variations, including the specific algal species, its harvest season, habitat, and the extraction methodology employed (Pramanik et al., 2024). The extraction of laminarin can be accomplished through hot water extraction at temperatures between 50 and 80 °C, acid extraction using dilute mineral acids, or enzyme-assisted extraction using cellulases and hemicellulases (Van Breda et al., 2023). The film-forming ability of laminarin enables the production of transparent and flexible films for food packaging. Furthermore, its profile as a biocompatible, non-toxic, and rapidly biodegradable polysaccharide positions it as a prime candidate for next-generation, eco-friendly packaging materials (Yang et al., 2025).

Application of Marine Macroalgal Polysaccharide Films and Coatings in Food Packaging

Marine macroalgal polysaccharide-based films and coatings have catalyzed transformative advancements in sustainable food packaging, particularly in edible coatings, biodegradable films, and active/intelligent packaging systems (Figure 1). These innovative solutions leverage the unique physicochemical properties of algal polysaccharides to enhance food quality, safety, and shelf life while addressing environmental concerns associated with conventional plastic packaging. The versatile nature of marine macroalgal materials enables incorporation of functional additives, biosensors, and nanoparticles, facilitating customized solutions tailored to specific food products and storage conditions. A key trend in current research is the development of advanced, multifunctional films and coatings engineered to synergistically combine essential barrier properties with active functionalities including antimicrobial and antioxidant effects and intelligent, real time monitoring features (Yang et al., 2025). These advancements align with industry demands for sustainable packaging that not only protects food but also communicates product freshness and quality to consumers. The integration of nanotechnology, bioactive compounds, and smart indicators into seaweed polysaccharides is advancing intelligent packaging systems. Key innovations demonstrating this paradigm shift are summarized in Table 2, highlighting materials with enhanced functionality for real-world applications. Edible Coatings from Marine Macroalgal Polysaccharides

Edible coatings formulated from marine macroalgal polysaccharides, particularly *alginate*, *carrageenan*, and *agar*, function as invisible protective barriers for perishable foods. These ultrathin layers create multi-functional shields that prevent moisture loss,

Table 1. Summarizes the key information of the Major Marine Macroalgae derived polysaccharides

Polysaccharide	Sources/Algae Species	Key Characteristics	Extraction Methods	Packaging Applications
<i>Agar</i>	<i>Gracilaria spp.</i> (Agar)	Forms transparent gels, high moisture permeability	Alkali treatment, hot water extraction, filtration,	Hydrogels for Food Preservation
<i>Carrageenan</i>	<i>Chondrus crispus</i> (Irish moss)	Water-soluble, Hydrophobic nature	Alkali treatment, precipitation. Microwave-assisted, enzyme-assisted.	Edible Coating and Packaging Films
<i>Alginates</i>	<i>Macrocystis pyrifera</i>	Biostable, nontoxic, stabilizes, thickens, emulsifies	Alkali treatment, Enzyme & ultrasound-assisted extraction	Oil Absorbent Materials
<i>Laminarin</i>	<i>Laminaria digitata</i> (Kelp)	Highly soluble in aqueous and organic solvents, Biodegradable	Varies based on algae species.	Edible Packaging Films
<i>Fucoidan</i>	<i>Fucus vesiculosus</i> (Bladderwrack)	Enzyme-assisted extraction can influence molecular weight	Enzyme-assisted extraction	Antimicrobial Packaging
<i>Ulvan</i>	<i>Ulva lactuca</i> (Sea Lettuce)	High metal-ion binding, low viscosities, gel-forming abilities.	Acid and enzymatic extraction, chemical cross-linking, ultrasonics, microwave-assisted extraction, autoclaving.	Biodegradable Food Packaging

limit oxygen exposure, and inhibit microbial contamination, thereby extending shelf life and reducing food waste. Nanocomposite coatings derived from algal polysaccharides are enhanced by incorporating nanoparticles, essential oils, and plant extracts to bolster their antimicrobial and antioxidant properties (Pastrana-Alta et al., 2025). For example, alginate coatings enriched with cinnamon essential oil and zinc oxide nanoparticles effectively extended strawberry shelf life by reducing respiration rates and inhibiting fungal growth (Ghasemi et al., 2023). Carrageenan-based coatings containing natural antioxidants like green tea extracts have shown remarkable effectiveness in preserving apple quality by preventing enzymatic browning and maintaining firmness (Kokkuvayil Ramadas et al., 2024). The field is advancing through multi-functional coating strategies. Double-layer polysaccharide coatings (e.g., chitosan-alginate) enhance preservation for seafood by optimizing barrier and mechanical properties (Jahangiri et al., 2024), while probiotic incorporation offers a new paradigm for active, health-promoting packaging. These solutions collectively address the critical demand for clean-label, sustainable preservation in the food industry.

Edible Films

Edible films derived from marine macroalgal polysaccharides are stand-alone, biodegradable sheets that provide protective barriers around food, controlling moisture migration, gas exchange, and microbial growth. These films are prepared independently and then applied to food products, offering flexible and efficient packaging solutions. The incorporation of reinforcing agents, plasticizers, and bioactive compounds has transformed simple polysaccharide films into multifunctional materials. For example, κ -carrageenan and alginate-based composite films have demonstrated

efficacy in cheese preservation, extending mold-free shelf life by up to 14 days under refrigerated storage compared to conventional packaging (Yerramathi et al., 2025). Similarly, alginate films reinforced with nanocellulose show enhanced strength and moisture barriers, while the incorporation of essential oils has been shown to extend the shelf life of poultry by 3-5 days during chilled storage via measurable antimicrobial action (Fotie et al., 2020). Advanced strategies like agar-carrageenan double-layers and cross-linking improve structural integrity, with nanoclays and metal oxides further enhancing barrier properties without losing its biodegradability (George et al., 2022), collectively paving the way for high-performance sustainable packaging.

Active and Intelligent Biofilms from Marine Macroalgal Polysaccharides

Active and intelligent biofilms derived from marine macroalgal polysaccharides represent advanced packaging technologies by dynamically interacting with food products and their storage environment. Active biofilms function by releasing antimicrobials or antioxidants, or by scavenging spoilage-inducing compounds like ethylene and oxygen, thereby directly extending shelf life. Intelligent biofilms integrate sensing mechanisms that respond to environmental changes, pH variations, temperature fluctuations, or microbial metabolite accumulation providing real-time information on food condition. The development of multifunctional packaging systems now emphasizes the convergence of active and intelligent properties. For example, nisin-containing alginate biofilms offer antimicrobial action (Wang et al., 2025), while carrageenan films with anthocyanin indicators provide visual spoilage detection, all within fully biodegradable matrices (Eghbaljoo et al., 2025). Emerging advances include nanosensors for volatile organic compounds and blockchain-integrated

QR codes on agar films for enhanced traceability (Palanisamy et al., 2025).

The commercialization of active and intelligent seaweed-based packaging is hindered by a fragmented global regulatory landscape. A primary challenge is the lack of harmonization between major markets, which dictates distinct and non-negotiable compliance pathways. In the United States, the Food and Drug Administration (FDA) typically evaluates components through either the Food Contact Notification (FCN) system or as "Generally Recognized as Safe" (GRAS) substances. This process demands exhaustive safety data and imposes strict, specific migration limits for any substance that may transfer to the food (Bhat et al., 2025). Whereas, in the European Union, the European Food Safety Authority (EFSA) governs under Framework Regulation (EC) No 1935/2004. While sharing the core goal of consumer safety, the EU framework often presents a more stringent and procedurally distinct hurdle. Key divergences include a different positive list of approved substances, unique migration testing methodologies and critically for innovation a requirement to demonstrate the efficacy of active packaging components is not explicitly mandated by the FDA (EFSA Panel on Food Additives and Nutrient Sources added to Food, 2012). Adherence to these frameworks is essential to ensure consumer safety and enable global market access for marine polysaccharide-based active and intelligent packaging (Sarkar et al., 2023). Where, this regulatory misalignment forces manufacturers to pursue separate, duplicative, and costly approval processes for each target market.

Smart Sensing Films and Coatings with Indicator Systems

Smart sensing films and coatings from marine

macroalgal polysaccharides integrate colorimetric fluorescent, or electrochemical indicators that monitor food quality and safety in real-time. These intelligent systems respond to specific chemical or biological markers associated with food deterioration, providing visual or electronic signals to consumers and supply chain stakeholders. Seaweed polysaccharides (alginate, carrageenan, agar) serve as versatile substrates for intelligent packaging, effectively hosting natural pH-sensitive pigments, oxygen sensors, and freshness indicators to monitor product quality (Guo et al., 2024). Alginate films embedded with curcumin or betacyanin extracted from beetroot exhibit distinct colour transitions across pH ranges, enabling detection of protein degradation and amine formation during meat spoilage (Khan et al., 2024). Carrageenan-based films containing TiO₂ nanoparticles demonstrate photocatalytic properties that enhance antimicrobial activity under UV exposure while serving as oxygen scavengers (Nugroho et al., 2025). Advanced systems incorporate multiple indicator functionalities within single film matrices, such as agar films with dual pH and ammonia sensors for comprehensive seafood freshness monitoring. Recent developments include electrochemical biosensors integrated into marine polysaccharide films that detect specific spoilage metabolites like histamine or biogenic amines through conductive nanomaterials (Torre et al., 2020). Smartphone-compatible colorimetric indicators represent emerging innovations, where consumers scan film colour changes using mobile applications that interpret freshness status and provide consumption recommendations. These smart sensing technologies bridge the gap between active preservation and intelligent communication, empowering consumers with transparent food quality information.

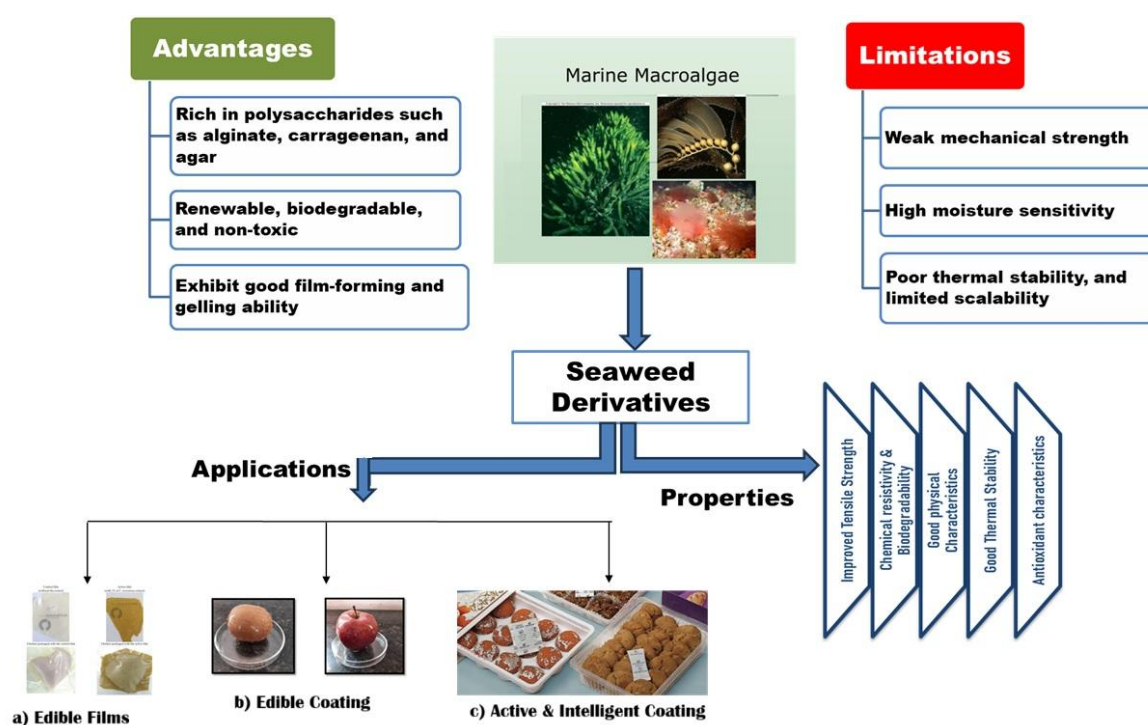


Figure 1. Properties and application of derived macroalgae: Seaweed

Table 2. Applications of Seaweed-Derived Biopolymers in Food Packaging

Biopolymer Composition (Coating Materials)	Food Application	Key Effects	Key Findings	Ref.
<i>Alginate + 1% pomegranate peel extract</i>	<i>Capsicum</i> (stored at 10 °C)	Inhibited <i>Colletotrichum gloeosporioides</i> growth	➤ Maintained color, firmness, weight, chlorophyll, and ascorbic acid content ➤ Extended shelf life to 20 days (sensory evaluation)	Setyawidati et al., 2018
<i>Kappa-carrageenan</i> (KC), <i>konjac glucomannan</i> (KGM), and <i>camellia oil</i> (CO)	<i>Chicken meat</i>	Reduced microbiological counts, total volatile nitrogen, and weight loss	Extended refrigerated storage to 10 days with 3.5% CO	Zhou et al., 2021
<i>Kappaphycus alvarezii</i> (red algae) extract	<i>Tomatoes</i>	Reduced weight loss, maintained juice content, ascorbic acid content, and acidity	Superior antimycotic and antibiotic activity compared to <i>Sargassum tenerrimum</i> (brown algae) extract	Ramani & Murugan, 2020
<i>Microalgal exopolysaccharide</i> (EPS) + <i>red seaweed extract</i> (<i>Gracilaria gracilis</i> , RSE)	<i>Shrimp</i> (chilled storage)	Reduced trimethylamine, reactive thiobarbituric acid, and total volatile bases	Improved color, hardness, and sensory attributes	Balti et al., 2020
<i>Algae extract</i>	<i>Apples</i> (freshly cut)	Inhibited enzymatic browning	Maintained peroxidase activity, lowest polyphenol oxidase activity	Augusto et al., 2022
<i>Semi-refined carrageenan</i> and <i>ulvan</i> blend	-	-	Enhanced metal ion chelation, significant hydroxyl radical scavenging activity (<i>ulvan</i>)	Ganesan et al., 2018
<i>Agar</i> , <i>starch</i> , <i>maltodextrin</i> , <i>Himanthalia elongata</i> , <i>Palmaria palmata</i> , <i>chitosan</i>	<i>Fish burgers</i>	Reduced microbial growth, delayed rancidity	-	Albertos et al., 2019
<i>Chitosan</i> , <i>alginate</i> , <i>fucoidan</i>	-	-	Improved antioxidant and barrier properties	Gomaa et al., 2018
<i>Alginate</i> with <i>tea polyphenols</i> , <i>essential oils</i> , or <i>capsaicin</i>	-	-	Enhanced antioxidant and antibacterial properties	Dou et al., 2018; Mahcene et al., 2020
<i>Sodium alginate</i> , <i>sodium carboxymethylcellulose</i> with <i>Lactococcus lactis</i>	-	-	Enhanced antibacterial properties	Zhang et al., 2018
<i>Sodium alginate</i> with <i>ferulic acid</i>	-	-	Enhanced antioxidant activity (negligible antibacterial effect)	Ma et al., 2019
<i>Agar</i> and <i>nano-bacterial cellulose</i> with <i>nanoparticles</i>	-	-	Improved mechanical strength, barrier properties, thermal stability, crystallinity	Yerramathi et al., 2021
<i>Seaweed polymers</i> with <i>coffee waste</i>	-	-	Enhanced thermal stability and mechanical properties	Wang et al., 2018
<i>κ-carrageenan + mulberry polyphenol extract</i> (MPE)	<i>Milk</i>	Enhanced water vapor and ramen-vis light barrier	➤ Antioxidant properties ➤ pH-sensitive & freshness monitoring capabilities	Rizal et al., 2023
<i>P. diocia</i> extract + <i>polyvinyl alcohol</i> (PVA)	<i>Minced chicken breast</i>	Reduced color deterioration	Antimicrobial properties of extract	Liu et al., 2019
<i>Laminaria japonica</i> & <i>Sargassum natans</i> extracts + <i>cellulose nanocrystals</i>	<i>Powders & instant foods</i>	Potential alternative to petroleum-based plastics	-	Reboleira et al., 2020
<i>Chitosan + Himanthalia elongata</i> & <i>Palmaria palmata</i> extracts	<i>Rainbow trout burgers</i>	Reduced microbial growth & lipid rancidity	Higher antioxidant activity	Doh et al., 2020
<i>Biofilms</i> with antioxidant compounds from <i>algae</i> extracts	<i>Various food products</i>	Reduced lipid oxidation & protein breakdown	Prevents food deterioration	He et al., 2016

Performance Optimization of Marine Algal Polysaccharide-Based Packaging Systems

Marine macroalgal polysaccharides possess inherent functional properties (Figure 2) that make them as promising candidates for advanced food packaging. While offering advantages in biodegradability, biocompatibility, and intrinsic bioactivity, their natural forms face limitations in mechanical strength, moisture resistance, and barrier performance. To overcome these challenges, targeted modifications through cross-linking, nanofiller reinforcement, and functional integration have been developed to tailor their properties for commercial applications (Thapliyal et al., 2024; Jagadeesh et al., 2021).

Mechanical Properties

The commercial viability of marine macroalgal polysaccharide films depends critically on their

mechanical performance, primarily Tensile Strength (TS), Young's modulus (YM), and elongation at break (EAB), which determine their ability to withstand physical stresses during handling and storage. Native polysaccharide films typically exhibit tensile strength values of 20-50 MPa, substantially lower than conventional petroleum-based plastics like polyethylene terephthalate (PET: 55-75 MPa) and bioplastic alternatives such as polylactic acid (PLA: 50-70 MPa).

Strategic modifications have demonstrated significant quantitative improvements in these parameters. For example, blending alginate with poly (lactic acid) enhances TS from 25-40 MPa to 35-56 MPa, representing an increase of approximately 40% compared to pure alginate films (Bayer, 2021), while incorporation of CaCO₃ fillers in carrageenan-based films increases TS by 25-50% (from 30-50 MPa to 37-75 MPa) and significantly improves stiffness (Chong et al.,

2019; Khalid, 2023). In agar-sugar palm starch composites, TS and YM show concentration dependent enhancement from 5-15 MPa to 10-30 MPa (>100% improvement) at 40% agar concentration (Rodríguez-Núñez et al., 2023; Fuzlin et al., 2025). Furthermore, the tensile strength and elongation properties of films made from sodium alginate improved with increasing CaCl_2 solution concentration (1%-3% w/v), effectively reducing film brittleness while maintaining flexibility (Metha et al., 2024).

Comparative analysis reveals that while pure marine polysaccharides show limited flexibility (EAB: 5-25%) compared to flexible plastics like low-density polyethylene (LDPE: 100-1000%), modified composites bridge this performance gap. Red algae polysaccharides show exceptional mechanical potential, with carrageenan-based films exhibiting superior TS (45-65

MPa), YM, and EAB compared to conventional mulch films (TS: 20-35 MPa) (Lopez Rodriguez, 2023; Caccamo et al., 2022). However, material modifications often involve properties compromises, like blending sodium alginate, carrageenan, and cellulose acetate blend show increased TS but reduced EAB from 15-25% to 8-12% due to restricted polymer chain mobility from hydrogen bonding (Ulrich & Faez, 2022). Different polysaccharides impart distinct characteristics, κ -carrageenan provides higher tensile strength (45-65 MPa) and elasticity (20-30% EAB), while alginate offers greater transparency (>85% light transmittance) and highly tunable mechanical properties through ionic cross-linking (Perera et al., 2021; Metha et al., 2024). These findings highlight that polymer compatibility and cross-linking mechanisms are critical for optimizing the functional profile of biopolymer film.

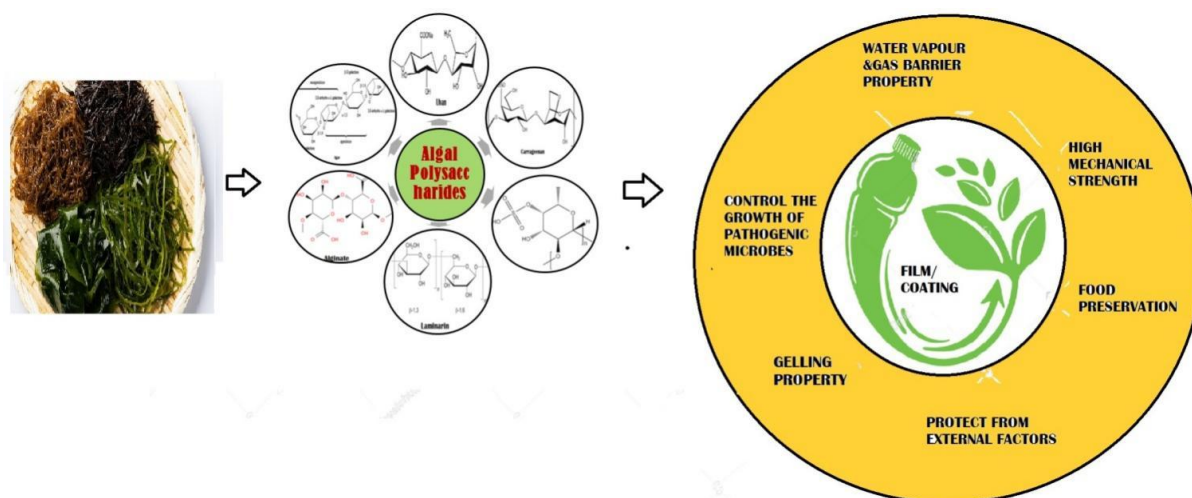


Figure 2. Key properties of macroalgae derivatives as sustainable food packaging material

Chemical Performances

Successful implementation of marine macroalgal polysaccharide films in food packaging demands thorough understanding of their chemical interactions with food products. These interactions govern safety, barrier behavior, and overall packaging functionality. The surface wettability of biopolymer composites, measured via contact angle, is directly influenced by marine polysaccharide incorporation. Research shows that while the addition of κ -carrageenan or fucoidan to PHB/PHBV matrices universally increases hydrophilicity, the degree of this effect varies, revealing distinct water interaction profiles based on the specific polysaccharide and polymer blend (Carina et al., 2021). The water interaction behavior was found to be polysaccharide-specific, with the PHB/ κ -CG blend demonstrating a marginally more hydrophobic character compared to the PHBV-based composites (Carina et al., 2021). Surface free energy analyses also support these observations. The hydrophilic hydroxyl and sulphate functionalities in κ -CG likely participate in polar interactions, resulting in elevated surface energy values. Fourier transform infrared (FTIR) spectroscopy provides additional powerful analytical capabilities for evaluating chemical modifications. Spectroscopic analyses revealed substantial increases in intermolecular

hydrogen bonding following agar incorporation (Bamps et al., 2023), confirming strong molecular compatibility between components. Since agar is a sulphated polysaccharide with inherently high hydrophilicity, its presence in composite films increased moisture absorption capacity. While marine polysaccharides consistently increase film hydrophilicity, swelling, and reduce water contact angles due to their anionic, hydrophilic character, their effect on crystallinity is highly system-specific. The ultimate crystalline structure, which governs key performance properties, depends critically on the structural compatibility between the polymer matrix and the polysaccharide.

Thermal Properties

Thermal characteristics, particularly melting temperature (T_m) and glass transition temperature (T_g), offer critical information about intermolecular interactions within marine macroalgal polysaccharide film matrices. These parameters are essential for food packaging performance, determining film behaviour under temperature fluctuations during manufacturing, distribution, storage, and consumer heating of packaged products (Bamps et al., 2023). Incorporating marine algal polysaccharides into biopolymer matrices substantially influences thermal stability characteristics.

Research on fucoidan-containing composite films has revealed improved thermal stability, indicating beneficial interactions between the marine polysaccharide and base polymer materials (Sharifian & Homaei, 2022). This enhancement likely originates from strengthened intermolecular forces and restricted polymer chain mobility following fucoidan integration into the film matrix. The molecular interactions between fucoidan's sulphated groups and hydroxyl functionalities in base polymers create more thermally stable networks that resist degradation at elevated temperatures. However, thermal property modifications depend heavily on specific polymer-polysaccharide combinations. Incorporating alginate into polylactic acid (PLA) films produced negligible thermal property changes (Baldwin, 2012), suggesting that alginate addition does not substantially interfere with PLA's crystalline organization. Whereas, polyhydroxybutyrate (PHB) films exhibited decreased thermal stability upon alginate incorporation, emphasizing the necessity of understanding specific molecular interactions between marine polysaccharides and base polymers, as these relationships fundamentally govern thermal behaviour.

The thermal response of composite films to marine macroalgal polysaccharides demonstrates complexity and strong dependence on component compatibility. While certain combinations such as fucoidan with particular base materials enhance thermal stability, other formulations show limited improvements (Iqbal et al., 2024). Impurities present in marine polysaccharide extracts can adversely impact thermal characteristics by disrupting polymer network formation or introducing thermally labile components. However, incorporating nanocellulose fibrils (Sharma & Hoque, 2023) has emerged as an effective universal approach for improving thermal stability across diverse biopolymer film systems. Nanocellulose's high crystallinity, extensive surface area, and ability to form strong interfacial bonds with polymer matrices contribute to enhanced thermal resistance, making it a valuable reinforcement strategy for developing temperature-stable packaging materials (Tian, 2024) from marine macroalgal polysaccharides.

Antimicrobial Properties

Marine macroalgal polysaccharides are promising candidates for advanced food packaging due to their intrinsic antimicrobial potential. While unprocessed algal extracts exhibit potent antibacterial activity (producing 12-18 mm inhibition zones against pathogens like *E. coli* and *S. aureus*), films made from purified alginate or carrageenan show markedly reduced efficacy, with microbial reductions typically below 1.0 log CFU/mL (Hamad et al., 2023; Badawy & Rabea, 2018). This efficacy gap highlights a key challenge and points to the need for incorporating additional antimicrobial agents into purified biopolymer matrices to develop effective active packaging. The functional performance of these films is highly dependent on the nature of the incorporated additives (Badawy & Rabea, 2018). Combining polysaccharides with natural antimicrobials enhances their preservative effect (Badawy & Rabea, 2018). Some nanomaterials (e.g., nanoclay, nanosilver) can reduce the intrinsic antibacterial activity of biopolymers like carrageenan, highlighting the need for

careful formulation (Majinyari, 2021). A more promising approach involves the targeted use of specific nanoparticles, e.g. agar films incorporating ZnO or Ag nanoparticles (0.5-1% w/w) exhibit effective and expanded antibacterial activity, achieving 2-4 log CFU/mL reductions against both Gram-positive and Gram-negative pathogens (Smola-Dmochowska et al., 2023). Such tailored approaches are essential for creating effective and sustainable active packaging solutions.

Antioxidant Properties

Contemporary biopolymer packaging technologies incorporating natural antioxidants provide sustainable, consumer-oriented alternatives to traditional packaging approaches. This evolution addresses growing demand for safer, healthier food packaging that reduces dependence on synthetic additives (Mazumder et al., 2025). Microwave-assisted extraction efficiently recovers polysaccharides from various algal species, particularly green seaweed, exhibiting exceptional radical scavenging abilities (Wu, 2017). For food packaging applications, aqueous seaweed extracts are highly advantageous due to their superior antioxidant capacity relative to extracts obtained using organic solvents (Saifullah et al., 2023).

Research confirms that the functional properties of carrageenan films are significantly enhanced through the strategic addition of natural antioxidants (mulberry extract, essential oils), which markedly increase their overall antioxidant capacity (Periyasamy et al., 2025). This demonstrates the considerable potential of marine algal polysaccharides in advanced active packaging. These advanced systems leverage synergistic effects to effectively inhibit lipid oxidation, prolong food shelf life (Singh et al., 2025), and reduce waste, thereby promoting a more sustainable food supply chain.

Morphological Structure Optimization

Morphological characteristics of marine macroalgal polysaccharide films critically influence their food packaging performance. Incorporating marine polysaccharides substantially affects film morphology; however, modification patterns depend on specific molecular interactions between marine polysaccharides and base biopolymers. Predicting morphological outcomes remains complex due to intricate material interplay. Consequently, achieving optimal blending is paramount, since structural inhomogeneities such as voids adversely impact the film's physicochemical properties and overall functionality (De Vargas et al., 2022).

Studies on composite films reveal that marine polysaccharides generally promote morphological homogeneity through strong interfacial compatibility. For example, PVA/sodium alginate (SA) films show uniform texture without phase separation, indicating robust molecular level interactions (Ghalsasi et al., 2025). Similarly, sugar palm starch (SPS)-agar composites form increasingly smooth and homogeneous surfaces with higher agar content, confirming favorable polymer compatibility (Rahman Khan et al., 2024). However, this trend can reverse at high concentrations, where excessive agar acts as a filler and creates

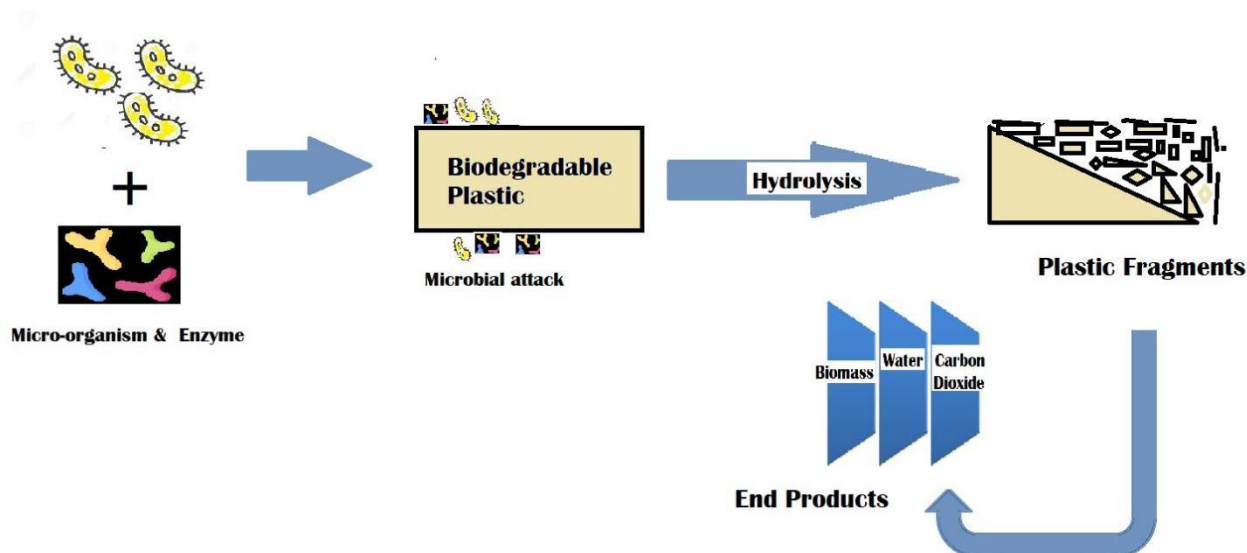


Figure 3. Biodegradability of Macroalgae derivative

cleavage structures, disrupting polymer-polymer bonding.

Scanning electron microscopy (SEM) examination of films incorporating κ -carrageenan into polyhydroxybutyrate (PHB) and PHBV matrices revealed smoother, more homogeneous surfaces compared to pure PHB films (Surendren, 2024). This indicates enhanced dispersion and compatibility between κ -carrageenan and biopolyesters, producing more uniform internal structures. The improved morphological characteristics translate to better mechanical integrity and barrier performance, essential for effective food packaging applications. These morphological improvements demonstrate that strategic selection and optimization of marine macroalgal polysaccharide-biopolymer combinations can yield films with superior structural uniformity, enhanced packaging functionality and commercial viability.

Gelling Properties

Marine macroalgal polysaccharides, particularly phycocolloids, offer compelling opportunities for developing innovative films and packaging materials. These natural gelling agents display exceptional hydrocolloidal characteristics, enabling water interaction and gel formation with adjustable textures (Rodríguez-Núñez et al., 2023). Specific gelling behavior depends on several critical parameters, including phycocolloid structure, concentration, temperature, pH, and syneresis tendency (Lomartire & Gonçalves, 2023). The distinctive gelling properties of marine phycocolloids, particularly carrageenan renowned for their exceptional strength, make them highly valuable as stabilizers, thickeners, and gelling agents (Lomartire & Gonçalves, 2023; Venugopal, 2019). For example, κ -carrageenan forms gels with remarkable room-temperature stability and superior strength (Qamar et al., 2024). These properties, combined with inherent high viscosity, establish them as ideal candidates for advanced biofilm and packaging systems (Li et al., 2025). However, their performance is directly influenced by extraction methods, while alkali treatment yields stronger gels, it often does so at the cost of production efficiency (Zheng et al., 2025). Therefore, a thorough understanding of these factors is crucial for

optimizing both the extraction and application of high-quality phycocolloids. The exploitation of marine macroalgal derivatives represents a strategic approach to sustainable packaging, capitalizing on their inherent gelling capacity and mechanical strength. This enables the design of films that reliably protect product quality and ensure safety, aligning perfectly with market and regulatory shifts toward bio-based, eco-friendly solutions (Alam et al., 2025).

Environmental Impact and Sustainability Assessment

Marine macroalgal polysaccharide-based packaging presents a transformative alternative to petroleum-derived plastics, significantly reducing dependence on finite fossil resources and mitigating the environmental impacts associated with conventional plastic production (Martins et al., 2022). The sustainability profile of these materials is fundamentally enhanced by macroalgae cultivation, which actively contributes to climate change mitigation through substantial CO₂ sequestration estimated at 1-8 tons per hectare annually, while simultaneously displacing carbon-intensive synthetic polymers (Webb & Silverman-Roati, 2023). Furthermore, algae farming demonstrates superior land-use efficiency, requiring 98% less land than traditional biopolymer feedstocks like corn, thereby minimizing deforestation pressure, preserving terrestrial habitats, and supporting biodiversity conservation (Alias et al., 2022).

A critical environmental advantage lies in their end-of-life characteristics. Under industrial composting conditions (58-65 °C, controlled humidity, and optimized microbial activity), these biopolymers typically degrade within 60-90 days, whereas home composting yields slower decomposition due to variable temperatures and microbial diversity (Tyagi et al., 2022). This controlled biodegradability prevents long-term environmental accumulation, reduces methane emissions from landfills, and aligns with circular economy principles by returning nutrients to soil systems (Tyagi et al., 2022; Mudhoo et al., 2011).

Advanced manufacturing approaches including bionanocomposite development, enzymatic

modification, and solvent-free processing are further enhancing material performance while minimizing ecological footprints (Acharyya et al., 2024). However, scalability challenges persist, particularly in optimizing cultivation systems, ensuring additive safety through comprehensive ecotoxicity assessments, establishing harmonized international regulations, and developing appropriate waste management infrastructure (Dhiman et al., 2023). Addressing these barriers through interdisciplinary research and policy support is essential for realizing the full potential of marine macroalgal polysaccharides in creating a sustainable packaging paradigm that effectively addresses plastic pollution, supports climate objectives, and advances circular bioeconomy principles (Liu et al., 2024).

Challenges and Future Prospects

Seaweed-derived biopolymers offer substantial potential for sustainable packaging; however, their commercial implementation faces significant challenges. Current limitations primarily concern material performance, with native polysaccharides exhibiting inadequate mechanical strength (tensile strength: 20-50 MPa compared to 50-70 MPa for PLA), high water vapor permeability (50-200 g·mm/m²·day·kPa versus <10 for synthetic films), and limited thermal stability (Krishnan et al., 2024). These fundamental property gaps restrict their application in demanding packaging scenarios where mechanical integrity and moisture barrier properties are critical.

The economic viability of seaweed-based packaging presents another substantial barrier. Current production costs for refined polysaccharides range from \$8-15/kg, significantly exceeding conventional petroleum-based plastics (\$1-2/kg) and competing biopolymers like PLA (\$2-3/kg) (Webb & Silverman-Roati, 2023; Tyagi et al., 2022). This cost disparity stems from multiple factors including energy-intensive extraction processes, seasonal variability in biomass composition, and underdeveloped supply chains. However, techno-economic analyses suggest that with optimized offshore cultivation systems, high-yield algal strains, and integrated biorefinery approaches, production costs could potentially be reduced to \$3-5/kg by 2030 (Ali et al., 2024). From a processing perspective, current extraction methodologies remain challenging. Conventional alkaline extraction generates substantial wastewater with high chemical oxygen demand (COD: 800-1200 mg/L), while mechanical methods often degrade polymer molecular weight, compromising functional properties (Sinha, 2024). Emerging technologies including enzyme-assisted extraction and microwave processing show promise for improving efficiency and sustainability, though scaling these approaches presents its own challenges (Sinha, 2024; Acharyya et al., 2024). In material science, strategic integration of nanofillers, hybrid blending approaches, and chemical modification protocols offer viable pathways to enhance mechanical performance and barrier properties. Simultaneously, regulatory alignment and standardized life-cycle assessments will be crucial for ensuring market access and environmental credibility.

The successful commercialization of seaweed-

based packaging will require strengthened collaboration among researchers, industry partners, and policymakers. This must be complemented by targeted consumer education initiatives highlighting the safety and sustainability benefits of seaweed-derived packaging materials. With coordinated efforts in research & development, process optimization, and supply chain development, seaweed-derived biopolymers are positioned to play a transformative role in the transition toward a circular bioeconomy, potentially capturing 3-5% of the global bioplastics market by 2030 (Sarker & Kaparaju, 2024; Liu et al., 2024).

Conclusion

The critical need for sustainable packaging alternatives has positioned macroalgae-derived biopolymers as promising candidates for advancing food packaging technologies. This review has systematically evaluated the promising capabilities of macroalgae-derived biopolymers offer exceptional functional properties including inherent film-forming capacity, effective barrier characteristics, and natural bioactive characteristics, which can be further enhanced through strategic modifications to create advanced active and intelligent packaging systems. Future progress depends on addressing key research gaps in four critical areas: (1) developing scalable and economically viable cultivation and extraction methodologies (2) enhancing mechanical strength and barrier performance through nano-reinforcement and cross-linking technologies (3) establishing comprehensive safety profiles and regulatory compliance pathways and (4) standardizing biodegradation protocols for both industrial and domestic composting environments. Through interdisciplinary collaboration focused on these priorities, macroalgae-derived biopolymers can substantially transform packaging sustainability, simultaneously addressing plastic pollution while advancing circular bioeconomy principles and establishing a new paradigm for high-performance, ecologically responsible food packaging.

References

- Acharyya, P. P., Sarma, M., & Kashyap, A. (2024). Recent advances in synthesis and bioengineering of bacterial nanocellulose composite films for green, active and intelligent food packaging. *Cellulose*, 31(12), 7163-7187. <https://doi.org/10.1007/s10570-024-05949-y>
- Albertos, P., Martin-Diana, A. B., & Leal, S. (2019). Edible films based on agar, starch, and maltodextrins with extracts from *Himanthalia elongata* and *Palmaria palmata* for fish burger preservation. *Food Hydrocolloids*, 89, 917-927. <https://doi.org/10.1016/j.foodhyd.2018.10.027>
- Alam, M. W., Kumar, J. V., Awad, M., Saravanan, P., Al-Sowayan, N. S., Rosaiah, P., & Nivetha, M. S. (2025). Emerging trends in food process engineering: integrating sensing technologies for health, sustainability, and consumer preferences. *Journal of Food Process Engineering*, 48(1), e70035. <https://doi.org/10.1111/jfpe.70035>

- Ali, M. Q., Azhar, M. A., Munaim, M. S. A., Ruslan, N. F., Alsubhi, L. M., Ahmad, N., & Noman, A. E. (2024). Seaweed organic compounds source of hydrocolloids and sustainable food packaging: Properties, application, and future direction. *Discover Food*, 4(1), 101. <https://doi.org/10.1007/s44187-024-00101-w>
- Alias, N. H., Abdullah, N., Othman, N. H., Marpani, F., Zainol, M. M., & Shayuti, M. S. M. (2022). Sustainability challenges and future perspectives of biopolymer. In *Biopolymers: Recent Updates, Challenges and Opportunities* (pp. 373-389). Springer International Publishing. https://doi.org/10.1007/978-3-031-15088-2_15
- Augusto, A., Carbone, I., Cosentino, S., & Pignatello, G. (2022). Application of a seaweed extract coating for the shelf-life extension of fresh-cut apples. *Journal of Food Processing and Preservation*, 46(1), e15761. <https://doi.org/10.1111/jfpp.15761>
- Badawy, M. E., & Rabea, E. I. (2018). Current applications in food preservation based on marine biopolymers. In *Polymers for Food Applications* (pp. 609-650). Springer. https://doi.org/10.1007/978-3-319-94625-2_22
- Baldwin, A. D. (2012). *Development of polymer-polysaccharide hydrogels for controlling drug delivery* (Doctoral dissertation, University of Delaware).
- Bamps, B., Buntinx, M., & Peeters, R. (2023). Seal materials in flexible plastic food packaging: A review. *Packaging Technology and Science*, 36(7), 507-532. <https://doi.org/10.1002/pts.2731>
- Balti, S., Ben Slama, R., Younes, I., Hajji, S., & Nasri, M. (2020). Effect of microalgal exopolysaccharide and red seaweed extract composite coatings on the quality changes of shrimp (*Litopenaeus vannamei*) during chilled storage. *Food Control*, 118, 107380. <https://doi.org/10.1016/j.foodcont.2020.107380>
- Caccamo, M. T., Zammuto, V., Spanò, A., Gugliandolo, C., & Magazù, S. (2022). Hydrating capabilities of the biopolymers produced by the marine thermophilic *Bacillus horneckiae* SBP3 as evaluated by ATR-FTIR spectroscopy. *Materials*, 15(17), 5988. <https://doi.org/10.3390/ma15175988>
- Carina, D., Sharma, S., Jaiswal, A. K., & Jaiswal, S. (2021). Seaweeds polysaccharides in active food packaging: A review of recent progress. *Trends in Food Science & Technology*, 110, 559-572. <https://doi.org/10.1016/j.tifs.2021.02.022>
- Charoensiddhi, S., Abraham, R. E., Su, P., & Zhang, W. (2020). Seaweed and seaweed-derived metabolites as prebiotics. *Advances in Food and Nutrition Research*, 91, 97-156.
- Chong, E. W. N., Jafarzadeh, S., Paridah, M. T., Gopakumar, D. A., Tajaruddin, H. A., Thomas, S., & Abdul Khalil, H. P. S. (2019). Enhancement in the physico-mechanical functions of seaweed biopolymer film via embedding fillers for plasticulture application—a comparison with conventional biodegradable mulch film. *Polymers*, 11(2), 210. <https://doi.org/10.3390/polym11020210>
- Doh, E. H., Park, S. Y., Park, J. H., Jung, J. A., Lee, M. H., Jeon, Y., & Paik, S. H. (2020). Bioactive films prepared from seaweed extracts and cellulose nanocrystals for food packaging applications. *Carbohydrate Polymers*, 241, 116344. <https://doi.org/10.1016/j.carbpol.2020.116344>
- Dou, J., Sun, Y., Xu, Y., Zhu, F., & Hou, H. (2018). Effects of tea polyphenols on the antioxidant and antimicrobial properties of chitosan-alginate films for fish preservation. *Food Control*, 84, 137-145. <https://doi.org/10.1016/j.foodcont.2017.08.038>
- Fuzlin, A. F., Aynharan, S., Hafidz, N. N. A., Ghazali, N. M., Diantoro, M., Nagao, Y., & Samsudin, A. S. (2025). Advances in gel biopolymer electrolytes: sustainable polymers for energy storage applications. *Polymers for Advanced Technologies*, 36(8), e70319. <https://doi.org/10.1002/pat.70319>
- Ganesan, V., Kang, C. H., & Kim, S. K. (2018). Characterization and antioxidant activity of semi-refined carrageenan and ulvan blend films. *International Journal of Biological Macromolecules*, 110, 780-788. <https://doi.org/10.1016/j.ijbiomac.2017.11.161>
- Ghalsasi, P., Chithiravelu, G., & Joddar, B. (2025). Seaweed Derived Polysaccharides as Sustainable Biomaterials for Tissue Engineering Applications. *ACS Biomaterials Science & Engineering*. <https://doi.org/10.1021/acsbiomaterials.5c00001>
- Gomaa, M. I., Abdel-Aziz, M. S., & Khalil, M. I. (2018). Development and characterization of bio-nanocomposite films based on chitosan, alginate and fucoidan for active food packaging. *International Journal of Biological Macromolecules*, 120, 193-203. <https://doi.org/10.1016/j.ijbiomac.2018.08.067>
- Hamad, G. M., Samy, H., Mehany, T., Korma, S. A., Eskander, M., Tawfik, R. G., ... & Khalifa, E. (2023). Utilization of algae extracts as natural antibacterial and antioxidants for controlling foodborne bacteria in meat products. *Foods*, 12(17), 3281. <https://doi.org/10.3390/foods12173281>
- He, Q., Sun, Y., Hu, H., Xu, Y., Jiang, W., Yu, A., & Jin, Y. (2016). Development of novel bioactive films from chitosan, carrageenan and ϵ -polylysine for extending shelf life of fresh meat. *Food Control*, 60, 442-450. <https://doi.org/10.1016/j.foodcont.2015.08.026>

- Iqbal, M. W., Riaz, T., Mahmood, S., Bilal, M., Manzoor, M. F., Qamar, S. A., & Qi, X. (2024). Fucoidan-based nanomaterial and its multifunctional role for pharmaceutical and biomedical applications. *Critical Reviews in Food Science and Nutrition*, 64(2), 354-380. <https://doi.org/10.1080/10408398.2022.2108365>
- Khalid, M. (2023). *Poly(lactic Acid)/Poly(hydroxyalkanoate)/Eggshell Based Hydroxyapatite Biocomposites for Bone Tissue Applications* (Doctoral dissertation, Universiti Tun Hussein Onn Malaysia).
- Li, Z., Rawdkuen, S., Fei, T., & Zhang, W. (2025). Recent advances in gellan gum-based films and its application in sustainable food packaging: a review. *Critical Reviews in Food Science and Nutrition*, 1-22. <https://doi.org/10.1080/10408398.2025.1234567>
- Liu, J., Wang, S., Liu, Q., Sun, J., Sun, Z., & Li, C. (2019). Development of κ-carrageenan based active bio-films incorporated with mulberry polyphenol extract for enhancing the quality of milk. *Food Hydrocolloids*, 89, 928-937. <https://doi.org/10.1016/j.foodhyd.2018.10.028>
- Ma, Q., Xu, Y., Wang, Z., Jin, Y., Tian, S., & Sun, Y. (2019). Fabrication and characterization of bio-nanocomposite films based on sodium alginate, sodium carboxymethyl cellulose and *Lactococcus lactis* for enhancing the shelf life of fresh meat. *Food Hydrocolloids*, 89, 108-118. <https://doi.org/10.1016/j.foodhyd.2018.10.009>
- Mahcene, Z., Chibane, Y., Habibi, Y., Paula, M. D., Helfaoui, M., & Mbarkia, A. (2020). Antimicrobial and antioxidant properties of eucalyptus essential oil loaded in chitosan--alginate films for food packaging applications. *International Journal of Biological Macromolecules*, 164, 3821-3830. <https://doi.org/10.1016/j.ijbiomac.2020.08.026>
- Majinyari, D. E. (2021). Synthesis, Characterization and Antimicrobial Evaluation of Carrageenan/TiO₂Nanocomposite Materials (Master's thesis, University of Dodoma).
- Mazumder, S., Bhattacharya, D., Lahiri, D., & Nag, M. (2025). Microbial-Mediated Biopolymers (Exopolysaccharide) in Food Packaging: A Current Time Approach in Food Safety. *ACS Food Science & Technology*. <https://doi.org/10.1021/acsfoodscitech.5c00001>
- Metha, C., Pawar, S., & Suvarna, V. (2024). Recent advancements in alginate-based films for active food packaging applications. *Sustainable Food Technology*, 2(5), 1246-1265. <https://doi.org/10.1039/D4FB00056K>
- Mudhoo, A., Mohee, R., Unmar, G. D., & Sharma, S. K. (2011). *Degradation of biodegradable and green polymers in the composting environment*.
- Perera, K. Y., Sharma, S., Pradhan, D., Jaiswal, A. K., & Jaiswal, S. (2021). Seaweed polysaccharide in food contact materials (active packaging, intelligent packaging, edible films, and coatings). *Foods*, 10(9), 2088. <https://doi.org/10.3390/foods10092088>
- Periyasamy, T., Asrafali, S. P., & Lee, J. (2025). Recent Advances in Functional Biopolymer Films with Antimicrobial and Antioxidant Properties for Enhanced Food Packaging. *Polymers*, 17(9), 1257. <https://doi.org/10.3390/polym17091257>
- Qamar, S. A., Junaid, M., Riasat, A., Jahangeer, M., Bilal, M., & Mu, B. Z. (2024). Carrageenan-based hybrids with biopolymers and nano-structured materials for biomimetic applications. *Starch-Stärke*, 76(1-2), 2200018. <https://doi.org/10.1002/star.202200018>
- Quitério, E., Grosso, C., Ferraz, R., Delerue-Matos, C., & Soares, C. (2022). A critical comparison of the advanced extraction techniques applied to obtain health-promoting compounds from seaweeds. *Marine Drugs*, 20(11), 677. <https://doi.org/10.3390/md20110677>
- Rahman Khan, M. M., Rumon, M. M. H., & Islam, M. (2024). Synthesis, Rheology, Morphology, and Mechanical Properties of Biodegradable PVA-Based Composite Films: A Review on Recent Progress. *Processes*, 12(12), 2345. <https://doi.org/10.3390/pr12122345>
- Ramani, M., & Murugan, K. (2020). Effect of seaweed *Kappaphycus alvarezii* extract coating on quality preservation of tomato fruits during storage. *Scientifica*, 2020, 8892183. <https://doi.org/10.1155/2020/8892183>
- Reboleira, J., Mendes, R., Amaro, M. I., Oliveira, A. P., Baptista, R. M., Malcata, F. X., & Pintado, M. (2020). Active biofilms based on *Plocamium diocia* extract and polyvinyl alcohol for minced chicken breast preservation. *Food Packaging and Shelf Life*, 25, 100593. <https://doi.org/10.1016/j.fpsl.2020.100593>
- Rizal, O., Nurhayati, R., Yuliana, M., & Syah, Y. M. (2023). Development of bio-based films from seaweed polymers (*Kappaphycus alvarezii*) and coffee waste for food packaging applications. *Food Research*, 5(2), 311-320. [https://doi.org/10.26656/fr.2023.5\(2\).821](https://doi.org/10.26656/fr.2023.5(2).821)
- Rodríguez-Núñez, J. R., Montoya-Anaya, D. G., Fortiz-Hernández, J., Freile-Pelegrín, Y., & Madera-Santana, T. J. (2023). Main Marine Biopolymers for Food Packaging Film Applications. In *Natural Materials for Food Packaging Application* (pp. 199-240). <https://doi.org/10.1002/9781119860563.ch10>
- Ross, F. W., Boyd, P. W., Filbee-Dexter, K., Watanabe, K., Ortega, A., Krause-Jensen, D., ... & Macreadie, P. I. (2023). Potential role of seaweeds in climate change mitigation. *Science of the Total Environment*, 885, 163699. <https://doi.org/10.1016/j.scitotenv.2023.163699>

- Salehi, B., Sharifi-Rad, J., Seca, A. M., Pinto, D. C., Michalak, I., Trincon, A., ... & Martins, N. (2019). Current trends on seaweeds: Looking at chemical composition, phytopharmacology, and cosmetic applications. *Molecules*, 24(22), 4182. <https://doi.org/10.3390/molecules24224182>
- Sarker, N. K., & Kaparaju, P. (2024). Microalgal bioeconomy: a green economy approach towards achieving sustainable development goals. *Sustainability*, 16(24), 11218. <https://doi.org/10.3390/su162411218>
- Setyawidati, I., Yahya, R., & Antonius, A. (2018). Effect of alginate coating with pomegranate peel extract on quality of capsicum during storage. *Food Research*, 2(2), 315-322. [https://doi.org/10.26656/fr.2017.2\(2\).047](https://doi.org/10.26656/fr.2017.2(2).047)
- Sharifian, S., & Homaei, A. (2022). Marine-derived polysaccharides: prospects for future pharmaceuticals and drug delivery systems. In *Marine Biomaterials: Drug Delivery and Therapeutic Applications* (pp. 403-453). Springer Nature Singapore. https://doi.org/10.1007/978-981-16-4785-2_12
- Sharma, B., & Hoque, M. E. (Eds.). (2023). *Polysaccharides: Advanced Polymeric Materials*. CRC Press.
- Sinha, S. (2023). Synthesis of biopolymer based superabsorbent: An eco-friendly approach towards future sustainability. In *Bio-based superabsorbents: recent trends, types, applications and recycling* (pp. 29-49). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-3094-4_2
- Sinha, S. (2024). An overview of biopolymer-derived packaging material. *Polymers from Renewable Resources*, 15(2), 193-209. <https://doi.org/10.1177/20412479241226884>
- Sinha, S. (2024). Food Security Challenges and Microplastics: A Comprehensive Review. In *Microplastics in African and Asian Environments: The Influencers, Challenges, and Solutions* (pp. 361-371). https://doi.org/10.1007/978-3-031-50033-2_18
- Sinha, S., Singh, S., & Dey, K. P. (2024). Microplastics: A significant threat to freshwater ecosystems. In *Sustainable Microbial Technology for Synthetic and Cellulosic Microfiber Bioremediation* (pp. 91-105). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-54542-7_4
- Smola-Dmochowska, A., Lewicka, K., Macyk, A., Rychter, P., Pamuła, E., & Dobrzyński, P. (2023). Biodegradable polymers and polymer composites with antibacterial properties. *International Journal of Molecular Sciences*, 24(8), 7473. <https://doi.org/10.3390/ijms24087473>
- Surendren, A. (2024). *Development of Thermoplastic Starch-based Polymeric Blends and Composites Engineered with Extrusion Cast and Blown Films for Packaging Applications* (Doctoral dissertation, University of Guelph).
- Thapliyal, D., Tewari, K., Verma, S., Bhargava, C. K., Sen, P., Mehra, A., ... & Arya, R. K. (2024). Introduction: The Evolution of Functional Coatings from Protection to Innovation. In *Functional Coatings for Biomedical, Energy, and Environmental Applications* (pp. 1-30). <https://doi.org/10.1002/9781394256379.ch1>
- Tian, J. (2024). *Advanced Structural Characterization of Nanocellulose-Based Materials for Environmental Applications* (Doctoral dissertation, State University of New York at Stony Brook).
- Tyagi, P., Agate, S., Velez, O. D., Lucia, L., & Pal, L. (2022). A critical review of the performance and soil biodegradability profiles of biobased natural and chemically synthesized polymers in industrial applications. *Environmental Science & Technology*, 56(4), 2071-2095. <https://doi.org/10.1021/acs.est.1c03335>
- Ulrich, G. D., & Faez, R. (2022). Thermal, mechanical and physical properties of composite films developed from seaweed polysaccharides/cellulose nanofibers. *Journal of Polymers and the Environment*, 30(9), 3688-3700. <https://doi.org/10.1007/s10924-022-02443-z>
- Venugopal, V. (2019). Applications of marine polysaccharides in food processing. In *Enzymatic Technologies for Marine Polysaccharides* (pp. 25-46). CRC Press.
- Wang, S., Liu, Q., Wang, Y., Sun, J., Sun, Z., & Li, C. (2018). Enhanced mechanical properties and water vapor barrier of agar films reinforced with bacterial cellulose nanofibers and halloysite nanotubes. *Carbohydrate Polymers*, 192, 144-153. <https://doi.org/10.1016/j.carbpol.2018.03.024>
- Webb, R. M., & Silverman-Roati, K. (2023). Ocean CDR approaches. In *Ocean Carbon Dioxide Removal for Climate Mitigation* (pp. 20-39). Edward Elgar Publishing.
- Wu, S. C. (2017). Antioxidant activity of sulfated seaweeds polysaccharides by novel assisted extraction. In *Solubility of Polysaccharides* (pp. 89-108). IntechOpen. <https://doi.org/10.5772/intechopen.68385>
- Yerramathi, R. R., Chaudhary, V., Rajput, M. K., Randhawa, G. S., & Jang, J. Y. (2021). Development of novel alginate-based biocomposite films incorporated with ferulic acid for enhanced antioxidant and antimicrobial activities. *International Journal of Biological Macromolecules*, 182, 1470-1481. <https://doi.org/10.1016/j.ijbiomac.2021.05.184>
- Zhang, Y., Sun, B., Xu, X., Wu, Y., Fan, Y., & Gao, Y. (2018). Physical, mechanical and antibacterial properties of sodium alginate/ε-polylysine blend films incorporated with capsaicin. *Food*

- Hydrocolloids*, 80, 307-316. <https://doi.org/10.1016/j.foodhyd.2018.02.016>
- Zheng, M., Wang, L., Hong, T., Li, Z., Zhu, Y., Jiang, Z., ... & Ou, Y. (2025). Impact of Ultra-High Pressure Assisted Alkaline Extraction on Properties and Structural Characteristics of Carrageenan. *Food Hydrocolloids*, 112039. <https://doi.org/10.1016/j.foodhyd.2025.112039>
- Zhou, F., Liu, Q., Wang, Y., Li, C., Zhu, X., & Fan, W. (2021). Development and characterization of edible coatings based on kappa-carrageenan, konjac glucomannan, and camellia oil for improving the quality of chicken breast during refrigerated storage. *Food Chemistry*, 362, 130222. <https://doi.org/10.1016/j.foodchem.2021.130222>