



A Monthly e Magazine

ISSN:2583-2212

May, 2026 Vol.6(5), 1447-1454

Popular Article

## Seaweed Biopolymers in Packaging

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[doi.org/10.5281/ScienceWorld.20454216](https://doi.org/10.5281/ScienceWorld.20454216)

### *Abstract*

The rapid increase in plastic pollution has intensified the search for sustainable and biodegradable packaging materials. Seaweed-derived biopolymers have emerged as promising alternatives due to their biodegradability, renewability, film-forming ability, and functional properties. Polysaccharides extracted from marine macroalgae, including alginate, carrageenan, and agar, are widely explored for edible films and bio-packaging applications. Seaweed biofilms possess excellent oxygen barrier properties, antimicrobial potential, and compatibility with active packaging systems (Sudhakar et al., 2021). Furthermore, industrial innovations such as edible water pods and biodegradable takeaway coatings demonstrate the commercial viability of seaweed-based packaging technologies (InsightAce Analytic, 2026). This review summarizes the chemistry, production methods, applications, advantages, limitations, and prospects of seaweed-derived biofilms for sustainable food packaging.

### **1. Introduction**

Conventional petroleum-based plastics contribute significantly to environmental pollution because of their non-biodegradable nature and accumulation in terrestrial and marine ecosystems. Global concerns regarding microplastic contamination, greenhouse gas emissions, and waste management have accelerated the development of biodegradable alternatives (Priyadarshi & Rhim, 2020). Among emerging biomaterials, seaweed-derived biopolymers are attracting considerable scientific and industrial attention due to their



sustainability and eco- friendly characteristics.

Seaweeds are renewable marine resources rich in polysaccharides such as alginate, agar, and carrageenan. These compounds exhibit strong film-forming abilities and can be processed into edible coatings, biodegradable packaging films, and active food packaging materials (Seaweed polysaccharide-based materials for advanced food packaging, 2025). Seaweed-based biofilms provide advantages including biodegradability, low toxicity, excellent oxygen barrier properties, and compatibility with bioactive compounds.

Recent advancements in marine biopolymer engineering have improved the mechanical strength, water resistance, and antimicrobial performance of seaweed derived packaging systems (Rhim & Wang, 2013). Commercial innovations, including edible “Ooho” water pods and grease-resistant takeaway coatings developed by Notpla, demonstrate the practical application potential of seaweed bio-packaging technologies (InsightAce Analytic, 2026).

## 2. Seaweed Polysaccharides Used in Biofilm Production

### 2.1 Alginate

Alginate is primarily extracted from brown seaweeds such as *Sargassum*, *Laminaria*, and *Macrocystis*. It is composed of  $\beta$ -D-mannuronic acid and  $\alpha$ -L-guluronic acid residues. Alginate forms transparent, flexible films with excellent oxygen barrier properties. Calcium ions are commonly used as cross-linkers to improve mechanical stability and water resistance (Priyadarshi & Rhim, 2020).

### 2.2 Carrageenan

Carrageenan is a sulfated polysaccharide obtained mainly from red seaweeds such as *Kappaphycus alvarezii* and *Eucheuma denticulatum*.  $\kappa$ -Carrageenan exhibits strong gel-forming characteristics and is widely utilized in edible coatings and antimicrobial films. Carrageenan based films can incorporate essential oils and antioxidants to enhance food preservation (Rhim & Wang, 2013).

### 2.3 Agar

Agar is extracted from red algae including *Gelidium* and *Gracilaria* species. Agar-based biofilms possess high transparency and moderate mechanical strength. Due to its thermo-reversible gel properties, agar is useful in edible coatings and moisture-sensitive packaging systems (Sudhakar et al., 2021).

## 3. Preparation of Seaweed-Based Biofilms

Seaweed biofilms are commonly prepared using solution casting techniques. The general preparation process includes extraction of polysaccharides from seaweed biomass,



dissolution in distilled water under heating, addition of plasticizers such as glycerol or sorbitol, incorporation of antimicrobial compounds, casting of the solution onto flat surfaces, and controlled drying conditions (Seaweed-derived biopolymers: A sustainable alternative for food packaging, 2026).

Advanced methods including extrusion, electrospinning, nanocomposite reinforcement, and multilayer film fabrication are increasingly applied to improve film performance. Nanotechnology-based modifications significantly improve tensile strength, thermal stability, and water resistance of marine biopolymer films (ScienceDirect, 2024).

#### **4. Functional Properties of Seaweed Biofilms**

##### **4.1 Mechanical Properties**

Mechanical strength depends on polymer concentration, cross-linking density, and plasticizer content. Alginate and carrageenan films generally exhibit good tensile strength but moderate flexibility. Polymer blending and nanoparticle incorporation have been reported to enhance film durability and elasticity (Rhim & Wang, 2013).

##### **4.2 Barrier Properties**

Seaweed films demonstrate excellent oxygen barrier properties, which help reduce oxidative spoilage in foods. However, moisture sensitivity remains a major limitation due to the hydrophilic nature of marine polysaccharides (Priyadarshi & Rhim, 2020).

##### **4.3 Antimicrobial and Antioxidant Activity**

Bioactive compounds such as essential oils, plant extracts, nanoparticles, and probiotics can be incorporated into seaweed films to improve antimicrobial and antioxidant functionality. Clove essential oil incorporated into alginate/ $\kappa$ -carrageenan films has shown strong inhibitory effects against foodborne pathogens and enhanced antioxidant activity during storage (Polymers, 2021).

##### **4.4 Biodegradability**

Seaweed-derived films are naturally biodegradable and decompose significantly faster than synthetic plastics. Their degradation products are generally non-toxic and environmentally safe, making them suitable alternatives for sustainable packaging systems (Sudhakar et al., 2021).

#### **5. Applications in Food Packaging**

##### **5.1 Edible Coatings**

Seaweed coatings are widely applied to fruits, vegetables, seafood, meat products, and confectionery items to reduce moisture loss and microbial contamination. Edible seaweed films also improve appearance and maintain texture quality during storage (Shahidi &



Ambigaipalan, 2015).

## **5.2 Active Packaging**

Seaweed films can act as carriers for antioxidants, antimicrobials, probiotics, and nutraceuticals, thereby extending shelf life and improving food safety. Active packaging systems based on marine biopolymers are increasingly used in minimally processed foods (ScienceDirect, 2025).

## **5.3 Intelligent Packaging**

Incorporation of pH-sensitive pigments and biosensors into seaweed films enables freshness monitoring and spoilage detection in packaged foods. Smart packaging technologies using natural pigments from marine algae are receiving growing scientific attention (Seaweed polysaccharide-derived biopolymers, 2026).

## **5.4 Commercial Innovations**

The company Notpla has successfully commercialized seaweed-based biodegradable packaging products including edible “Ooho” water pods and grease-resistant takeaway box coatings. These innovations demonstrate the scalability and industrial relevance of marine biopolymer packaging technologies (InsightAce Analytic, 2026).

## **6. Advantages of Seaweed-Based Packaging**

Seaweed-based packaging materials offer several advantages including biodegradability, compostability, renewability, non-toxicity, and compatibility with edible packaging applications. They also reduce dependence on petroleum-based plastics and support circular economy strategies for sustainable waste management (Gujarat Agro Industries Corporation Report).

## **7. Limitations and Challenges**

Despite their advantages, seaweed biofilms face several challenges including high moisture sensitivity, lower mechanical durability compared to synthetic plastics, limited thermal stability, and higher production costs at industrial scale. Variability in seaweed composition due to seasonal and environmental factors also affects film quality and consistency (ScienceDirect, 2024).

Future research should focus on nanocomposite reinforcement, hydrophobic modifications, bioactive incorporation, and scalable industrial processing technologies to improve commercial competitiveness.

## **8. Market Outlook and Future Perspectives**

The global market for seaweed-based packaging is experiencing rapid growth due to increasing consumer demand for sustainable alternatives. According to the InsightAce



Analytic Seaweed Packaging Report (2026), the market is projected to expand significantly over the coming decade owing to rising environmental regulations and adoption of biodegradable materials in the food and beverage industry.

Increasing investment in marine biopolymer technology, circular economy strategies, and green packaging innovations is expected to accelerate commercialization. Emerging technologies involving nanotechnology, bioactive packaging, and smart sensors may further improve the functionality and industrial competitiveness of seaweed-based biofilms (InsightAce Analytic, 2026).

## **9. Economic Importance and Industrial Potential**

The increasing demand for sustainable packaging materials has created significant economic opportunities for seaweed-based industries. The global biodegradable packaging market is expanding rapidly due to rising environmental awareness, changing consumer preferences, and government regulations restricting plastic use. Seaweed-derived packaging materials are expected to become an important segment within the green packaging industry.

Seaweed cultivation and processing also provide economic benefits to coastal communities. Many developing countries with extensive coastlines, including India, Indonesia, China, and the Philippines, have favorable environmental conditions for large-scale seaweed farming. Expansion of the seaweed industry can create employment opportunities in cultivation, harvesting, processing, extraction of polysaccharides, and manufacturing of biodegradable products.

Industries are increasingly investing in marine biopolymer technologies for commercial packaging applications. Several companies have already introduced seaweed-based edible films, biodegradable sachets, takeaway containers, and water-soluble packaging products. Innovations in active and intelligent packaging are further enhancing the commercial value of seaweed-derived materials.

India has strong potential for developing seaweed-based packaging industries due to its long coastline and rich marine biodiversity. Government initiatives promoting blue economy development, marine biotechnology, and sustainable aquaculture may further support industrial growth in this sector. Collaboration among research institutions, food industries, and marine biotechnology companies is essential to improve production technologies and reduce manufacturing costs.

However, certain economic challenges still exist. Large-scale industrial production requires advanced extraction technologies, quality standardization, and efficient supply



chain systems. High processing costs and limited consumer awareness currently restrict widespread commercialization. Continued technological advancements and policy support are expected to improve the affordability and industrial adoption of seaweed packaging materials in the future.

#### **10. Future Research Directions**

Future research on seaweed-based biofilms should focus on improving their physical, chemical, and functional properties for large-scale commercial applications. One of the major limitations of seaweed biofilms is their high sensitivity to moisture due to the hydrophilic nature of marine polysaccharides. Research involving hydrophobic coatings, polymer blending, and nanotechnology-based reinforcement may significantly improve water resistance and mechanical durability.

Nanocomposite technology is considered one of the most promising approaches for enhancing film performance. Incorporation of nanoparticles such as nanocellulose, silver nanoparticles, zinc oxide, and clay minerals can improve tensile strength, thermal stability, antimicrobial activity, and barrier properties. Development of multifunctional packaging systems combining biodegradability with active preservation capabilities will likely become a major research focus.

Another important area is the development of smart and intelligent packaging systems. Incorporation of biosensors, pH-sensitive pigments, and freshness indicators into seaweed films can allow real-time monitoring of food quality during storage and transportation. Such innovations may improve food safety, reduce spoilage, and minimize food waste.

Research is also needed to optimize seaweed cultivation and extraction methods to ensure sustainable raw material supply and consistent polymer quality. Seasonal variations in seaweed composition often influence the physicochemical characteristics of extracted polysaccharides. Advanced biotechnological approaches including genetic improvement, controlled cultivation systems, and biorefinery techniques may improve production efficiency.

Future studies should additionally evaluate the consumer acceptance, economic feasibility, biodegradation kinetics, and regulatory aspects of seaweed-based packaging materials. Integration of marine biotechnology, food science, materials engineering, and environmental sustainability research will play a crucial role in advancing the next generation of biodegradable packaging systems.



## 11. Conclusion

Seaweed-derived biofilms represent a promising and sustainable alternative to conventional plastic packaging. Polysaccharides such as alginate, carrageenan, and agar possess excellent film-forming abilities and can be utilized in edible coatings, active packaging, and biodegradable food containers. Recent industrial innovations and increasing market demand indicate strong future potential for seaweed-based packaging systems. However, improvements in moisture resistance, mechanical properties, and production scalability are essential for widespread commercialization. Continued interdisciplinary research integrating marine biotechnology, materials science, and food engineering will play a crucial role in advancing sustainable bio-packaging solutions.

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