polysaccharides

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Editorial

Seaweed Polysaccharides: Innovations in Isolation, Characterization, Chemical Modification and Processing

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1. Introduction

Seaweed biomass has been utilized for centuries, particularly in coastal communities, where it traditionally served as a food source and in folk medicine [1–3]. From the perspective of a raw material, seaweeds are highly attractive in the context of modern socioeconomic discussions. They are renewable and fast-growing, yet they do not compete directly with food and feed production in terms of water and land usage [4,5]. Some seaweeds are even considered invasive ecological threats, making their valorization into innovative materials even more attractive [6,7].

Seaweeds are an excellent source for harvesting functional polysaccharides from economic, ecological, and scientific points of view. Seaweed polysaccharides differ in many ways from polysaccharides like cellulose, starch, and hemicelluloses that are ubiquitous in land-based plants, thus creating new avenues for innovative fundamental and applied research. As examples, uronic acids and sulfate groups are common structural features in seaweed polysaccharides that directly translate into specific physical, chemical, and biological properties. Alginates are able to form stable complexes with various metal ions, which is essential for their renowned ability to form mechanically stable hydrogel materials. Other seaweed polysaccharides, like fucoidans, are valued for their pronounced bioactivity, which can be exploited in biomedical applications.

This Special Issue aims to advance research on seaweed polysaccharides by highlighting innovative contributions in the areas of biomaterials and biomedical applications (Figure 1). In a comprehensive review, Khammassi et al. provided an up-to-date overview of the most important types of polysaccharides from brown algae in the context of industrial uses, along with their isolation and characterization methods as well as fundamental biological activities [8]. The review is followed by original publications that describe the use of alginates, fucoidans, and carrageenan in different applications.

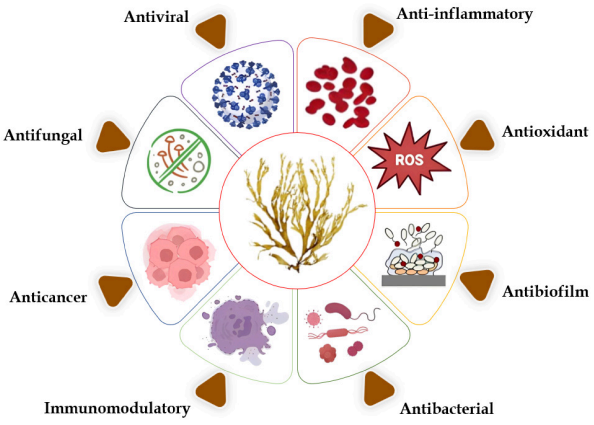


Figure 1. Overview of potential biological properties of seaweed polysaccharides [8].

Check for updates

Received: 7 May 2026
Accepted: 12 May 2026
Published: 20 May 2026

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2. Highlights from the Special Issue

2.1. Functional Films from Seaweed Polysaccharides

A novel approach for enhancing the mechanical properties of alginate-based materials is proposed by Fasulo et al. [9]. The authors describe the use of a glycerol–silicate (GS) as a new plasticizer for alginate films (Figure 2). The materials were characterized spectroscopically and with respect to their mechanical and thermal properties. The brittleness of sodium alginate and calcium alginate films could be reduced by the incorporation of GS. Moreover, the tensile strength and elongation of the materials were affected, demonstrating that the incorporation of silicate-based plasticizers that can undergo sol–gel transition is a viable approach for constructing mechanically stable alginate materials.

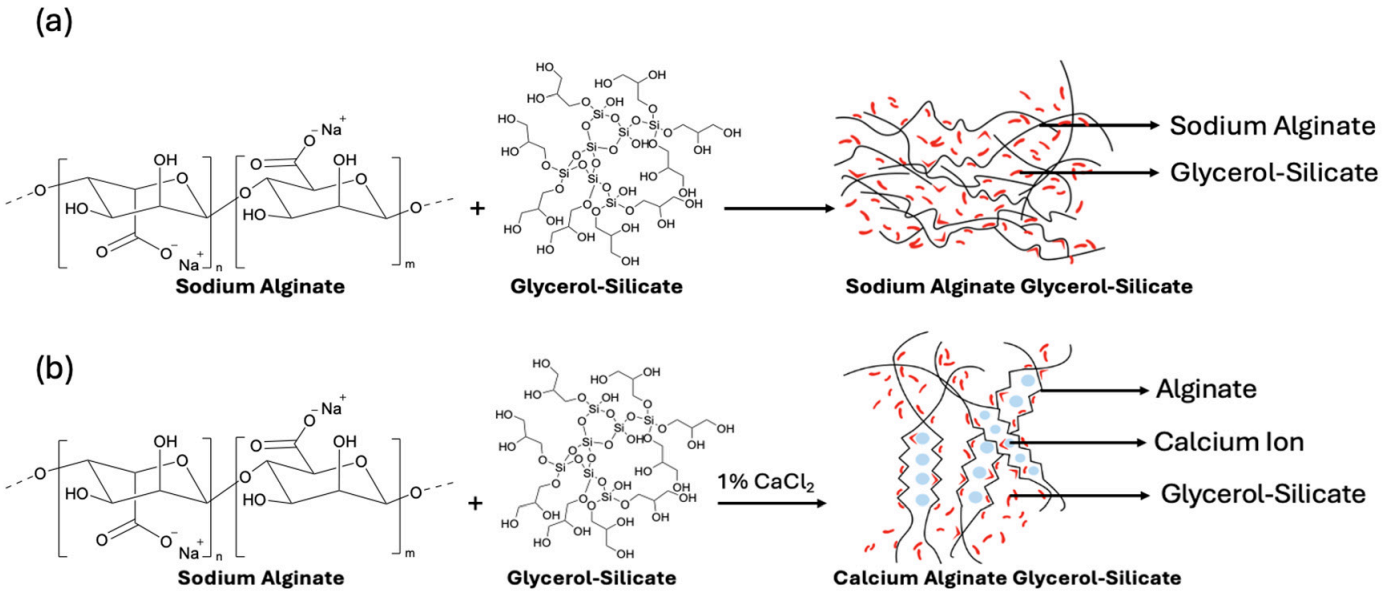


Figure 2. Reaction Scheme (**a**): A reaction involving a glycerol–silicate plasticizer and sodium alginate (NaAlg). Reaction Scheme (**b**): Plasticization of sodium alginate with glycerol–silicate immersed in 1 wt% $CaCl_2$ [9].

Two articles in this Special Issue describe functional composite films for biomedical applications in which seaweed polysaccharides, as a structural matrix, are combined with nanomaterials to incorporate a specific bioactive response. Vincens et al. prepared films of κ-carrageenan and polyethylene oxide containing magnesium oxide nanoparticles (MgO-NP) to enhance bio-interaction [10]. The effect of the polymer concentration and molecular weight on the film properties (thickness, tensile strength, and swelling capacity) was evaluated. The incorporation of MgO-NP had no direct influence on the biocompatibility and antimicrobial properties of the composite films, and it was concluded that the materials should be investigated further for their potential in treating chronic wounds.

Composite films prepared from calcium alginate and partially acetylated cellulose nanocrystals (paCNC) were studied by Torlopov and co-workers [11]. In this work, the mass fraction of incorporated nanomaterial varied over a broad range, from 1% to 30%, to evaluate the effect on essential physicochemical properties, such as surface chemistry, swelling behavior, and contact angle for liquids of different polarity. Based on the findings, a model was proposed that describes the integration of paCNC within the calcium alginate matrix. Moreover, it was demonstrated that composite films are biocompatible and possess a procoagulant effect.

A method for enhancing the applicability of sodium alginate as an active food packaging material is described in the article by Ren et al. [12]. Therein, a network of phenolic

acid and Fe^{3+} is incorporated into the polysaccharide material along with an emulsion of geranium essential oil. Among other effects, the combination of both additives can induce antimicrobial properties and UV light shielding, which are desirable for improving the shelf life of packaged food.

2.2. Seaweed Polysaccharides as Matrices for Incorporating Bioactive Compounds

Seaweed polysaccharides are a rare source of native sugars with L-configuration, such as L-fucose. As such, they can potentially mimic the action of glycoproteins and glycolipids in cellular processes. In the study by Palafox-Félix et al., the effect of fucoidan and fucoidan oligomers on the growth and biofilm formation of *Campylobacter jejuni*, a bacterial strain associated with gastroenteritis infections, was investigated [13]. The authors describe how molecular recognition of the fucose motif in poly- and oligosaccharides can inhibit the adhesion of bacteria.

The study by Cruz-Casas and co-authors describes the encapsulation of amaranth protein hydrolysate, which is known as an effective inhibitor of the angiotensin-I converting enzyme (ACE-I), within alginate-based capsules [14]. They investigated the effect of different loading and drying conditions on the encapsulation efficiency as well as the size and shape of the capsule particles. Moreover, the effect of incorporating pectin as a second functional polysaccharide was studied. The authors demonstrated that the encapsulation of the protein hydrolysates within an alginate matrix preserved bioactivity and proposed further studies to optimize the encapsulation process and the release of the therapeutic agent (Table 1).

Table 1. Peptide release and ACE-I inhibitory activity of alginate/pectin beads containing amaranth protein hydrolysate under simulation of gastrointestinal digestion [14].

Digestion Phase	Peptide Release (mg/mL)			ACE-I Inhibition (%)		
	100% AG	75% AG 25% PC	Non-Encapsulated	100% AG	75% AG 25% PC	Non-Encapsulated
Oral	0.005 ± 0.001^{c}	0.007 ± 0.003^{b}	0.050 ± 0.003^{c}	9.97 ± 11.33	23.68 ± 10.05	0 ± 0
Gastric	0.142 ± 0.005^{b}	0.108 ± 0.006^{b}	0.108 ± 0.006^{b}	0 ± 0	17.46 ± 5.03	0 ± 0
Intestinal	0.532 ± 0.091^{a}	0.548 ± 0.015^{a}	0.515 ± 0.059^{a}	19.93 ± 6.30	16.10 ± 8.77	0 ± 0
Total	0.679 ± 0.097^{b}	0.663 ± 0.024^{b}	0.691 ± 0.069^{b}	29.9 ± 17.63	57.24 ± 23.85	0 ± 0

Different letters indicate a significant difference between the means of each digestive phase. AG: Alginate, PC: Pectin.

2.3. Bioactive Fucoidans for Biomedical Applications

Fucoidans are a class of sulfated seaweed polysaccharides that are well known for their pronounced bioactivity. Santos and co-workers utilized Fucoidan B, a strong antithrombotic compound, and described an approach to increase the antioxidant activity of the biopolymer [15]. Gallic acid was covalently bound by a redox conjugation approach. While the benzoic acid derivative itself showed no measurable activity, conjugation to the seaweed polysaccharide backbone significantly improved the superoxide radical scavenging activity, the ability to complex metal ions, and the overall antioxidant capacity (Figure 3). The study's results suggest that the unique molecular structure of Fucoidan B synergistically supports the capability of gallic acid to act as an electron donor. It also identified routes for future studies to further explore the utilization of chemically modified fucoidan derivatives.

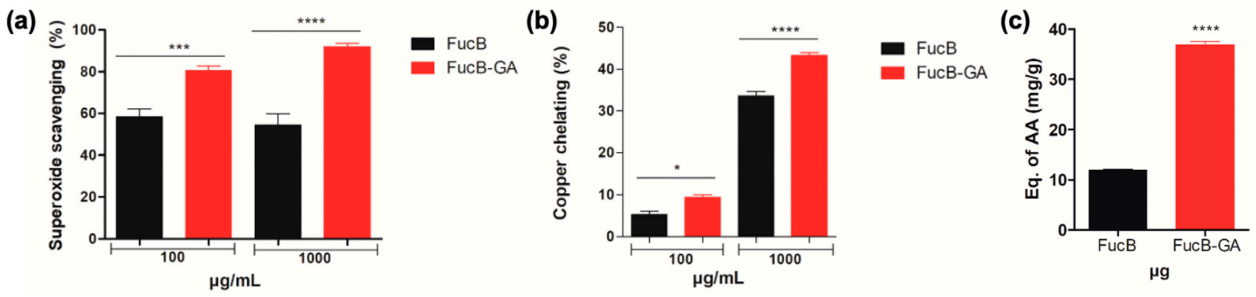


Figure 3. Superoxidase radical scavenging (**a**), copper chelating (**b**), and antioxidant activity (**c**), expressed as equivalents of ascorbic acid/AA) of Fucoidan B (FucB) and Fucoidan B gallic acid adduct (FucB-GA). Asterisks indicate statistically significant differences between sample treatments at the same concentration ((**a**) (**** $p < 0.0002$; *** $p < 0.002$), (**b**) (**** $p < 0.0001$; * $p < 0.05$), (**c**) (**** $p < 0.0001$)). Adapted from Santos et al., 2025 [15]

3. Conclusions and Outlook on Future Developments

This Special Issue has collected scientific contributions that highlight the potential of seaweed polysaccharides for the preparation of functional biomaterials and the development of bioactive compounds. Key driving forces for research and development are the specific structural motifs of these biopolymers that distinguish them from polysaccharides found in land-based plants like cellulose and starch. As a result, seaweed polysaccharides enable unique approaches for fabricating functional materials (e.g., by exploiting their native ability to form hydrogels) and provide unique physicochemical and biological properties (e.g., electrostatic interaction, complexation of metal ions, and innate bioactivity).

In the field of biomaterial engineering, current research approaches often aim to incorporate additional functional components into the matrix of seaweed polysaccharides to complement material properties such as mechanical stability or bioactivity. Potential fields of application can span a broad value chain, from packaging to biomedical applications. Open questions that need to be addressed include the biodegradation of the materials under different environmental conditions after their designated end-of-use. Research in the field of seaweed polysaccharides is also strongly driven by the desire to exploit their inherent bioactivity. Common approaches aim to increase the therapeutic activity via chemical functionalization and/or incorporation of the bioactive seaweed polysaccharides into biomaterials, e.g., for wound treatment or tailored drug release. It can be expected that these research avenues will gain further importance in the future.

In the broader context of advancements in the fields of polysaccharide and fundamental polymer research, it can be postulated that research and development activities will also shift towards other fundamental and applied topics. Studies aiming for chemical modification of seaweed polysaccharides and the synthesis of tailored polysaccharide derivatives are expected to increase in the future. Potential fields of application can range from sustainable alternatives for petro-based mass products (e.g., bioplastics) over functional food additives to high-value-added products for pharmaceutical uses. Of particular scientific interest are novel chemoselective approaches that specifically address structural features, such as uronic acid groups, that are present in seaweed polysaccharides like alginate. Moreover, task-specific homogeneous and heterogeneous reaction media are topics of high relevance.

The valorization of invasive seaweed biomass, currently considered a residue, will become increasingly important in the future, considering global climate change. As such, studies that aim to identify and isolate polysaccharides from these renewable feedstocks can be expected to intensify. Another research area with great prospects for future developments is the incorporation of biotechnology. Tailoring the biosynthesis of seaweed polysaccharides and oligosaccharides through genetic engineering holds great potential.

Ultimately, it can be postulated that research on seaweed polysaccharides will benefit greatly from innovative multidisciplinary studies that combine complementary approaches from fundamental polysaccharide chemistry and biomaterials design with expertise in the areas of biotechnology and biomedicine. These have the greatest potential to translate fundamental academic research into applied product developments.

Conflicts of Interest: The author declares no conflicts of interest.

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