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Review

Marine Macroalgal Polysaccharides as Precision Tools for Health and Nutrition

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Abstract

Macroalgal polysaccharides represent a diverse group of structurally complex biopolymers with significant potential in biomedicine and functional food applications. This review provides a comprehensive examination of their structural features, biological activities, and molecular targets, with an emphasis on precision applications. Key polysaccharides such as alginates, carrageenans, fucoidans, ulvans, and laminarans are highlighted, focusing on their unique chemical backbones, degrees of sulfation, and branching patterns that underlie their bioactivity. Special attention is given to their roles in modulating inflammation, oxidative stress, apoptosis, gut microbiota, and metabolic pathways. Comparative assessment of extraction strategies, structure–function relationships, and bioactivity data highlights the importance of tailoring polysaccharide processing methods to preserve bioefficacy. Emerging insights from computational modelling and receptor-binding studies reveal promising interactions with immune and apoptotic signalling cascades, suggesting new therapeutic opportunities. Finally, the review outlines challenges related to standardisation, scalability, and regulatory approval, while proposing avenues for future research toward clinical translation and industrial innovation. By integrating structural biology, pharmacology, and nutraceutical sciences, this work underscores the potential of macroalgal polysaccharides as precision agents in health-promoting formulations and next-generation functional foods.

Keywords: algal polysaccharides; bioactive polysaccharides; functional foods; green extraction; immunomodulation; marine macroalgae; molecular characterisation; structure–function relationships; tissue engineering; therapeutic applications

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1. Introduction

Marine macroalgae, or seaweeds, have emerged as sustainable biorefineries of high-value polysaccharides, with annual global harvests now exceeding 30 million tonnes and a market forecast to reach USD 22 billion by 2027 [1,2]. These polymers, synthesised by the three major algal phyla (Phaeophyceae, brown; Rhodophyta, red; and Chlorophyta, green), exhibit remarkable structural heterogeneity, driven by variations in monosaccharide building blocks, glycosidic linkages and degrees of sulfation. Such molecular diversity translates into a spectrum of techno-functional and bioactive properties, including hydrogel formation, thickening, antioxidant activity, immunomodulation and tissue regeneration, underpinning their rapid adoption in biomedical, pharmaceutical and nutritional industries [3,4].

Brown seaweeds, such as *Laminaria*, *Macrocystis* and *Fucus* spp., are particularly valued for three polysaccharide classes [5,6]. Alginates are linear copolymers of β-D-mannuronic (M) and α-L-guluronic (G) acids that undergo Ca^{2+}-mediated "egg-box" gelation; by adjusting the mannuronate/guluronate (M/G) block ratio, gel stiffness, porosity and biodegradation rates can be finely tuned, facilitating applications in 3D bioprinting, wound dressings and oral delivery matrices [7]. Fucoidans are fucose-rich, sulfated heteropolysaccharides variably decorated with galactose, xylose or glucuronic acid; their defined sulfation patterns and chain lengths confer potent anticoagulant, anti-inflammatory and antitumour activities through selectin–ligand mimicry and modulation of coagulation pathways [8,9]. Laminarins, storage β-(1 → 3)/(1 → 6) glucans of 5–10 kDa, engage Dectin-1 and complement receptors on macrophages, eliciting cytokine release and reinforcing antioxidant defences, which has fuelled interest in their use as immunoadjuvants and in tissue-engineering scaffolds [10].

Green macroalgae, most notably *Ulva* spp., produce ulvans, complex sulfated heteropolymers rich in rhamnose, glucuronic and iduronic acids and xylose [11,12]. Their repeating ulvanobiuronic motifs and high sulphate density impart "vegan heparin"-like anticoagulant activity, together with prebiotic and antimicrobial effects. Ulvans' ability to form cold-set gels has been harnessed in edible films, wound-healing hydrogels and vaccine-delivery matrices that preserve thermolabile antigens [13].

Red macroalgae, such as *Kappaphycus*, *Gigartina*, and *Chondrus* spp., are the principal sources of carrageenans and agaroses [11]. Carrageenans occur as κ, ι and λ isoforms, distinguished by sulfation at C2, C4 or C6 of galactose units; κ-carrageenan forms strong, potassium-stable gels, ι-carrageenan yields elastic, calcium-mediated networks, and non-gelling λ-carrageenan acts as a high-viscosity thickener. These materials are now repurposed as mucoadhesive drug carriers and hydrogel scaffolds for controlled delivery, as demonstrated in recent experimental studies on carrageenan-based nasal formulations and alginate wound dressings [14–16]. Agarose, a neutral copolymer of alternating β-D-galactose and 3,6-anhydro-α-L-galactose, forms thermoreversible, high-clarity gels with exceptional mechanical integrity, underpinning its continued use in electrophoresis, chromatography and three-dimensional cell culture platforms [17].

Figure 1 compares the key polysaccharides found in brown, red and green seaweeds by showing their typical abundance ranges. Brown algae are richest in alginate (20–40%), with lower levels of laminarin (5–15%), fucoidan (2–8%) and trace ascophyllan (1–3%). Red algae primarily contain agarose (60–70%) and carrageenan (20–75%), alongside smaller amounts of porphyran (4–10%). In green algae, ulvan (8–29%) predominates, with rhamnan sulphate (15–25%) and galactan (around 12%) also present.

The functional specificity of these marine polysaccharides derives from precise structure–activity relationships. In biomedical contexts, alginate's M/G ratio dictates network architecture, enabling fine control over cell-encapsulation efficiency and release kinetics for growth factors and therapeutics [18]. Fucoidan's sulfation topography and molecular weight distribution determine its affinity for coagulation factors, selectins and viral proteins, underpinning anticoagulant, antiviral and anticancer modalities [8]. Laminarin's β-glucan backbone modulates macrophage phenotypes via Dectin-1 and complement pathways, offering routes to immunotherapy and vaccine adjuvancy [10].

In nutritional applications, ulvan and carrageenan resist mammalian enzymes yet are fermented by gut microbiota to produce short-chain fatty acids (SCFAs) that support epithelial barrier integrity and systemic metabolic regulation [13,14]. Alginate gels slow gastric emptying and enhance satiety, while serving as vehicles for encapsulated vitamins and minerals in nutraceutical formulations [18]. Beyond their native forms, chemical and enzymatic modifications, such as oversulfation, acetylation and targeted depolymerisation,

enable bespoke tuning of charge density, hydrophobicity and molecular weight, facilitating the design of advanced wound-healing hydrogels, stimuli-responsive nanocarriers and tailored tissue scaffolds [19].

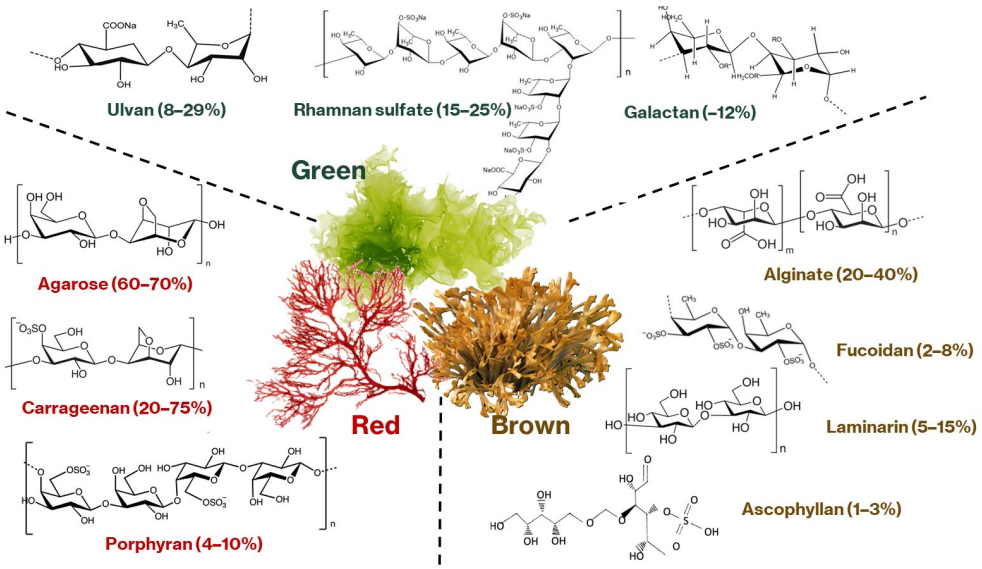


Figure 1. Comparative overview of the principal polysaccharide classes and their typical abundance ranges in the three macroalgal phyla: Phaeophyceae (brown algae), Rhodophyta (red algae) and Chlorophyta (green algae).

Although seaweed supplies valuable compounds such as polysaccharides, the environmental impacts of large-scale harvesting, the ecological consequences of valorising invasive species, and the ethical considerations of marine resource use warrant careful attention and further study.

Large-scale seaweed harvesting presents both environmental benefits and risks. On the positive side, seaweed farms can mitigate climate change by sequestering carbon, absorbing excess nutrients to improve water quality, and providing habitats that support marine biodiversity [20]. However, potential drawbacks include pollution from farming materials such as plastic ropes and buoys, alterations in local water chemistry and light penetration, and the release of nutrients from decomposing seaweed litter, which may negatively affect surrounding ecosystems if not properly managed [20]. The valorisation of invasive seaweed species also carries trade-offs. It can enhance productivity and deliver economic benefits by creating new products, yet invasive species often displace native flora and fauna, reduce biodiversity, and disrupt ecosystem services [21]. Ethical considerations emphasise the need for sustainable practices, equitable benefit-sharing, and collaborative governance [22]. Balancing economic gains with environmental stewardship remains a pressing challenge, especially given regulatory gaps in international waters [22].

This article aims to classify marine algal polysaccharides by phylum, evaluate their defining structural motifs and optimal extraction strategies, elucidate their bioactivity mechanisms through a structure–function lens, explore their applications in food, nutraceutical, pharmaceutical, and biomedical fields, and address advances in sustainable extraction and derivatisation. Ultimately, it seeks to identify translational challenges and propose future directions, leveraging multi-omics, artificial intelligence and integrated biorefinery models to enable the precision exploitation of marine algal polysaccharides in health-oriented industries.

2. Methodology

To ensure comprehensive coverage of marine algal polysaccharides and their structure–function relationships, literature searches were performed in four principal academic databases: PubMed, Scopus, Web of Science and Google Scholar. A targeted keyword strategy combined terms related to polysaccharide class and application, such as "fucoidan", "alginate", "laminarin", "carrageenan", "ulvan", "structure–activity", "bioactivity", "nutraceutical", "drug delivery", "tissue engineering" and "extraction method". Boolean operators (AND, OR) refined the searches, for example, "fucoidan AND anticoagulant" or "ulvan OR rhamnose uronic acid AND prebiotic", and backwards citation tracking of key reviews and primary studies captured additional relevant articles not retrieved in database queries.

Inclusion was limited to peer-reviewed articles published in English that focused on marine-derived polysaccharides from brown, green or red macroalgae and reported at least one of the following: detailed structural characterisation, bioactivity assays or biomedical/nutritional applications. Studies on freshwater algae, microbial polysaccharides or non-polysaccharide algal metabolites were excluded unless they provided mechanistic insights directly translatable to macroalgal polymers. Editorials, conference proceedings and non-peer-reviewed sources were omitted. In vitro investigations were considered only when they elucidated mechanisms that supported findings from cell-based or in vivo models.

The literature surveyed in this review encompasses publications from 2009 to the present. Although no strict date restriction was imposed, priority was given to research published between 2015 and 2025 to capture the latest advances in extraction technologies, structure elucidation and functional testing. Foundational studies predating this window were included selectively when they offered essential context for polysaccharide biosynthesis or early characterisation methods. Meta-analyses and systematic reviews were consulted to synthesise quantitative trends, while life-cycle assessments and sustainability reports provided perspectives on green extraction and scalability.

3. Structural Diversity of Macroalgal Polysaccharides

Marine macroalgal polysaccharides display remarkable heterogeneity in their monosaccharide building blocks, glycosidic linkage patterns, degree and position of sulfation, molecular weight distributions and branching architectures. This diversity underpins a wide array of techno-functional and bioactive properties, from hydrogel formation and thickening to antioxidant activity and immunomodulation. A concise overview of the principal polymers, their structural characteristics, main activities and typical applications is provided in Table 1.

Table 1. Overview of major marine-derived polysaccharides, their structural features, bioactivities and common application areas, organised by phylum and polysaccharide name.

Polysaccharide	Monosaccharide Composition	Major Glycosidic Linkages	MW (kDa)/Sulfation (% *w*/*w*)	Principal Bioactivities	Typical Applications	Reference
			Brown phylum			
Alginate	Copolymer of β-D-mannuronic acid (M) and α-L-guluronic acid (G) in M- and G-blocks	β(1 → 4) linking M and G units in homo- and heteropolymeric blocks	32–400/0	Immunomodulatory; anti-inflammatory; antioxidant (low-MW fractions); gelation for haemostasis	Wound-healing dressings; drug-delivery hydrogels; cell-encapsulation scaffolds; food stabiliser	[23]

Table 1. *Cont.*

Polysaccharide	Monosaccharide Composition	Major Glycosidic Linkages	MW (kDa)/Sulfation (% *w*/*w*)	Principal Bioactivities	Typical Applications	Reference
Ascophyllan	Heteropolysaccharide of fucose, xylose, glucuronic acid; minor glucose and peptide fragments	Alternating α(1 → 3) and α(1 → 4) backbone with fucose/xylose side chains	100–400/~10	Potent immunostimulant; anti-tumour; anti-metastatic; antioxidant; anti-inflammatory	Vaccine/cancer immunoadjuvant; functional food supplement for immune health	[24]
Fucoidan	L-fucose (>75 mol%) with minor galactose, xylose, and glucuronic acid	Alternating α(1 → 3) and α(1 → 4) fucopyranose with branching and O-2/O-4 sulfation	10–1000/5–30	Heparin-like anticoagulant; antiviral entry inhibitor; anti-inflammatory; immunomodulatory; anticancer	Nutraceuticals, antiviral sprays, cancer adjuvant therapy, and hydrogel component	[25]
Laminarin	β-D-glucose linear glucan with occasional β(1 → 6) branches; may terminate in mannitol	β(1 → 3) backbone with ~3% β(1 → 6) branching	3–6/0	Antioxidant; immunostimulatory; anti-tumour; antimicrobial	Prebiotic dietary fibre, cancer immunotherapy adjuvant, immunity-boosting wound-healing sprays	[10]
			Green phylum			
Codium sulfated galactan	~70% galactose backbone with minor arabinose, glucose, xylose; pyruvate acetals	Primarily β(1 → 3)-D-galactose backbone with sulphates at C-4/C-6; arabinose branches	<20/~20	Antioxidant; anticoagulant; anticancer; anti-inflammatory	Nutraceutical antioxidant; potential anticancer and anti-inflammatory therapeutics	[26]
Rhamnan sulfate	>90% L-rhamnose backbone with branching; sulfation at C-2/C-3	Linear α(1 → 3)-L-rhamnose backbone with α(1 → 2) branches	50–200/~25	Anticoagulant; antiviral; anti-hyperlipidaemic; prebiotic	Cardiovascular nutraceutical, antiviral coatings, heparinoid research	[27]
Ulvan	L-rhamnose (16–45%), D-glucuronic acid (6–19%), L-iduronic acid (1–9%), D-xylose (2–12%) + others	Ulvanobiuronic motifs: β-D-GlcA/α-L-IdoA-(1 → 4)-α-L-Rha-3-sulphate; highly branched	10–2000/2–40	Anticoagulant; anti-inflammatory; antioxidant; immunostimulatory; prebiotic; antiviral	Edible films, drug-delivery hydrogels, vaccine adjuvants, and agricultural biostimulants	[28]
			Red phylum			
Agarose	Alternating D-galactose and 3,6-anhydro-L-galactose units	β(1 → 4) (D-galactose) alternating with α(1 → 3) (L-anhydrogalactose)	80–140/0	Inert, biocompatible, strong thermo-reversible gelation	Gel electrophoresis; 3D cell scaffolds; soft capsule shells; wound dressings; food gelling	[17]
Carrageenan (ι-type)	Repeating β-D-galactose-4-sulphate and α-L-3,6-anhydrogalactose-2-sulfate	β(1 → 3)-D-galactose and α(1 → 4)-galactose (3,6-anhydro bridge)	100–1000/28–30	Antiviral; immunomodulatory; soft elastic hydrogel formation	Food gelling (puddings); mucoadhesive drug-delivery; wound dressings	[29]
Carrageenan (κ-type)	Repeating β-D-galactose-4-sulphate and α-D-3,6-anhydrogalactose	β(1 → 3)-D-galactose and α(1 → 4)-galactose (3,6-anhydro bridge)	100–1000/25–30	Strong thermo-reversible gelling with K^+; antiviral; mild anticoagulant	Firm gels in foods, tablet binder, antiviral microbicides	[30]
Carrageenan (λ-type)	Repeating β-D-galactose-2,6-disulfate and α-D-galactose-2-sulphate	β(1 → 3)- and α(1 → 4)-linked galactose (fully sulfated, non-anhydrous)	100–1000/32–39	Non-gelling polyelectrolyte; antiviral; anticoagulant	Viscosity modifier in dairy, toothpaste thickener, experimental antiviral sprays	[30]
Porphyran	Alternating α-L-galactose-6-sulphate and β-D-galactose	β(1 → 3) and α(1 → 4) alternating (similar to agarose, partially sulfated)	100–500/15–20	Antioxidant; anti-inflammatory; anti-diabetic; anticancer	Nutraceuticals from nori, edible films, nanocarriers, and metabolic health supplements	[31]

Abbreviations: Ca^{2+}, Calcium ion; DW, Dry weight; G, α-L-Guluronic acid; kDa, Kilodalton; M, β-D-Mannuronic acid; M/G, Mannuronic/Guluronic acid ratio; MW, Molecular weight; *w*/*w*, Weight-by-weight.

3.1. Major Classes of Polysaccharides

Marine macroalgal polysaccharides group into several principal classes, each defined by distinctive monosaccharide backbones, linkage patterns and functional substituents (see Table 1). The biological activity of marine polysaccharides is strongly influenced by molecular weight and structural features. For example, fucoidan from *Fucus vesiculosus* shows distinct effects depending on its molecular weight, with lower fractions often exhibiting

stronger antioxidant, anticoagulant, or anticancer activity. Similar trends are observed in laminarins, alginates, and carrageenans, where size and sulfation patterns affect bioactivity.

Alginate, isolated from brown algae (20–40% dry weight), is a linear block copolymer of β-D-mannuronic (M) and α-L-guluronic (G) acids. The M/G ratio, ranging from 0.5 to 2.0 in commercial extracts, controls gel stiffness, porosity and biodegradation kinetics upon Ca^{2+} crosslinking. Low-G alginates (M/G > 1) yield soft, elastic gels suited to wound-healing dressings and probiotic encapsulation, whereas high-G alginates (M/G < 1) provide rigid scaffolds for 3D bioprinting and controlled drug release [23]. Ascophyllan (1–3% DW), a less-studied brown-algal heteropolysaccharide, combines fucose, xylose and glucuronic acid in an alternating α(1 → 3)/α(1 → 4) backbone with minor peptide fragments. With an MW of 100–400 kDa and ~10% sulfation, it exhibits potent immunostimulatory, anti-tumour and antioxidant activities, making it a promising vaccine adjuvant and nutraceutical ingredient [24]. Fucoidan (2–8% DW) is characterised by a backbone of l-fucopyranose residues linked to α(1 → 3) and α(1 → 4), variably sulfated at O-2/O-4 (5–30% *w/w*) and decorated with minor galactose, xylose or glucuronic acid side chains. Its MW spans 10–1000 kDa, with low-MW fractions (<50 kDa) showing enhanced anticoagulant and antiviral potency due to improved receptor access. Fucoidan's heparin-like anticoagulant, anti-inflammatory and immunomodulatory functions have been confirmed in numerous recent experimental models, including studies showing prolonged APTT without affecting thrombin time in vivo, and apoptosis induction in breast and liver cancer cell lines [25,32,33]. Laminarin, a storage β-glucan prevalent in *Laminariaceae* (5–15% DW), consists of a β(1 → 3) backbone with ~3% β(1 → 6) branching and may terminate in mannitol. Its low MW (3–6 kDa) facilitates solubility and enables potent antioxidant and immunostimulatory effects via Dectin-1 and complement receptor engagement in macrophages. Laminarin's adjuvant properties have been explored in cancer immunotherapy and wound-healing formulations [34].

In green algae, codium sulfated galactan (~12% DW) features a predominantly β(1 → 3) galactose backbone with C-4/C-6 sulfation (~20%) and arabinose branches, conferring antioxidant, anticoagulant and anticancer activities at MW <20 kDa [26]. Rhamnan sulphate (15–25% DW), a linear α(1 → 3) L-rhamnose polymer with α(1 → 2) branches and 25% sulfation, exhibits anticoagulant and antiviral effects at 50–200 kDa, positioning it as a "vegan heparin" candidate [27]. Ulvan (8–29% DW), composed of ulvanobiuronic motifs (GlcA/IdoA–Rha-3-sulphate), spans 10–2000 kDa with 2–40% sulfation, yielding robust prebiotic, immunomodulatory and antiviral activities in edible films and hydrogel vaccines [28,35].

Red-algal agarose (60–70% DW) consists of alternating β(1 → 4) D-galactose and α(1 → 3) 3,6-anhydro-L-galactose, forming high-clarity, thermo-reversible gels (80–140 kDa) critical for electrophoresis and 3D culture scaffolds [17]. Carrageenans (20–75% DW) occur as κ, ι and λ isoforms (100–1000 kDa; 25–39% sulfation). κ-Carrageenan yields firm, K^+-stabilised gels; ι-carrageenan produces elastic Ca^{2+}-mediated gels; λ-carrageenan remains non-gelling, offering high viscosity for dairy applications and antiviral formulations [29,30]. Porphyran (4–10% DW), a partially sulfated agarose analogue (15–20% sulfation), predominantly found in *Porphyra* spp. Structurally, porphyran consists mainly of repeating units of 3-linked β-D-galactopyranose and 4-linked α-L-galactopyranose, with variable methylation and sulfation patterns [31]. Recent studies have highlighted its antioxidant, anti-inflammatory, and anticancer properties, as well as its potential prebiotic activity [36,37]. Given these biofunctional attributes and its widespread use in traditional diets (notably in nori), porphyran holds promise as a nutraceutical ingredient in functional food formulations. Beyond traditional biomedical uses, agarose has recently been investigated as a promising material for soft capsule shells. A study on the rheological behaviour of agar hydrogels demonstrated that agarose-based systems offer excellent viscoelastic properties,

mechanical integrity, and thermo-reversible gelling suitable for encapsulating sensitive bioactives in pharmaceutical applications. These findings support its viability in replacing gelatine-based capsules for vegetarian or temperature-sensitive formulations [17].

3.2. Variability Driven by Species, Habitat, and Extraction Parameters

The structural attributes of marine algal polysaccharides are profoundly influenced by both intrinsic biological factors and downstream processing choices. Seasonal and geographic variations in seawater temperature, salinity and nutrient availability modulate algal metabolism, leading to significant shifts in monosaccharide ratios, branching patterns and sulfation degrees [38]. For instance, fucoidans from *Fucus vesiculosus* harvested in cold Atlantic waters exhibit higher O-4 sulfation and increased low-molecular-weight fractions compared to those collected in warmer months, correlating with stronger anticoagulant and antiviral potencies [9,39]. Comparable patterns have been documented in Arctic *Fucus* and *Ascophyllum* species, where the extreme conditions of low temperatures and high salinity favour accumulation of sulfated fucoidans with potent antiradical properties [40–43].

Similarly, the M/G ratio in alginates can vary from 0.3 to 2.0 across different *Laminaria* and *Macrocystis* strains, directly tuning gel viscoelasticity for tailored wound healing versus drug release applications [44]. This aligns with broader evidence that alginate composition strongly reflects environmental and species-specific drivers, shaping its biomedical suitability [39]. In *Laminaria digitata*, elevated nutrient levels boost β-1,6 branching in laminarin by up to 20%, enhancing its Dectin-1-mediated immunostimulation [45]. Across red algae, carrageenan isoform proportions (κ:ι:λ) shift from 2:1:0.5 during vegetative growth to 1:1:1 in reproductive stages, altering gel strength and thermal hysteresis in food and biomedical gels [46]. Ulvans from *Ulva lactuca* display a twofold increase in rhamnose content under high-light, low-nutrient conditions, strengthening their prebiotic fermentation profiles and immunomodulatory efficacy [47].

Superimposed on this natural heterogeneity, extraction and fractionation protocols introduce additional variability in yield, molecular-weight distribution, purity and functional-group retention (Table 2). Acid extraction (0.05 M HCl, 60 °C, 3 h) typically produces 40–45% total polysaccharides but can selectively cleave glycosidic bonds in heat-labile laminarins and alginates, reducing average MW by ~30% and potentially diminishing antioxidant activity [48]. Alkaline extraction (60% KOH, 80 °C, 3 h) is favoured for carrageenan, boosting 3,6-anhydrogalactose content by 10–15% and improving gel strength, albeit at the expense of some sulphate loss (<5%) [49]. By contrast, deep-eutectic solvents (choline chloride/glycerol 1:2 + 10% H_2O, 80 °C, 1 h) offer yields comparable to alkaline methods (~60%) while preserving native sulfation patterns and enabling solvent recycling [50,51].

A recent comparative study evaluated the efficiency and bioactivity outcomes of dynamic maceration versus ultrasonic-assisted extraction (UAE) for fucoidan recovery from four Arctic brown algae species. The findings revealed that the UAE not only improved the extraction yield but also preserved structural integrity and enhanced antioxidant and anticancer properties of the resulting fucoidan fractions [52]. These results are consistent with the work of Obluchinskaya and colleagues, who demonstrated that UAE treatment of Arctic *Fucus distichus* and *Fucus spiralis* preserved sulfation motifs critical for radical scavenging, thereby translating into enhanced antiradical activity and reduced potential human health risks [41,42].

In addition to extraction conditions, purification methods have a substantial impact on the structural integrity and biological activity of fucoidan. A recent comparative study examining fucoidans from brown seaweed species demonstrated that differences in purification steps, such as ethanol precipitation, dialysis, and ion-exchange chromatography, significantly influenced the in vitro anti-inflammatory effects, including cytokine sup-

pression and inhibition of NO production in macrophage assays [53]. This agrees with Arctic fucoidan studies, where variations in dialysis cut-offs and ethanol concentrations altered the MW distribution and, consequently, the antioxidant and immunomodulatory responses in vitro [40,43]. These findings highlight the importance of post-extraction processing in determining final product efficacy [53]. In line with recent trends in green and non-thermal extraction methods, UAE has also been shown to significantly influence the chemical composition and bioactivity of fucoidan. Specifically, treatment of *Fucus* extracts with ultrasound modified the molecular weight distribution and enhanced anticoagulant properties through improved sulfation retention and structural integrity. This mechanistic relationship between sulfation preservation and bioactivity mirrors the outcomes observed in Arctic *Ascophyllum nodosum*, where polysaccharides obtained via UAE demonstrated both higher antioxidant potential and lower levels of heavy-metal co-extraction, reinforcing the dual benefits of efficacy and safety [43]. These effects support the utility of UAE not only for increasing extraction efficiency but also for preserving or improving biofunctional properties [54].

Enzyme-assisted extraction (cellulase or Alcalase, pH 5–7, 50 °C, 2–4 h) is uniquely capable of isolating fucoidan with >90% sulfation retention and minimal depolymerisation, although yields remain modest (4–6%) due to incomplete cell-wall digestion [55]. Emerging non-thermal technologies such as high-hydrostatic pressure (300 MPa, 5 min), microwave-assisted extraction (800 W, 90 °C, 10 min), and pulsed-electric-field treatments (10–20 $kVcm^{-1}$ pulses) can increase total polysaccharide recovery by 10–15% while maintaining high-MW fractions and native conformations, thus maximising bioactivity [56–59]. By strategically matching macroalgal species, harvest conditions and extraction parameters, researchers can tailor polysaccharide preparations with defined molecular-weight, sulfation and branching profiles, ensuring consistent functional properties for targeted biomedical, pharmaceutical and nutraceutical applications.

Furthermore, fucoidans isolated from *Dictyota dichotoma* have recently demonstrated potent antioxidant and antitumor properties, highlighting how sulphate positioning and MW distribution govern bioactivity [60]. Collectively, these findings align with the growing body of Arctic seaweed research, which consistently demonstrates that both environmental stressors and gentle, non-thermal extraction strategies can synergistically enhance fucoidan quality, providing biofunctional polysaccharides with reliable efficacy and reduced safety risks [40–43].

Table 2. Extraction methods for marine algal polysaccharides.

Method	Target Polysaccharide	Key Parameters	Yield (%)	Advantages	Reference
Acid extraction	Fucoidan, alginate, laminarin (e.g., from *Durvillaea potatorum*)	0.05 M HCl; 60 °C; 3 h	~43.6 (total polysaccharides)	Simple; disrupts cell walls and H-bonds; yields high-MW fractions with strong bioactivity	[48]
Alkaline extraction	Carrageenan (e.g., from *Kappaphycus alvarezii*)	60% KOH; 80 °C; 3 h	~33.0 (carrageenan)	Improves gel strength and 3,6-anhydrogalactose content; industrially established	[49]
Deep eutectic solvent (DES)	Carrageenan (e.g., from *Kappaphycus alvarezii*)	ChCl:Glycerol (1:2) + 10% H_2O; 80 °C; 1 h	~60.3 (carrageenan)	Green, recyclable solvent; tuneable selectivity; comparable yields to conventional methods	[50]
Dynamic Maceration (DM)	Fucoidan (crude, unfractionated) from four arctic brown algae	Maceration with mechanical stirring, 60 °C, 200 rpm, two macerations	Baseline (control) vs. UAE	Preserves higher phlorotannin content; yields lower than UAE but gives higher antioxidant/anticancer activity in some species	[52]

Table 2. *Cont.*

Method	Target Polysaccharide	Key Parameters	Yield (%)	Advantages	Reference
Enzyme-assisted extraction (EAE)	Fucoidan (e.g., from *Nizamuddinia zanardinii*)	Cellulase or Alcalase (E/S 1:50); pH 5–7; 50 °C; 2–4 h	~4–6 (fucoidan)	Mild conditions preserve MW and bioactivity; lower energy and solvent use	[55]
High hydrostatic pressure (HHP)	Mixed polysaccharides (e.g., fucoidan/alginate from *A. nodosum and Saccharina latissima*	350 MPa, for 5 min at 20 ± 2 °C	23 and 14% for *A. nodosum* and *S. latissima*	Rapid, non-thermal permeabilization; preserves heat-sensitive compounds, higher yields	[58]
Hot water extraction	Ulvan from *Ulva papenfussii*	pH 7; 90–100 °C; ~2–3 h	~29%	Uses water as a non-toxic, food-grade solvent; preserves structural sulphate groups relevant for biological activity	[61]
Ionic liquid extraction	Agarose (e.g., from *Gracilaria dura*)	Choline laurate (4% *w/w*) in hot water; RT	~14.0 (agarose)	Selective separation, mild conditions, IL recycling, high purity without freeze/thaw	[62]
Microwave-assisted extraction (MAE)	Carrageenan (e.g., from *Solieria chordalis*); other polysaccharides	800 W; 90 °C; 10 min; water (1:20 *w/v*)	~29.3 (carrageenan)	Very rapid, precise heating; higher yields with less degradation; solvent-efficient	[56,57]
Multi-step purification (e.g., ethanol, dialysis, chromatography)	Fucoidan (5 brown algae species)	Sequential purification post-extraction	not available	Enhances anti-inflammatory activity by enriching bioactive fractions; removes inhibitory impurities	[53]
Pressurised liquid extraction (PLE)	Fucoidan (e.g., from *Saccharina japonica*)	140 °C; 5 MPa; 15 min; subcritical water (+0.1% NaOH)	~8.2 (fucoidan)	Fast, green (water only), tuneable conditions; automated, extracts show strong bioactivity	[63]
Pulsed electric field (PEF)	Polysaccharides from *Laminaria digitata*	Biomass concentration (0.17–3.28% dry weight), 12–268 pulses, initial temperature 12–48 °C	2.6 ± 2.9 mg g^{-1} DW	Non-thermal; electroporation accelerates release, preserves heat-sensitive components	[59]
Supercritical fluid extraction (SFE)	-Fucoidan from *Undaria pinnatifida* -Sulfated polysaccharides from *Gracilaria mammillaris*	-Fucoidan: CO_2 at 40 MPa; 40 °C (+5–10% EtOH co-solvent) -Sulfated polysaccharides: Solvent: CO_2 at 10–30 MPa+ ethanol (2%, 5%, or 8% as co-solvent); 40–60 °C	Fucoidan: higher recovery with co-solvent and microwave pretreatment -Sulfated polysaccharides: highest antioxidant activity: 30 MPa, 60 °C, 8% ethanol.	Uses non-toxic CO_2 + ethanol. Low temperature preserves thermolabile polysaccharides. Sulfated polysaccharides with high antioxidant activity.	[64]
Ultrasound-assisted extraction (UAE)	Sulfated polysaccharides (e.g., fucoidan from *Sargassum muticum*); alginate, carrageenan, etc.	20–500 W; 20 kHz; ≤30 °C; 5–30 min	~24.8 (vs. 11.1 by hot water)	Cavitation ruptures cells; much faster, higher yield, low temp preserves sensitive molecules; enhances anticoagulant activity; preserves sulfation and MW distribution	[55,65]
UAE	Fucoidan (crude, unfractionated) from four arctic brown algae	Sonication (22 kHz) at room temperature, 20 min × 2 cycles	~+43.2% increase over DM (i.e., yield higher)	Higher extraction yield, increased uronic acid content; but lower phlorotannin co-extracted content (~−53.7%)	[52]

Abbreviations: ChCl, choline chloride; DES, deep-eutectic solvent; EAE, enzyme-assisted extraction; E/S, enzyme/substrate ratio; EtOH, ethanol; HCl, hydrochloric acid; HHP, high-hydrostatic pressure; IL, ionic liquid; KOH, potassium hydroxide; MAE, microwave-assisted extraction; MPa, megapascal; PEF, pulsed electric field; RT, room temperature; SFE, supercritical fluid extraction; UAE, ultrasound-assisted extraction; *w/v*, weight/volume.

3.3. Advanced Characterisation Techniques

A full understanding of marine polysaccharide structure–function relationships requires a multidisciplinary analytical toolbox. Nuclear Magnetic Resonance (NMR) spectroscopy remains the gold standard for defining monosaccharide stereochemistry, linkage patterns and substitution sites. One-dimensional ^{1}H and ^{13}C experiments reveal anomeric configurations and chemical shifts of ring carbons, while two-dimensional techniques (COSY, TOCSY, HSQC, HMBC) map inter-residue connectivity and pinpoint O-sulfation at C-2, C-4 or C-6 positions [66]. Diffusion-ordered spectroscopy (DOSY) further distinguishes co-existing oligomeric fractions without chromatographic separation [67].

Mass spectrometry (MS) complements NMR by delivering high-resolution molecular weight profiles and sequence information. MALDI-TOF MS rapidly screens intact polymers up to 200 kDa, whereas ESI-MS/MS fragments oligosaccharides to localise branches and substituents. Coupling MS to ion-mobility separation resolves structural isomers and conformers, critical for heterogeneous fucoidan and ulvan fractions [68].

Chromatographic methods provide orthogonal separations: Size-Exclusion Chromatography with Multi-Angle Light Scattering (SEC-MALS) yields absolute molar mass and radius-of-gyration without calibration standards, while High-Performance Anion-Exchange Chromatography with Pulsed Amperometric Detection (HPAEC-PAD) quantifies monosaccharide composition to ppm sensitivity. Asymmetric Flow Field-Flow Fractionation (AF4) extends MW analysis to supramolecular assemblies up to 1 MDa, preserving native conformations [69].

These core platforms are often augmented by spectroscopic and microscopic approaches. FTIR and Raman spectroscopy rapidly screen functional-group vibrations, S=O stretches at 1250–1260 cm^{-1} for sulphates and C=O bands at 1640–1650 cm^{-1} for uronic acids, while Circular Dichroism (CD) reports on higher-order conformations such as triple-helical β-glucan structures [70]. Atomic-Force Microscopy (AFM) and Transmission Electron Microscopy (TEM) visualise chain alignment, fibrillar networks and gel microstructures in hydrogels, linking molecular detail to macroscopic rheology [31].

By integrating these complementary techniques, researchers can assemble a comprehensive "molecular fingerprint" for each polysaccharide class, enabling rational design, precise modification and robust quality control for applications across biomedicine, nutraceuticals and sustainable materials.

4. Mechanisms of Bioactivity

This section outlines how marine macroalgal polysaccharides (carrageenan, fucoidan, laminarin, and ulvan) modulate key cellular pathways: activating antioxidant defences via Nrf2, suppressing pro-inflammatory NF-κB signalling, engaging pattern-recognition receptors to shape immune responses and gut microbiota, inducing caspase-mediated apoptosis in cancer models, and blocking viral entry. It also highlights the rise of in silico tools, molecular docking and QSAR, to predict polysaccharide–protein interactions and guide the design of more potent, targeted derivatives. The therapeutic potential of compounds such as fucoidan, laminarin, or carrageenan is not uniform across all sources or molecular forms. Instead, these activities are highly dependent on factors such as molecular weight, degree and position of sulfation, monosaccharide composition, and extraction or purification methods. As such, all claims of bioactivity are contextualised by the source species, structural features, and experimental models from which the data were derived.

4.1. Antioxidant and Anti-Inflammatory Pathways

Marine macroalgal polysaccharides combat oxidative stress and inflammation by coordinately activating the nuclear factor erythroid 2-related factor 2 (Nrf2)–antioxidant response element (ARE) axis while suppressing the nuclear factor kappa B (NF-κB) pathway. Recent in vitro studies using fucoidan from *Fucus vesiculosus* have demonstrated Keap1 dissociation and Nrf2 nuclear translocation in keratinocytes and hepatocytes, leading to the upregulation of antioxidant enzymes (HO-1, NQO1, SOD-1) and reduced oxidative stress markers [71,72]. Low-molecular-weight fucoidan (SCF) from *Sargassum confusum* similarly attenuates TNF-α/IFN-γ-induced oxidative stress in HaCaT cells by activating Nrf2/HO-1 signalling and reducing Keap1 expression by 40%. Fucoidan from *Fucus vesiculosus* (100–500 μg/mL) was shown to reduce ROS levels and activate Nrf2/HO-1 signalling

in HaCaT keratinocytes exposed to UV stress for 24 h, with untreated and vehicle-only controls used for comparison [71].

Additional evidence indicates that fucoidan from Arctic *Fucus vesiculosus* enhances mitochondrial antioxidant defence by upregulating SOD-2 and catalase, while simultaneously downregulating lipid peroxidation markers such as MDA. Moreover, these protective effects were dose-dependent and linked to increased glutathione peroxidase activity, suggesting a broader reinforcement of endogenous redox homeostasis [73]. Concomitantly, both fucoidan and laminarin attenuate pro-inflammatory signalling by preventing IκBα phosphorylation and p65 nuclear translocation. In LPS-stimulated RAW 264.7 macrophages, fucoidan reduces production of TNF-α and IL-6 by >60%, inhibits COX-2 and iNOS expression and dampens MAPK-driven NF-κB activation. Laminarin, via Dectin-1 engagement, blocks LPS-induced p38 and ERK phosphorylation, further lowering IL-1β secretion in murine macrophage models [74].

In line with these findings, fucoidan from *Fucus vesiculosus* collected in the Barents Sea has been shown to modulate both NF-κB and JAK/STAT signalling cascades, thereby exerting dual anti-inflammatory and immunomodulatory effects. This includes suppression of pro-inflammatory cytokines (IL-1β, TNF-α) and enhancement of anti-inflammatory mediators such as IL-10, highlighting its role as an immunoregulatory agent beyond classical NF-κB inhibition [73]. In vitro testing of fucoidans from five brown seaweed species revealed that their total antioxidant capacity was strongly correlated with polyphenol content and only weakly with xylose content. For the first time, synergistic effects between fucoidan carbohydrates and polyphenols were quantified, with significant synergy in the DPPH assay observed for FV1 and FV3 fractions. This synergism was closely linked to polyphenol and, to a lesser extent, fucose content. Anti-inflammatory activity was further demonstrated through concentration-dependent inhibition of protein denaturation, strongly associated with fucose and moderately with sulphate content. Notably, purified fucoidan FV2 exhibited the highest anti-inflammatory potential (IC_{50} = 0.20 mg/mL), surpassing diclofenac sodium, and also stabilised red blood cell membranes, confirming its protective effects [75].

Importantly, pharmacokinetic studies have shown that fucoidan is bioavailable both after oral and topical administration. Following oral dosing in rats, *Fucus vesiculosus* fucoidan was detected in plasma and distributed across several tissues (kidney, spleen, liver), confirming systemic absorption and retention in key metabolic and immune organs [76]. Complementary investigations demonstrated that topically applied fucoidan can also penetrate the skin barrier, achieving measurable plasma levels and tissue distribution [77]. These findings provide crucial in vivo support for the antioxidant and anti-inflammatory mechanisms observed in vitro, validating fucoidan's translational potential in systemic and dermal applications.

Beyond fucoidan, pharmacokinetic challenges are common to other marine-derived polysaccharides. As reviewed by Shikov et al. [78], high molecular weight, polyanionic charge, and limited membrane permeability restrict systemic uptake of sulfated glycans and related macromolecules. Absorption may occur via partial degradation, paracellular uptake, or vesicular transport, while elimination primarily involves renal clearance and biliary excretion. Moreover, detection of circulating polysaccharides requires sensitive bioanalytical techniques, such as radiolabeling or derivatization, given their typically low plasma concentrations. These insights align with the modest but measurable bioavailability reported for fucoidan and highlight the importance of delivery strategies that overcome intrinsic ADME barriers to fully realise the antioxidant and anti-inflammatory potential of marine polysaccharides.

In addition to systemic and cellular models, the anti-inflammatory potential of fucoidan has also been demonstrated in topical applications. In a recent in vivo study, a fucoidan-based cream was formulated and optimised for dermal delivery, and its anti-inflammatory efficacy was evaluated using a mouse model of induced skin inflammation. The treatment significantly reduced ear thickness, myeloperoxidase activity, and local cytokine levels (e.g., TNF-α, IL-1β), confirming the bioactivity of topically delivered fucoidan and its suitability for dermatological applications [79].

4.2. Immunomodulation and Gut Microbiota Interactions

Beyond direct cellular effects, algal polysaccharides shape immune function via gut-microbiota-mediated metabolites. Fucoidan engage Toll-like receptors (TLR-2/4) and Dectin-1 on dendritic cells and macrophages, skewing cytokine profiles towards anti-tumour (increased IL-12, IFN-γ) and anti-pathogen (enhanced phagocytosis) responses in murine splenocyte cultures [80].

Oral administration of several algal polysaccharides resists upper-GI digestion yet is fermented by colonic bacteria into SCFAs, notably butyrate and propionate. These SCFAs reinforce epithelial tight junctions, promote regulatory T-cell (Treg) differentiation and suppress endotoxin leakage in murine colitis models, reducing serum LPS and IL-17 levels by ~50% [81].

4.3. Anticancer Actions: Apoptosis, Anti-Metastatic Effects

Fucoidan exerts multi-targeted anticancer effects through both intrinsic (mitochondrial) and extrinsic (death receptor) apoptotic pathways. In MCF-7 breast-cancer cells, fucoidan induces Bax/Bcl-2 imbalance, triggers cytochrome-c release and activates caspase-3/9, culminating in >70% apoptosis, while concurrently inhibiting PI3K/Akt and MAPK signalling to arrest cells at G0/G1 [82,83]. Laminarin similarly prompts intrinsic apoptosis in HCT-116 colon cancer cells via p53 and p21 up-regulation, and suppresses MMP-9-mediated invasion by 60% [84]. These data underline β-glucans as promising adjuvants to chemo- and immunotherapy. In an in vivo breast cancer model, low-molecular-weight fucoidan (20 mg/kg/day, orally administered for 21 days) significantly reduced tumour volume and downregulated PI3K/Akt/mTOR signalling, with saline-treated and 5-FU-treated groups serving as controls [85].

4.4. Antiviral and Antimicrobial Mechanisms

Sulfated galactans such as ι-carrageenan act as viral entry inhibitors by binding positively charged regions of viral envelope proteins. In human airway epithelial cultures, low-MW ι-carrageenan (λ = 20 kDa) reduces SARS-CoV-2 and OC43 infectivity by >90% through spike-protein sequestration on the cell surface [86]. Fucoidan and ulvan also disrupt bacterial biofilms, and fucoidan inhibits *Staphylococcus aureus* adhesion on catheter surfaces by blocking teichoic acid interactions, while ulvan compromises Gram-negative outer membranes, reducing *E. coli* viability by 3 log units [87].

4.5. In Silico Insights: Molecular Docking and Predictive Modelling

Computational docking and QSAR approaches are rapidly elucidating the molecular bases of polysaccharide–protein interactions. Fucoidan oligosaccharide fragments display high-affinity binding (Kd∼50 nM) to SARS-CoV-2 main protease in silico, with key interactions at His41 and Cys145, guiding the design of fucoidan-peptide conjugates for targeted antiviral delivery [88]. Likewise, docking of ulvan repeating units to cyclooxygenase-2 predicts favourable binding energies (−7.9 kcal/mol), supporting its anti-inflammatory potential [89]. Molecular-dynamics simulations further suggest that enhancing O-sulfation

density and optimising chain length can improve selectivity and potency, accelerating the rational design of next-generation therapeutic glycomaterials.

Recent advances in molecular docking and machine learning have expanded the utility of in silico methods for predicting the bioactivity of sulfated polysaccharides. For example, docking studies using molecular fragments of ulvan and fucoidan have revealed potential interactions with TLR4, TNF-α, and SARS-CoV-2 spike proteins [90,91]. More recently, machine learning-assisted QSAR models have been developed using annotated polysaccharide libraries to predict immunomodulatory potential, offering promising tools for rational polysaccharide design [92].

As shown in Figure 2, fucoidan, carrageenan, laminarin, and ulvan modulate key pathways to deliver antioxidant, anti-inflammatory, immunomodulatory, apoptotic and antiviral effects. Fucoidan and carrageenan activate Nrf2 and inhibit NF-κB, boosting antioxidant enzymes and reducing cytokines. They also engage TLR-2/4 to balance immune responses. Laminarin triggers apoptosis via Dectin-1–mediated caspase-3/-9 activation. All four blocks of viral entry and replication through steric and charge interactions. Ulvan adds further immunomodulatory and anti-inflammatory activity, highlighting the multifunctional bioactivity of these marine polysaccharides.

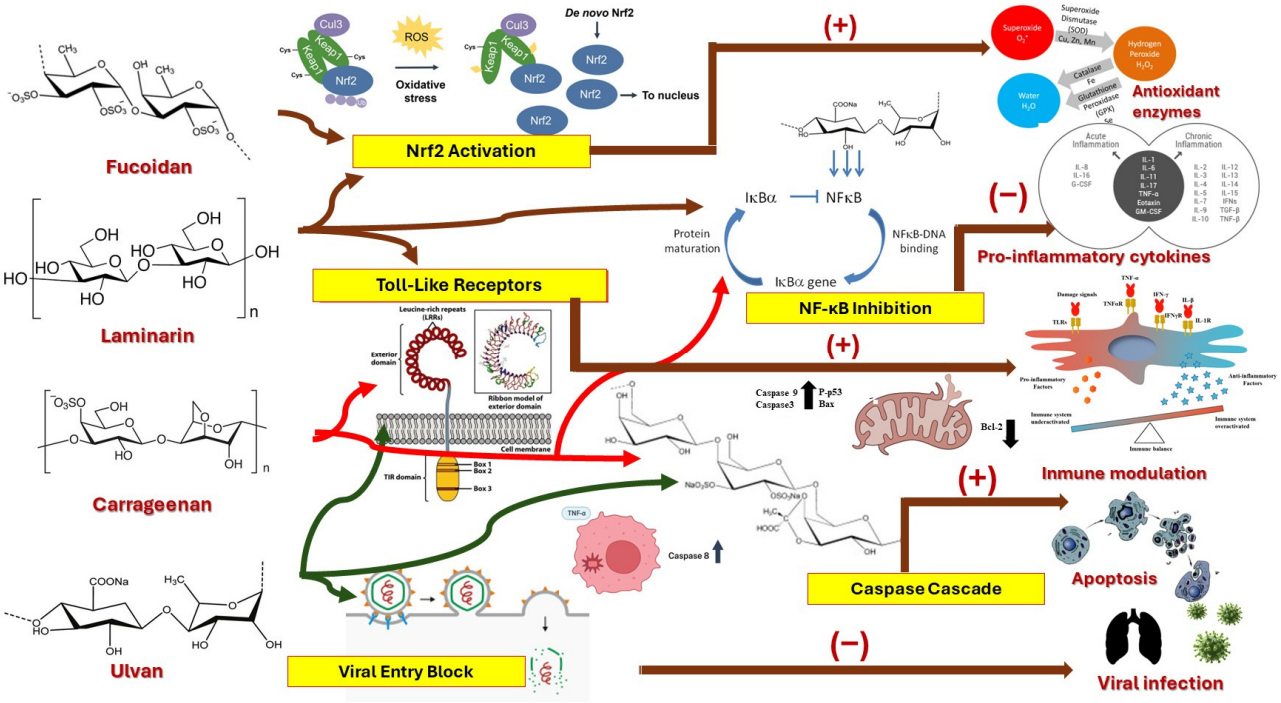


Figure 2. Schematic overview of the molecular pathways through which key marine-derived polysaccharides (left) engage specific signalling axes (centre) to produce distinct bioactivities (right). Brown arrows represent activation or signalling pathways initiated by algal polysaccharides; Red arrows represent stimulatory or enhancing effects ("positive regulation"); Green arrows represent inhibitory or blocking actions, often against pathogens or harmful processes.

5. Structure–Function Relationships

Marine polysaccharides exhibit a remarkable versatility of bioactivities and material properties that are intrinsically linked to their molecular architecture. In this section, we explore how variations in sulphate content, positional substitution and chain length modulate charge density, protein interactions and supramolecular assembly. We then consider the role of monosaccharide composition and glycosidic branching in dictating solubility, conformational motifs and receptor binding. Finally, we highlight the power

of post-extraction derivatisation, including oversulfation, acetylation and other chemical modifications, to tailor both biological potency and functional performance.

5.1. Influence of Sulphate Content, Position, and Molecular Weight

The degree of sulfation constitutes one of the most critical determinants of biological activity in marine polysaccharides. An increased sulphate content generally enhances anticoagulant, antiviral and anti-inflammatory properties by raising the negative charge density, thereby better mimicking host glycosaminoglycans and promoting stronger electrostatic interactions with clotting factors or viral envelope proteins [93]. Interestingly, the exact position of the sulphate ester, whether at O-2, O-3 or O-4 of the monosaccharide moiety, can dramatically alter target specificity: O-2 sulfation in fucoidans, for example, has been linked to potent thrombin inhibition, whereas O-4-sulfated fractions preferentially block selectin-mediated cell adhesion [94].

Molecular weight (MW) further modulates function. Low-MW fractions ($\leq$10 kDa) often exhibit superior antioxidant capacity and enhanced cellular uptake, owing to their reduced steric hindrance and improved diffusion across biological membranes [95]. In contrast, high-MW polymers (>100 kDa) generate more cohesive networks, yielding robust hydrogels suited to sustained-release drug delivery or tissue scaffolding [96]. A finely tuned balance of sulfation degree, substitution pattern and MW thus enables bespoke design of polysaccharide biotherapeutics.

5.2. Monosaccharide Composition and Glycosidic Branching

Variability in monosaccharide composition, such as the fucose/galactose ratio in fucoidans or the rhamnose/glucuronic-acid content in ulvans, directly governs solubility, chain conformation and receptor affinity, thereby modulating immunomodulatory, antioxidant and prebiotic effects [97]. For instance, fucoidans enriched in α-(1 $\rightarrow$ 3)-linked fucose display enhanced binding to dendritic-cell lectins, boosting cytokine release, whereas galactose-rich fractions preferentially interact with galectin receptors on T-cells [98].

Branching patterns also play a pivotal role in three-dimensional architecture. Highly branched β-(1 $\rightarrow$ 3)(1 $\rightarrow$ 6) glucans adopt a stable triple-helix conformation that engages Dectin-1 on macrophages, triggering phagocytosis and nitric oxide production. By contrast, more linear chains favour random, coil or single helix forms that excel in forming gels and promoting cell–matrix interactions in wound-healing dressings [66]. Controlled enzymatic depolymerisation can be employed to adjust branching density, thereby fine-tuning both biophysical properties and innate immune activation.

5.3. Chemical Modifications: Sulfation, Acetylation, and Derivatisation

Post-extraction chemical modification of marine polysaccharides provides a powerful means of fine-tuning both their biological activities and material properties. Controlled oversulfation, for example, introduces additional sulphate esters into the native backbone under regioselective conditions. By targeting positions such as O-2 on galactose or fucose residues, researchers have achieved three- to five-fold enhancements in anticoagulant potency, measured by anti-factor Xa activity, and similarly dramatic increases in antiviral efficacy against enveloped viruses compared with native extracts [99]. Such oversulfated fractions owe their intensified bioactivity to an elevated negative charge density, which promotes stronger electrostatic interactions with coagulation proteins and viral surface glycoproteins.

Acetylation represents a complementary strategy that balances hydrophilicity and hydrophobicity to modulate cell permeability and immune recognition. When laminarin chains are partially acetylated, the introduction of acetyl moieties increases lipophilicity sufficiently to facilitate membrane translocation, thereby enhancing intracellular access and

downstream signalling effects. In vitro studies of acetylated laminarin have demonstrated a marked reduction in lipopolysaccharide-induced TNF-α secretion from macrophages, indicating a shift towards an anti-inflammatory phenotype [100]. Moreover, by carefully controlling the degree of substitution, it is possible to avoid excessive hydrophobic clustering that might otherwise compromise solubility.

Beyond sulfation and acetylation, a host of other derivatisation techniques have been deployed to endow marine polysaccharides with bespoke functionality. Phosphorylation, for instance, mimics the pattern of naturally occurring glycosaminoglycans, enhancing metal-ion chelation and osteoinductive signalling; phosphorylated alginate scaffolds have been shown to potentiate bone morphogenetic protein activity and support mineral deposition in vitro [101]. Similarly, carboxymethylation dramatically increases water solubility and mucoadhesive strength, which exhibit superior oral bioavailability and selective promotion of beneficial gut microbiota [102].

Through judicious selection and combination of these chemical modification strategies, marine polysaccharides can be optimised to meet the exacting demands of diverse biomedical and biotechnological applications.

6. Targeted Applications

Marine macroalgal polysaccharides possess a unique combination of physicochemical and bioactive properties that make them exceptionally versatile for both nutritional and therapeutic applications. Their diverse structures, ranging from sulfated galactans and fucans (composed primarily of L-fucose residues, neutral or sulfated) to neutral glucans and ulvans, enable resistance to upper gut digestion, selective microbial fermentation and specific interactions with cellular receptors. As a result, these biopolymers have been harnessed to support gut health, modulate immune and inflammatory responses, target cancer cells, augment antiviral defences, and serve as bioactive scaffolds in tissue engineering. In the following sections, we explore how distinct classes of marine polysaccharides are being tailored for use in functional foods, disease models and regenerative medicine platforms, highlighting their mechanisms of action and preclinical efficacy.

6.1. Functional Foods and Gut Health: Prebiotic Algal Fibres

Marine macroalgal polysaccharides escape digestion in the upper gastrointestinal tract and are selectively fermented by the colonic microbiota, yielding SCFAs that strengthen the intestinal barrier, modulate local immunity and improve host metabolism [103]. In vitro fermentation of ulvan generates acetate, propionate and butyrate, which favour the growth of *Bifidobacterium* and *Lactobacillus* spp. while suppressing opportunistic pathogens [103]. Laminarin likewise augments SCFA production, particularly butyrate, enriching *Faecalibacterium prausnitzii* and exerting anti-inflammatory effects in human faecal batch cultures [104]. In vivo, dietary fucoidan fractions have been shown to reshape rodent gut communities, enhance mucosal tight-junction protein expression and improve systemic lipid profiles [105].

6.2. Inflammation and Autoimmune Disorders

By interacting with immune-cell receptors and redox-sensitive pathways, algal polysaccharides can rebalance cytokine networks and alleviate oxidative damage in inflammatory and autoimmune models. Fucoidan attenuates dextran sulphate sodium-induced colitis in mice through inhibition of NF-κB signalling and activation of Nrf2, leading to significant reductions in colonic TNF-α and IL-1β [106]. Laminarin derivatives diminish joint swelling and cartilage erosion in murine arthritis by downregulating COX-2 and iNOS expression in synovial tissues [107]. Ulvan oligosaccharides further inhibit angiotensin I converting

enzyme (ACE) and can have anti-inflammatory effects by reducing pro-inflammatory molecules and activating immune cells like regulatory T cells, underscoring their potential as nutraceutical adjuncts [108].

6.3. Oncology: Colon, Breast and Liver Cancer Models

Algal polysaccharides exhibit multi-modal antitumour actions, including induction of apoptosis, cell-cycle arrest and inhibition of metastatic processes. Laminarin inhibits colorectal cancer cell growth by activating caspase-3 and increasing the Bax/Bcl-2 ratio and, in combination with 5-fluorouracil, enhances tumour suppression in xenograft models [109]. Fucoidan extracted from *Fucus vesiculosus* induces apoptosis and autophagy in breast cancer cell lines via PI3K/Akt/mTOR pathway inhibition and ROS generation, with recent in vivo models confirming its tumour-reduction efficacy and downregulation of VEGF and matrix-metalloproteinase-9 (MMP-9) in hepatocellular carcinoma [33,110].

6.4. Antiviral Strategies and Immune Priming

Sulfated algal galactans and fucans block viral attachment and prime host antiviral defences. Iota-carrageenan nasal formulations curb SARS-CoV-2 replication in human airway epithelial cultures by binding to the spike protein and preventing ACE2 engagement [86]. Fucoidan supplementation in influenza-infected mice boosts type I interferon production and natural-killer cell activity, resulting in lower pulmonary viral loads and reduced lung injury [111].

Recent advances in formulation science have also enabled the development of fucoidan-based oral delivery systems. Lee et al. [112] optimised the composition and production parameters of fucoidan tablets, demonstrating favourable biopharmaceutical properties such as mechanical strength, controlled release profiles, and the preservation of bioactivity post-compression. Their results confirmed that high-molecular-weight fucoidan retains its anticoagulant and anti-inflammatory properties within solid dosage forms, supporting its use in therapeutic and nutraceutical applications targeting cardiovascular health, inflammation, and metabolic regulation [112]. Iota-carrageenan nasal sprays have been tested in several placebo-controlled clinical trials for respiratory infections, demonstrating both safety and efficacy in reducing viral load and symptom duration in adults and children [113]. Similarly, oral supplementation with fucoidan from *Undaria pinnatifida* has been evaluated in human studies, showing good tolerability and potential immunomodulatory effects, including enhanced natural killer cell activity and reduced inflammatory cytokines [114]. These clinical data support the safe use of algal polysaccharides in therapeutic and functional food applications and underscore the need for further large-scale trials to validate their efficacy across broader health indications.

6.5. Tissue Engineering and Wound Healing: Hydrogels and Scaffolds

Alginate, agarose and ulvan serve as biocompatible matrices with tuneable mechanical and bioactive properties for regenerative medicine applications. Calcium-crosslinked alginate hydrogels loaded with vascular endothelial growth factor and basic fibroblast growth factor accelerate wound closure and neovascularisation in diabetic rat models [115]. Composite agarose–collagen scaffolds support chondrocyte adhesion and proliferation in cartilage-repair studies through controlled porosity and stiffness [17]. Sulfated ulvan hydrogels further exhibit intrinsic haemostatic and antimicrobial activities, promoting rapid re-epithelialisation with minimal scarring in porcine-skin wounds [116].

6.6. Cardiovascular Health and Haemostasis

Rhamnan sulphate and fucoidan demonstrate anti-atherogenic and anticoagulant effects in preclinical models. In ApoE (−/−) mice, rhamnan sulphate reduces aortic plaque

burden, vascular lipid accumulation and NF-κB-mediated inflammation, while fucoidan prolongs activated partial thromboplastin time without adversely affecting prothrombin or thrombin times [32,117].

6.7. Metabolic Syndrome and Type 2 Diabetes

Dietary fucoidan and rhamnan sulphate mitigate features of metabolic syndrome by modulating adiposity, insulin sensitivity and gut microbiota. In high-fat-diet-induced obese mice, these polysaccharides reduce body-weight gain, decrease adipocyte hypertrophy and dampen adipose-tissue inflammation, concomitant with improvements in fasting glucose, serum cholesterol and SCFA production [118,119].

6.8. Neuroprotective Applications

Algal fucans and κ-carrageenan oligosaccharides afford neuroprotection in models of Alzheimer's disease and neuroinflammation. In Aβ-infused rodent models, fucoidan enhances spatial memory retention, upregulates hippocampal BDNF and CNTF expression and strengthens insulin signalling; in LPS-activated microglia, carrageenan derivatives reduce TNF-α release, ROS generation and neuronal apoptosis [120,121].

Table 3 summarises key applications of marine macroalgal polysaccharides, listing the polysaccharide type, model system and main findings, to illustrate their roles in areas such as gut health, cardiovascular protection, inflammation, oncology, antiviral defence and tissue repair.

Table 3. Summary of targeted applications of marine algal polysaccharides in biomedicine and functional foods, organised alphabetically.

Application Area	Polysaccharide(s)	Model/System	Key Outcomes	Reference
Antiviral Strategies & Immune Priming	Iota-carrageenan, Fucoidan	Human airway epithelial cultures; influenza-infected mice	↓ SARS-CoV-2 replication; ↑ type I IFN, NK-cell activity; blocked viral entry	[86]
Cardiovascular Health & Hemostasis	Rhamnan sulphate, Fucoidan	$ApoE^{-/-}$ atherosclerotic mice; in vitro and in vivo coagulation models	↓ aortic plaque area; ↓ vascular lipid deposition and NF-κB inflammation; prolonged aPTT without affecting PT/TT	[117]
Functional Foods & Gut Health	Ulvan, Laminarin, Fucoidan	In vitro faecal fermentation; rodent feeding studies	↑ SCFA (acetate, propionate, butyrate); ↑ *Bifidobacterium*/*Lactobacillus*; improved barrier integrity	[103]
Inflammation & Autoimmune Disorders	Fucoidan, Acetylated Laminarin, Ulvan oligosaccharides	DSS-induced colitis, murine arthritis, human synoviocytes	↓ TNF-α, IL-1β; ↓ COX-2/iNOS; ↑ Nrf2 activity; ↓ pro-inflammatory cytokines	[106,107]
Metabolic Syndrome & Type 2 Diabetes	Fucoidan, Rhamnan sulphate	HFD-induced obese mice, diabetic rodent models	↓ adiposity and adipocyte size; ↓ adipose inflammation; improved insulin sensitivity; ↓ blood glucose and cholesterol; ↑ SCFA; gut microbiota modulation	[118,119]
Neuroprotective Applications	Fucoidan, κ-Carrageenan oligosaccharides	Aβ-infused AD rodent models; LPS-activated microglia	↑ spatial memory; ↑ BDNF/CNTF; enhanced hippocampal insulin signalling; ↓ microglial TNF-α, ROS; ↓ neuronal apoptosis	[120,121]
Oncology (Colon, Breast, Liver)	Laminarin, Fucoidan	Colon-cancer xenograft; breast and liver cell lines	↑ Caspase-3, Bax/Bcl-2 ratio; ↓ PI3K/Akt/mTOR; ↓ VEGF, MMP-9; enhanced chemosensitivity	[33,109,110]
Tissue Engineering & Wound Healing	Alginate, Agarose, Ulvan	Diabetic-rat wounds, cartilage scaffolds, porcine skin	↑ neovascularisation; accelerated wound closure; ↑ chondrocyte proliferation; hemostasis and antimicrobial action	[16,80,115]

Abbreviations: Aβ, amyloid beta; AD, Alzheimer's disease; APTT, activated partial thromboplastin time; BDNF, brain-derived neurotrophic factor; COX-2, cyclooxygenase-2; CNTF, ciliary neurotrophic factor; DSS, dextran sulphate sodium; HFD, high-fat diet; IFN, interferon; IL-1β, interleukin-1β; iNOS, inducible nitric oxide synthase; LPS, lipopolysaccharide; MMP-9, matrix metalloproteinase-9; NF-κB, nuclear factor kappa B; NK, natural killer; Nrf2, nuclear factor erythroid 2-related factor 2; PI3K, phosphoinositide 3-kinase; PT, prothrombin time; ROS, reactive oxygen species; SCFA, short-chain fatty acids; TNF-α, tumour necrosis factor-α; TT, thrombin time; VEGF, vascular endothelial growth factor. Arrows before the various key outcomes indicate the direction of change relative to control: ↑ increase; ↓ decrease.

6.9. Adverse Effects of Algal Polysaccharides on Gut Health

Beyond their widely promoted health benefits, algal polysaccharides such as carrageenan, fucoidan, alginate, and ulvan can also exert harmful effects on gut integrity, metabolism, and overall health.

The most debated is carrageenan, a red-seaweed extract. Animal and in vitro studies indicate that carrageenan can thin the intestinal mucus layer, disrupt gut microbiota, and trigger pro-inflammatory cytokine release through NF-κB and TLR4 pathways [122,123]. A recent randomised human trial reported that two weeks of food-grade carrageenan increased gut permeability and inflammatory markers, especially in participants with higher BMI [124].

Other polysaccharides show fewer risks but still warrant caution. Fucoidan from brown algae is often studied for anti-inflammatory effects, yet high intake can impair coagulation and cause gastrointestinal discomfort [125]. Alginate, widely used as a thickener, is generally safe, though excessive doses may cause bloating and interfere with mineral absorption [126]. Ulvan from green algae has immune-modulating activity; in some animal models, it stimulated responses that could worsen inflammation in susceptible hosts [127].

In summary, carrageenan shows the strongest evidence for adverse gut effects, while fucoidan, alginate, and ulvan appear safer but can cause gastrointestinal or metabolic disturbances at high levels. Long-term human data remain scarce for all these polysaccharides.

7. Translational Challenges

Marine macroalgal polysaccharides possess extraordinary bioactive versatility, yet their translation from laboratory discovery to commercial reality is hampered by intertwined analytical, regulatory and manufacturing complexities. Their structural heterogeneity demands robust standardisation and reproducibility; varied regional frameworks impose divergent safety and approval requirements; and the high molecular weight and charge density of native extracts pose formidable bioavailability and formulation barriers. Meanwhile, large-scale cultivation and extraction must contend with seasonal, species-dependent variability that can undermine product consistency and efficacy.

7.1. Reproducibility and Standardisation of Polysaccharide Preparations

The intrinsic heterogeneity of algal polysaccharides, dictated by species, season and extraction method, complicates reproducible isolation and characterisation. For instance, alginate's M/G block ratio can vary dramatically between harvests, altering gel strength and viscosity [128]. Likewise, κ/ι/λ–carrageenan proportions depend on both seaweed species and processing conditions, affecting sulfation patterns and impurity profiles [129]. To harmonise interlaboratory workflows, certified reference materials and affinity-based probes (e.g., monoclonal antibodies against defined carbohydrate epitopes) have been proposed, alongside standard protocols for desalting, fractionation and molecular-weight determination [130].

7.2. Regulatory Considerations in Food and Pharmaceutical Sectors

Polysaccharide classification diverges markedly by region and intended use. In the United States, alginic acid and its salts are GRAS (21 CFR 184.1735), and carrageenan is approved as a food additive (21 CFR 172.620), though both are excluded from infant-formula applications. Fucoidan from *Undaria pinnatifida* holds a GRAS notice (GRN 565) only for limited uses, while laminarin and ulvan currently lack food-additive status and must undergo Novel-Food approval under EU Reg. 2015/2283 for entry into European markets. In the European Union, carrageenan (E 407/E 407a) was re-evaluated in 2018, leading to a temporary Acceptable Daily Intake (ADI) due to concerns over molecular-weight distribu-

tion and contaminants. Alginate (E 400–E 404) remains authorised without an ADI, but fucoidan, rhamnan sulphate and ulvan still await full Novel-Food authorisation. Pharmaceutical exploitation typically demands compliance with GMP manufacture, establishment of pharmacopeial monographs (e.g., USP sodium alginate, Ph. Eur. carrageenan) and IND dossiers, often relegating many extracts to medical-device or nutraceutical classifications rather than true drug markets.

7.3. Bioavailability and Delivery Barriers

Native polysaccharides, especially those with high molecular weight (e.g., fucoidan up to 1500 kDa) and dense negative charge, exhibit poor epithelial permeability and limited systemic exposure following oral dosing [131]. Strategies to overcome these barriers include controlled depolymerisation to tailor molecular-weight distributions, chemical desulfation or oversulfation to modulate charge density, and encapsulation within nanoparticles or mucoadhesive matrices [132]. Such approaches have demonstrated enhanced uptake in preclinical pharmacokinetic studies, improved tissue targeting and reduced dosing requirements.

Recent pharmacokinetic studies have also shed light on the distribution of high-molecular-weight fucoidan in rodent models following oral and topical administration, revealing its accumulation in liver, kidney, and lymphatic tissues and its limited systemic absorption [76,133]. Complementary studies on topical application revealed significant dermal retention and measurable concentrations in subcutaneous tissues, supporting its use in localised anti-inflammatory or wound-healing formulations without systemic exposure [133]. These findings help contextualise the delivery challenges and support the ongoing development of site-specific and sustained-release fucoidan formulations.

7.4. Batch-to-Batch and Species-to-Species Variability in Scale-Up

Commercial-scale production accentuates every source of variability. Fucoidan extracts from different *Fucus* species, and even from the same species harvested at different times, can range from 52 to 1548 kDa in molecular weight, with corresponding shifts in sulfation degree and bioactivity [134]. Laminarin yields fluctuate with temperature and nutrient availability, impacting solubility and rheology [135]. Ulvan's broad molecular-weight and sulfation spectra necessitate tight process control. Addressing these challenges requires end-to-end quality systems: from selection of robust seaweed strains and defined cultivation conditions, through standardised extraction and fractionation protocols, to real-time monitoring of key parameters such as M/G ratio, molecular-weight distribution and residual salt content.

Table 4 summarises current regulatory approvals and key scale-up bottlenecks for major polysaccharides; the following sections discuss these challenges in greater depth.

Table 4. Regulatory status and scale-up hurdles for major marine macroalgal polysaccharides, ordered by name.

Polysaccharide	US Regulatory Status	EU Regulatory Status	Pharmacopoeia Monographs	Key Scale-Up Hurdles	Reference
Alginate	GRAS as alginic acid and its salts (21 CFR 184.1735)	Food additives E 400–E 404; EFSA re-evaluated 2017 (no ADI needed)	USP "Sodium Alginate"; Ph. Eur. monograph on alginic acid	Variation in M/G block ratio affecting gel properties; broad MW distribution requiring fractionation, desalting, and purity control	[126,128]
Carrageenan	GRAS (21 CFR 172.620, 182.7255); not authorised in infant formulae	Food additive E 407/E 407a; EFSA ANS Panel re-evaluation 2018 (temporary ADI)	USP "Carrageenan"; Ph. Eur. monograph on carrageenan	Species-dependent κ/ι/λ isoform ratios; control of 3,6-anhydrogalactose and sulfation patterns; removal of trace impurities	[46,129]

Table 4. *Cont.*

Polysaccharide	US Regulatory Status	EU Regulatory Status	Pharmacopoeia Monographs	Key Scale-Up Hurdles	Reference
Fucoidan	GRAS Notice GRN 565 (fucoidan from *Undaria pinnatifida*)	No authorised food-additive status; Novel-Food applications pending	-	Extreme heterogeneity (MW 50–1500 kDa; variable sulfation); lack of certified reference materials; seasonal/species reproducibility issues	[8]
Laminarin	Not listed as GRAS; considered dietary fibre under 21 CFR 101.9	No authorised food-additive status; may require Novel-Food approval	-	Polydisperse MW (3–6 kDa) affecting solubility/viscosity; yield variation by harvest conditions; branching pattern variability	[45]
Rhamnan sulphate	None (under preclinical investigation for heparinoid applications)	Not authorised	-	No regulatory framework; requires toxicity/safety evaluation; structural complexity; lack of scalable isolation methods	[27]
Ulvan	No GRAS status (would require GRAS notification as dietary fibre)	No authorised food-additive status; Novel-Food dossier under EU Reg. 2015/2283	-	Very broad MW (2–2000 kDa) and sulfation (2–40%) ranges; safety-data gaps; need for standardised extraction protocols	[13]

Abbreviations: ADI, Acceptable Daily Intake (EFSA); GRAS, Generally Recognised As Safe (US FDA); Ph. Eur., European Pharmacopoeia; USP, United States Pharmacopoeia.

7.5. Economic and Environmental Feasibility of Commercial-Scale Production

The large-scale production of macroalgae for polysaccharides hinges on both economic and environmental feasibility, with cultivation costs playing a decisive role. Efficient seaweed farming is essential, as demonstrated by biofuel studies showing a minimum ethanol selling price of $1.17 per gallon, which highlights the importance of reducing production expenses [136]. Market trends also support this potential, with the macroalgal hydrocolloid industry growing steadily at 2–3% annually, indicating rising demand for polysaccharide-based products [137].

At the same time, macroalgae cultivation provides notable ecological benefits: optimised systems can reduce CO_2 emissions by up to 90% through carbon sequestration [136]. Their polysaccharides are increasingly used in biodegradable bioplastics for food packaging, offering sustainable alternatives to petroleum-derived plastics [138]. Advances in extraction methods, particularly ultrasound- and microwave-assisted technologies, further improve sustainability by reducing chemical inputs and enhancing recovery efficiency [137]. Despite challenges linked to the structural complexity of polysaccharides, progress in enzymatic tools and microbial engineering is paving the way for more competitive and environmentally beneficial production, strengthening the case for macroalgae as a renewable resource [139].

8. Conclusions and Future Perspectives

Macroalgal polysaccharides (MAPs) represent one of the most functionally versatile classes of marine-derived biomolecules. Their structural diversity—arising from variations in monosaccharide composition, molecular weight distribution, sulfation degree, branching patterns, and glycosidic linkages—confers a broad range of physicochemical properties and biological functions. These structural features underpin their ability to interact with molecular and cellular targets involved in oxidative stress, inflammation, immune modulation, apoptosis, coagulation, and microbial pathogenesis. As such, MAPs have emerged as promising candidates for applications in both biomedicine and functional food formulations, situating them at the nexus of marine biotechnology and human health innovation.

8.1. Key Insights and Current Advances

Over the past decade, significant progress has been made in identifying structure–function relationships in MAPs. Sulfated polysaccharides such as fucoidans and carrageenans have shown strong anticoagulant, antiviral, and immunomodulatory properties, often linked to the position and density of sulphate groups. Laminarans and ulvans, by contrast, have demonstrated antioxidant and prebiotic activities, with branching patterns and molecular weight playing central roles. These insights are gradually shifting research from a descriptive phase toward precision applications, where specific MAP structures are matched to defined therapeutic or nutritional targets.

Another important advance has been the integration of advanced analytical methods (NMR spectroscopy, mass spectrometry, molecular docking, and omics approaches), which allow a deeper understanding of MAP structural complexity and its biological relevance. Concurrently, MAPs are being explored in novel formulations, including hydrogels, nanoparticles, and encapsulated systems, to enhance their bioavailability and targeted delivery. These developments support their potential integration into next-generation functional foods, nutraceuticals, and biopharmaceuticals.

8.2. Limitations, Challenges and Gaps

Despite this promise, several challenges continue to limit the translation of MAPs into clinical and industrial applications:

1. Heterogeneity and variability: The composition of MAPs varies widely depending on algal species, geographical origin, growth conditions, and extraction protocols. This variability complicates reproducibility across studies and hampers the establishment of standardised functional claims.
2. Research is uneven across polysaccharide classes and algal taxa: while fucoidans are extensively studied, ulvans, laminarins, and carrageenans remain underexplored.
3. Incomplete mechanistic understanding: Although many biological activities have been reported, the molecular mechanisms of action remain insufficiently defined. Few studies provide detailed insights into receptor binding, downstream signalling, or metabolic fate in vivo.
4. Bioavailability and metabolism: Pharmacokinetic investigations are scarce and often rely on non-standardised methods, limiting understanding of absorption, distribution, metabolism, excretion, and long-term safety. MAPs often show limited intestinal absorption due to their high molecular weight and complex structures. Their metabolic pathways in humans, including microbial fermentation in the gut, remain underexplored.
5. Limited translational data: The majority of studies remain confined to in vitro or preclinical models. Well-designed human clinical trials are still scarce, making it difficult to substantiate health claims or establish safe and effective dosages.
6. Sustainability and scalability: Expanding the use of MAPs in food and biomedicine requires sustainable macroalgal cultivation, cost-effective processing, and scalable purification technologies. Environmental impacts and supply chain feasibility remain critical considerations.

8.3. Future Perspectives

Addressing these challenges will be essential for unlocking the full potential of MAPs. Key future directions include:

1. Deepening structure–function relationships
    - Systematic mapping of how specific sulfation patterns, branching motifs, or molecular weights influence defined biological activities.

- Integration of computational modelling, molecular docking, and artificial intelligence to predict bioactivity based on structure.

2. Elucidating molecular mechanisms
   - Multi-omics and systems biology approaches to link MAPs to cellular pathways in immunity, inflammation, apoptosis, and metabolism.
   - High-resolution structural biology to clarify receptor binding and target specificity.
3. Enhancing bioavailability and targeted delivery
   - Development of nanoencapsulation, hydrogel systems, or conjugates to improve stability, intestinal uptake, and tissue targeting.
   - Exploration of controlled-release formulations for precision delivery in functional foods or pharmaceuticals.
4. Standardisation and scalability
   - Establishment of international standards for the extraction, purification, and characterisation of MAPs.
   - Optimisation of sustainable aquaculture and biorefinery models to ensure reproducible supply chains and minimise ecological impacts.
5. Expanding translational and clinical research
   - More in vivo studies and human clinical trials to validate health claims and define safety profiles.
   - Exploration of MAPs as adjuvants in conventional therapies, particularly in inflammation, metabolic disorders, and immune regulation.
6. Precision applications in biomedicine and nutrition
   - Tailoring MAP structures for personalised nutrition strategies, aligning dietary polysaccharide intake with individual microbiome profiles and health risks.
   - Exploiting MAPs as precision therapeutics, where structural modifications or combinations with other bioactives target specific disease pathways.

8.4. Broader Implications

Beyond health, MAPs hold relevance for sustainable marine biotechnology. They embody the potential to valorise marine biomass in line with circular economy principles, converting macroalgal resources into high-value functional ingredients. The integration of MAP-based solutions into functional foods, nutraceuticals, and biopharmaceuticals can also stimulate blue economy innovation, linking biodiversity conservation with health and industrial development.

8.5. Final Remarks

In conclusion, macroalgal polysaccharides represent a unique convergence of marine diversity and biomedical innovation. While their complexity presents challenges, it also provides opportunities for highly tailored, precision-based applications. By advancing structural characterisation, mechanistic understanding, delivery strategies, and translational validation, MAPs can transition from promising biomolecules to evidence-based functional ingredients and therapeutics. Their future lies not only in addressing immediate nutritional and biomedical needs but also in shaping sustainable, health-oriented applications that bridge the marine and human worlds.

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