International Journal of Biological Macromolecules 330 (2025) 148071

Contents lists available at ScienceDirect

International Journal of Biological Macromolecules

journal homepage: www.elsevier.com/locate/ijbiomac

Review

Review on seaweed derived sulfated and non-sulfated marine polysaccharides as multifunctional food ingredients: Structure–function relationships, bioactivities and applications in functional foods

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ARTICLE INFO

Keywords:
Marine hydrocolloid
Techno-functional properties
Structure–function relationship

ABSTRACT

Seaweed-derived hydrocolloids encompass both sulfated and non-sulfated polysaccharides that play a pivotal role in food technology and human health. Sulfated polysaccharides such as carrageenan, fucoidan, ulvan, and porphyran exhibit distinctive structural features that confer potent bioactive properties, including antioxidant, immunomodulatory, antimicrobial, and prebiotic activities. Non-sulfated polysaccharides such as alginate and agar (although primarily a galactan, contains sulfated agaropectin fractions) are equally important for their remarkable gel-forming abilities, rheological modulation, and stabilization functions in diverse food matrices. The functionality of these compounds is governed by their macromolecular architecture, degree of sulfation or uronic acid content, and extraction methods, which collectively influence gelation behavior, viscosity, and bioavailability. Recent advances in green extraction and chemical/physical modification strategies have further enhanced both the techno-functional and bioactive performance of these hydrocolloids. This review critically examines the structure–function relationships of major sulfated and non-sulfated seaweed polysaccharides, highlighting their gel-forming capacity and multifunctional health benefits. By integrating insights from food chemistry, marine biotechnology, and nutrition, the manuscript underscores the potential of seaweed polysaccharides as next-generation functional food ingredients that combine technological versatility with bioactive value.

1. Introduction

The utilization of hydrocolloids derived from natural sources for food applications has seen a significant rise. Traditionally, hydrocolloids are obtained from various plant sources, such as pectin, gum Arabic, guar gum, and modified starches, etc. Similarly, hydrocolloid gelatin derived from animal sources has demonstrated extensive applications within the food industry, particularly as a stabilizing agent [1]. Furthermore, microbial hydrocolloids like curdlan, xanthan gum, bacterial celluloses, dextran, and gellan gum are utilized for their health advantages. Recently, hydrocolloids from marine sources have gathered significant attention due to their potential applications in the development of functional food products [2]. Hydrocolloids derived from seaweeds represent a unique class of polysaccharides that are increasingly recognized for both their technological and biological significance [3]. Among them, sulfated polysaccharides such as carrageenan, fucoidan, ulvan, and porphyran are particularly important owing to their structural diversity, high sulfate content, and wide-ranging bioactivities including antioxidant, immunomodulatory, and prebiotic effects. In parallel, non-sulfated polysaccharides such as alginate and agar, although primarily a galactan, contains sulfated agaropectin fractions, are indispensable in the food industry for their gel-forming, thickening,

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https://doi.org/10.1016/j.ijbiomac.2025.148071
Received 23 June 2025; Received in revised form 23 September 2025; Accepted 1 October 2025
Available online 5 October 2025

and stabilising properties, which directly impact texture, rheology, and consumer acceptability of functional foods [4]. Together, these compounds constitute the core of marine hydrocolloids, with their functionality determined by factors such as monosaccharide composition, molecular weight distribution, sulfation pattern, and extraction methodology. As global demand for natural and health-promoting food additives rises, seaweed-derived hydrocolloids both sulfated and non-sulfated are emerging as multifunctional ingredients with the capacity to deliver technological performance and health benefits simultaneously [5]. The hydrocolloid-based industry is advancing rapidly, exhibiting an average annual growth rate of 2–3 %. Global yearly production reaches up to 100,000 tons, valued at 1.1 billion US dollars [6]. More generally, the global hydrocolloids market has expanded considerably, valued at around USD 8.5 billion in 2022, and is expected to expand to USD 10 billion by 2025, with a compound annual growth rate (CAGR) of 5.8 % [7]. The expansion is spearheaded by rising consumer demand for health-focused, natural, and functional food. Asia, and China in particular, represents more than 60 % of global hydrocolloid consumption, with China producing almost half of that demand alone. The food and beverages sector are the largest application sector, where hydrocolloids find use for texturing, stabilization, shelf life, and nutritional enhancement. In spite of this gelling market trend, industrial application of marine hydrocolloids remains plagued by several significant challenges [8]. These include fluctuation in raw material supply based on environmental and seasonally variable conditions, compositional heterogeneity among microbial and seaweed sources, and high extraction, purification, and standardization costs. Conventional extraction procedures compromise bioactive activity, and the lack of optimized, scalable, and environmentally friendly processes deters broader application in commercialized food systems [9]. In addition, supply chain uncertainty e.g., guar gum supply chain volatility based on geopolitical or economic factors also deters uniform product formulation and pricing in functional food production. These constraints highlight the vital importance of developing more sustainable extraction procedures and regulatory harmonization to enable utilization of marine hydrocolloids in large-scale functional food production [7].

Marine hydrocolloids exhibit remarkable physicochemical and biological properties that are highly significant to the food industry. The intrinsic ability of marine hydrocolloids to create hydrogels has become evident in their applications within the food industry, serving as film-forming substances, gelling agents, and thickeners [10]. Nonetheless, there has been a reported limitations on the application of marine hydrocolloids within the food industry, attributed to the extensive pretreatments necessary for their extraction through conventional techniques. The traditional methods most frequently utilized encompass acid-based extraction, hot water extraction, and alkali-assisted extraction. The traditional extraction methods present numerous drawbacks, primarily characterized by the extensive use of chemical reagents and prolonged extraction durations. These factors contribute to safety issues, increased expenses, and the deterioration of bioactive compounds and chemical structures [6,11]. Consequently, there has been a shift towards utilizing contemporary extraction methods to enhance the yield of these important compounds. Advanced techniques frequently utilized for the extraction of marine hydrocolloids encompass enzyme-assisted extraction, microwave extraction, pressurized fluid extraction, ultrasound extraction, and the auto-hydrolysis process of extraction [12]. Recent studies have demonstrated that deep eutectic solvents (DES), pulsed electric field (PEF) extraction [13], and subcritical water extraction enable higher recovery of sulfated polysaccharides with preserved bioactivity, while reducing solvent usage and processing time [14]. Integration of process intensification approaches such as combined microwave–enzyme systems has further improved scalability and cost-effectiveness [15]. Therefore, enhancing contemporary extraction methods for marine hydrocolloids is crucial for their efficient application in the food sector. Investigations have indicated that the biochemical, physical, and functional properties of marine hydrocolloids are influenced by the extraction method and its parameters. The functionality of extracted marine hydrocolloids is influenced by various factors such as time, temperature, pH, hydrolysis, and extraction media, among others. It is essential to manage the extraction parameters carefully to ensure that the overall characteristics and functional properties of marine hydrocolloids remain intact. The contemporary green industry is eager to investigate innovative and effective techniques for extracting marine hydrocolloids, aiming to refine extraction conditions and enhance yield [11]. Hydrocolloids find widespread application in various food products, including yoghurt, ice creams, sauces, dressings, and mayonnaise. Their roles include serving as thickeners, gelling agents, foaming agents, edible coatings, emulsifiers, and stabilizers within food systems [16]. Hydrocolloids possess the capability to alter flow behavior, referred to as viscosity, as well as the mechanical solid property known as texture in food products. The alteration of viscosity and texture in food will have a direct impact on the organoleptic properties that influence consumer acceptance of the product. Hydrocolloids represent a significant category of food additives utilized within the food industry [17]. The consumption of hydrocolloids offers various health advantages, including the prevention of cardiovascular diseases, effective weight management, regulation of postprandial blood glucose levels, modulation of glycemic response, and support for colonic health. In addition to their inherent functional properties, hydrocolloids have gained interest for their dietary fiber content, which offers a diverse range of health benefits for consumers. The majority of food hydrocolloids can be classified as dietary fiber. Consequently, there are cases in which hydrocolloids are utilized to enhance the fiber content of food products [5]. Fiber plays a crucial role in maintaining a healthy diet. The suggested average daily intake of dietary fiber in the USA and UK is 25–30 g and over 18 g, respectively [18]. The integration of marine hydrocolloids is responsible for reducing the glucose release rate in the bloodstream and eventually decreasing the digestion rate [19]. In spite of increasing research interest, wide knowledge gaps exist in the structure–function relationship at the molecular level of marine hydrocolloids, particularly mixed hydrocolloid systems and under new food matrices. In addition, new marine hydrocolloids from less investigated sources like green seaweeds (e.g., *Ulva* spp.), red microalgae (*Porphyridium*), cyanobacteria, and marine microbial exopolysaccharides possess potential functional and bioactive characteristics but are not exploited. With increasing numbers of researches on marine hydrocolloids underway, it is only natural to look into their multi-functionality and structural diversity in food systems. The present review highlights to unveil the most important structural characteristics that define their techno-functional and bioactive properties. Particular focus is laid on their functionality in functional foods, i.e., their nutritional functionality and their technological relevance. Challenges in the present scenario, future modification strategies, and future scopes towards improved innovations have also been incorporated in the review.

2. Molecular structure and classification of bioactive marine hydrocolloids

2.1. Sulfated polysaccharides

2.1.1. Carrageenan

Carrageenan is a group of sulfated polysaccharides that make up a high amount (30–80 %) of the dry weight of marine red algae [20]. The molecules are made up of a repeating chain of D-galactose and 3,6-anhydrogalactose units. They are linked together by alternate α (1,3) and β (1,4) glycosidic bonds and contain one or two sulfate groups on the O-2 and/or O-6 positions of the galactose units [21,22]. Three major types of carrageenan exist: kappa (κ), iota (ι), and lambda (λ) (Fig. 1). These are distinguished based on how much sulfate they have and if they have 3,6-anhydrogalactose or not. κ-type has 22–30 % sulfate and 28–35 % 3,6-anhydrogalactose, ι-type has 28–32 % sulfate and 25–30 % 3,6-

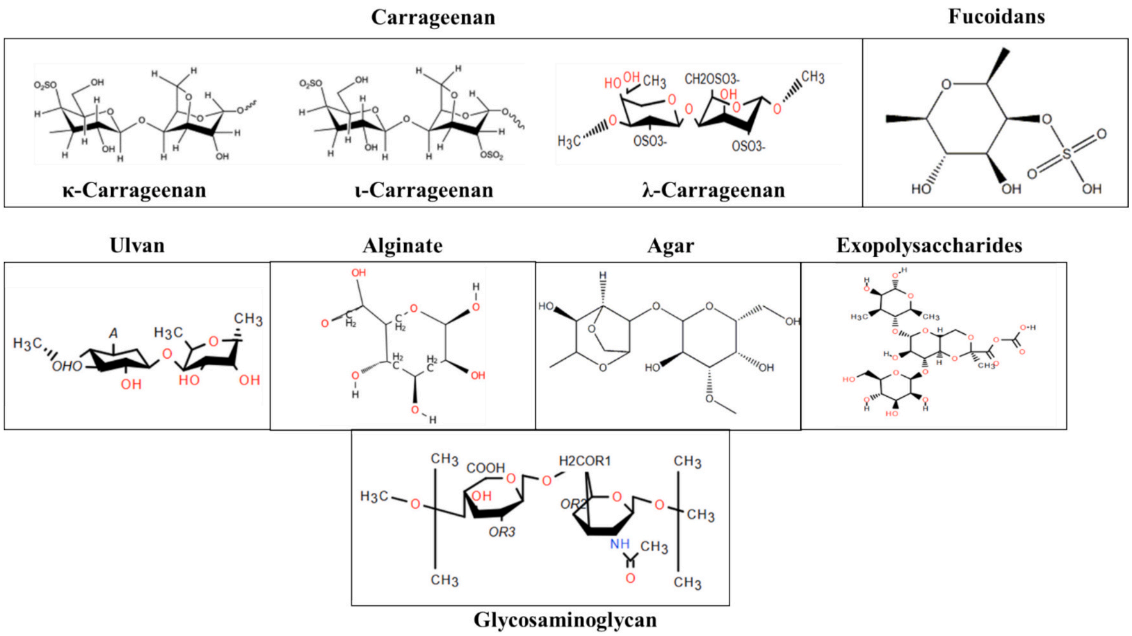

Fig. 1. Chemical structure of hydrocolloids derived from major marine organisms.

anhydrogalactose, and λ-type has 32–39 % sulfate but no 3,6-anhydrogalactose [23]. Structurally, κ-carrageenan is composed of repeating units of D-galactose-4-sulfate and 3,6-anhydro-D-galactose. ι-carrageenan has additional sulfate at the O-2 position, while λ-carrageenan is made up of disaccharide units with extra sulfate groups but no 3,6-anhydrogalactose [24]. Number, position, and distribution of sulfate groups as well as the proportion of 3,6-anhydrogalactose greatly influence carrageenan physical and chemical properties such as gel strength, heat stability, and solubility. More sulfation usually makes gels weaker and less stable. *Kappaphycus alvarezii* is the principal source of carrageenan for commercial use. It produces 20.4–28.4 % refined product and has a molecular weight that usually falls between 100 and 1000 kDa (with food-grade carrageenan averaging 200–400 kDa) [25]. Carrageenan is widely used as a gelling, thickening, and stabilizing agent in foods, cosmetics, pharmaceuticals, and other industries, but consuming more than 2 % in food products may cause health concerns, and the use of degraded carrageenan is banned due to its potential carcinogenicity [26]. Other similar polysaccharides like furcellaran (from *Laminaria*) and porphyran (from *Porphyra/nori*) offer unique gelling and prebiotic benefits but are not as widely used as carrageenan, and the functional qualities of all these polysaccharides are influenced by factors such as the species of algae, their age, extraction methods, and environmental pH, which can affect their activity, especially under acidic conditions [27,28].

2.1.2. *Fucoidans*

Fucoidan is a sulfated polysaccharide primarily composed of α-L-fucose units connected by glycosidic bonds, forming either linear or branched chains [29]. It is predominantly found in the cell wall matrices of brown seaweeds, but has also been identified in certain marine invertebrates such as sea urchins and sea cucumbers [30]. Fucoidans from invertebrates tend to have similar structures, whereas fucoidans from brown algae have a lot of different molecular structures that change with species and age [31]. It is interesting to note that the composition of fucoidan is higher in the reproductive phase of algae [32], and the chemical composition and structure of brown algal species differ considerably from one another [33]. Fucoidan consists mainly of sulfated fucose, which forms over 60 % of it. It is possibly along with minor amounts of other polysaccharides such as mannose, galactose, glucose, xylose, and uronic acids. Depending on where it is extracted from, fucoidan may contain between 7.66 % and 38.3 % sulfate [34]. Fucoidan molecular weight may range from 7 kDa to 2379 kDa depending on the species, the period during which it was harvested, and its geographical origin. Fucoidan can be classified into two broad categories depending on its structure: Type I, consisting of α-L-fucose residues connected with 1,3- and 1,4- and containing sulfate groups in the O-2 and O-4 positions; and Type II, consisting of alternating 1,3- and 1,4-linked α-L-fucose units with sulfation at O-2, O-3, and O-4 [35]. Recent research has shown more structural variations with varying branching patterns, sulfation, molecular weight, and polysaccharide composition, but still the underlying backbone is the same [31]. Although all of them are referred to as fucoidan, these structural variations may modify the manner in which the substance acts in living organisms [36,37].

2.1.3. *Ulvan*

Sulfated polysaccharides, specifically ulvan, are found in green seaweed between 9 and 36 % *w/v*. The molecular weight of Ulvan, a polyanionic heteropolysaccharide of a complex nature, ranges between 150 and 2000 kDa [38]. Ulva species are the primary sources of ulvans, among which *U. conglobata* and *U. prolifera* yield more. Monosaccharides such as rhamnose (45 %), glucuronic acid (22.5 %), xylose (9.6 %), and iduronic acid (5 %), are included in the composition [39]. These monosaccharides are connected to disaccharide units via the α- and β-(1,4) linkages. The particular disaccharide types found in ulvans dictate their categorization into A_{3s}, B_{3s}, U_{3s}, and U_{2s}, creating three separate groups. In type A_{3s}, β-D-glucuronic acid and α-L rhamnose 3-sulfate are connected by a (1,4) bond. α-L-iduronic acid (1,4) is connected to α-L-rhamnose 3-sulfate in type B3s. β-D-xylose and α-L-rhamnose 3-sulfate are connected at the (1, 4) location in type U_{3s}. β-D-xylose 2-sulfate (1,4) is conjugated to α-L-rhamnose 3-sulfate in type $U_{2's}$, 3_s [40]. Using a chelator-assisted hot water extraction method, followed by alcohol precipitation and purification using HPLC, is the best way to extract ulvan while maintaining its bioactive components [40]. Purified ulvan yields range from 8 % to 29 % of the seaweed's dry weight. It is appropriate for use in antimicrobial coatings, micro/nano-formulations, and wound dressings due to its non-adhesive qualities, spontaneous supramolecular aggregation behavior, and antibacterial qualities [36]. Since the digestive system's enzymes cannot break down ulvan, a therapeutic dose of less than 500 μg is advised [27].

2.1.4. Other sulfated polysaccharides

Marine algae are a rich source of structurally diverse sulfated polysaccharides, many of which extend beyond the commonly studied carrageenans and fucoidans (Table 1). Among these, porphyrans, various sulfated galactans, and newly identified polysaccharides are drawing increasing interest for their unique molecular features and biological activities [36]. Porphyran, a major sulfated polysaccharide from red seaweeds of the genus *Porphyra* (widely known as *nori*), is composed of repeating galactose and 3,6-anhydrogalactose units, linked by α-1,4 and β-1,3 glycosidic bonds and modified with sulfate groups. The structure of porphyran can change based on the kind of Porphyra and the environment. This affects how well it can fight free radicals and how good it could be for your health. These differences make porphyran a promising candidate for application in functional foods and nutraceuticals [41]. Red algae also yield a wide variety of sulfated galactans, such as agaran and carrageenan. These are composed of galactose-containing backbones and characteristic sulfation patterns. The type and position of sulfate groups and the presence of 3,6-anhydrogalactose determine the activity of these galactans, such as whether they are capable of gelling or thickening [42]. These structural elements play a major role in their biological activities, such as antiviral, anticoagulant, and immune-modulating activities [41]. Novel sulfated polysaccharides have been found in red and brown algae with the development of new extraction and analysis methods. These novel molecules differ from traditional polysaccharides in that they will allow for unusual branching, unusual polysaccharide residues, or standard sulfation patterns. Some of these novel molecules have high levels of antioxidant, anti-inflammatory, and prebiotic activities. This means that they can be used for new applications in health-related products and the food industry [43]. Scientists are now investigating how new sulfated galactans and hybrid polysaccharides from previously under investigated algae species may be used for functional and medicinal applications. The expanding array of sulfated polysaccharides from marine sources reflects a rich source of natural compounds with prospective applications in biotechnology, medicine, and nutrition.

2.2. Non-sulfated and carboxylated polysaccharides

2.2.1. Alginate

Alginate was first discovered by E.C.C. Stanford in 1881. Alginate is distinguished by the occurrence of β-D-mannuronic acid (M) and α-L-guluronic acid (G), which are joined by a β-(1,4) bond [44]. The sequence of the monomers can differ in the chain, leading to the development of differing segments that are ultimately either homogeneous (MM, GG) or heterogeneous (MG, GM). The physical properties of alginate are established by the varying combinations of the three forms of blocks [45]. Alginates that contain a greater proportion of M-segments exhibit increased viscosity, while those that are more abundant in G-blocks serve as more effective gelling agents [44]. Alginate exists as alginic acid or as sodium and calcium salts, constituting about 40 % of the dry weight of the seaweed. Alginate exhibits a molecular weight ranging from 500 to 1000 kDa [46]. This polysaccharide is predominantly utilized in the cosmetic and food sectors. Specifically, it finds extensive application as a gelling agent, texturiser, and stabilizer across a range of products. The unique ion-binding characteristics of alginate allow it to selectively bind divalent metal ions, such as calcium, which accounts for these properties [47].

Table 1
Classification of major seaweed-derived polysaccharides by algal source.

Seaweed group	Sulfated polysaccharides	Non-sulfated polysaccharides
Red algae (Rhodophyta)	Carrageenan, Porphyran, Agaran Agar (Agarose – largely neutral; Agaropectin – contains sulfated fractions)	–
Brown algae (Phaeophyceae)	Fucoidan, Laminarin (partially sulfated)	Alginate
Green algae (Chlorophyta)	Ulvan	–

2.2.2. Agar

Agar was initially identified in Japan during the 17th century and is predominantly located within the genera *Gelidium* and *Gracilaria*. Agar contributes to the structural elasticity of algae, enabling it to endure the forces exerted by ocean currents [48]. This polysaccharide is a phycocolloid made up of two distinct components: agarose (the major fraction, which is neutral and essentially free of sulfate groups) and agaropectin (a minor component that can have some acidic side-groups such as sulfates), with agarose comprising as much as 70 % of agar [49]. Nonetheless, the weight-based proportion of agar can differ among species, as can the agar content and the quality of the resulting gel, both of which are influenced by environmental factors. Agarose is a neutral linear polysaccharide with a molecular weight exceeding 100 kDa, consisting of agarobiose units. These units are formed by the alternating linkage of β-D-galactose and 3,6-anhydro-L-galactose monosaccharides through α-1,3 and β-1,4 glycosidic bonds [50]. Agaropectin, conversely, is characterized as an acidic polysaccharide with a molecular weight of approximately 14 kDa. In addition to its agarobiose structure, it may also feature ramifications, including sulphate groups located at the C-6 position [51]. Furthermore, certain β-D-galactose units might include pyruvic acid and D-glucuronic acid groups, which can hinder the polysaccharide from achieving a consistent structure. Therefore, agarose contributes to gelling properties through the hydrogen bonds established along its linear chain, while agaropectin exhibits a thickening capability [50]. Agar finds its primary application in the food industry, serving as a gelling and stabilizing agent, having already received GRAS status. Nonetheless, it is also commonly utilized in the preparation of growth media within the field of microbiology. This compound cannot be digested by the human gastrointestinal tract, leading to its proposed application as a prebiotic [47].

2.2.3. Marine microbial exopolysaccharides

Marine microbial exopolysaccharides (EPSs), a class of high-molecular-weight biopolymers secreted predominantly by marine bacteria, particularly those inhabiting extreme environments, exhibit remarkable chemical diversity and structural complexity, being composed of a wide variety of monosaccharide units such as glucose, galactose, rhamnose, mannose, fucose, and uronic acids, along with diverse non-carbohydrate substituents including sulfate, phosphate, acetyl, and pyruvate groups that contribute to their polyanionic nature, hydration potential, and rheological behavior [52], and this extensive heterogeneity in structure characterized by variations in sugar composition, branching patterns, linkage types, and the presence of charged functional groups imparts a unique range of physicochemical and biological properties that set them apart from macroalgal polysaccharides, which typically possess more uniform and linear structures with limited reactive group diversity, thereby making microbial EPSs superior in terms of functional versatility, bioactivity, and adaptability to varied environmental and industrial contexts [53,54]; for instance, marine EPSs demonstrate enhanced antioxidant, anti-inflammatory, immunomodulatory, and metal-chelating activities, attributes largely influenced by the presence of sulfate groups and specific monosaccharide residues, which also facilitate their interactions with biological targets and heavy metals in therapeutic and environmental applications [55,56], and these properties are particularly pronounced in EPSs synthesized by extremophilic marine bacteria those adapted to high-pressure, high-salinity, cold, or thermally extreme habitats such as *Pseudoalteromonas*, *Alteromonas*, and deep-sea *Vibrio* species, whose polysaccharides display exceptional stability, solubility, cryoprotective activity, and resistance to enzymatic degradation under extreme physical and chemical conditions, making them suitable for use in polar biotechnology, bioremediation, cosmetics, and drug delivery systems where robustness and functionality are critical [57,58]; furthermore, the production of these EPSs is highly dependent on cultivation parameters such as temperature, pH, salinity, carbon and nitrogen sources, and oxygen levels, all of which can be optimized through fermentation technologies to improve yield, consistency, and structural control [59,60], while recent advances in metabolic and genetic engineering have enabled targeted manipulation of EPS biosynthetic gene clusters, allowing for the design of tailor-made polysaccharides with specified functional groups, sugar residues, and molecular weights that meet precise industrial and biotechnological demands, whether for high-viscosity gelling agents, emulsifiers, bioactive components, or stabilizers in food, pharmaceutical, or environmental products [61], and with the integration of systems biology tools such as genomics, transcriptomics, and proteomics into fermentation process monitoring and strain improvement, the customization potential of marine microbial EPSs is rapidly expanding [62], offering sustainable, marine-derived alternatives to synthetic and plant-based polymers while also unlocking novel bioactivities and functionalities that remain underexplored in macroalgal counterparts, thereby reinforcing the strategic importance of marine microbial exopolysaccharides as multifunctional, environmentally adaptive, and industrially versatile biopolymers for current and future applications across health, food, materials, and ecological remediation sectors [63,64].

2.3. Glycosaminoglycan-like marine polysaccharides

Polysaccharides that closely resemble the structure and function of mammalian glycosaminoglycans (GAGs) may be found in marine environments. One well-known example is chitosan, which is made by deacetylating chitin found in the shells of several marine fungus and crustaceans [65]. It is well known that chitosan and its modified forms are compatible with biological systems, degrade easily, and exhibit a variety of biological functions, such as antibacterial activity, wound healing promotion, and the ability to function as carriers in drug delivery systems [66]. Aside from that, marine animals like fish and certain crustaceans contain chondroitin sulfate and heparin-like polysaccharides. These marine-derived compounds have the same biological activities as animal GAGs, including inhibiting blood clots, preventing inflammation, and healing tissues. This is because they contain repeating disaccharide units and sulfation patterns [67]. Interestingly, marine animal heparin-like polysaccharides have distinct sulfation patterns from those of terrestrial animals. The sulfation patterns may become variable and at times more effective in their biological activities. Their mammalian GAG-like structure is an important part of the function of these marine polysaccharides in living organisms. Small variations within the quantity of polysaccharides, glycosidic linkage type, quantity, and sulfation pattern can greatly affect the way these molecules interact with cells and proteins. This can change such things as how the immune system works, how cells communicate, and how blood is thinned [68]. To employ marine GAG-like polysaccharides in the creation of new biomedical therapies, there is a need to investigate these structure–function correlations [69].

2.4. Analytical approaches for structural characterization

Structural information of marine polysaccharides is critical to predict their biological activity and potential use. Since the monosaccharide building blocks are critical to the development of the bioactivities of the polysaccharide, e.g., immunomodulation, anti-inflammatory, and anticoagulant activities, the initial step in this approach is the identification of the types and configurations of the monosaccharide units that make up these polymers [70–72]. Researchers usually start by hydrolyzing these structures, which reduces the big, complicated molecules into smaller, easier-to-manage monosaccharides or oligosaccharides [73]. Acids such as hydrochloric acid, sulfuric acid, or trifluoroacetic acid are most often used for complete hydrolysis, and the conditions must be carefully controlled to avoid excessive degradation or undesirable side effects [74]. The percentage of straight-chain glucose formed with hydrochloric acid is larger than that with sulfuric acid, indicating that the kind of acid employed may affect the ratio of straight-chain to cyclic forms of glucose produced [75]. Branching and the arrangement of hydrocolloid residues within the polysaccharide are investigated by partial hydrolysis, which can be carried out with either diluted acids or particular enzymes. Temperature, acid concentration, and time all affect the degree of hydrolysis and the yield of oligosaccharides (Table 2) [76]. Because it enables the exact breaking of glycosidic linkages, enzymatic hydrolysis is particularly useful for its selectivity and for avoiding the damaging effects of strong acids. It has also been demonstrated that chemical depolymerization methods, including using hydrogen peroxide, may produce oligosaccharides with different structures and sometimes better antioxidant properties [77]. After hydrolysis, chromatographic procedures are used to separate and identify the resulting monosaccharides (Table 3). One of the best things about pulsed amperometric detection (PAD) in high-performance anion exchange chromatography (HPAEC) is that it can separate different hydrocolloids, including uronic acids and isomers, without needing to be derivatized [78]. Desalting is occasionally necessary for marine materials, although this method is quite sensitive and may find hydrocolloids even when salts are present. HPAEC-PAD has also been able to show the enzymatic degradation of fucoidans from marine algae [79,80]. Gas chromatography (GC) is another common method that requires hydrocolloids to be derivatized to make them volatile, particularly for linkage analysis. GC may be time-consuming because of the derivatization step and the necessity to remove salt, even if it gives outstanding resolution and quick [81]. GC demonstrates compatibility with a range of detectors, including thermal conductivity detectors (TCD), mass spectrometry (MS), and flame ionization detectors (FID), providing versatility for diverse analytical applications. Two methods of high-performance liquid chromatography (HPLC) that are commonly used to separate and measure monosaccharides are hydrophilic interaction liquid chromatography (HILIC) and reverse-phase HPLC. Derivatization is one of the most prevalent ways of sensitizing and specifying detection [82].

2.5. Chemical modifications of marine polysaccharides

One of the most important structural alterations in marine polysaccharides is sulfate substitution, which is essential to define their physicochemical and bioactive characteristics. Sulfation can be naturally achieved during biosynthesis in algae, where sulfotransferase enzymes catalyze the transfer of a sulfate group to hydroxyl positions of sugar residues, forming compounds like carrageenan, fucoidan, and ulvan [36,42]. Besides, sulfation can be conducted artificially to increase or alter bioactivity. This is most often done by sulfating polysaccharides with sulfating agents like chlorosulfonic acid–pyridine complexes or sulfur trioxide–amine complexes, which add sulfate esters at C-2, C-4, or C-6 hydroxyl groups of monosaccharide units [43,83]. These modifications enhance negative charge density, solubility, and have been found to significantly increase antioxidant, anticoagulant, and immunomodulatory activities [83,84]. The extent and location of sulfation play a pivotal role, as they not only impact the bioactivity but also affect the rheological behavior and gel-forming ability of the polysaccharides. Optimized chemical sulfation, in conjunction with enzymatic or green synthesis methods, thus represents a valuable route to customize marine polysaccharides for functional food and biomedical applications [43,85].

Advanced spectroscopic and mass spectrometric methods are used to provide more information on the structure, specifically on the order and connectivity of hydrocolloids residues [104]. One-dimensional and two-dimensional nuclear magnetic resonance (NMR) spectroscopy are of great use in defining the organization of polysaccharides and how their interconnections work [105]. Mass spectrometry (MS) with matrix-

Table 2
Comparative analysis of extraction methods for marine hydrocolloids: yields, conditions, and efficiency.

Hydrocolloids	Methods	Pretreatment	Extraction	Purification	Yield	Advantages	Limitations	References
Alginate	Heat assisted extraction	–	MeOH: DCH, RT, 48 h	$CaCl_2$ pre. and EtOH pre.	18.93 %, 66.72 %	Simple, inexpensive, widely used	Harsh conditions may degrade structure, lower bioactivity	[86]
	Pressurized liquid extraction	–	H_2O-DES (50–70 %), 100– 150 °C, 5–50 bar, 10–25 min	$CaCl_2$ pre./ EtOH pre.	5–27.2 %	High efficiency, greener solvents	Requires specialized equipment	[87]
	Ultrasound-assisted extraction	–	Water, 20:1 (*v/w*), 150 W, 50 Hz, 5 min	$CaCl_2$ pre.	5.7 %	Rapid, energy-efficient, improves extraction	Risk of depolymerisation if intensity is too high	[88]
	Soxhlet extraction	50 °C, 24 h	0.2 M HCl, 3 h at 60 °C	$CaCl_2$ pre./ EtOH pre	20.8 %			[89]
	Microwave-assisted extraction	400 mL 99 % ethanol for 3 h at room temperature	pH 1 (HCl), MAE conditions: 10 min at 45 °C, 400 W	EtOH pre	21.2 %	High yield in short time, eco-friendly	Possible alteration of functional groups	[90]
	Enzyme-assisted extraction	–	Enzyme: Alginate lyase (from *E. chevalieri*, fungal inoculum), 72 h at 28 °C	–	21.8 %	Selective, preserves functional groups, eco-friendly	Expensive enzymes, scalability issues	[91]
Ulvan	Heat assisted extraction	–	H_2O-HCl (pH 1.5, 2), 80 and 90 °C, 1 h	EtOH pre.	3.04-13.06 %	Simple, standardised	Harsh pH causes partial degradation	[92]
	Ultrasound-assisted extraction	80 % EtOH, RT, overnight (x2)	H_2O, 66 °C, 53 kHz, 180 W, 40 min	EtOH pre.	8.30 %	Faster, preserves some activity	Equipment-dependent, not easily scalable	[93]
	Enzyme-assisted extraction		Cellulase, Protease, pH 7, 50 °C, 2 h	Dialysis/EtOH pre.	17.14 %	Higher yield, preserves bioactivity	Costly, optimisation required	[92]
	Microwave-assisted extraction	–	2.45 GHz at different temperature for 15 min	BaCl2-gelation, n 1 M HCl for 5 h at 110 °C	36.38 %	High yield, reduced time	Structural modifications possible	[94]
Laminarin	Heat assisted extraction	96 % EtOH, 40 °C, 24 h	0.1 M HCl, RT, 3 h	Dialysis/EtOH pre./IEC	0.4 % d-DW			[95]
	Ultrasound-assisted extraction		H_2O and 0.03 M HCl; 15 min; 60 % amplitude; 20 Hz	EtOH pre.	5.29–6.24 %	Short extraction time, preserves activity	Limited scalability	[96]
Fucoidan	Heat assisted extraction	85 % EtOH, RT, overnight	H_2O, 65 °C, 3 h (x2)	$CaCl_2$ pre./ EtOH pre.	5.2 %	Easy, common, moderate yield	Harsh heat reduces sulfate content	[97]
	Heat assisted extraction	95 % EtOH, 4 h	H_2O, 100 °C, 1 h	Dialysis (14 kDa)/EtOH pre./IEC	5.08 %			[98]
	Soxhlet extraction	99 % EtOH 2 %	$CaCl_2$, 85 °C, 2 h	EtOH pre./ Dialysis	10.9-31.7 % DW			[99]
	Microwave-assisted extraction	95 % EtOH, 4 h	H_2O, 750 W, 10 min	Dialysis (14 kDa)/EtOH pre./IEC	6.94 %	Rapid, eco-friendly	May alter sulfation	[98]
	Ultrasound-assisted extraction	95 % EtOH, 4 h	H_2O, RT, 21–25 kHz, 950 W, 10 min	Dialysis (14 kDa)/EtOH pre./IEC	4.78 %	Energy-efficient, preserves bioactivity	Risk of structural breakdown	[98]
	Ultrasound-assisted extraction	85 % EtOH, RT, overnight	H_2O, 55 °C, 20 kHz, 200 W (x2)	$CaCl_2$ pre./ EtOH pre.	3.51 %			[97]
	Pressurized liquid extraction	85 % EtOH, RT, overnight	H_2O; 90–150 °C, 7.5 bar, 10–30 min	$CaCl_2$ pre./ EtOH pre.	4.9–23.7 % DW	High efficiency, green solvents	High pressure requires expensive systems	[97]
	Enzyme-assisted extraction	–	Cellulase/alginate lyase, pH 6, 40 °C, 24 h	$CaCl_2$ pre. and EtOH pre./IEC	40 % and 29 %	High yield, preserves sulfate esters, bioactivity	Costly enzymes, complex control	[100]
Carrageenan	Ultrasound-assisted extraction	80 % EtOH, RT, overnight	H_2O, 90 °C, 25 kHz, 150 W, 15–30 min	Hot filtration	50 %; 55 % DW	Energy-efficient, short extraction	Heat may reduce gel strength	[101]
	Pressurized liquid extraction	–	H_2O, (60–180 °C), 50 bar, 5 min 1 % ILs, (60–180 °C), 50 bar, 5 min	2-Propanol pre.	κ-carr. 55–70 %	High recovery, greener process	Equipment cost, possible modification of sulfate groups	[102]
	Microwave-assisted extraction	–	425 W, water to the raw material ratio of 30 mL/g, and time of 12 min	–	7.99 %	Quick, eco-friendly	Risk of depolymerisation	[103]

pre: precipitation, DW: dry weight; d-DW: deffated dry weight; RT: room temperature; EtOH: ethanol; IEC: ion-exchange chromatography; DES: deep eutectic solvents; MeOH: methanol; ILs: ionic liquids.

Table 3
Updated analytical methods for structural characterization of marine hydrocolloids.

Source/Compound	Analytical Method	Detector/Technique	Structural Information Obtained	References (2020–2024)
Fucoidan, Fucans	HPAEC–PAD	Pulsed amperometric detection	Monosaccharide composition, sulfation distribution	[78,109]
Alginate	LC–MS/UPLC–MS	ESI-MS, HR-MS	Monomer sequence, uronic acid ratio, block structure	[109,110]
Carrageenan	MALDI-TOF-MS, FTIR	Mass spectral profiling, functional group analysis	Degree of sulfation, glycosidic linkages	[111,112]
Laminarin	HPLC–PAD	Refractive index, PAD	Molecular weight, β-glucan linkage confirmation	[113,114]
Ulvan	NMR (1D & 2D: HSQC, HMBC, DOSY)	^{1}H, ^{13}C, multidimensional NMR	Fine structural details, branching patterns, sulfate substitutions	[115,116]
Agar & Agaro-oligosaccharides	Raman spectroscopy + Chemometrics	Vibrational modes	Rapid fingerprinting, gel quality prediction	[117,118]
Extracellular polysaccharides	GC–MS, LC–MS/MS	FID, MS	Monosaccharide linkage and branching	[119,120]
Novel microbial EPS	UPLC-QTOF-MS, Orbitrap HR-MS	High-resolution mass accuracy	Oligosaccharide sequencing, unusual residues	[57,62]
General hydrocolloids	FTIR–ATR	Infrared spectroscopy	Functional group identification, sulfate/carboxyl groups	[121,122]
Computational Glycomics	In silico molecular modelling, ML-assisted docking	–	Structure–activity predictions, binding to proteins/enzymes	[107,123]

assisted laser desorption ionization (MALDI-MS) is of great use in sequencing oligosaccharides and defining changes such as acetylation or sulfation [106]. Glycomics is a new discipline that uses these analytical methods to study how structure and function are connected and how glycoproteins and lipids interact with other biomolecules [107]. Scientists can deduce a comprehensive picture of the main and secondary structures of marine polysaccharides through the combination of hydrolysis, chromatography, spectroscopy, and computational methods. This leaves room for their exploitation in biotechnology, food science, and medicine [108].

2.6. *Emerging marine hydrocolloids: Novel sources and applications*

The expanding frontier of marine biotechnology has unveiled a diverse array of underexplored hydrocolloid sources that extend far beyond traditional seaweed-derived polysaccharides. These emerging marine hydrocolloids represent a paradigm shift in functional ingredient development, offering unprecedented structural complexity, enhanced bioactivities, and novel technological properties that position them as next-generation components for advanced food applications.

2.6.1. *Deep-sea and extremophilic marine sources*

Deep-sea environments and extreme marine habitats harbor unique microorganisms that produce structurally distinct polysaccharides with exceptional functional properties. Hydrocolloids from deep-sea bacteria such as *Alteromonas infernus* and *Pseudoalteromonas* species demonstrate remarkable stability under high-pressure, high-salinity, and temperature-extreme conditions, making them ideal candidates for challenging food processing applications [57,58]. These exopolysaccharides exhibit enhanced cryoprotective properties, superior gel strength maintenance under acidic conditions, and resistance to enzymatic degradation compared to conventional marine hydrocolloids. The polysaccharide Infernan, produced by *Alteromonas infernus*, shows unique calcium-mediated gelation properties and three-dimensional network formation that surpasses traditional alginate systems in stability and mechanical strength [108].

2.6.2. *Marine microalgae and cyanobacterial polysaccharides*

Microalgae and cyanobacteria represent an emerging frontier for novel hydrocolloid production, offering advantages in controlled cultivation, consistent quality, and scalable production. Red microalgae such as *Porphyridium* species produce sulfated polysaccharides with unique branching patterns and high uronic acid content, resulting in superior antioxidant and immunomodulatory activities compared to macroalgal counterparts [74]. Cyanobacterial exopolysaccharides from marine *Arthrospira* and *Leptolyngbya* species demonstrate exceptional rheological properties and biocompatibility, with applications extending from food stabilization to functional ingredient delivery systems [76,121]. These microalgal hydrocolloids offer the additional advantage of sustainable production through photobioreactor cultivation, addressing supply chain challenges associated with wild-harvested seaweeds.

2.6.3. *Marine invertebrate-derived polysaccharides*

Marine invertebrates, including sea cucumbers, mollusks, and crustaceans, represent underutilized sources of bioactive polysaccharides with distinct structural features and functional properties. Glycosaminoglycans from marine snails and sea cucumbers exhibit unique sulfation patterns that enhance their anticoagulant and anti-inflammatory activities beyond those of terrestrial animal sources [67,124]. Chitosan derivatives from marine crustacean shells demonstrate superior biocompatibility and antimicrobial properties when compared to terrestrial chitin sources, owing to their distinct molecular weight distributions and acetylation patterns [125]. These marine invertebrate polysaccharides offer opportunities for developing specialized functional foods targeting cardiovascular health and immune system support.

2.6.4. *Hybrid and engineered marine polysaccharide systems*

The development of hybrid polysaccharide systems through controlled fermentation and genetic engineering represents a cutting-edge approach to marine hydrocolloid innovation. Engineered marine bacteria can be programmed to produce tailor-made polysaccharides with specific functional groups, molecular weights, and bioactivities designed for targeted applications [61,62]. Hybrid systems combining different marine polysaccharide sources, such as alginate-chitosan complexes or carrageenan-fucoidan blends, demonstrate synergistic effects that exceed the sum of their individual components in terms of gel strength, antioxidant activity, and bioavailability enhancement [126,127]. These engineered systems enable precise control over functional properties while maintaining the natural origin and clean-label appeal of marine-derived ingredients.

2.6.5. *Commercial potential and future prospects*

Emerging marine hydrocolloids present significant commercial opportunities, with the global marine biotechnology market projected to reach substantial growth in the coming decade. However, successful commercialization requires addressing challenges related to extraction optimization, quality standardization, regulatory approval, and scale-up feasibility [128,129]. Recent advances in bioprocessing technologies, including enzyme-assisted extraction, membrane separation, and controlled fermentation, are enabling more efficient and sustainable production of these novel hydrocolloids [130,131]. The integration of systems biology approaches and metabolic engineering further enhances the potential for developing commercially viable emerging marine hydrocolloids with tailored functionalities for specific food applications [62,123].

3. Technological and biofunctional properties relevant to food applications

3.1. Gelation mechanisms and modulation

Gelation is the most important functional attribute of marine polysaccharides in food because it influences the texture, stability, and organoleptic properties of the majority of foods [132]. Polysaccharides from the marine sources like agar, carrageenan and alginate, gel by different mechanisms that can be broadly classified as thermoreversible, thermoirreversible or ionic crosslinking [133]. Some of the carrageenan have a distinctive ability to gel by cooling and can be reverted back to liquid state when reheated; this distinctive quality is termed thermoreversible gelation. In these cases, the polysaccharide chains align and aggregate during cooling, resulting in the formation of 3D structures which hold large amounts of water and other materials [134]. This property of gelation is very useful in food technology for many products that undergo repeated melting and freezing: confectionery and dessert gels, for instance [135]. Marine hydrocolloids exhibit diverse mechanisms of gelation and thickening, which are governed by their molecular structures and interactions. Alginate, a brown seaweed polysaccharide, forms thermoirreversible gels having ionic crosslinks with divalent cation such as calcium. Crosslink gelatinisation is a key mechanism observed. In this process, divalent cations, particularly calcium (Ca^{2+}), bind to specific regions of the alginate chain that are rich in guluronic acid residues (G-blocks). The Ca^{2+} ions fit into the cavities formed by these G-blocks, creating ionic bridges between adjacent polymer chains. This arrangement, often referred to as the "egg-box" model, results in a three-dimensional network structure that stabilizes the gel [136]. Similarly, ι-carrageenan undergoes ionic cross-linking in the presence of divalent cations, enhancing gel strength and elasticity [137]. Marine hydrocolloids also participate in complex coacervate formation, such as κ-carrageenan interacting with casein micelles in dairy systems or fucoidan–chitosan forming polyelectrolyte complexes in encapsulation matrices [138]. Furthermore, ulvan and laminarin act predominantly as viscosity enhancers, thickening food matrices through chain entanglement without true gelation [139]. Based on the M/G block ratio, alginates vary in their gelling ability. Alginates with high G-block content produce hard, brittle gels through calcium ion-dense junctions, while alginates with high M content produce soft, elastic gels [137]. The versatility of alginate allows it to be used in a broad range of food applications, from reconstituted fruit to low-fat milk products. Mixed gel systems of marine polysaccharides blended with other hydrocolloids or proteins are increasingly being studied due to their ability to attain synergistic effects, such as enhanced gel strength, enhanced water retention, and new textures. A blend of carrageenan and locust bean gum produces gels that are harder and elastic, which is advantageous in dairy and meat products [126]. Structure at the molecular level of all polysaccharides, such as chain length, density of branching, and presence of sulfate or carboxyl groups, determines firmness, elasticity, and water-holding capacity of gels. Structural characteristics and processing can be altered by industrial experts to design textural and functional characteristics of gels according to specific applications according to industrial need and consumer demand [140].

3.1.1. Cold-set/low-temperature soft gels (agar & carrageenan)

In modern formulations, consumers and manufacturers seek soft, elastic gels with minimal heating. For carrageenan systems pre-solubilised by brief heat, ι-carrageenan in the presence of Ca^{2+} forms soft, cohesive gels that set at ambient/low temperatures upon cooling. Texture can be tuned by κ/ι blending, ionic strength, and molecular-weight distribution. κ-rich systems with K^{+} favor stronger, brittle networks; adding ι-carrageenan and moderating K^{+} shifts the matrix towards softness and elasticity. Agarose helices stabilize via hydrogen bonding and hydrophobic stacking during cooling, resulting in thermoreversible gels useful in desserts and confectionery [141].

For agar, soft-gel design relies on lower agarose concentration, moderate Mw, and slightly higher substitution in agaropectin (e.g., residual sulfate/pyruvate), which weakens helix aggregation and yields pliable, low-modulus gels after solubilisation/cooling. Commercial "cold-soluble" grades (physically/chemically pre-treated) enable room-temperature hydration and no-cook soft-gel applications (instant gels, toppings), complementing traditional cook-up agar products [142].

While modified "cold-soluble" agar/carrageenan products permit room-temperature processing, native agar and κ/ι-carrageenan generally still require initial thermal solubilisation before low-temperature setting [143]. Future work should: (i) design tailored Mw distributions and substitution patterns that hydrate and form helices at ambient conditions; (ii) optimize ion pairing and co-solutes (sugars, polyols) to stabilize helices without heat; and (iii) develop green pre-treatments that retain clean-label status while enabling true cold-set gelation for heat-sensitive foods.

3.2. Rheological behavior

The rheological behavior of marine hydrocolloid solutions is significant to their application as thickeners, stabilizers, and texture modifiers in foods (Table 4). These polymers usually possess non-Newtonian flow behavior, with viscosity depending on the application of shear stress. This is of great benefit in food processing, as products are stable in thickness during storage yet still easy to spread or pour when in use [144]. For example, xanthan gum or carrageenan solutions are shear-thinning, a characteristic that is beneficial in products for use in salad dressings, sauces, and drinks. Viscoelasticity is an important characteristic of marine polysaccharides, and both elastic (solid-like) and viscous (fluid-like) behavior is exhibited [145]. This dual characteristic is important in delivering the optimal mouthfeel and texture of products including gels, desserts, and dairy substitutes. The characteristic of thixotropy, where there is potential to recover viscosity after shear, is of great importance in products that need stability as well as ease of application, such as dips and spreads [146]. The rheological behavior of marine hydrocolloids is very sensitive to a variety of environmental conditions, for example, temperature, pH, and ionic strength. For instance, the addition of some ions can increase or decrease gel strength and viscosity, while temperature changes can affect flow behavior and the rate of gelation [147]. Understanding on these parameters allows industry experts to design products with tailored textures and stability characteristics (Fig. 2). Furthermore, the structure of the polysaccharide at a molecular level, for example, molecular weight and degree of branching, has a great impact on rheological performance [148]. With the selection of proper types and quantities of marine polysaccharides, manufacturers can achieve the desired flow properties, optimize processing efficiency, and improve consumer satisfaction.

3.3. Stabilization mechanisms

Marine hydrocolloids are effective stabilizers in foods due to their ability to thicken, create protective films, and interact with other food components at interfaces [149]. Polymers in mayonnaise and salad dressing emulsions act to prevent coalescence of oil droplets. They achieve this by thickening the continuous phase and creating interfacial films on the droplets. This type of stabilization mechanism is highly critical in product stability and shelf life [150]. In suspensions like

Table 4
Functional properties of marine hydrocolloids and their potential applications in food products. This table provides the common functional characteristics of marine hydrocolloids like carrageenan, alginate, agar, fucoidan and ulvan representing their effect on the food stability, structure and the bioactivity.

Functional properties	Application and effects on food products	Hydrocolloids	References
Stabilizing and thickening properties	Reducing syneresis rate; improving creaming and foaming stability; affecting pasting, dough rheology, and baking in plant oil, stirred yogurts, bread, and other bakery products.	κ-carrageenan, alginate	[162,163]
Emulsifying activity and emulsion stability	Firmness and elasticity; stability of oil-and-water emulsions; egg white replacements in sausages, baked products, and ice creams.	fucoidan, carrageenan	[164]
Viscosity	Increase viscosity; affects rheology/fruit and vegetable juices, salad sauces, baked foods	ulvan, laminarin	[139,165,166]
Thermal stability	Active ingredient in heat-processed/thermally treated food	agar, carrageenan	[167]
Prebiotic capacity	Fruit tea and functional foods boost *Lactobacillus rhamnosus* survival and proliferation in the gut.	alginate, laminarin, agar-oligosaccharides	[168]
Edible films	Smart edible films incorporating carrageenan or fucoidan with bioactive nanoparticles are being developed to extend food shelf-life and deliver antimicrobial activity in situ.	carrageenan, fucoidan, chitosan blends	[169]
Sensory-affecting properties	Sensory enhancement of bread or other culinary products	agar, carrageenan	[170]
Water holding and oil binding capacities	Texture improvement; meat water retention; bread, meat, and baked items visual appeal, structure, and porosity.	alginate, carrageenan	[171]
Shear thinning and gelling properties	Increase food viscosity/gelling	κ-carrageenan, agarose	[172]
Coating properties	Coatings prevent microbiological deterioration and preserve taste, extending shelf life. This method encapsulates unstable components in fruits, cheese, oils, volatile substances, and other foods to prevent oxidative degradation.	chitosan, fucoidan	[173]

chocolate milk or fruit juices, marine polysaccharides play a key function of creating a network that is useful in entrapping and holding solid particles in suspension during the liquid and preventing them from settling. Freeze-thaw stability is a very critical property, especially in frozen foods. Marine polysaccharides play a key function of preventing the development of big ice crystals and syneresis (water loss) during freezing and thawing operations, thus maintaining texture and preventing phase separation [151]. Stabilization properties at the molecular level are imparted through the integration of steric hindrance, electrostatic repulsion, and network formation. The polysaccharide structure like charge density, molecular weight, and branching controls its stabilizer performance [122]. Through these functions, designing products that are more stable, longer shelf life, and improved sensory properties can be achieved.

3.4. Water binding and textural contributions

The functionality of marine polysaccharides in the food industry particularly relates to texture and quality stems from the capability of the polysaccharides in question to bind and retain water [152]. The molecular structure of a polysaccharide includes its hydrophilic constituents, how flexible its chains are, and the degree of branching. The degree of hydration affects many things from preserving moisture to preventing syneresis in gels and dairy products [153]. For example, alginates and carrageenan are frequently used in processed meat and dairy products to retain moisture and increase juiciness. Control of syneresis is important in yogurts and jellies; water released from the syneresis has an undesirable effect on texture and appearance. Marine polysaccharides perform functions of considerable textural modification, aiding in the creation of soft, creamy to firm, elastic products. [154]. Ensuring stability of the product during texture altering processes such as storage and processing is still an important hurdle, even if the texture is regarded as an important quality feature considering it has a major impact on consumer choices in food products. Researchers frequently incorporate hydrocolloids into various food formulations as a means of enhancing textural stability, primarily by increasing the solution's viscosity. The most common hydrocolloids used to thicken food items include starch, xanthan gum, guar gum, and carboxymethyl cellulose (CMC) [155]. The concentration of hydrocolloid molecules in food items has a major impact on the textural characteristics of a food system [156]. According to the literature, marine hydrocolloids have been used extensively as texture-modifying agents in a variety of food products, such as dairy products (yoghurt, cheese), meat products (patties, sausages, and salami), fruit-based products (fruit leathers, juices, and purees), and bakery goods (bread, muffins, and cakes) [157]. Due to its cheap availability and low extraction costs, starch is one of them that is often employed as a texture modifier agent in a variety of food systems, including jam, jelly, fruit purées, fruit leathers, fruit fillings, ketchup, and sausages [158]. Native starch's usage in the creation of food products is limited by its poor water solubility and retrogradation [159,160]. Researchers are actively incorporating tiny amounts of gums with starch before using it in food systems in an effort to enhance its functioning [161]. This reason can be attributed to the formation of intermolecular interactions, including hydrogen bonds, cation-based cross-linking between polymer chains, and hydrophobic interactions between hydrocolloids and food system molecules [152].

3.5. Interactions with other food components

Marine polysaccharides engage in significant interactions with various food components, influencing the overall functionality and quality of food products [152]. The interactions between proteins and polysaccharides can result in the creation of complexes or coacervates, which play a significant role in determining gelation, stability, and texture. The interactions in question frequently exhibit a dependence on pH and can be influenced by ionic strength as well as the presence of additional solutes [174]. Carrageenan, for instance, engages with milk proteins to create stable gels in dairy desserts [175]. Marine polysaccharides have the ability to form complexes with lipids, which influences emulsion stability and the distribution of fats. Certain substances, such as alginate and chitosan, possess the capability to bind minerals, thereby potentially improving nutritional value or reducing negative mineral-induced alterations in food. Interactions among starch

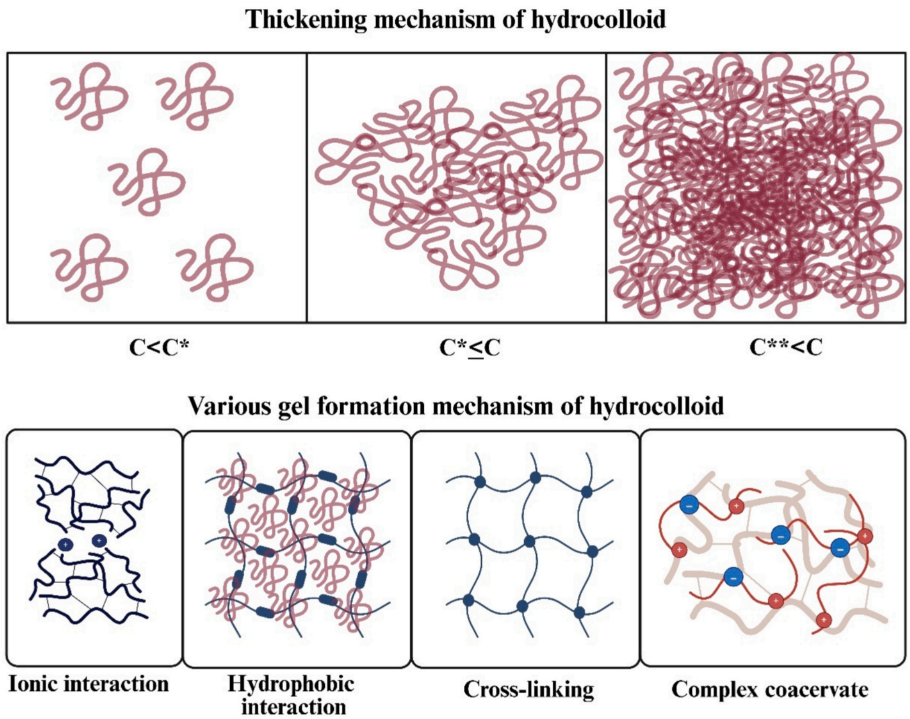

Fig. 2. Hydrocolloid gelation and thickening processes schematically shown with their respective molecular interactions. (i) Ionic interactions and cross-linking: alginate forms calcium-mediated "egg-box" junction zones; ι-carrageenan also gels in the presence of Ca^{2+}. (ii) Hydrophobic contacts: agarose helices stabilize via hydrogen bonding and hydrophobic stacking during cooling. (iii) Complex coacervate formation: carrageenan–protein complexes in dairy systems (e.g., κ-carrageenan with casein micelles) and fucoidan–chitosan polyelectrolyte complexes in encapsulation. (iv) Thickening behavior: ulvan and laminarin act as viscosity enhancers through chain entanglement without true gelation.

and various carbohydrates can influence gelatinization, retrogradation, and digestibility, presenting avenues for the creation of functional foods that provide enhanced health benefits [176]. Comprehending these interactions is crucial for enhancing product formulation, processing, and sensory characteristics, as they have a direct influence on texture, stability, and nutritional quality. To further illustrate this continuum, a conceptual model is included (Fig. 3), outlining how functional and structural properties correlate with physiological and bioactive effects on the human body.

4. Bioactive properties and health benefits

4.1. Gastrointestinal behavior and digestibility

Hydrocolloids, encompassing a range of proteins and polysaccharides, play a crucial role in the processing of foods and nutrients in the digestive system (Fig. 4). Their behaviors initiate from their distinct solubility and physical properties, which dictate their dissolution, swelling, or retention in the fluid milieu of the gastrointestinal tract [177]. Certain hydrocolloids, including modified starches and gum arabic, exhibit a high degree of solubility and integrate seamlessly with

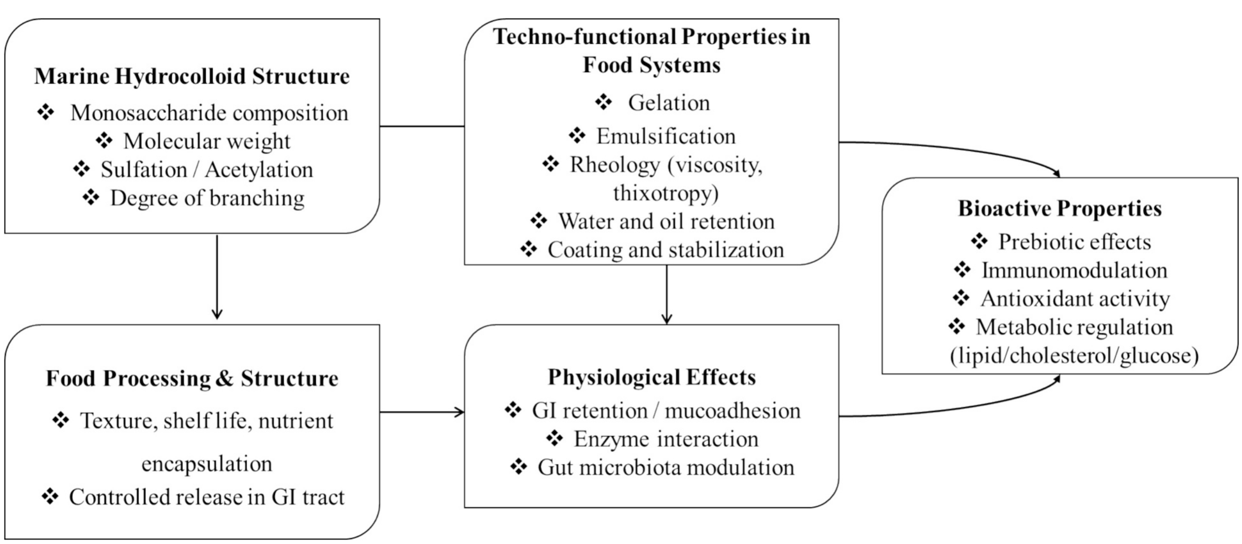

Fig. 3. Conceptual model linking the techno-functional properties of marine hydrocolloids to their bioactive properties and health benefits.

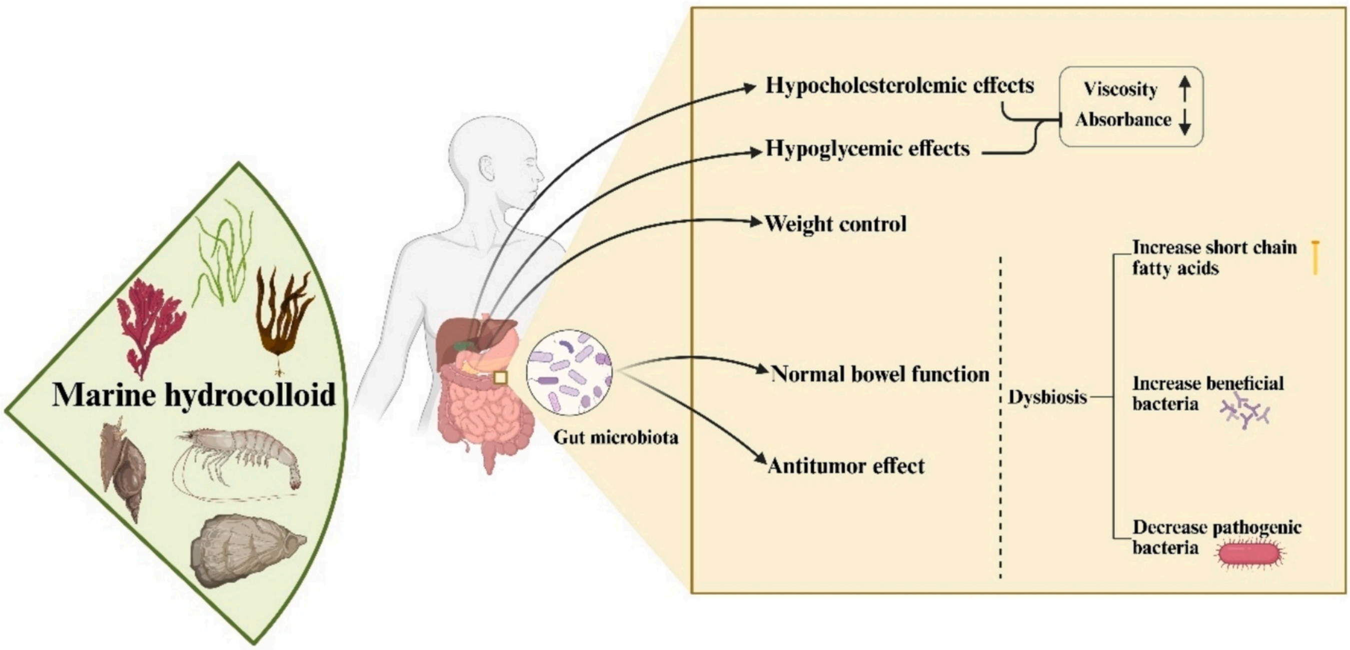

Fig. 4. Hydrocolloids and their health impacts via gut modulation [179].

digestive fluids. In contrast, substances like cellulose and chitin demonstrate lower solubility, potentially leading to the formation of structured particles that influence nutrient release and absorption [178,179]. An essential element of their role is their engagement with digestive enzymes. Hydrocolloids can also interact with nutrient molecule or enzyme molecules, thereby influencing the efficiency of macronutrient degradation, such as carbohydrates, fats, and proteins [180]. Viscosity and flow of digestive fluids can be modified by hydrocolloids, retarding the enzymatic breakdown of food, which could be beneficial in facilitating the slow release of nutrients and in the control of blood sugar spikes after meals [181]. Another important feature is the ability of some hydrocolloids to interact with bile acids. Polysaccharides such as acetylated lupin fibers and chitosan, for example, can interact with bile salts through hydrophobic or electrostatic forces. This interaction prevents the reabsorption of bile acids, thereby potentially reducing cholesterol levels and influencing the digestion and absorption of dietary lipids [182]. Some hydrocolloids also possess mucoadhesive properties, which enable them to stick to the mucosal lining of the gastrointestinal tract. Adhesion can extend the transit time of these substances in the gut, which may improve the delivery of nutrients or bioactive compounds to target locations. The interaction of hydrocolloids with gut bacteria can also be affected, making them more useful as prebiotics [183,184]. The integration of hydrocolloids in food formulations or within sophisticated delivery systems, such as emulsions, nanoparticles, or microgels, facilitates meticulous regulation of nutrient digestion, absorption, and bioavailability. This advancement fosters the creation of functional foods specifically designed to enhance health and wellness [97].

4.2. Prebiotic effects and gut microbiota modulation

Marine hydrocolloid polysaccharides, especially those sourced from seaweeds and various marine algae, are gaining attention for their prebiotic potential in food and health applications. Prebiotics are characterized as non-digestible, selectively fermented substrates that positively affect the composition and activity of the gut microbiota, thus promoting host health and well-being [185]. To classify a marine hydrocolloid as a prebiotic, it is essential that it withstands digestion in the upper gastrointestinal tract, is fermentable by beneficial gut bacteria, and selectively promotes the growth or activity of these microbes. This process results in the production of health-promoting metabolites, including short-chain fatty acids (SCFAs) [186]. The indigestible characteristics of marine polysaccharides, including alginate, laminarin, fucoidan, carrageenan, and ulvan, enable them to arrive in the colon unaltered, where they serve as substrates for fermentation by the local microbiota. This fermentation process mainly produces SCFAs such as acetate, propionate, and butyrate, which play a vital role in supporting intestinal health. These SCFAs act as energy substrates for colonocytes, modulate immune response, increase glucose metabolism, and have the ability to decrease the risk of disease like colon cancer, obesity, and metabolic syndrome. Also, marine hydrocolloids hold the potential to act as electron sinks in the gut, facilitating anaerobic respiration and increased availability of minerals [17]. Different research indicates that marine polysaccharides hold the potential to selectively increase the growth of probiotic microbes like *Lactobacillus* and *Bifidobacterium* and suppress the growth of disease-causing microbes. It has been indicated that seaweed polysaccharides hold the potential to increase the growth of *Lactobacillus plantarum* but suppress the growth of enteric pathogens, thereby creating a well-balanced gut microbiota [185]. The presence of these health-enhancing bacteria strengthens the gut barrier and modulates the immune system, leading to resistance against infection and inflammation. Fermentation of these polysaccharides results in a decrease in colonic pH, which again suppresses the growth of disease-causing bacteria but stimulates favorable species [159]. Prebiotic activity and efficacy of marine hydrocolloids are highly reliant on their molecular weight and structure. Lower molecular weight polysaccharides or partially hydrolyzed polysaccharides easily get fermented by gut microbes, leading to higher production of SCFAs and increased prebiotic activity. Specific oligosaccharides obtained from marine polysaccharides have demonstrated a greater ability to enhance the population of *Bifidobacterium* and *Lactobacillus* in comparison to their high-molecular-weight equivalents. The presence in gut microflora of certain carbohydrate-active enzymes is essential to the breakdown and utilization of such complex carbohydrates [187]. The information rather suggests that marine hydrocolloid polysaccharides could be used as superior prebiotic ingredients, which can be used to create new functional foods and symbiotic products. The capacity to modulate gut microbiota, promote SCFA production, and maintain host metabolic and immune health makes them good candidates for further study and use in human nutrition [17].

4.3. Immunomodulatory properties

Marine hydrocolloids represent a very large group of polysaccharides including alginates, carrageenan, agar, laminarin, chitosan, and sulfated polysaccharides (Fig. 5). Their complex mechanisms of modulating immune responses are being discovered and hence they are important food constituents that contribute to immune strength [188,189]. The mechanism of interaction between these molecules and immune cells is through direct interaction with pattern recognition receptors like Toll-like receptors (TLRs) on macrophages, dendritic cells, and lymphocytes. They also possess the capability of inducing indirect effects by modulating the gut microbiota and increasing gut barrier function, both of which have significant roles to play in immune homeostasis [34]. Immunomodulatory activity of marine hydrocolloids is directly proportional to their structure. Structure of the sulfate group, molecular weight, and some sugar residues of sulfated polysaccharides could be responsible for the ability of such molecules to stimulate immune cells. Acetylation, branching, and gel character of chitosan, alginate, and agar are important in immunomodulatory activity [190]. It has been demonstrated in experiments the ability of oligosaccharides derived from alginate to stimulate macrophages and release cytokines and chitosan to modulate innate and adaptive immunity by stimulating macrophages and lymphocyte proliferation [189]. Carrageenan has been reported to exhibit anti-inflammatory activity by inhibiting the release of pro-inflammatory cytokines and modulating immune cell activity, including T-cells and macrophages. The addition of agar and laminarin to food systems has also been correlated with increased immune response and decreased inflammation, partly due to their therapeutic effect on healthy gut bacteria and capacity to suppress gut-derived inflammatory signals [36]. These marine hydrocolloids play a role in immune balance regulation by influencing the Th1/Th2 response and possibly suppressing allergic or autoimmune responses. As multifunctional and structure-dependent immunomodulators, marine hydrocolloids are being added to more functional foods, beverages, and dietary supplements for immune health promotion either by direct action on immune cells or by establishing a healthy gut environment [191]. Their properties of being able to gel or bind to mucosal surfaces make them especially suited to the newest food products for immune support enhancement.

4.4. Antioxidant and cellular protection

Marine hydrocolloids from marine life like algae, bacteria, and crustaceans have been of great interest due to their diverse antioxidant as well as cell-protective activities since they can scavenge the free radicals generated during aerobic metabolism effectively [192]. Such action avoids oxidative stress, which otherwise disturbs the oxidant/antioxidant equilibrium, causing cellular damage to lipids, proteins, and DNA (Table 5). Such damage is associated with the onset of chronic diseases, including diabetes, cancer, and cardiovascular disorders [125,192]. The mechanisms of free radical scavenging function by donating hydrogen atoms or electrons to unstable radicals, thereby stabilizing them and interrupting the chain reactions that lead to the oxidative degradation of biomolecules [83]. This activity has been

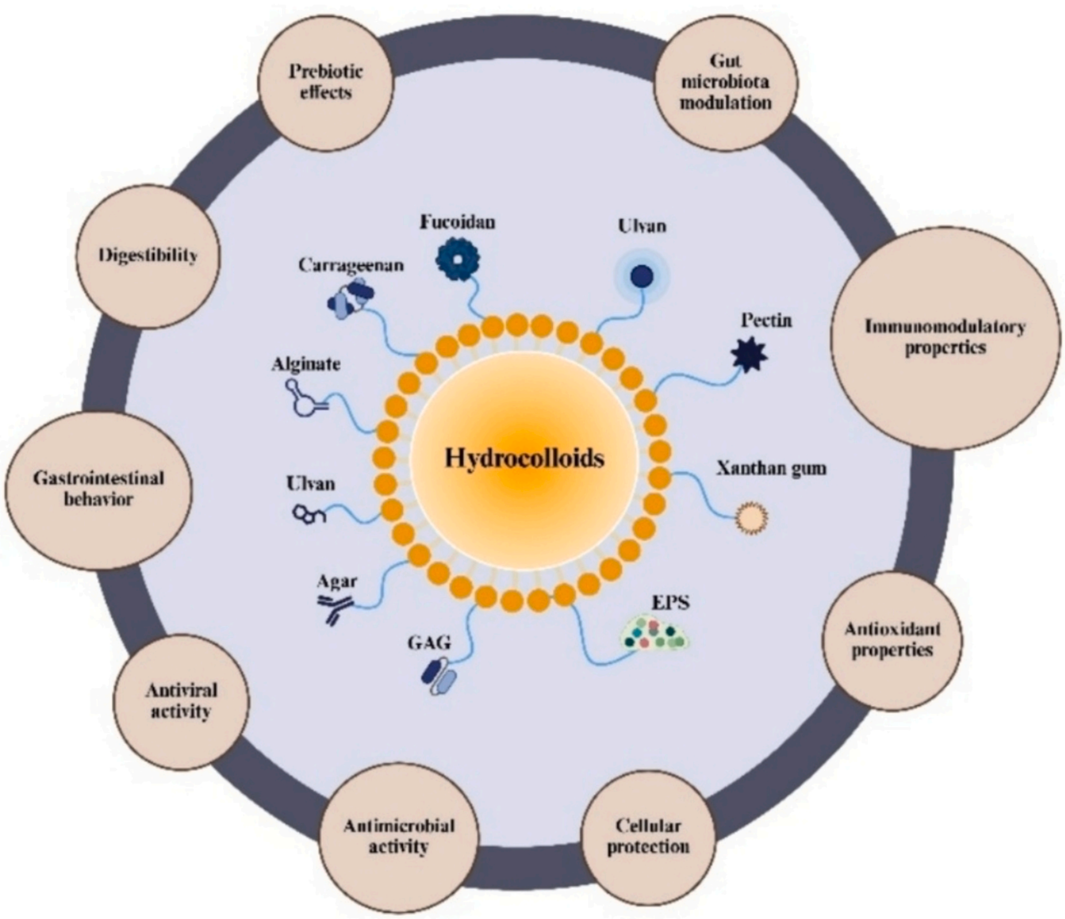

Fig. 5. Marine hydrocolloids in human health contributing in gastrointestinal behavior, immune responses, antiviral and antimicrobial activities.

Table 5
Table on the studies of antioxidant activity of marine hydrocolloids.

Compounds	Experimental method	Reported antioxidant activity	Results	References
in vitro				
Agar	DPPH assay	67.03 ± 3.30 %, 33.49 ± 2.14 %, 6.77 ± 1.08 % at a concentration of 200, 100 & 50 μL	Radical scavenging activity	[117,196]
Alginate	ABTS and SOD assays	12.45 % to 72.36 % at a concentration of 0.05-2.5 mg/mL	Radical scavenging activity	[110,197]
Carrageenan	Total antioxidant and reducing power activity	10.04 ± 1.68 % to 30.76 ± 3.21 %	Reducing power	[112]
Chitosan	DPPH, ferrous ion chelating, and hydroxyl radical scavenging assay	24.38 ± 0.34 %	Radical scavenging activity	[125,198]
GAG	ABTS and FRAP assays	47.05 ± 3.27 %	Radical scavenging activity	[124]
Laminarin	DPPH and FRAP assays	7.5 % to 79.7 %, as the average molecular weight of laminarin degraded from 15 kDa to 6 kDa	Radical scavenging activity	[114]
LSP and LMP	DPPH and ferrous ion chelating assays	15.9 % to 71.8 %	Radical scavenging activity	[199,200]
Other models				
Agaro-oligosaccharides	Intracellular oxidant stress assay Biochemical assays	60.34 to 83.84 % & 10.94 to 24.59 %	Radical scavenging activity Inhibiting MDA, AST, and ALT	[47,118]
Chitosan	Total plasma antioxidant capacity (TPAC), DPPH and ABTS assays	0.4 ± 0.1 & 2.3 ± 0.2	Increase in TPA; Radical scavenging activity	[120]
Fucoidan	Estimation of plasma malondialdehyde (MDA)	16.27 ± 0.73 to 71.76 ± 3.23 at various concentrations from 0.1 to 5	Decrease in MDA levels	[201,202]
Laminarin	Intracellular ROS levels and GSH assay	0.4 to 0.8 %	ROS scavenging activity, increase in GSH levels	[116,203]

validated through numerous in vitro assays, such as DPPH, ABTS, ferric reducing-antioxidant power (FRAP), and superoxide dismutase (SOD), along with in vivo animal studies that affirm their biological effectiveness. Beyond their direct neutralization of reactive oxygen species (ROS), marine polysaccharides including fucoidan, laminarin, agar, carrageenan, chitosan, glycosaminoglycans, and exopolysaccharides demonstrate significant metal chelation capabilities [84]. They effectively bind transition metals such as iron, which are recognized for their role in catalyzing the Fenton reaction and producing highly reactive hydroxyl radicals, thereby alleviating oxidative stress on cells. The effectiveness of these polysaccharides as antioxidants is intricately linked to their structural characteristics, such as the degree of sulphation, molecular weight, monosaccharide composition, and glycosidic linkages [83]. Each of these factors plays a crucial role in determining their capacity to donate hydrogen atoms and engage with free radicals. In addition to scavenging and chelation directly, these marine-derived compounds also enhance cellular protective processes via activation of endogenous antioxidant enzymes such as SOD, catalase (CAT), and glutathione (GSH). These compounds also influence signaling pathways such as SIRT1/AMPK/PGC1α and MAPK that are essential to cellular defense against oxidative stress [85]. For instance, thermal processing-derived low molecular weight alginates are more effective antioxidants than polymeric analogs, possibly because of the creation of new functional groups that allow them to interact better with reactive oxygen species. Moreover, fucoidan can inhibit oxidative renal damage and inhibit the risk of kidney stones via its strong antioxidant activity [114]. Furthermore, laminarin has shown the capability to reduce reactive oxygen species levels in both cell cultures and animal models, with its effectiveness varying based on algal species and polysaccharide structure. In a similar vein, agar derived from *Gracilaria tenuistipitata* through alkali methods exhibits optimal physiochemical and functional properties, rendering it a compelling and economical antioxidant for food applications [117]. Furthermore, the antioxidant activity of carrageenan is directly proportional to its purity while being inversely related to temperature. Chitosan, obtained from the chitin of lobster shells, has shown antioxidant properties in human studies, evidenced by a reduction in lipid hydroperoxides and a suppression of oxidative stress [125,193]. This indicates possible therapeutic uses in conditions such as renal failure. Glycosaminoglycans derived from marine snails, along with exopolysaccharides sourced from marine bacteria and cyanobacteria, have demonstrated noteworthy antioxidant and metal-chelating properties. Research indicates their effectiveness in scavenging hydroxyl and superoxide radicals, as well as in capturing iron ions. Antioxidant activity stability in food matrices relies on extraction conditions, extraction techniques, and molecular structure [124]. Evidence indicates that lower molecular weight, higher purity, and optimized extraction techniques, such as alkali extraction for agar, enhance both the functional and physiochemical properties of these polysaccharides. This confirms their use of strong, stable, and health-promoting food additives in functional foods [121]. However, despite carrageenan's desirable bioactivities, safety issues have been raised, especially with degraded carrageenan (poligeenan), which is not yet approved for use in food. Poligeenan differs chemically from food-grade carrageenan and has been demonstrated in certain animal experiments to have pro-inflammatory properties [194]. Food-grade carrageenan is safe according to government agencies such as the FAO/WHO and EFSA to be consumed in approved quantities, albeit continuous evaluation still tracks its long-term consequences. Therefore, while assessing the functional and biological applications of carrageenan in food systems, it is critical to distinguish between different kinds and purities [195]. The findings collectively highlight the promise of marine polysaccharides as potent agents for antioxidant and cellular protection. They provide both direct and indirect mechanisms to address oxidative stress and uphold cellular health across various biological and food systems [47].

4.5. Antimicrobial and antiviral activities

The increasing issue of antibiotic-resistant microbes has heightened the necessity for innovative antimicrobial strategies that ensure both safety and efficacy. Marine-derived macromolecules, particularly hydrocolloid polysaccharides, are gaining attention as promising candidates because of their natural origin, safety profile, and a wide range of biological activities [204]. he antimicrobial effects of these compounds can be attributed to a diverse array of bioactive substances, such as distinctive phenolic compounds and intricate polysaccharides. For instance, compounds like anthraquinones, flavonoids, and coumarins found in different marine algae have shown potential in inhibiting bacterial growth in controlled laboratory experiments [205]. A significant example is 1,8-dihydroxy anthraquinone derived from the red alga *Porphyra haitanensis*, which has demonstrated the ability to compromise the membrane integrity of *Staphylococcus aureus*, resulting in hindered bacterial growth [17]. Alongside phenolic compounds, marine polysaccharides have demonstrated notable antibacterial properties. Extracts from seaweeds such as *Myagropsis myagroides* have been shown to inhibit the growth of harmful bacteria like *Listeria monocytogenes* by damaging bacterial cell walls and inducing leakage of cellular ATP, indicating a bactericidal mechanism [17]. In addition to direct inhibition, certain marine polysaccharides have the potential to bolster the immune system's capacity to combat infections [25]. For example, fungi or yeast-derived β-glucans are known to stimulate innate immune cells, which in their turn release molecules such as nitric oxide that are part of the pathogen killing process. In poultry, experimental evidence has demonstrated that dietary β-D-glucan could enhance resistance to disease and lower the level of infections by stimulating antimicrobial peptides and enhancing immune defense [206]. Marine hydrocolloids are increasingly being acknowledged for their antiviral properties. Sulfated polysaccharides, including carrageenan and fucoidans, have the capability to disrupt viral life cycles by binding to viral particles, thereby inhibiting their attachment to and entry into host cells [207]. Certain polysaccharides have the potential to interfere with viral replication or assembly, offering a multifaceted approach to combat viral infections. Carrageenan-based nasal sprays have demonstrated effectiveness in lowering the risk of respiratory viral infections in clinical studies [208]. The diverse antimicrobial and antiviral properties of marine hydrocolloids are gaining traction as natural preservatives within the food industry [209]. The incorporation of these polysaccharides into edible coatings, films, or packaging demonstrates their ability to inhibit spoilage organisms and foodborne pathogens, which in turn extends shelf life and minimizes the necessity for synthetic additives. This is in accordance with the increasing consumer interest in clean-label, naturally preserved foods [210]. With the progression of studies, marine hydrocolloids are anticipated to assume a more significant position in ensuring food safety and preservation, providing natural alternatives to address microbial challenges and align with consumer preferences.

4.6. Structure–bioactivity relationship

The bioactivity of seaweed-derived polysaccharides is highly dependent on their structural characteristics. The degree and position of sulfation have been shown to directly influence antioxidant and immunomodulatory activities, where higher sulfation generally enhances radical scavenging capacity but may reduce gel strength [14]. Similarly, the molecular weight plays a dual role; high molecular weight polysaccharides often provide superior rheological properties [14], whereas low molecular weight fractions or oligosaccharides demonstrate enhanced prebiotic effects due to their better fermentability by gut microbiota [211]. The monosaccharide composition (e.g., proportion of uronic acids, galactose, or fucose) and the presence of substituents such as pyruvate or acetyl groups further modulate specific bioactivities, including anti-inflammatory and antiviral actions. Thus, the structural complexity of alginate, carrageenan, agar, fucoidan, and ulvan forms the basis of their diverse functional and biological roles, reinforcing the critical importance of structure–function relationships in marine hydrocolloids [212].

5. Modification strategies to enhance functionality

Modification strategies for marine hydrocolloids can be broadly classified into four categories: physical, chemical, enzymatic, and conjugation approaches. Physical modifications (e.g., ultrasonication, HPP, microwave, and thermal treatments) primarily alter molecular weight, crystallinity, or chain interactions without introducing new chemical groups. Chemical modifications, on the other hand, deliberately add functional substituents such as sulfate, phosphate, or acetyl groups to tune solubility, viscosity, or bioactivity. Enzymatic methods achieve selective depolymerisation or hydrolysis under mild conditions, generating oligosaccharides with enhanced functional properties. Conjugation technologies, including deep eutectic solvents, subcritical water extraction, or hybrid enzyme–microwave systems, aim to improve efficiency and sustainability while preserving structural integrity. Together, these strategies provide a comprehensive toolbox to tailor hydrocolloid functionality for specific food and biomedical applications.

5.1. Physical modifications

Marine hydrocolloids, such as alginates, carrageenan, agar, and ulvans, are valued for their functional properties, including gelling, thickening, and film-forming abilities. However, their native forms often exhibit limitations like high molecular weight, limited solubility, or weak mechanical performance under diverse environmental conditions (Fig. 6). Physical modification techniques particularly those involving thermal and non-thermal methods can improve the physicochemical and functional performance of these polysaccharides without introducing new chemical groups, making them attractive for clean-label formulations and industrial applications.

5.1.1. Ultrasonication and high-pressure processing (HPP)

Ultrasonication, which uses sound waves typically above 20 kHz, has emerged as an eco-friendly and efficient method to modify the structural features of hydrocolloids. In cereal starches, this method was shown to disrupt the amorphous regions of starch granules, leading to surface cracking and increased water solubility and swelling capacity [213–215]. For marine polysaccharides, ultrasonication can enhance cold-water solubility, reduce viscosity, and generate microstructural changes favorable for film formation or encapsulation. High-pressure processing (HPP), operating within a range of 100–1000 MPa, causes starch gelatinization even at room temperature [216,217]. In barley starch, HPP altered molecular packing, enabling lower gelatinization temperatures and novel pasting behavior [218]. For marine polysaccharides, HPP can modify gel strength, improve emulsification properties, and reduce microbial loads without compromising nutritional quality, making it an attractive method for high-value functional ingredients [219,220].

5.1.2. Microwave treatment effects

Microwave energy rapidly heats polar regions of biomolecules, producing structural rearrangements. When applied to starch, microwave treatment increases solubility, reduces gelatinization temperature, and modifies crystalline structure [221]. Marine hydrocolloids could

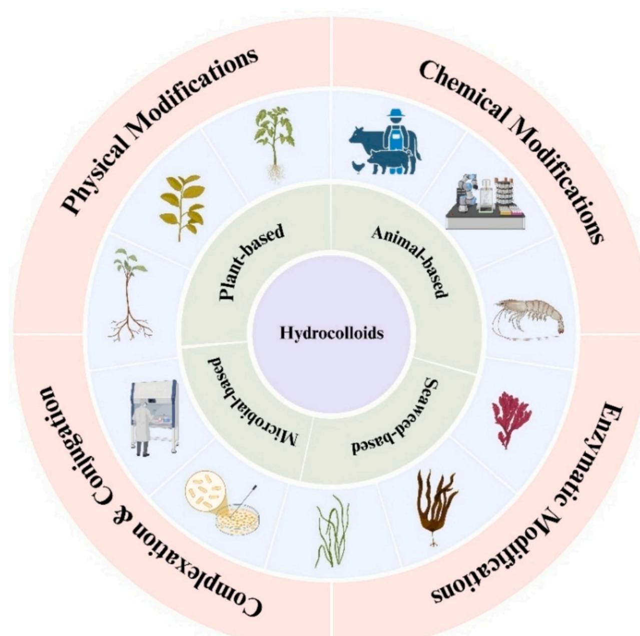

Fig. 6. Strategies employed on hydrocolloids in modifying their structure and functionalities.

similarly benefit from microwave-induced disruption of polysaccharide chains, which may enhance dissolution rates and gel elasticity. Although limited data exists specifically for seaweed polysaccharides, microwave-assisted extraction and modification of sulfated galactans and ulvans have shown promise in improving yield and functionality [222].

5.1.3. Radiation-induced modifications

Gamma irradiation and other radiation methods induce oxidative scission in polymer chains, resulting in decreased molecular weight and viscosity. In barley starch, gamma irradiation (10 Mrad) was found to degrade amylose and amylopectin, leading to the loss of viscosity and a shift in gelatinization behavior [223]. While preserving external morphology, internal breakdown within granules was evident. Similar outcomes have been reported in irradiated alginates and carrageenans, where depolymerization enhances their use in drug delivery systems and bioactive formulations due to better bioavailability and altered gelation behavior [224].

5.1.4. Thermal treatments and their impact

Thermal modifications include pre-gelatinization, annealing, and heat-moisture treatment, which influence polysaccharide structure by altering crystalline regions without introducing chemical agents. Pre-gelatinization of starch, performed via drum drying, spray drying, or extrusion, improves solubility and allows cold-water dispersibility [225]. These methods, when adapted to marine polysaccharides, can similarly enhance processing convenience and instant gelling behavior. Annealing involves treating starch granules with water at temperatures below their gelatinization point to increase crystallinity and thermal stability [226]. In barley starch, annealing raised gelatinization temperatures and narrowed temperature ranges without destroying granule structure [227]. When extended to marine hydrocolloids, this method could stabilize gel structures under acidic or high-heat conditions often encountered in food processing or gastrointestinal environments [228]. Heat-moisture treatment subjects' starch to high temperatures (80–140 °C) at low moisture content (<35 %), resulting in reduced swelling power, amylose leaching, and retrogradation [229,230]. These benefits can be translatable to sulfated polysaccharides like fucoidans or ulvans, enabling their use in resistant hydrogel matrices or in formulations requiring slow dissolution rates.

5.2. Chemical derivatization

Chemical derivatization is a widely employed strategy to enhance the physicochemical and functional properties of marine hydrocolloids, including alginates, carrageenans, and fucoidans. These polysaccharides possess a high density of reactive groups such as hydroxyl, carboxyl, and sulfate, making them suitable substrates for targeted chemical modifications [82]. Techniques such as sulfation, acetylation, carboxymethylation, and crosslinking have been successfully adapted from starch systems to marine polysaccharides to improve solubility, thermal stability, bioactivity, and functional versatility [231]. Sulfation remains one of the most important modification techniques, especially for marine polysaccharides that are either naturally sulfated (e.g., fucoidan, carrageenan) or structurally similar to sulfated plant polysaccharides [73]. The chlorosulfonic acid pyridine method is one of the most commonly used routes, wherein sulfate groups are introduced by replacing hydroxyl groups on the polysaccharide backbone, typically at the C-2, C-4, or C-6 positions. The degree of substitution is a critical determinant of bioactivity, with higher DS generally correlating with enhanced antioxidant, anticoagulant, and immunomodulatory properties [226]. Such modification significantly alters charge density and conformation of the polymer and hence improves solubility and interaction with biologically relevant targets. Acetylation modifies hydrophilicity and crystallinity of polysaccharides through acetyl substitution of hydroxyl groups. In starch systems, acetylation has been shown to inhibit retrogradation, reduce gelatinization temperatures, and enhance solubility [219]. Such functionalities can be transferred to marine polysaccharides like agar or ulvan, where acetylation can enhance emulsification, rheology, and interaction with hydrophobic molecules [232]. Acetylated marine polysaccharides can also exhibit improved film-forming ability and flexibility in food coatings or drug delivery matrices. Carboxymethylation introduces carboxymethyl groups that improve solubility and metal-chelating ability. The reaction is most typically carried out in an alkaline environment with monochloroacetic acid and has been widely reviewed in starch and cellulose systems [233]. Marine hydrocolloids carboxymethylated exhibit enhanced aqueous dispersibility and metal-binding activity and are hence suitable for application in nutraceuticals and wastewater treatment. Crosslinking enhances the polysaccharide's structural network and stabilizes them under harsh processing conditions. Crosslinkers like phosphoryl chloride and sodium trimetaphosphate (STMP) result in covalent bridges between polymer chains and hence enhance resistance to shear, pH, and heat degradation [225]. In marine polysaccharides like alginate and carrageenan, crosslinking has been shown to improve gel strength and elasticity, making them extremely valuable for application in wound dressings, encapsulation systems, and controlled release formulations [234]. Latest advances in CRISPR-based metabolic engineering and synthetic biology now allow targeted modification of biosynthetic pathways in marine microorganisms to produce tailor-made hydrocolloids with controlled sulfation and molecular weights [235]. Similarly, nanostructuring approaches such as nanoparticle conjugation and nanoencapsulation are being applied to enhance stability, bioavailability, and delivery of sulfated seaweed polysaccharides in food and nutraceutical systems [236]. Chemical derivatization provides versatile tools for targeted modification of marine polysaccharides. Hatched from starch chemistry, these approaches can be crafted to meet needs in industrial or biomedical applications by optimizing structure–function relationships.

5.3. Enzymatic modifications

Enzymatic modification is a selective and environmentally friendly method of structural and functional modification of marine hydrocolloids. Enzymatic specificity permits control over depolymerization and structure tailoring of polysaccharides like alginate, agar, carrageenan, and fucoidan in the absence of chemicals [130]. This is particularly useful for the protection of sensitive bioactive functions like sulfate esters, which are essential for biological activity. Enzymatic depolymerization utilizes polysaccharide-specific enzymes like alginate lyases, agarases, and fucoidanases. In starch systems, α-amylase and pullulanase are typically used to produce short-chain oligosaccharides and resistant starch fractions [237]. Comparable methodologies applied to marine polysaccharides produce low-molecular-weight derivatives that are more soluble and bioactive. For example, enzymatically depolymerized fucoidan fragments show increased antioxidant and anticancer activity due to increased bioavailability and interaction with cellular receptors. Enzyme-assisted extraction (EAE) is another promising strategy, particularly for sulfated marine polysaccharides embedded in algal cell walls [131]. Addition of cellulases, hemicellulases, or proteases during extraction allows the yield and purity of target polysaccharides to be significantly improved [238]. This method preserves bioactive functional groups while limiting the need for high-temperature or strong acid/base treatment, making it ideal for functional food or pharmaceutical use. Apart from hydrolysis, enzymes can be used to specifically modify functional groups. For example, specific esterases or sulfatases may be used to remove acetyl or sulfate groups, thereby modifying the physicochemical profile and bioactivity of the resultant polysaccharide [239]. Although such targeted enzymatic functionalization has been well developed in terrestrial systems, its application to marine polysaccharides is an emerging area of research. One of the major uses of enzymatic modification is the production of bioactive oligosaccharides. Enzymatic hydrolysis of starch systems produces prebiotic and antidiabetic oligosaccharides [240]. Enzymatic hydrolysis of marine polysaccharides has also produced low-molecular-weight fuco-oligosaccharides and laminarin fragments with established immunomodulatory and anti-inflammatory activities [241]. Enzymatic modification overall is a clean and targeted method of managing marine hydrocolloid functionality. It allows the production of bioactive ingredients of marine origin for use in pharmaceuticals, nutraceuticals, and functional foods.

5.4. Complexation and conjugation

Complexation and conjugation technologies has gained popularity in enhancing the functionality, stability, and bioavailability of marine hydrocolloids for food and health product uses. These technologies entail the formation of complexes or covalent bonds between marine polysaccharides and other molecules such as proteins, minerals, lipids, or bioactive compounds [182,222]. Conjugates of polysaccharides and proteins are widely used to enhance the emulsifying, foaming, and gelling capacity of marine hydrocolloids. The conjugation of alginate or carrageenan with whey or soy proteins can lead to stable gels and emulsions with enhanced texture and phase separation [242]. Mineral complexation, e.g., alginate-calcium or carrageenan-potassium gelation, enhances the strength of the gel and heat stability [243]. Which is advantageous in plant-based meat substitutes and 3D food printing. The complexes also allow for the controlled release of nutrients and bioactive, advantageous in functional food development. Lipid conjugation and bioactive compound complexation further enhance the functional potential of marine hydrocolloids. Lipid-modified agar or alginate can be utilized to develop edible films with improved moisture and oxygen barrier properties, which can be utilized for food packaging [244]. Encapsulation of vitamins, antioxidants, or probiotics in hydrocolloid matrices protects sensitive compounds from degradation and allows for controlled release in the gastrointestinal tract [245]. These complexation and conjugation technologies not only enhance the functional property of marine hydrocolloids but also provide new opportunities for their utilization in functional foods, nutraceuticals, and food packaging materials, which allows food science and technology to develop in new ways.

5.5. Extraction methods and structural integrity

Extraction strategies play a decisive role in determining both the yield and the bioactivity of marine polysaccharides by preserving or altering their structural integrity [14]. Conventional methods such as hot water and alkali treatments are effective but often lead to depolymerisation, loss of sulfate groups, or reduced biological activity [246]. In contrast, green extraction technologies (enzyme-assisted extraction, microwave-assisted extraction, ultrasound, subcritical water, and deep eutectic solvents) have been demonstrated to maintain functional groups and molecular weight distribution more effectively, thereby enhancing antioxidant, prebiotic, and immunomodulatory activities [247]. For instance, enzyme-assisted extraction preserves sulfate esters in fucoidans, leading to improved bioactivity, while microwave and ultrasound methods enhance solubility and antioxidant potential without significant degradation [14]. Hence, the choice of extraction method is not only a technical decision but also a determinant of biological efficacy, directly linking processing to the functional potential of seaweed polysaccharides.

6. Applications in functional food development

6.1. Marine hydrocolloids as delivery systems for bioactive compounds

Marine hydrocolloids like alginate, carrageenan, and agar are seaweed- and aquatic organism-derived polysaccharides. These biopolymers are of interest because of their potential in formulating novel delivery systems for bioactive compounds due to the safety, biological compatibility, and intriguing physical properties of these biopolymers [248]. Marine like hydrocolloids, when used to formulate nanocarriers, are able to protect sensitive bioactive compounds from degradation, improve the efficiency of encapsulation, and optimize the absorption and distribution of these compounds in the body. The major advantage of using marine hydrocolloids in delivery systems is the feasibility of gel and hydrogel formation through cross-linking [249]. This research depicts a three-dimensional network structure with high inner surface area and pores, which renders such materials extremely efficient in sequestration and slow release of active molecules. For example, alginate and carrageenan can be cross-linked with calcium or other metal ions to form hydrogels that can withstand the acidic gastric environment while, simultaneously, release their contents in the more alkaline intestinal pH environment, thus delivering nutrients or drugs in controlled and targeted fashion [250]. Additionally, marine hydrocolloids also prove useful when blended with other natural polymers to create hybrid nanoparticles or nanocomplexes. Such blends can improve the stability of the delivery system, provide good resistance to digestive enzymes, and have better control over the timing and site of the release of bioactive molecules [251]. An example is blending kappa-carrageenan with bovine serum albumin to create edible nanotubes that can encapsulate curcumin, a molecule with established anticancer activity. Studies have shown that such nanotubes are highly effective in encapsulation and release their contents effectively to target cells. Chitosan, a polysaccharide of marine crustacean shells' chitin, is a well-known marine hydrocolloid for drug delivery [252]. Because of the cationic nature of chitosan, it can bind with negatively charged molecules, and therefore it is selectively valuable for the preparation of nanoparticles targeted to a specific tissue, for example, to tumor tissues. Chitosan nanoparticles can be further targeted by functionalization with target molecules such as folic acid to increase their drug delivery capability directly to cancer cells, as found from therapy studies in colorectal cancer [253]. Particle size and composition are of vital importance in the bioactivity of hydrocolloid-based nanoparticles. Small particle sizes are more endocytosed by the cell and can release the content in a more controlled manner [254]. For example, almond gum-coated iron-oxide nanoparticles have been designed for delivery of the anticancer drug doxorubicin, with efficient encapsulation and controlled release under acidic pH in tumor tissue. In the same way, nano-micelles from konjac glucomannan, another aquatic organism polysaccharide, have been employed for delivery of curcumin into cancer cells, where acidic environment releases the curcumin [255]. Marine hydrocolloids as a whole are an easy and efficient carrier for encapsulation, protection, and targeted delivery of bioactive molecules. Its hydrogel and nanoparticle formation capability, sensitivity to environmental stimuli such as pH, and compatibility to blend with other biopolymers provide them tremendous value in food and pharmaceutical industries [256]. New possibilities still keep emerging from recent research, particularly in controlled and site-specific delivery.

6.2. Hydrocolloids in dairy and dairy based products

Dairy foods are a crucial component of the global human diet, not only prized for their sensory attributes but also prized for their nutritional attributes (Fig. 7). They are rich sources of antioxidants, vitamins, oligosaccharides, organic acids, bioactive peptides, calcium in a highly bioavailable form, probiotic bacteria, and conjugated linoleic acid [257]. Owing to this multiplicity of bioactive compounds, daily consumption of dairy foods is linked to a number of health benefits, including lowered risk of cardiovascular disease, dental caries, metabolic syndromes, and some types of cancer. Nevertheless, the maintenance of the quality and storage stability of these foods is still a daunting challenge throughout their entire processing and supply chain [181]. The most efficient method of overcoming such issues is the application of hydrocolloids. Hydrocolloids, the gel-forming or thickened solution-

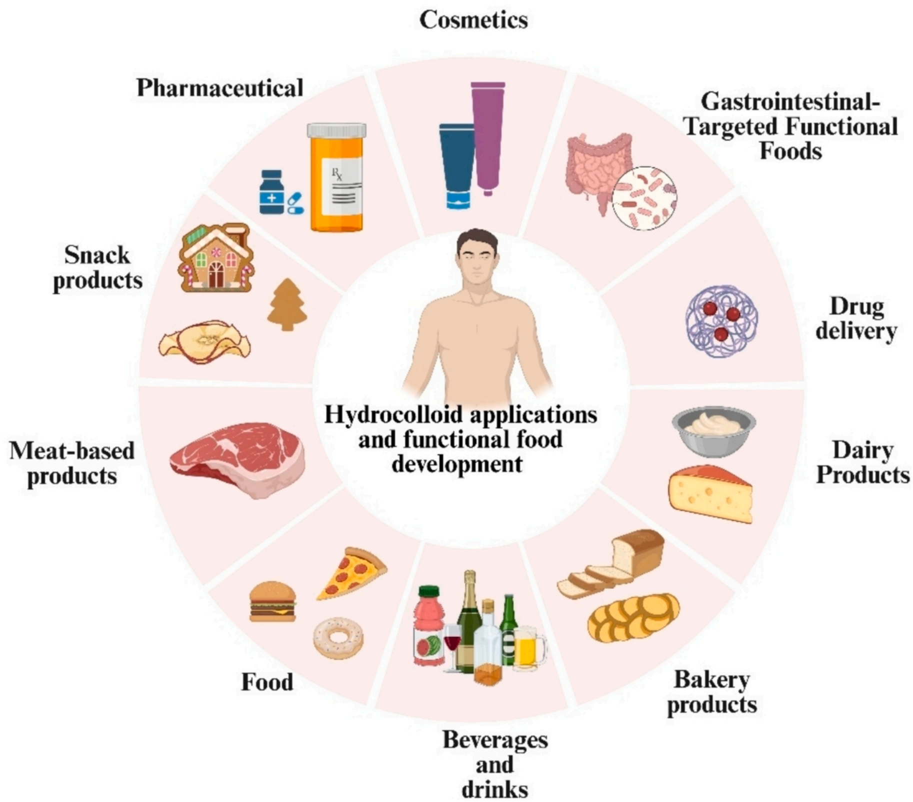

Fig. 7. Broad spectrum of hydrocolloids in pharmaceuticals, cosmetics, drug delivery system and food applications.

forming polysaccharides or proteins when dispersed in water, are of utmost importance in enhancing the functional and structural properties of dairy foods. They are mostly applied to substitute fat, improve texture, avoid phase separation, and improve shelf life. These compounds interact with the casein micelles and other milk proteins and create stable matrices that maintain the desired consistency and decrease the tendency towards wheying-off or protein flocculation [156]. A case in point is their employment in acidified milk products, which are manufactured by mixing milk with acidified ingredients like fruit juices. The products are favored for their freshness of taste, but the low pH (usually less than 5) destabilizes milk proteins, especially casein micelles and whey proteins, causing phase separation and sedimentation [159]. Hydrocolloids like carrageenan, pectin, and carboxymethyl cellulose (CMC) stabilize the proteins by creating protective networks. Out of these, high methoxyl pectin (HMP) is more stable at pH 3.5 ± 1.0 and is therefore to be used instead of low methoxyl pectin (LMP) under acidic conditions [257]. Carrageenan, which exists in λ, κ, and ι forms, shows different interactions depending on its conformation. For example, coil λ-carrageenan can interact with milk proteins at varying temperatures, while κ- and ι-carrageenan need helix formation initiated at low temperatures to interact with proteins to form firmer gel structures [156]. Cheese is another big dairy product where hydrocolloids have widespread uses, especially in the creation of low-fat cheese. Although low-fat cheese is in great demand because of health issues, its production leads to compromised texture, less moisture content, and sensorial attractiveness. Hydrocolloids act as fat replacers by altering the microstructure of the cheese and enhancing water retention. Polysaccharides like carrageenan, konjac glucomannan, sodium alginate, and β-glucan contribute to creaminess and softness by breaking protein crosslinks and retaining water. For instance, sodium alginate is a filler within the protein matrix, resulting in higher moisture content and sensorial properties comparable to full-fat Cheddar cheese [176]. Such interactions can easily overcome textural and flavor deficiencies typically found in reduced-fat cheeses. Likewise, yoghurt a fermented milk product famous for its nutritional value and digestibility suffers from low-fat versions in terms of compromised viscosity and unwanted syneresis. Hydrocolloids are extensively added to yoghurt preparations to counteract such issues. They ensure a more robust protein network, preserve ion balance, and enhance final product viscosity and mouthfeel [257,258]. Anionic hydrocolloids such as carrageenan, CMC, and pectin bind to positively charged casein micelles, affecting gel structure and casein precipitation [259]. Neutral gums such as guar and locust bean gum, on the other hand, have an impact mainly on viscosity. New-age formulations tend to use new ingredients such as partially hydrolyzed guar gum (PHGG) and orange peel fiber (OPF). PHGG serves as a filler, whereas OPF serves as a bridging agent within the yoghurt matrix. Mary et al. [260] stated that the incorporation of 0.25 % PHGG and 0.1 % OPF into low-fat yoghurt considerably enhanced gel elasticity, hardness, and compactness of structure, and lowered gelation time and syneresis. In ice cream, a frozen emulsion of complex structure made up of fat globules, air bubbles, ice crystals, and a highly viscous aqueous phase, hydrocolloids are crucial to the accomplishment of a desired texture as well as physical stability. Hydrocolloids enhance overrun, slow the rate of melting, control viscosity, and maximize the sensory experience [261]. Hydrocolloids such as cellulose derivatives, inulin, guar gum, basil seed gum, and modified starches are common fat replacers in low-fat ice cream. For example, resistant starch and maltodextrin enhance structural strength and slow down melting; however, too much resistant starch can destroy sensory acceptability, while maltodextrin preserves flavor and texture even at high concentrations. Synergism is also present in studies involving combined seed gums such as guar gum and basil seed gum, which enhance overall viscosity and consistency [261]. Other additives such as quince seed powder reduce the formation of ice crystals by absorbing free water, which leads to lower hardness with improved mouthfeel [262]. Reducing fat from 10 % to 5 % typically increases melt rate and overrun; however, increasing the concentration of hydrocolloids (up to 0.55 %) can reverse the trend and re-establish desirable textural behavior. In general, hydrocolloids are an essential factor in dairy product development and enhancement, particularly fat reduction and functional enhancement. By engaging in intricate molecular interactions with milk proteins, hydrocolloids not only improve structural stability and sensory attributes but also respond to the issues regarding quality and stability of conventional dairy processing [152].

6.3. Hydrocolloids in bakery based products

Bakery products such as bread, pasta, noodles, muffins, and cookies are gaining popularity due to their exceptional nutritional benefits. In addition to dietary fiber and essential micronutrients such as vitamins and minerals, these products also offer macronutrients, specifically proteins and carbohydrates [263]. The processes of handling and storing materials frequently result in challenges such as oxidation, aging, mildew, and unpleasant odors. Natural hydrocolloids find extensive application in bakery products, enhancing their color, flavor, texture, and nutritional content to address these challenges. The exceptional physical and chemical properties of hydrocolloids, including their capacity to retain water, thicken, and gel, significantly improve the quality of the final product [264]. Attributes such as increased volume, uniform crumb structure, extended shelf life, resistance to staling, and tenderness is indicative of superior bakery products. The characteristics of texture, volume, and appearance in bakery products are greatly affected by the crumb structure [160]. Hydrocolloids have shown the ability to enhance the volume and porosity of bread, cakes, and muffins, resulting in a softer and more enjoyable texture. The incorporation of various gums significantly improves the water absorption capacity of bakery compositions. Moreover, hydrocolloids enhance the water-holding capacity (WHC) of starch-based systems, leading to improved moisture retention and overall product quality [265]. The incorporation of hydrocolloids has a notable impact on the rheological characteristics of batter, leading to a decrease in gas diffusion during the baking process and enhancing the volume of the final products. Hydrocolloids play a crucial role in bakery products by acting as substitutes for gluten [264]. Their incorporation alters the viscoelastic characteristics of gluten, rendering bakery items appropriate for those with celiac disease. The Codex Alimentarius Commission defines gluten-free (GF) products as "food products containing less than 20 mg/kg of gluten" [266]. Horstmann et al. [267] created gluten-free bread utilizing potato starch along with six distinct hydrocolloids: locust bean gum, pectin, sodium alginate, guar gum, hydroxypropyl methylcellulose, and xanthan gum. The study demonstrated that negatively charged hydrocolloids, including pectin and sodium alginate, notably enhanced the volume of bread. This phenomenon was linked to the repulsive forces arising from the negative charges of the hydrocolloids interacting with the negatively charged phosphate groups present in potato starch. The interactions resulted in a delay in the pasting and gelatinization of starch granules, which led to a reduction in starch viscosity and facilitated greater gas cell expansion, ultimately enhancing the volume of the bread. In contrast, neutral high-molecular-weight hydrocolloids like locust bean gum and guar gum did not display comparable repulsive forces, leading to a distinct impact on the structure of bread. Di Renzo et al. [268] examined the formulation of fermented gluten-free quinoa bread by utilizing four hydrocolloids: xanthan gum, sodium alginate, k-carrageenan, and hydroxypropyl methylcellulose (HPMC), each added at a concentration of 3 %. Among these, HPMC demonstrated remarkable gas retention (93 %) during dough fermentation, resulting in the highest dough development height. Furthermore, breads formulated with 3 % HPMC demonstrated the lowest baking loss, the highest loaf volume, and an open crumb structure, underscoring its efficacy in enhancing the quality of gluten-free bread. Saeidy et al. [269] developed gluten-free muffins incorporating xanthan, guar, tara gum, locust bean gum (LBG), and carrageenan. The formulation that included xanthan resulted in the highest batter viscosity, with guar, tara, LBG, and carrageenan following in that order. Muffins made with guar gum exhibited the greatest hardness, succeeded by those incorporating xanthan, carrageenan, tara, and LBG [152].

6.4. Beverages and drink systems

Hydrocolloids are fundamental to the formulation of beverages and drink systems, where they stabilize functional smoothies and juices by preventing sedimentation, improving mouthfeel, and enhancing the suspension of insoluble components, while in protein drinks and sports nutrition beverages [270]. Hydrocolloids such as carrageenan and xanthan gum ensure uniform dispersion of proteins, prevent phase separation, and contribute to a creamy, appealing texture, and in coffee and tea applications [271]. Hydrocolloids can be used to stabilize foams, control viscosity, and improve the sensory experience of ready-to-drink products, whereas in alcoholic beverage innovations [272]. It also facilitates the stabilization of emulsified flavors, improve clarity, and enable the development of novel textures in cocktails and low-alcohol drinks, and their multifunctional properties also support the fortification of beverages with vitamins, minerals, and bioactive compounds by protecting these ingredients from degradation and ensuring their even distribution, as documented in recent beverage industry research [273]. And with additional studies confirming the role of hydrocolloids in extending shelf life and maintaining product quality during storage and distribution [274]. New product development efforts leveraging hydrocolloid technology to create clean-label, plant-based, and functional beverages that cater to evolving consumer preferences, all while ongoing advancements in hydrocolloid science continue to drive innovation in beverage formulation, enabling the creation of stable, nutritious, and sensorially appealing drinks for a wide range of markets [271].

6.5. Hydrocolloids application in meat-based products

Over the past half-century, meat products have continued to be in high demand all over the world because of their good taste and high nutritional value, such as proteins, vitamins, and essential nutrients that are healthy to human bodies [275]. However, normal meats contain saturated fats and cholesterol, which lead to cardiovascular diseases, obesity, high blood pressure, and certain types of cancer. That has prompted the need to develop healthier products like low-fat or fat-free meat products. Second, although meat contains high protein content, cooking procedures like collagen contraction and myofibrillar protein coagulation tend to render the texture hard, which is not suitable in the case of dysphagia patients [159]. To address such issues, hydrocolloids are increasingly applied in meat products to reduce fat and salt levels, improve freeze-thaw stability, and textural modification. Certain hydrocolloids also have health benefits: psyllium helps in the relief of constipation; inulin is a prebiotic that supports gut health and can reduce the risk of colon cancer; and beta-glucan controls blood sugar and resists hyperglycemia [265]. Functionally, hydrocolloids form viscoelastic networks through crosslinking water-retentive polymer chains, enhancing the texture of meat products [181]. Heating causes myofibrillar proteins to gel and denature. Polysaccharide hydrocolloid additions strengthen protein–polysaccharide gel networks that affect texture and protein denaturation. Hydrocolloids also affect sensory and mechanical properties such as mouthfeel, lubrication, microstructure, and mastication dynamics. The selection of a proper hydrocolloid is complex and depends on the product's formulation, processing, and storage [276]. They affect texture, composition, yield, pH, color, emulsion stability, and sensory quality, and even a slight variation in concentration dramatically affects the product characteristics. There are various researchers who have produced meat items like patties, sausages, salami, and meatballs with various hydrocolloids. Beef patties were developed by Pematilleke et al. [277] with 14 hydrocolloids (e.g., xanthan gum, agar-agar, CMC, carrageenan, tapioca starch) at 1 % level. Except for modified corn starch, all raised cooking yield. Hardness and cohesiveness were decreased when hydrocolloids were incorporated, and adhesiveness was increased with gums and decreased with starches. Pematilleke et al., [278] formulated beef patties with CMC and tapioca starch (0 %–1 % w/w) that were within the IDDSI Level 6 requirements. Texture was analyzed through manual and instrumental IDDSI analysis. Hydrocolloids such as konjac glucomannan, xanthan gum, carrageenan, inulin, basil seed gum, and CMC are added in sausage making to improve texture and decrease fat content [152]. For example, Jommark et al. [279] noted that 50 % phosphate replacement with konjac glucomannan improved sausage stability. Ferjančič et al. [280] noted improved texture and appearance with 3 % inulin in chicken sausages. Abdulrahem et al. [281] noted improved water-holding capacity and reduced fat content with up to 1.5 % basil seed gum. These findings point to the potential of hydrocolloids to enhance the nutritional and functional quality of meat products.

6.6. Confectionery and snack products

Within confectionery and snack products, hydrocolloids are essential for the production of gummy and jelly confections, where they provide the desired gel strength, elasticity, and clarity, while in chocolate applications, hydrocolloids such as pectin and carrageenan can control viscosity, improve mouthfeel, and reduce fat content without compromising texture or flavor, and in extruded snack products [282]. Hydrocolloids act as expansion agents and texture modifiers, contributing to crispness, uniformity, and the incorporation of functional ingredients like fiber and protein, whereas in nutritional bars and bites [283]. It also serve as binders and moisture regulators, ensuring product cohesion, preventing hardening, and extending shelf life, as demonstrated in recent confectionery and snack technology research [284], with additional studies highlighting the role of hydrocolloids in reducing sugar and fat content while maintaining desirable sensory attributes [285], and ongoing innovation in hydrocolloid applications is enabling the development of clean-label, functional, and indulgent snack products that cater to health-conscious consumers, all while advancements in hydrocolloid science continue to expand the possibilities for creative and nutritious confectionery and snack formulations [266].

6.7. Gastrointestinal-targeted functional foods

Hydrocolloids are at the forefront of gastrointestinal-targeted functional foods, where they are used in prebiotic formulations to selectively stimulate beneficial gut microbiota, enhance short-chain fatty acid production, and support overall digestive health [286]. The synbiotic systems with probiotics rely on hydrocolloid matrices to protect live cultures during processing and passage through the stomach, ensuring their effective delivery to the intestine, and digestive system [287]. Health products often incorporate soluble fibers and hydrocolloids such as inulin, pectin, and resistant starch to modulate gut transit, improve stool consistency, and support regularity [288]. While satiety-enhancing food design leverages the viscosity and gel-forming properties of hydrocolloids to slow gastric emptying, promote feelings of fullness, and aid in weight management, as evidenced by recent research in nutrition and gut health [182]. Further studies confirming the role of hydrocolloids in the controlled release of bioactive compounds and the targeted delivery of nutrients to specific regions of the gastrointestinal tract [289]. The ongoing exploration of novel hydrocolloid structures and combinations is advancing the development of next-generation functional foods that address digestive wellness and metabolic health, ensuring that consumers benefit from scientifically validated, effective, and enjoyable dietary solutions.

7. Technological challenges and future perspectives

7.1. Processing stability of bioactive properties of marine hydrocolloids

Marine hydrocolloids such as alginate, carrageenan, and agar are increasingly employed as encapsulating agents to stabilize and deliver food bioactive, and their functionality is strongly process condition-dependent [12]. Thermal processing, such as pasteurization or sterilization, might affect the gelation and molecular architecture of marine hydrocolloids, potentially to induce destruction of their three-dimensional networks (3DNs) and impaired encapsulation efficiency for sensitive actives such as polyphenols or omega-3 fatty acids: for example, alginate fish oil-loaded beads can be damaged by leakage or oxidation of oils if heated beyond a certain temperature, while carrageenan gels may become weakened and syneresis-resistant after multiple thermal cycles [290]. High-pressure processing (HPP) is typically more applicable to marine hydrocolloid systems, as it might inactivate spoilage microorganisms and enzymes without thermal degradation of hydrocolloid matrix or encapsulated bioactive [291]. HPP-treated alginate microcapsules were reported to exhibit better retention of vitamin C and probiotics in functional beverages compared to heat-treated controls [292]. Mechanical treatments such as extrusion and homogenization might modify the particle size and surface properties of marine hydrocolloid-based delivery systems [293]. For example, extrusion of alginate-starch mixture was reported to enhance dispersibility and controlled release of encapsulated carotenoids in bakery application, while homogenization might enhance stability of carrageenan-stabilized emulsions in dairy alternatives. Storage stability is a further concern, as marine hydrocolloid matrices are sensitive to moisture, pH, and ionic strength [294,295]. For example, alginate-encapsulated polyphenols in fruit juices may undergo premature release or degradation if the beverage pH drops below 3.5 or if calcium ions are depleted, and agar-based gels can lose water and shrink during long-term storage, affecting both texture and bioactive retention [296]. Advances in encapsulation, such as multilayered alginate-chitosan microcapsules or carrageenan-pectin hybrid gels, have improved the protection of labile bioactive against environmental stressors, while packaging innovations like oxygen-barrier films help prevent oxidation and maintain shelf life [127,297]. Overall, the processing stability of marine hydrocolloid-based delivery systems depends on careful selection of the hydrocolloid type, optimization of process parameters, and integration with appropriate packaging solutions.

7.2. Sensory challenges and formulation strategies

Sensory quality is a pivotal factor in consumer acceptance of foods containing marine hydrocolloid-based delivery systems, as these materials can influence taste, mouthfeel, and appearance. Many marine hydrocolloids are nearly tasteless at low concentrations, but at higher levels, they may impart a slight seaweed or mineral note, which can interact with the flavors of encapsulated bioactive; for example, alginate microbeads used to fortify yoghurt with fish oil can mask undesirable fishy notes, while also providing a novel "popping" texture that appeals to some consumers [258]. Carrageenan is widely used in chocolate milk and plant-based beverages to provide a creamy, stable texture and to suspend cocoa or plant proteins, but excessive use can lead to gelation or sliminess, which may be perceived as negative [298]. Taste masking is often achieved by encapsulating bitter or astringent polyphenols within alginate or agar gels, as seen in the stabilization of green tea catechins in beverage applications, where the hydrocolloid matrix prevents direct interaction with taste receptors [296]. Texture optimization is another key strategy: marine hydrocolloids can be combined with other gums (like locust bean gum or guar) to fine-tune viscosity, gel strength, and mouthfeel, as in the case of carrageenan-locust bean gum blends used for dairy-free puddings and desserts [299]. Clean label trends favor marine hydrocolloids, as they are naturally derived, vegan, and often recognized by consumers, making them attractive for plant-based and "free-from" formulations [12]. Consumer acceptance is further enhanced by the ability of marine hydrocolloids to stabilize color and prevent phase separation in fruit juices and smoothies, resulting in visually appealing and stable products [296]. In summary, marine hydrocolloids offer versatile sensory and formulation benefits, but their successful use requires balancing concentration, interactions with other ingredients, and consumer expectations.

7.3. Emerging processing technologies

Emerging technologies are expanding the potential of marine hydrocolloids in bioactive delivery [300]. Cold plasma treatment, for example, can modify the surface of alginate or carrageenan particles, enhance their encapsulation efficiency and impart antimicrobial properties without affecting their gelling ability; plasma-treated alginate beads have shown improved probiotic viability in refrigerated dairy products [301]. Ultrasound-assisted processing is used to break down the molecular chains of agar or alginate, producing lower-viscosity solutions that are easier to disperse and more effective at encapsulating hydrophobic actives like curcumin or carotenoids [302]. Pulsed electric field (PEF) treatments can be applied to seaweed slurries to enhance the extraction of carrageenan and agar, increasing yield and purity while preserving the functional properties of the hydrocolloid; PEF has also been used to modify the gelation kinetics of alginate, enabling rapid encapsulation of heat-sensitive bioactive [303]. 3D printing with marine hydrocolloids is a cutting-edge application, allowing the creation of customized food structures with precise spatial distribution of nutrients and controlled release profiles. For instance, 3D-printed snacks using alginate or agar gels can incorporate multiple layers of vitamins, probiotics, or antioxidants, tailored to individual dietary needs [304]. These technologies not only improve the functional and sensory attributes of marine hydrocolloid-based delivery systems but also support the development of minimally processed, clean label, and personalized nutrition products.

7.4. Regulatory status and safety considerations

Marine hydrocolloids such as alginate, carrageenan, and agar are generally recognized as safe (GRAS) by major regulatory agencies, but their use is subject to specific purity, labeling, and usage limits depending on the application and region [305]. In the European Union, EFSA evaluates the safety of marine hydrocolloids and sets maximum allowable levels for different food categories, with particular scrutiny on degraded carrageenan (poligeenan) due to potential gastrointestinal concerns [305,306]. In the US, the FDA maintains GRAS status for food-grade alginate, carrageenan, and agar, but requires detailed toxicological data for novel uses or modified forms [307]. The Codex Alimentarius provides international guidelines for purity, labeling, and maximum usage levels, supporting global trade and harmonization. Safety assessment approaches include in vitro and in vivo studies, with particular attention to gastrointestinal tolerance, allergenicity, and potential for bioaccumulation. For example, high-purity food-grade carrageenan has been shown to be safe at typical dietary levels, but regulatory agencies recommend caution with low-molecular-weight fractions [308]. Traceability and certification are increasingly important, especially for organic or sustainably sourced marine hydrocolloids, with new blockchain-based systems being piloted to track seaweed from harvest to finished product [309]. In summary, marine hydrocolloids remain a safe and versatile class of food ingredients, but ongoing monitoring and transparent labeling are essential for consumer trust and regulatory compliance.

7.5. Sustainability and sourcing challenges

Sustainable sourcing of marine hydrocolloids is a growing concern as demand for alginate, carrageenan, and agar increases globally [128]. Wild harvesting of seaweed can lead to habitat disruption, over-exploitation, and negative impacts on marine biodiversity if not managed responsibly. In response, seaweed aquaculture has expanded, particularly in Asia, providing a more controlled and sustainable supply of raw material while supporting coastal economies and reducing pressure on wild stocks [310]. Environmental impacts linked to production of marine hydrocolloids are carbon footprint of processing and transport, waste management issues with regard to seaweed residues. Life cycle assessment (LCA) continues to measure and minimize these impacts, and certification schemes like the Marine Stewardship Council (MSC) and organic certifications are becoming more prevalent to guarantee sustainable sourcing [311]. Quality consistency is a persistent problem, as gelling properties and purity of marine hydrocolloids can vary depending on seaweed type, procurement season, and extraction; for example, *Laminaria digitata* alginate can have different viscosity and gel strength compared to *Macrocystis pyrifera*, and therefore, stringent quality control is required [129,310]. Traceability systems, including blockchain, are being piloted to provide transparency all the way through the whole process from harvesting to end product, thus supporting regulatory enforcement and consumer confidence [123]. Overall, sustainable production and sourcing of marine hydrocolloids require coordinated efforts among producers, processors, regulators, and consumers.

7.6. Future research directions

Future research on marine hydrocolloid-based delivery systems will focus on demonstrating the efficacy and bioavailability of encapsulated bioactive using advanced in vitro digestion models, animal studies, and human clinical trials. Alginate-encapsulated probiotics have shown enhanced survival through the gastrointestinal tract and improved colonization in the gut, supporting their use in digestive health products [12]. Elucidating the structure-function relationships of marine hydrocolloids such as the effect of molecular weight, sulfation pattern, and gel network on release kinetics will enable the rational design of delivery systems for targeted and controlled release. Optimization of extraction and modification technologies, including enzymatic, ultrasound, and green chemistry approaches, will help improve yield, purity, and functional properties while reducing environmental impact [158]. Clinical validation of health benefits, such as anti-inflammatory, prebiotic, or cholesterol-lowering effects, will be essential for substantiating claims and informing regulatory approval; for example, multi-center trials on carrageenan-enriched foods are underway to assess their impact on gut health and immune function. Interdisciplinary collaboration between food scientists, marine biologists, nutritionists, and clinicians will drive innovation, with a focus on sustainable, personalized, and next-generation functional foods based on marine hydrocolloids.

8. Conclusion

Marine polysaccharides are a structurally heterogenous group of biomolecules with wide-ranging applications in food and health. There is a distinct division between sulfated and non-sulfated polysaccharides, which characterizes both their techno-functional and bioactive functions. Sulfated polysaccharides like carrageenan, fucoidan, ulvan, and porphyran have high charge density as a result of sulfate substitution, which facilitates their interaction with proteins, enzymes, and cellular receptors. This structural component supports their superior antioxidant, anticoagulant, immunomodulatory, and antiviral activities, qualifying them as potential foods of function and nutraceuticals. Non-sulfated polysaccharides like alginate and agar, on the other hand, are more appreciated for their rheological and gelling behaviors, which endow viscosity, stability, and textural modification in various food systems. However, they also offer prebiotic and dietary fiber–related health benefits, connecting their techno-functionality with nutritional benefits. In combination, the complementary properties of sulfated and non-sulfated polysaccharides reveal how structure-dominated characteristics directly influence bioactivity and functional uses, pointing to their multifunctional roles as ingredients in future-generation functional foods. However, despite rapid advances, several research weaknesses and challenges remain. Current extraction and purification methods are often energy-intensive, chemically demanding, and lead to variable yields or loss of bioactivity. The structure–function relationships of many underexplored polysaccharides are still poorly understood, particularly at the molecular level, limiting their targeted use in advanced applications. Furthermore, scalability, quality standardization, and regulatory harmonization remain critical barriers to commercial translation. The biological potential of seaweed polysaccharides is a direct consequence of their structural features and the extraction strategies employed, underscoring the importance of integrating structure–function insights into future applications. Looking forward, the development of sustainable and innovative technologies will be essential. Emerging green extraction methods such as enzyme-assisted processes, deep eutectic solvents, and subcritical water extraction need to be further optimized for yield, bioactivity preservation, and industrial feasibility. Advances in biotechnology, including metabolic engineering and synthetic biology, offer opportunities to tailor polysaccharide structures for enhanced functional and therapeutic performance. At the application level, nanotechnology and smart delivery systems can be harnessed to improve stability, bioavailability, and targeted release in food and nutraceutical products. By addressing these research weaknesses and investing in future-oriented technologies, seaweed polysaccharides can be more effectively positioned as next-generation functional ingredients, bridging technological performance with human health benefits.

CRediT authorship contribution statement

Rinish Mortin John: Writing – original draft, Software. **Aishwarya Lakshmi Thasvanth Raj:** Writing – original draft. **Yuvaraj Dinakarkumar:** Writing – review & editing, Conceptualization. **Arokiyaraj Selvaraj:** Writing – review & editing. **Muthezhilan Radhakrishnan:** Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] J. Yan, Z. Zhang, B. Lai, C. Wang, H. Wu, Recent advances in marine-derived protein/polysaccharide hydrogels: classification, fabrication, characterization, mechanism and food applications, Trends Food Sci. Technol. 151 (2024) 104637, https://doi.org/10.1016/J.TIFS.2024.104637.

[2] H.D. Goff, Q. Guo, Chapter 1: The Role of Hydrocolloids in the Development of Food Structure, Food Chemistry, Function and Analysis 2020-January (2020) 3–28. doi:https://doi.org/10.1039/9781788016155-00001.

[3] C. Xie, Z.J. Lee, S. Ye, C.J. Barrow, F.R. Dunshea, H.A.R. Suleria, A review on seaweeds and seaweed-derived polysaccharides: nutrition, chemistry, bioactivities, and applications, Food Rev. Intl. 40 (2024) 1312–1347, https://doi.org/10.1080/87559129.2023.2212055.

[4] A. Sharma, S. Dubey, K. Singh, R. Mittal, P. Quille, G. Rajauria, Innovative processing and industrial applications of seaweed, Phycology 5 (2025) 10, https://doi.org/10.3390/PHYCOLOGY5010010.

[5] A. Yemenicioğlu, S. Farris, M. Turkyilmaz, S. Gulec, A review of current and future food applications of natural hydrocolloids, Int. J. Food Sci. Technol., Wiley Online Library 55 (2020) 1389–1406. doi:https://doi.org/10.1111/IJFS.14363.

[6] L.P. Gomez, C. Alvarez, M. Zhao, U. Tiwari, J. Curtin, M. Garcia-Vaquero, B. K. Tiwari, Innovative processing strategies and technologies to obtain hydrocolloids from macroalgae for food applications, Carbohydr. Polym. 248 (2020) 116784, https://doi.org/10.1016/J.CARBPOL.2020.116784.

[7] S.M.A. Razavi, Introduction to emerging natural hydrocolloids, in: Emerging Natural Hydrocolloids: Rheology and Functions, 2019, pp. 1–52, https://doi.org/10.1002/9781119418511.CH1.

[8] Hydrocolloids Market Size, Share, Growth Drivers, and Forecast, (n.d.). https://www.marketsandmarkets.com/Market-Reports/hydrocolloid-market-1231.html (accessed July 23, 2025).

[9] Chemical Economics Handbooks (CEH) | S&P Global, (n.d.). https://www.spglobal.com/commodityinsights/en/ci/products/chemical-economics-handbooks.html (accessed July 23, 2025).

[10] M.M. Jayakody, M.P.G. Vanniarachchy, I. Wijesekara, Seaweed derived alginate, agar, and carrageenan based edible coatings and films for the food industry: a review, J. Food Meas. Charact., Springer 16 (2022) 1195–1227. doi:https://doi.org/10.1007/S11694-021-01277-Y.

[11] L.P. Gómez Barrio, E.M. Cabral, M. Zhao, C. Álvarez García, R. Senthamaraikannan, R.B. Padamati, U. Tiwari, J.F. Curtin, B.K. Tiwari, Comparison study of an optimized ultrasound-based method versus an optimized conventional method for agar extraction, and protein co-extraction, from *Gelidium sesquipedale*, Foods 11 (2022) 805, https://doi.org/10.3390/FOODS11060805.

[12] A. Ishaq, M. Nadeem, R. Ahmad, Z. Ahmed, N. Khalid, Recent advances in applications of marine hydrocolloids for improving bread quality, Food Hydrocoll. 148 (2024) 109424, https://doi.org/10.1016/J.FOODHYD.2023.109424.

[13] J. Li, W. Chen, D. Niu, R. Wang, F.Y. Xu, B.R. Chen, J.W. Lin, Z.S. Tang, X.A. Zeng, Efficient and green strategy based on pulsed electric field coupled with deep eutectic solvents for recovering flavonoids and preparing flavonoid aglycones from noni-processing wastes, J. Clean. Prod. 368 (2022) 133019, https://doi.org/10.1016/J.JCLEPRO.2022.133019.

[14] P. Otero, M. Carpena, P. Garcia-Oliveira, J. Echave, A. Soria-Lopez, P. Garcia-Perez, M. Fraga-Corral, H. Cao, S. Nie, J. Xiao, J. Simal-Gandara, M.A. Prieto, Seaweed polysaccharides: emerging extraction technologies, chemical modifications and bioactive properties, Crit. Rev. Food Sci. Nutr. 63 (2023) 1901–1929, https://doi.org/10.1080/10408398.2021.1969534.

[15] G. Cravotto, Reshaping chemical manufacturing towards green process intensification: recent findings and perspectives, Processes 13 (2025) 459, https://doi.org/10.3390/PR13020459.

[16] M.M. Jayakody, M.P.G. Vanniarachchy, W.L.I. Wijesekara, Development and characterization of a seaweed snack using *Ulva fasciata*, J. Food Sci. Technol. 58 (2021) 1617–1622, https://doi.org/10.1007/S13197-020-04880-X.

[17] M. Manzoor, J. Singh, J.D. Bandral, A. Gani, R. Shams, Food hydrocolloids: functional, nutraceutical and novel applications for delivery of bioactive compounds, Int. J. Biol. Macromol. 165 (2020) 554–567, https://doi.org/10.1016/j.ijbiomac.2020.09.182.

[18] M.M. Jayakody, K.G. Kaushani, M.P.G. Vanniarachchy, I. Wijesekara, Hydrocolloid and water soluble polymers used in the food industry and their functional properties: a review, Polym. Bull. 80 (2023) 3585–3610, https://doi.org/10.1007/S00289-022-04264-5.

[19] L. Guo, H.D. Goff, F. Xu, F. Liu, J. Ma, M. Chen, F. Zhong, The effect of sodium alginate on nutrient digestion and metabolic responses during both *in vitro* and *in vivo* digestion process, Food Hydrocoll. 107 (2020) 105304, https://doi.org/10.1016/J.FOODHYD.2019.105304.

[20] Q. Wei, G. Fu, K. Wang, Q. Yang, J. Zhao, Y. Wang, K. Ji, S. Song, Advances in research on antiviral activities of sulfated polysaccharides from seaweeds, Pharmaceuticals 15 (2022) 581, https://doi.org/10.3390/PH15050581.

[21] A. Frediansyah, The antiviral activity of iota-, kappa-, and lambda-carrageenan against COVID-19: a critical review, Clin. Epidemiol. Glob. Health 12 (2021), https://doi.org/10.1016/J.CEGH.2021.100826.

[22] Y. Dong, Z. Wei, C. Xue, Recent advances in carrageenan-based delivery systems for bioactive ingredients: a review, Trends Food Sci. Technol. 112 (2021) 348–361, https://doi.org/10.1016/J.TIFS.2021.04.012.

[23] N.M. Liyanage, D.P. Nagahawatta, T.U. Jayawardena, K.K.A. Sanjeewa, H.H.A.C. K. Jayawrdhana, J.-I. Kim, Y.-J. Jeon, Sulfated polysaccharides from seaweeds: a promising strategy for combatting viral diseases—a review, Mar. Drugs 21 (2023) 461, https://doi.org/10.3390/MD21090461.

[24] M. Khotimchenko, V. Tiasto, A. Kalitnik, M. Begun, R. Khotimchenko, E. Leonteva, I. Bryukhovetskiy, Y. Khotimchenko, Antitumor potential of carrageenans from marine red algae, Carbohydr. Polym., Elsevier 246 (2020). doi:https://doi.org/10.1016/j.carbpol.2020.116568.

[25] S. Lomartire, A.M.M. Gonçalves, Algal phycocolloids: bioactivities and pharmaceutical applications, Mar. Drugs 21 (2023) 384, https://doi.org/10.3390/MD21070384.

[26] B.B. Sedayu, M.J. Cran, S.W. Bigger, A review of property enhancement techniques for carrageenan-based films and coatings, Carbohydr. Polym. 216 (2019) 287–302, https://doi.org/10.1016/J.CARBPOL.2019.04.021.

[27] J. Muthukumar, R. Chidambaram, S. Sukumaran, Sulfated polysaccharides and its commercial applications in food industries—a review, J. Food Sci. Technol. 58 (2021) 2453–2466, https://doi.org/10.1007/S13197-020-04837-0.

[28] K. Nishinari, Y. Fang, Molar mass effect in food and health, Food Hydrocoll. 112 (2021) 106110, https://doi.org/10.1016/J.FOODHYD.2020.106110.

[29] T.I. Imbs, T.N. Zvyagintseva, S.P. Ermakova, Is the transformation of fucoidans in human body possible? Int. J. Biol. Macromol. 142 (2020) 778–781, https://doi.org/10.1016/J.IJBIOMAC.2019.10.018.

[30] B. Pradhan, S. Patra, R. Nayak, C. Behera, S.R. Dash, S. Nayak, B.B. Sahu, S. K. Bhutia, M. Jena, Multifunctional role of fucoidan, sulfated polysaccharides in human health and disease: a journey under the sea in pursuit of potent therapeutic agents, Int. J. Biol. Macromol. 164 (2020) 4263–4278, https://doi.org/10.1016/J.IJBIOMAC.2020.09.019.

[31] S.M. Etman, Y.S.R. Elnaggar, O.Y. Abdallah, Fucoidan, a natural biopolymer in cancer combating: from edible algae to nanocarrier tailoring, Int. J. Biol. Macromol. 147 (2020) 799–808, https://doi.org/10.1016/J.IJBIOMAC.2019.11.191.

[32] C.C.F. Do-Amaral, B.S. Pacheco, F.K. Seixas, C.M.P. Pereira, T. Collares, Antitumoral effects of fucoidan on bladder cancer, Algal Res., Elsevier (2020). 47, 101884 doi:https://doi.org/10.1016/j.algal.2020.101884 (accessed May 28, 2025).

[33] T.S. Vo, The role of algal fucoidans in potential anti-allergic therapeutics, Int. J. Biol. Macromol. 165 (2020) 1093–1098, https://doi.org/10.1016/J.IJBIOMAC.2020.09.252.

[34] Y. Wen, L. Gao, H. Zhou, C. Ai, X. Huang, M. Wang, Y. Zhang, C. Zhao, Opportunities and challenges of algal fucoidan for diabetes management, Trends Food Sci. Technol. 111 (2021) 628–641, https://doi.org/10.1016/J.TIFS.2021.03.028.

[35] Q. Shang, Revisit the effects of fucoidan on gut microbiota in health and disease: what do we know and what do we need to know? Bioact. Carbohydr. Diet. Fibre 23 (2020) 100221 https://doi.org/10.1016/J.BCDF.2020.100221.

[36] J. Kang, X. Jia, N. Wang, M. Xiao, S. Song, S. Wu, Z. Li, S. Wang, S.W. Cui, Q. Guo, Insights into the structure-bioactivity relationships of marine sulfated polysaccharides: a review, Food Hydrocoll. 123 (2022) 107049, https://doi.org/10.1016/J.FOODHYD.2021.107049.

[37] C. Oliveira, N.M. Neves, R.L. Reis, A. Martins, T.H. Silva, A review on fucoidan antitumor strategies: from a biological active agent to a structural component of fucoidan-based systems, Carbohydr. Polym. 239 (2020) 116131, https://doi.org/10.1016/J.CARBPOL.2020.116131.

[38] M.M. de Carvalho, M.D. Noseda, J.C.C. Dallagnol, L.G. Ferreira, D.R.B. Ducatti, A. G. Gonçalves, R.A. de Freitas, M.E.R. Duarte, Conformational analysis of ulvans from *Ulva fasciata* and their anticoagulant polycarboxylic derivatives, Int. J. Biol. Macromol. 162 (2020) 599–608, https://doi.org/10.1016/J.IJBIOMAC.2020.06.146.

[39] L.A. Tziveleka, E. Ioannou, V. Roussis, Ulvan, a bioactive marine sulphated polysaccharide as a key constituent of hybrid biomaterials: a review, Carbohydr. Polym. 218 (2019) 355–370, https://doi.org/10.1016/J.CARBPOL.2019.04.074.

[40] J.T. Kidgell, M. Magnusson, R. de Nys, C.R.K. Glasson, Ulvan: a systematic review of extraction, composition and function, Algal Res. 39 (2019) 101422, https://doi.org/10.1016/J.ALGAL.2019.101422.

[41] K.L. Cheong, K. Liu, W. Chen, S. Zhong, K. Tan, Recent progress in Porphyra haitanensis polysaccharides: extraction, purification, structural insights, and their impact on gastrointestinal health and oxidative stress management, Food Chem.: X 22 (2024) 101414, https://doi.org/10.1016/J.FOCHX.2024.101414.

[42] D. Yang, F. Lin, Y. Huang, J. Ye, M. Xiao, Separation, purification, structural analysis and immune-enhancing activity of sulfated polysaccharide isolated from sea cucumber viscera, Int. J. Biol. Macromol. 155 (2020) 1003–1018, https://doi.org/10.1016/J.IJBIOMAC.2019.11.064.

[43] F. Zhao, Q. Liu, J. Cao, Y. Xu, Z. Pei, H. Fan, Y. Yuan, X. Shen, C. Li, A sea cucumber (*Holothuria leucospilota*) polysaccharide improves the gut microbiome to alleviate the symptoms of type 2 diabetes mellitus in Goto-Kakizaki rats, Food Chem. Toxicol. 135 (2020) 110886, https://doi.org/10.1016/J.FCT.2019.110886.

[44] A.D. Dobrinči'c, S. Balbino, Z. Zori'c, S.P. Pedisi'c, D. Bursa'cbursa'c, K. Kovačevi'c, Advanced technologies for the extraction of marine brown algal polysaccharides, Mar. Drugs, mdpi.Com 18 (2020). doi:https://doi.org/10.3390/md18030168.

[45] R.E. Abraham, P. Su, M. Puri, C.L. Raston, W. Zhang, Optimisation of biorefinery production of alginate, fucoidan and laminarin from brown seaweed Durvillaea potatorum, Algal Res. 38 (2019), https://doi.org/10.1016/J.ALGAL.2018.101389.

[46] M. Sterner, F. Gröndahl 2021, Extraction of laminarin from Saccharina latissima seaweed using cross-flow filtration, J. Appl. Phycol., Springer 33 (2021) 1825–1844. doi:https://doi.org/10.1007/S10811-021-02398-Z.

[47] A. Rahman, J. Carrasqueira, S. Bernardino, R. Bernardino, C. Afonso, Marine-derived polysaccharides and their potential health benefits in nutraceutical applications, Mar. Drugs 23 (2025) 60, https://doi.org/10.3390/MD23020060.

[48] B. Zhu, F. Ni, Q. Xiong, Z. Yao, Marine oligosaccharides originated from seaweeds: source, preparation, structure, physiological activity and applications, Crit. Rev. Food Sci. Nutr. 61 (2021) 60–74, https://doi.org/10.1080/10408398.2020.1716207.

[49] M.D. Torres, N. Flórez-Fernández, H. Domínguez, Integral utilization of red seaweed for bioactive production, Mar. Drugs 17 (2019) 314, https://doi.org/10.3390/MD17060314.

[50] M. Carpena, P. Garcia-Perez, P. Garcia-Oliveira, F. Chamorro, P. Otero, C. Lourenço-Lopes, H. Cao, J. Simal-Gandara, M.A. Prieto, Biological properties and potential of compounds extracted from red seaweeds, Phytochem. Rev., Springer 22 (2023) 1509–1540. doi:https://doi.org/10.1007/S11101-022-09826-Z.

[51] S. Ścieszka, E. Klewicka, Algae in food: a general review, Crit. Rev. Food Sci. Nutr., Taylor & Francis 59 (2019) 3538–3547. doi:https://doi.org/10.1080/10408398.2018.1496319.

[52] M. Ayyash, B. Abu-Jdayil, A. Olaimat, G. Esposito, P. Itsaranuwat, T. Osaili, R. Obaid, J. Kizhakkayil, S.Q. Liu, Physicochemical, bioactive and rheological properties of an exopolysaccharide produced by a probiotic *Pediococcus pentosaceus* M41, Carbohydr. Polym. 229 (2020), https://doi.org/10.1016/J.CARBPOL.2019.115462.

[53] M. Krishnamurthy, C. Jayaraman Uthaya, M. Thangavel, V. Annadurai, R. Rajendran, A. Gurusamy, Optimization, compositional analysis, and characterization of exopolysaccharides produced by multi-metal resistant *Bacillus cereus* KMS3-1, Carbohydr. Polym. 227 (2020), https://doi.org/10.1016/J.CARBPOL.2019.115369.

[54] M. Wei, L. Geng, Q. Wang, Y. Yue, J. Wang, N. Wu, X. Wang, C. Sun, Q. Zhang, Purification, characterization and immunostimulatory activity of a novel exopolysaccharide from *Bacillus* sp. H5, Int. J. Biol. Macromol. 189 (2021) 649–656, https://doi.org/10.1016/J.IJBIOMAC.2021.08.159.

[55] B.E. Dhanya, A. Prabhu, P.D. Rekha, Extraction and characterization of an exopolysaccharide from a marine bacterium, Int. Microbiol., Springer 25 (2022) 285–295. doi:https://doi.org/10.1007/S10123-021-00216-7.

[56] M.H. Almutairi, M.M.I. Helal, Biological and microbiological activities of isolated Enterobacter sp. ACD2 exopolysaccharides from Tabuk region of Saudi Arabia, J. King Saud Univ. - Sci. 33 (2021), https://doi.org/10.1016/J.JKSUS.2020.101328.

[57] K.S. Sran, B. Bisht, S. Mayilraj, A. Roy Choudhury, Structural characterization and antioxidant potential of a novel anionic exopolysaccharide produced by marine *Microbacterium aurantiacum* FSW-25, Int. J. Biol. Macromol. 131 (2019) 343–352, https://doi.org/10.1016/J.IJBIOMAC.2019.03.016.

[58] T.G. Sahana, P.D. Rekha, A novel exopolysaccharide from marine bacterium *Pantoea* sp. YU16-S3 accelerates cutaneous wound healing through Wnt/β-catenin pathway, Carbohydr. Polym. 238 (2020), https://doi.org/10.1016/J.CARBPOL.2020.116191.

[59] T. Hong, J.Y. Yin, S.P. Nie, M.Y. Xie, Applications of infrared spectroscopy in polysaccharide structural analysis: Progress, challenge and perspective, Food Chem.: X 12 (2021), https://doi.org/10.1016/J.FOCHX.2021.100168.

[60] M. Martin-Pastor, A.S. Ferreira, X. Moppert, C. Nunes, M.A. Coimbra, R.L. Reis, J. Guezennec, R. Novoa-Carballal, Structure, rheology, and copper-complexation of a hyaluronan-like exopolysaccharide from Vibrio, Carbohydr. Polym. 222 (2019), https://doi.org/10.1016/J.CARBPOL.2019.114999.

[61] Y. Lin, J. Yang, L. Luo, X. Zhang, S. Deng, X. Chen, Y. Li, A.E.D.A. Bekhit, B. Xu, R. Huang, Ferroptosis related immunomodulatory effect of a novel extracellular polysaccharides from marine fungus *Aureobasidium melanogenum*, Mar. Drugs 20 (2022), https://doi.org/10.3390/MD20050332.

[62] A. Zayed, M.K. Mansour, M.S. Sedeek, M.H. Habib, R. Ulber, M.A. Farag, Rediscovering bacterial exopolysaccharides of terrestrial and marine origins: novel insights on their distribution, biosynthesis, biotechnological production, and future, Crit. Rev. Biotechnol., Taylor & Francis 42 (2022) 597–617. doi:https://doi.org/10.1080/07388551.2021.1942779.

[63] M.A. López-Ortega, N. Chavarría-Hernández, M. del R. López-Cuellar, A. I. Rodríguez-Hernández, A review of extracellular polysaccharides from extreme niches: an emerging natural source for the biotechnology. From the adverse to diverse!, Int. J. Biol. Macromol. 177 (2021) 559–577, https://doi.org/10.1016/J.IJBIOMAC.2021.02.101.

[64] D.N. Carvalho, R.L. Reis, T.H. Silva, Marine origin materials on biomaterials and advanced therapies to cartilage tissue engineering and regenerative medicine, Biomater. Sci. 9 (2021) 6718–6736, https://doi.org/10.1039/D1BM00809A.

[65] A.F. Aldairi, Evaluation of various methodologies used in purification of biologically active carbohydrates derived from marine life, Biomed. J. Sci. Tech. Res. 27 (2020), https://doi.org/10.26717/BJSTR.2020.27.004531.

[66] M. Abdallah, N. Fernández, A.A. Matias, M. Do Rosário Bronze, Hyaluronic acid and chondroitin sulfate from marine and terrestrial sources: extraction and purification methods, Carbohydr. Polym., Elsevier 243 (2020). doi:https://doi.org/10.1016/j.carbpol.2020.116441 (accessed May 28, 2025).

[67] L. Thomas, M. Kp, S. Mathew, Fish gills of *Thunnus albacares*: a novel source of chondroitin sulphate glycosaminoglycans, Int. J. Fish. Aquat. Stud. 9 (2021) 146–152, http://www.fisheriesjournal.com (accessed May 28, 2025).

[68] R. Sharma, A. Kataria, S. Sharma, B. Singh, Structural characterisation, biological activities and pharmacological potential of glycosaminoglycans and oligosaccharides: a review, Int. J. Food Sci. Technol., academic.oup.com 57 (2022) 4–15. doi:https://doi.org/10.1111/IJFS.15379.

[69] Y. Kong, Y. Li, Z.R. Dai, M. Qin, H.L. Fan, J.G. Hao, C.X. Zhang, Q.P. Zhong, C. Qi, P. Wang, Glycosaminoglycan from *Ostrea rivularis* attenuates hyperlipidemia and regulates gut microbiota in high-cholesterol diet-fed zebrafish, Food Sci. Nutr., Wiley Online Library 9 (2021) 5198–5210. doi:https://doi.org/10.1002/FSN3.2492.

[70] Y.D. Berezhnaya, A.S. Kazachenko, A.S. Kazachenko, Y.N. Malyar, V. S. Borovkova, Sulfation of various polysaccharide structures: different methods and perspectives, Chemistry (Switzerland) 6 (2024) 640–665, https://doi.org/10.3390/CHEMISTRY6040038.

[71] Q. Bu, P. Li, Y. Xia, X. Wei, K. Song, Mannose metabolism and immune regulation: insights into its therapeutic potential in immunology-related diseases, Biocell 47 (2023) 2535–2546, https://doi.org/10.32604/BIOCELL.2023.030781.

[72] T.U. Jayawardena, K.K. Asanka Sanjeewa, D.P. Nagahawatta, H.-G. Lee, Y.-A. Lu, A.P.J.P. Vaas, D.T.U. Abeytunga, C.M. Nanayakkara, D.-S. Lee, Y.-J. Jeon, Anti-inflammatory effects of sulfated polysaccharide from *Sargassum swartzii* in macrophages via blocking TLR/NF-Kb signal transduction, Mar. Drugs, mdpi.com 18 (2020). doi:https://doi.org/10.3390/md18120601.

[73] B. Cai, X. Yi, Q. Han, J. Pan, H. Chen, H. Sun, P. Wan, Structural characterization of oligosaccharide from *Spirulina platensis* and its effect on the faecal microbiota *in vitro*, Food Sci. Human Wellness 11 (2022) 109–118, https://doi.org/10.1016/J.FSHW.2021.07.012.

[74] E.V. Medina-Cabrera, B. Rühmann, J. Schmid, V. Sieber, Characterization and comparison of *Porphyridium sordidum* and *Porphyridium purpureum* concerning growth characteristics and polysaccharide production, Algal Res. 49 (2020), https://doi.org/10.1016/J.ALGAL.2020.101931.

[75] S. Van Wychen, S.M. Rowland, K.C. Lesco, P. V. Shanta, T. Dong, L.M.L. Laurens, Advanced mass balance characterization and fractionation of algal biomass composition, J. Appl. Phycol., Springer 33 (2021) 2695–2708. doi:https://doi.org/10.1007/S10811-021-02508-X.

[76] M. Phélippé, O. Gonçalves, G. Thouand, G. Cogne, C. Laroche, Characterization of the polysaccharides chemical diversity of the cyanobacteria *Arthrospira platensis*, Algal Res. 38 (2019), https://doi.org/10.1016/J.ALGAL.2019.101426.

[77] B.S. Padam, C.K. Siew, F.Y. Chye, Optimization of an innovative hydrothermal processing on prebiotic properties of *Eucheuma denticulatum*, a tropical red seaweed, Appl. Sci., mdpi.com 13 (2023). doi:https://doi.org/10.3390/app13031517.

[78] A. Sichert, C.H. Corzett, M.S. Schechter, F. Unfried, S. Markert, D. Becher, A. Fernandez-Guerra, M. Liebeke, T. Schweder, M.F. Polz, J.H. Hehemann, Verrucomicrobia use hundreds of enzymes to digest the algal polysaccharide fucoidan, Nat. Microbiol. 5 (2020) 1026–1039, https://doi.org/10.1038/S41564-020-0720-2.

[79] J. Nikolić Chenais, L. Marion, R. Larocque, M. Jam, D. Jouanneau, L. Cladiere, S. Le Gall, M. Fanuel, N. Desban, H. Rogniaux, D. Ropartz, E. Ficko-Blean, G. Michel, Systematic comparison of eight methods for preparation of high purity sulfated fucans extracted from the brown alga *Pelvetia canaliculata*, Int. J. Biol. Macromol. 201 (2022) 143–157, https://doi.org/10.1016/J.IJBIOMAC.2021.12.122.

[80] S. Amamou, C. Sambusiti, F. Monlau, E. Dubreucq, A. Barakat, Mechano-enzymatic deconstruction with a new enzymatic cocktail to enhance enzymatic hydrolysis and bioethanol fermentation of two macroalgae species, Molecules, mdpi.com 23 (2018). doi:https://doi.org/10.3390/molecules23010174.

[81] S. Tomás-Martínez, E.J. Zwolsman, F. Merlier, M. Pabst, Y. Lin, M.C.M. van Loosdrecht, D.G. Weissbrodt, Turnover of the extracellular polymeric matrix of granules performing biological phosphate removal, Appl. Microbiol. Biotechnol., Springer 107 (2023) 1997–2009. doi:https://doi.org/10.1007/S00253-023-12421-7.

[82] K.C. Lesco, S.K.R. Williams, L.M.L. Laurens, Marine algae polysaccharides: an overview of characterization techniques for structural and molecular elucidation, Mar. Drugs 23 (2025) 105, https://doi.org/10.3390/MD23030105.

[83] J.O. Tavares, J. Cotas, A. Valado, L. Pereira, Algae food products as a healthcare solution, Mar. Drugs 21 (2023) 578, https://doi.org/10.3390/MD21110578.

[84] T.R.L. Senadheera, A. Hossain, F. Shahidi, Marine bioactives and their application in the food industry: a review, Appl. Sci. (Switzerland) 13 (2023), https://doi.org/10.3390/APP132112088.

[85] Q. Zhong, B. Wei, S. Wang, S. Ke, J. Chen, H. Zhang, H. Wang, The antioxidant activity of polysaccharides derived from marine organisms: an overview, Mar. Drugs 17 (2019), https://doi.org/10.3390/MD17120674.

[86] M.D. Abid, S. Lajili, H.H. Ammar, D. Cherif, N. Eltaief, H. Majdoub, A. Bouraoui, Chemical and biological properties of sodium alginates isolated from tow brown algae *Dictyopteris Membranaceae* and *Padina Pavonica*, Trends J. Sci. Res. 4 (2019) 62–67, https://doi.org/10.31586/PHARMACOLOGY.0402.03.

[87] P.S. Saravana, Y.N. Cho, H.C. Woo, B.S. Chun, Green and efficient extraction of polysaccharides from brown seaweed by adding deep eutectic solvent in subcritical water hydrolysis, J. Clean. Prod. 198 (2018) 1474–1484, https://doi.org/10.1016/J.JCLEPRO.2018.07.151.

[88] N. Flórez-Fernández, H. Domínguez, M.D. Torres, A green approach for alginate extraction from *Sargassum muticum* brown seaweed using ultrasound-assisted technique, Int. J. Biol. Macromol. 124 (2019) 451–459, https://doi.org/10.1016/J.IJBIOMAC.2018.11.232.

[89] E. Caballero, A. Flores, A. Olivares, Sustainable exploitation of macroalgae species from Chilean coast: characterization and food applications, Algal Res. 57 (2021) 102349, https://doi.org/10.1016/J.ALGAL.2021.102349.

[90] P. Torabi, N. Hamdami, J. Keramat, Microwave-assisted extraction of sodium alginate from brown macroalgae *Nizimuddinia zanardini*, optimization and physicochemical properties, Sep. Sci. Technol. (Philadelphia) 57 (2022) 872–885, https://doi.org/10.1080/01496395.2021.1954020.

[91] A.F. Hifney, M.A. Fawzy, K.M. Abdel-Gawad, M. Gomaa, Upgrading the antioxidant properties of fucoidan and alginate from *Cystoseira trinodis* by fungal fermentation or enzymatic pretreatment of the seaweed biomass, Food Chem. 269 (2018) 387–395, https://doi.org/10.1016/J.FOODCHEM.2018.07.026.

[92] H. Yaich, A. Ben Amira, F. Abbes, M. Bouaziz, S. Besbes, A. Richel, C. Blecker, H. Attia, H. Garna, Effect of extraction procedures on structural, thermal and antioxidant properties of ulvan from *Ulva lactuca* collected in Monastir coast, Int. J. Biol. Macromol. 105 (2017) 1430–1439, https://doi.org/10.1016/J.IJBIOMAC.2017.07.141.

[93] F. Rahimi, M. Tabarsa, M. Rezaei, Ulvan from green algae *Ulva intestinalis*: optimization of ultrasound-assisted extraction and antioxidant activity, J. Appl. Phycol. 28 (2016) 2979–2990, https://doi.org/10.1007/S10811-016-0824-5/FIGURES/6.

[94] Y. Yuan, X. Xu, C. Jing, P. Zou, C. Zhang, Y. Li, Microwave assisted hydrothermal extraction of polysaccharides from *Ulva prolifera*: functional properties and bioactivities, Carbohydr. Polym. 181 (2018) 902–910, https://doi.org/10.1016/J.CARBPOL.2017.11.061.

[95] T.I. Imbs, S.P. Ermakova, O.S. Malyarenko, V.V. Isakov, T.N. Zvyagintseva, Structural elucidation of polysaccharide fractions from the brown alga *Coccophora langsdorfii* and *in vitro* investigation of their anticancer activity, Carbohydr. Polym. 135 (2016) 162–168, https://doi.org/10.1016/J.CARBPOL.2015.08.062.

[96] S.U. Kadam, C.P. O'Donnell, D.K. Rai, M.B. Hossain, C.M. Burgess, D. Walsh, B. K. Tiwari, Laminarin from Irish brown seaweeds *Ascophyllum nodosum* and *Laminaria hyperborea*: ultrasound assisted extraction, characterization and bioactivity, Mar. Drugs 13 (2015) 4270–4280, https://doi.org/10.3390/MD13074270.

[97] M. Alboofetileh, M. Rezaei, M. Tabarsa, M. Rittà, M. Donalisio, F. Mariatti, S. G. You, D. Lembo, G. Cravotto, Effect of different non-conventional extraction methods on the antibacterial and antiviral activity of fucoidans extracted from *Nizamuddinia zanardinii*, Int. J. Biol. Macromol. 124 (2019) 131–137, https://doi.org/10.1016/J.IJBIOMAC.2018.11.201.

[98] S.H. Wang, C.Y. Huang, C.Y. Chen, C.C. Chang, C.Y. Huang, C. Di Dong, J. S. Chang, Isolation and purification of brown algae fucoidan from *Sargassum siliquosum* and the analysis of anti-lipogenesis activity, Biochem. Eng. J. 165 (2021) 107798, https://doi.org/10.1016/J.BEJ.2020.107798.

[99] K.S. Bittkau, S. Neupane, S. Alban, Initial evaluation of six different brown algae species as source for crude bioactive fucoidans, Algal Res. 45 (2020) 101759, https://doi.org/10.1016/J.ALGAL.2019.101759.

[100] T.T. Nguyen, M.D. Mikkelsen, V.H. Nguyen Tran, V.T. Dieu Trang, N. Rhein-Knudsen, J. Holck, A.B. Rasin, H.T. Thuy Cao, T.T. Thanh Van, A.S. Meyer, Enzyme-assisted fucoidan extraction from brown macroalgae *Fucus distichus* subsp. *evanescens* and *Saccharina latissima*, Mar. Drugs 18 (2020) 296. doi:https://doi.org/10.3390/MD18060296.

[101] L. Youssouf, L. Lallemand, P. Giraud, F. Soulé, A. Bhaw-Luximon, O. Meilhac, C. L. D'Hellencourt, D. Jhurry, J. Couprie, Ultrasound-assisted extraction and structural characterization by NMR of alginates and carrageenans from seaweeds, Carbohydr. Polym. 166 (2017) 55–63, https://doi.org/10.1016/J.CARBPOL.2017.01.041.

[102] C.R.N. Gereniu, P.S. Saravana, B.S. Chun, Recovery of carrageenan from Solomon Islands red seaweed using ionic liquid-assisted subcritical water extraction, Sep. Purif. Technol. 196 (2018) 309–317, https://doi.org/10.1016/J.SEPPUR.2017.06.055.

[103] N. Maleki, L. Roomiani, M. Tadayoni, Microwave-assisted extraction optimization, antimicrobial and antioxidant properties of carrageenan from red algae (*Gracilaria acerosa*), J. Food Meas. Charact. 17 (2023) 1156–1166, https://doi.org/10.1007/S11694-022-01682-X/METRICS.

[104] S. Pramanik, A. Singh, B.M. Abualsoud, A. Deepak, P. Nainwal, A.S. Sargsyan, S. Bellucci, From algae to advancements: laminarin in biomedicine, RSC Adv., pubs.rsc.org 14 (2024) 3209–3231. doi:https://doi.org/10.1039/d3ra08161c.

[105] Y. Wang, M. Xing, Q. Cao, A. Ji, H. Liang, S. Song, Biological activities of fucoidan and the factors mediating its therapeutic effects: a review of recent studies, Mar. Drugs, mdpi.com 17 (2019). doi:https://doi.org/10.3390/md17030183.

[106] Z. Xia, J.B. Degrandchamp, E.R. Williams, Native mass spectrometry beyond ammonium acetate: effects of nonvolatile salts on protein stability and structure, Analyst 144 (2019) 2565–2573, https://doi.org/10.1039/C9AN00266A.

[107] J. Wang, J. Zhao, S. Nie, M. Xie, S. Li, Rapid profiling strategy for oligosaccharides and polysaccharides by MALDI TOF mass spectrometry, Food Hydrocoll. 124 (2022), https://doi.org/10.1016/J.FOODHYD.2021.107237.

[108] O. Makshakova, A. Zykwinska, S. Cuenot, S. Colliec-Jouault, S. Perez, Three-dimensional structures, dynamics and calcium-mediated interactions of the exopolysaccharide, Infernan, produced by the deep-sea hydrothermal bacterium *Alteromonas infernus*, Carbohydr. Polym. 276 (2022), https://doi.org/10.1016/J.CARBPOL.2021.118732.

[109] F. Hadjkacem, J. Elleuch, M. Aitouguinane, F. Chakou, A.V. Ursu, P. Dubessay, N. Bourgougnon, M. Traikia, D. Le Cerf, Z. El Alaoui-Talibi, C. El Modafar, Z. Boual, M.D.O. El Hadj, C. Delattre, G. Christophe, P. Michaud, I. Fendri, S. Abdelkafi, G. Pierre, Primary structural features, physicochemical and biological properties of two water-soluble polysaccharides extracted from the brown Tunisian seaweed *Halopteris scoparia*, Int. J. Biol. Macromol. 253 (2023), https://doi.org/10.1016/J.IJBIOMAC.2023.126757.

[110] B. Yang, G.H. Joe, W. Li, Y. Shimizu, H. Saeki, Comparison of maillard-type glycated collagen with alginate oligosaccharide and glucose: its characterization, antioxidant activity, and cytoprotective activity on H_2O_2-induced cell oxidative damage, Foods 11 (2022) 2374, https://doi.org/10.3390/FOODS11152374.

[111] Z. Li, K.L. Cheong, B. Song, H. Yin, Q. Li, J. Chen, Z. Wang, B. Xu, S. Zhong, Preparation of κ-carrageenan oligosaccharides by photocatalytic degradation: structural characterization and antioxidant activity, Food Chem.: X 22 (2024), https://doi.org/10.1016/J.FOCHX.2024.101294.

[112] H.T. Ha, D.X. Cuong, L.H. Thuy, P.T. Thuan, D.T.T. Tuyen, V.T. Mo, D.H. Dong, Carrageenan of red algae *Eucheuma gelatinae*: extraction, antioxidant activity, rheology characteristics, and physicochemistry characterization, Molecules 27 (2022) 1268, https://doi.org/10.3390/MOLECULES27041268.

[113] Y. Cui, L. Zhu, Y. Li, S. Jiang, Q. Sun, E. Xie, H. Chen, Z. Zhao, W. Qiao, J. Xu, C. Dong, Structure of a laminarin-type β-(1→3)-glucan from brown algae *Sargassum henslowianum* and its potential on regulating gut microbiota, Carbohydr. Polym. 255 (2021), https://doi.org/10.1016/J.CARBPOL.2020.117389.

[114] G. Rajauria, R. Ravindran, M. Garcia-Vaquero, D.K. Rai, T. Sweeney, J. O'Doherty, Molecular characteristics and antioxidant activity of laminarin extracted from the seaweed species *Laminaria hyperborea*, using hydrothermal-assisted extraction and a multi-step purification procedure, Food Hydrocoll. 112 (2021) 106332, https://doi.org/10.1016/J.FOODHYD.2020.106332.

[115] K.M. Barakat, M.M. Ismail, H.E. Abou El Hassayeb, N.A. El Sersy, M.E. Elshobary, Chemical characterization and biological activities of ulvan extracted from *Ulva fasciata* (Chlorophyta), Rend. Lincei Sci. Fis. Nat., Springer 33 (2022) 829–841. doi:https://doi.org/10.1007/S12210-022-01103-7.

[116] H. Jiang, S. Liang, X.R. Yao, Y.X. Jin, X.H. Shen, B. Yuan, J.B. Zhang, N.H. Kim, Laminarin improves developmental competence of porcine early stage embryos by inhibiting oxidative stress, Theriogenology 115 (2018) 38–44, https://doi.org/10.1016/J.THERIOGENOLOGY.2018.04.019.

[117] M. Mohibbullah, M.A. Talha, M.A. Baten, A.W. Newaz, J.S. Choi, Yield optimization, physicochemical characterizations, and antioxidant properties of food grade agar from *Gracilaria tenuistipitata* of Cox's Bazar coast, Bangladesh,

Food Sci. Nutr., Wiley Online Library 11 (2023) 2852–2863. doi:https://doi.org/10.1002/FSN3.3265.
[118] O.L. Kang, M. Ghani, O. Hassan, S. Rahmati, N. Ramli, Novel agaro-oligosaccharide production through enzymatic hydrolysis: physicochemical properties and antioxidant activities, Food Hydrocoll. 42 (2014) 304–308, https://doi.org/10.1016/J.FOODHYD.2014.04.031.
[119] F. Hentati, C. Delattre, A.V. Ursu, J. Desbrières, D. Le Cerf, C. Gardarin, S. Abdelkafi, P. Michaud, G. Pierre, Structural characterization and antioxidant activity of water-soluble polysaccharides from the Tunisian brown seaweed *Cystoseira compressa*, Carbohydr. Polym. 198 (2018) 589–600, https://doi.org/10.1016/J.CARBPOL.2018.06.098.
[120] F. Canbolat, İ. Acar, R.N. Tezel, Development of chitosan nanoparticle loaded with *Tricholoma fracticum* extract and evaluation of *in vitro* antioxidant activity, Int. J. Food Sci. Technol. 59 (2024) 7971–7986, https://doi.org/10.1111/IJFS.17585.
[121] W. Gongi, N. Cordeiro, J.L.G. Pinchetti, H. Ben Ouada, Functional, rheological, and antioxidant properties of extracellular polymeric substances produced by a thermophilic cyanobacterium *Leptolyngbya* sp., J. Appl. Phycol., Springer 34 (2022) 1423–1434. doi:https://doi.org/10.1007/S10811-022-02695-1.
[122] R. Liu, H. Liang, S.G. Sutariya, P. Salunke, Effect of hyaluronic acid and kappa-carrageenan on milk properties: rheology, protein stability, foaming, water-holding, and emulsification properties, Foods, mdpi.com 12 (2023). doi:https://doi.org/10.3390/foods12050913.
[123] C. Short, J.L. Smith, J. Bones, S. Diggon, A. Heidt, C. Mcdougall, K.A. Pawluk, Marine zoning for the marine plan partnership (MaPP) in British Columbia, Canada, Mar. Policy 152 (2023), https://doi.org/10.1016/J.MARPOL.2023.105524.
[124] A. Gaspar-Pintiliescu, L.M. Stefan, E. Mihai, C. Sanda, V.S. Manoiu, D. Berger, O. Craciunescu, Antioxidant and antiproliferative effect of a glycosaminoglycan extract from *Rapana venosa* marine snail, PLoS One, journals.plos.org 19 (2024). doi:https://doi.org/10.1371/JOURNAL.PONE.0297803.
[125] B. Arasukumar, G. Prabakaran, B. Gunalan, M. Moovendhan, Chemical composition, structural features, surface morphology and bioactivities of chitosan derivatives from lobster (*Thenus unimaculatus*) shells, Int. J. Biol. Macromol. 135 (2019) 1237–1245, https://doi.org/10.1016/J.IJBIOMAC.2019.06.033.
[126] K.S. Postolović, M.D. Antonijević, B. Ljujić, M.M. Kovačević, M.G. Janković, Z. D. Stanić, pH-responsive hydrogel beads based on alginate, κ-carrageenan and poloxamer for enhanced curcumin, natural bioactive compound, encapsulation and controlled release efficiency, Molecules 27 (2022), https://doi.org/10.3390/MOLECULES27134045.
[127] S.U.D. Wani, M. Ali, S. Mehdi, M.H. Masoodi, M.I. Zargar, F. Shakeel, A review on chitosan and alginate-based microcapsules: mechanism and applications in drug delivery systems, Int. J. Biol. Macromol. 248 (2023) 125875, https://doi.org/10.1016/J.IJBIOMAC.2023.125875.
[128] R. Zhang, Q. Wang, H. Shen, Y. Yang, P. Liu, Y. Dong, Environmental benefits of macroalgae products: a case study of agar based on life cycle assessment, Algal Res. 78 (2024) 103384, https://doi.org/10.1016/J.ALGAL.2023.103384.
[129] A. Priyadarshini, B.K. Tiwari, G. Rajauria, Assessing the environmental and economic sustainability of functional food ingredient production process, Processes 10 (2022), https://doi.org/10.3390/PR10030445.
[130] N. Rhein-Knudsen, A.S. Meyer, Chemistry, gelation, and enzymatic modification of seaweed food hydrocolloids, Trends Food Sci. Technol. 109 (2021) 608–621, https://doi.org/10.1016/j.tifs.2021.01.052.
[131] M. Bäumgen, T. Dutschei, U.T. Bornscheuer, Marine polysaccharides: occurrence, enzymatic degradation and utilization, ChemBioChem 22 (2021) 2247–2256, https://doi.org/10.1002/CBIC.202100078.
[132] R. Fredrick, A. Podder, A. Viswanathan, S. Bhuniya, Synthesis and characterization of polysaccharide hydrogel based on hydrophobic interactions, J. Appl. Polym. Sci., Wiley Online Library 136 (2019). doi:https://doi.org/10.1002/APP.47665.
[133] M. Dattilo, F. Patitucci, S. Prete, O.I. Parisi, F. Puoci, Polysaccharide-based hydrogels and their application as drug delivery systems in cancer treatment: a review, J. Funct. Biomater., mdpi.com 14 (2023). doi:https://doi.org/10.3390/jfb14020055.
[134] T. Fenton, K. Kanyuck, T. Mills, E. Pelan, Formulation and characterisation of kappa-carrageenan gels with non-ionic surfactant for melting-triggered controlled release, Carbohydr. Polym. Technol. Appl. 2 (2021) 100060, https://doi.org/10.1016/J.CARPTA.2021.100060.
[135] I. Diañez, C. Gallegos, E.B. La Fuente, I. Martínez, C. Valencia, M.C. Sánchez, M.J. Diaz, 3D printing in situ gelification of κ-carrageenan solutions: effect of printing variables on the rheological response, Food Hydrocoll., Elsevier 87 (2019) 321–330. doi:https://doi.org/10.1016/j.foodhyd.2018.08.010 (accessed May 29, 2025).
[136] F. Sepe, A. Valentino, L. Marcolongo, O. Petillo, R. Conte, S. Margarucci, G. Peluso, A. Calarco, Marine-derived polysaccharide hydrogels as delivery platforms for natural bioactive compounds, Int. J. Mol. Sci. 26 (2025) 764, https://doi.org/10.3390/IJMS26020764.
[137] H. Zhang, J. Cheng, Q. Ao, Preparation of alginate-based biomaterials and their applications in biomedicine, Mar. Drugs 19 (2021) 264, https://doi.org/10.3390/MD19050264.
[138] J. Nishad, P. Wahi, S. Kumari, R. Negi, Hydrocolloids as Potential Additives, in: Advances in Pasta Technology, 2025, pp. 239–256, https://doi.org/10.1007/978-3-031-84497-3_11.
[139] J. Bak, B. Yoo, Rheological and tribological properties of hydroxypropyl methylcellulose-Fucoidan mixtures: effect of fucoidan concentration and salt, Food Bioproc. Tech. 18 (2024) 548–558, https://doi.org/10.1007/S11947-024-03468-Z/TABLES/6.
[140] J. Yang, R. Pal, Investigation of surfactant-polymer interactions using rheology and surface tension measurements, Polymers, mdpi.com 12 (2020). doi:https://doi.org/10.3390/polym12102302 (accessed May 29, 2025).
[141] C. Wen, N. Wang, Y. Dong, J. Tian, S. Song, H. Qi, Calcium-induced-gel properties for ι-carrageenan in the presence of different charged amino acids, LWT 146 (2021) 111418, https://doi.org/10.1016/J.LWT.2021.111418.
[142] K. Banaś, J. Harasym, Natural gums as oleogelators, Int. J. Mol. Sci. 22 (2021) 12977, https://doi.org/10.3390/IJMS222312977.
[143] B. Bakhai, Temperature-Dependent Study of Gelling Biopolymers Using Infrared Spectroscopy, 2022.
[144] J. Singthong, R. Oonsivilai, Structural and rheological properties of Yanang gum (*Tiliacora triandra*), Foods 11 (2022), https://doi.org/10.3390/FOODS11142003.
[145] X. Gao, S. Yang, J. You, T. Yin, S. Xiong, R. Liu, Changes in gelation properties of silver carp myosin treated by combination of high intensity ultrasound and NaCl, Foods 11 (2022), https://doi.org/10.3390/FOODS11233830.
[146] H. Niu, X. Chen, T. Luo, H. Chen, X. Fu, The interfacial behavior and long-term stability of emulsions stabilized by gum arabic and sugar beet pectin, Carbohydr. Polym. 291 (2022), https://doi.org/10.1016/J.CARBPOL.2022.119623.
[147] Y. Gao, R. Liu, H. Liang, Food hydrocolloids: structure, properties, and applications, Foods 13 (2024) 1077, https://doi.org/10.3390/FOODS13071077.
[148] X. Zhuang, L. Wang, X. Jiang, Y. Chen, G. Zhou, Insight into the mechanism of myofibrillar protein gel influenced by konjac glucomannan: moisture stability and phase separation behavior, Food Chem. 339 (2021) 127941, https://doi.org/10.1016/J.FOODCHEM.2020.127941.
[149] U. Bazylí Nska, R. Campardelli, Y. Tian, J. Zhou, C. He, L. He, X. Li, H. Sui, The formation, stabilization and separation of oil–water emulsions: a review, Processes, mdpi.com 10 (2022). doi:https://doi.org/10.3390/pr10040738.
[150] Z. Sun, X. Yan, Y. Xiao, L. Hu, M. Eggersdorfer, D. Chen, Z. Yang, D.A. Weitz, Pickering emulsions stabilized by colloidal surfactants: role of solid particles, Particuology 64 (2022) 153–163, https://doi.org/10.1016/J.PARTIC.2021.06.004.
[151] B. Murray, R. Ettelaie, A. Sarkar, A.R. Mackie, E. Dickinson, The perfect hydrocolloid stabilizer: imagination versus reality, Food Hydrocoll., Elsevier 117 (2021). doi:https://doi.org/10.1016/j.foodhyd.2021.106696.
[152] M. Alam, I. Majid, S. Kaur, B.N. Dar, V. Nanda, An updated review on exploring hydrocolloids application in food matrix: current insights into fruit, bakery, meat, and dairy based products, J. Texture Stud. 56 (2025), https://doi.org/10.1111/JTXS.70020.
[153] M. Ma, T. Mu, H. Sun, L. Zhou, Evaluation of texture, retrogradation enthalpy, water mobility, and anti-staling effects of enzymes and hydrocolloids in potato steamed bread, Food Chem. 368 (2022) 130686, https://doi.org/10.1016/J.FOODCHEM.2021.130686.
[154] B. Filipčev, M. Pojić, O. Šimurina, A. Mišan, A. Mandić, Psyllium as an improver in gluten-free breads: effect on volume, crumb texture, moisture binding and staling kinetics, LWT 151 (2021) 112156, https://doi.org/10.1016/J.LWT.2021.112156.
[155] M. Alam, S. Malakar, K. Pant, B.N. Dar, V. Nanda, Comparative studies on the rheological characteristics, functional attributes, and baking stability of xanthan and guar gum formulated honey gel matrix, Food Sci. Technol. Int. 31 (2023) 490–505, https://doi.org/10.1177/10820132231219715.
[156] M. Yousefi, S.M. Jafari, Recent advances in application of different hydrocolloids in dairy products to improve their techno-functional properties, Trends Food Sci. Technol. 88 (2019) 468–483, https://doi.org/10.1016/J.TIFS.2019.04.015.
[157] M. Alam, B.N. Dar, V. Nanda, Hydrocolloid-based fruit fillings: a comprehensive review on formulation, techno-functional properties, synergistic mechanisms, and applications, J. Texture Stud. 55 (2024) e12861, https://doi.org/10.1111/JTXS.12861.
[158] M. Alam, S. Kaur, B.N. Dar, V. Nanda, Classification, techno-functional properties, and applications of diverse hydrocolloids in fruits-based products: a concise review, J. Food Sci. 90 (2025) e70119, https://doi.org/10.1111/1750-3841.70119.
[159] N. Pematilleke, M. Kaur, C.T. Rai Wai, B. Adhikari, P.J. Torley, Effect of the addition of hydrocolloids on beef texture: targeted to the needs of people with dysphagia, Food Hydrocoll. 113 (2021) 106413, https://doi.org/10.1016/J.FOODHYD.2020.106413.
[160] A. Culetu, D.E. Duta, M. Papageorgiou, T. Varzakas, The role of hydrocolloids in gluten-free bread and pasta; rheology, characteristics, staling and glycemic index, Foods 10 (2021) 3121, https://doi.org/10.3390/FOODS10123121.
[161] G.B. Raj, K.K. Dash, Development of hydrocolloids incorporated dragon fruit leather by conductive hydro drying: characterization and sensory evaluation, Food Hydrocoll. Health 2 (2022) 100086, https://doi.org/10.1016/J.FHFH.2022.100086.
[162] S. Basiri, N. Haidary, S.S. Shekarforoush, M. Niakousari, Flaxseed mucilage: A natural stabilizer in stirred yogurt, Carbohydr. Polym. 187 (2018) 59–65, https://doi.org/10.1016/J.CARBPOL.2018.01.049.
[163] J. Sun, W. Yan Liu, M. Qin Feng, X. Lian Xu, G. Hong Zhou, Characterization of olive oil emulsions stabilized by flaxseed gum, J. Food Eng. 247 (2019) 74–79, https://doi.org/10.1016/J.JFOODENG.2018.11.023.
[164] E. Dickinson, Hydrocolloids acting as emulsifying agents – how do they do it? Food Hydrocoll. 78 (2018) 2–14, https://doi.org/10.1016/J.FOODHYD.2017.01.025.
[165] R. Peñalver, J.M. Lorenzo, G. Ros, R. Amarowicz, M. Pateiro, G. Nieto, Seaweeds as a functional ingredient for a healthy diet, Mar. Drugs 18 (2020), https://doi.org/10.3390/MD18060301.

[166] J. Gao, Z. Chen, P. Kaewprachu, C. Jaisan, Y. Liu, P. Sangsawad, A. Theppawong, S. Deng, N. Bunyameen, S. Kraithong, Structural and rheological properties of ulvan polysaccharides and their potential for food packaging applications, Food Chem. 488 (2025) 144850, https://doi.org/10.1016/J.FOODCHEM.2025.144850.
[167] V. Sasi Rekha, K. Sankar, S. Rajaram, P. Karuppiah, T.M.S. Dawoud, A. Syed, A. M. Elgorban, Unveiling the impact of additives on structural integrity, thermal and color stability of C-phycocyanin – agar hydrocolloid, Food Chem. 448 (2024) 139000, https://doi.org/10.1016/J.FOODCHEM.2024.139000.
[168] J. Praiboon, S. Chantorn, W. Krangkratok, P. Choosuwan, O. La-ongkham, Evaluating the prebiotic properties of agar oligosaccharides obtained from the red alga *Gracilaria fisheri* via enzymatic hydrolysis, Plants 12 (2023) 3958, https://doi.org/10.3390/PLANTS12233958.
[169] K.Y. Perera, S. Sharma, D. Pradhan, A.K. Jaiswal, S. Jaiswal, Seaweed polysaccharide in food contact materials (active packaging, intelligent packaging, edible films, and coatings), Foods 10 (2021) 2088, https://doi.org/10.3390/FOODS10092088.
[170] J. Solinho, S. Gonçalves, S. Machado, R. Pereira-Pinto, M. Vázquez, R. Pinheiro, Development of nutritionally enhanced fish burgers: integrating Atlantic bonito (*Sarda sarda*) with seaweed and hydrocolloids for sustainable food innovation, LWT 215 (2025) 117247, https://doi.org/10.1016/J.LWT.2024.117247.
[171] S. Bascuas, P. Morell, I. Hernando, A. Quiles, Recent trends in oil structuring using hydrocolloids, Food Hydrocoll. 118 (2021) 106612, https://doi.org/10.1016/J.FOODHYD.2021.106612.
[172] L. Hilliou, Structure–elastic properties relationships in gelling carrageenans, Polymers 13 (2021) 4120, https://doi.org/10.3390/POLYM13234120.
[173] X. Gao, H. Pourramezan, Y. Ramezan, S. Roy, W. Zhang, E. Assadpour, J. Zou, S. M. Jafari, Application of gums as techno-functional hydrocolloids in meat processing and preservation: a review, Int. J. Biol. Macromol. 268 (2024) 131614, https://doi.org/10.1016/J.IJBIOMAC.2024.131614.
[174] A. Carcelli, A. Albertini, E. Vittadini, E. Carini, A fibre syrup for the sugar reduction in fruit filling for bakery application, Int. J. Gastron. Food Sci. 28 (2022) 100545, https://doi.org/10.1016/J.IJGFS.2022.100545.
[175] F. Saberi, M. Karami, A. Shiri, M. Rasouli, R. Karimi, M. Kieliszek, Using grape pomace powder as a pectin replacer to prepare low water activity bake-stable fruit filling, J. Food Meas. Charact. 18 (2024) 4314–4322, https://doi.org/10.1007/S11694-024-02495-W/METRICS.
[176] B.K. Sharma Khanal, B. Bhandari, S. Prakash, N. Bansal, Simulated oral processing, in vitro digestibility and sensory perception of low fat Cheddar cheese containing sodium alginate, J. Food Eng. 270 (2020) 109749, https://doi.org/10.1016/J.JFOODENG.2019.109749.
[177] B. Duan, Y. Huang, A. Lu, L. Zhang, Recent advances in chitin based materials constructed via physical methods, Prog. Polym. Sci. 82 (2018) 1–33, https://doi.org/10.1016/J.PROGPOLYMSCI.2018.04.001.
[178] J.A. Tapia-Hernández, C.L. Del-Toro-Sánchez, F.J. Cinco-Moroyoqui, J.E. Juárez-Onofre, S. Ruiz-Cruz, E. Carvajal-Millan, G.A. López-Ahumada, D.D. Castro-Enriquez, C.G. Barreras-Urbina, F. Rodríguez-Felix, Prolamins from cereal by-products: classification, extraction, characterization and its applications in micro- and nanofabrication, Trends Food Sci. Technol. 90 (2019) 111–132, https://doi.org/10.1016/J.TIFS.2019.06.005.
[179] D. Ağagündüz, G. Özata-Uyar, B. Kocaadam-Bozkurt, A. Özturan-Şirin, R. Capasso, S. Al-Assaf, F. Özoğul, A comprehensive review on food hydrocolloids as gut modulators in the food matrix and nutrition: The hydrocolloid-gut-health axis, Food Hydrocoll. 145 (2023) 109068, https://doi.org/10.1016/j.foodhyd.2023.109068.
[180] L. Liu, W.L. Kerr, F. Kong, Characterization of lipid emulsions during in vitro digestion in the presence of three types of nanocellulose, J. Colloid Interface Sci. 545 (2019) 317–329, https://doi.org/10.1016/J.JCIS.2019.03.023.
[181] M. Alam, K. Pant, D.S. Brar, B.N. Dar, V. Nanda, Exploring the versatility of diverse hydrocolloids to transform techno-functional, rheological, and nutritional attributes of food fillings, Food Hydrocoll. 146 (2024) 109275, https://doi.org/10.1016/J.FOODHYD.2023.109275.
[182] D.J. McClements, Food hydrocolloids: application as functional ingredients to control lipid digestion and bioavailability, Food Hydrocoll. 111 (2021) 106404, https://doi.org/10.1016/J.FOODHYD.2020.106404.
[183] A. Taheri, S.M. Jafari, Gum-based nanocarriers for the protection and delivery of food bioactive compounds, Adv. Colloid Interface Sci. 269 (2019) 277–295, https://doi.org/10.1016/J.CIS.2019.04.009.
[184] Y. Wei, Z. Tong, L. Dai, D. Wang, P. Lv, J. Liu, L. Mao, F. Yuan, Y. Gao, Influence of interfacial compositions on the microstructure, physiochemical stability, lipid digestion and β-carotene bioaccessibility of Pickering emulsions, Food Hydrocoll., Elsevier (2020) 104, 105738. doi:https://doi.org/10.1016/j.foodhyd.2020.105738 (accessed May 29, 2025).
[185] M. Ajanth Praveen, K.R. Karthika Parvathy, R. Jayabalan, P. Balasubramanian, Dietary fiber from Indian edible seaweeds and its in-vitro prebiotic effect on the gut microbiota, Food Hydrocoll. 96 (2019) 343–353, https://doi.org/10.1016/J.FOODHYD.2019.05.031.
[186] E.S. Chambers, T. Preston, G. Frost, D.J. Morrison, Role of gut microbiota-generated short-chain fatty acids in metabolic and cardiovascular health, Curr. Nutr. Rep. 7 (2018) 198–206, https://doi.org/10.1007/S13668-018-0248-8.
[187] G. Wang, Y. Yu, Y.Z. Wang, J.J. Wang, R. Guan, Y. Sun, F. Shi, J. Gao, X.L. Fu, Role of SCFAs in gut microbiome and glycolysis for colorectal cancer therapy, J. Cell. Physiol. 234 (2019) 17023–17049, https://doi.org/10.1002/JCP.28436.
[188] Y. Qiu, H. Jiang, L. Fu, F. Ci, X. Mao, Porphyran and oligo-porphyran originating from red algae *Porphyra*: preparation, biological activities, and potential applications, Food Chem. 349 (2021) 129209, https://doi.org/10.1016/J.FOODCHEM.2021.129209.
[189] J. Qi, S.M. Kim, Effects of the molecular weight and protein and sulfate content of *Chlorella ellipsoidea* polysaccharides on their immunomodulatory activity, Int. J. Biol. Macromol. 107 (2018) 70–77, https://doi.org/10.1016/J.IJBIOMAC.2017.08.144.
[190] U. Surayot, S.M. Lee, S.G. You, Effects of sulfated fucan from the sea cucumber *Stichopus japonicus* on natural killer cell activation and cytotoxicity, Int. J. Biol. Macromol. 108 (2018) 177–184, https://doi.org/10.1016/J.IJBIOMAC.2017.11.102.
[191] L. Huang, M. Shen, G.A. Morris, J. Xie, Sulfated polysaccharides: immunomodulation and signaling mechanisms, Trends Food Sci. Technol. 92 (2019) 1–11, https://doi.org/10.1016/J.TIFS.2019.08.008.
[192] M. Qi, C. Zheng, W. Wu, G. Yu, P. Wang, Exopolysaccharides from marine microbes: source, structure and application, Mar. Drugs 20 (2022), https://doi.org/10.3390/MD20080512.
[193] G. Ribaudo, H. Thai Ha, D. Xuan Cuong, L. Huong Thuy, P. Thanh Thuan, D. Thi Thanh Tuyen, V. Thi Mo, D. Huu Dong, Carrageenan of red algae *Eucheuma gelatinae*: extraction, antioxidant activity, rheology characteristics, and physicochemistry characterization, Molecules, mdpi.com 27 (2022) 1268. doi:https://doi.org/10.3390/molecules27041268.
[194] H.M. Chen, X.J. Yan, F. Wang, W.F. Xu, L. Zhang, Assessment of the oxidative cellular toxicity of a κ-carrageenan oxidative degradation product towards Caco-2 cells, Food Res. Int. 43 (2010) 2390–2401, https://doi.org/10.1016/J.FOODRES.2010.09.019.
[195] N. Kimilu, K. Gładyś-Cieszyńska, M. Pieszko, D. Mańkowska-Wierzbicka, M. Folwarski, Carrageenan in the diet: friend or foe for inflammatory bowel disease? Nutrients 16 (2024) 1780 https://doi.org/10.3390/NU16111780.
[196] B.S. Reshma, T. Aavula, V. Narasimman, S. Ramachandran, M.M. Essa, M. W. Qoronfleh, Antioxidant and antiaging properties of agar obtained from brown seaweed *Laminaria digitata* (Hudson) in D-galactose-induced Swiss albino mice, Evid. Based Complement. Alternat. Med. 2022 (2022) 7736378, https://doi.org/10.1155/2022/7736378.
[197] P. Lukova, V. Kokova, A. Baldzhieva, M. Murdjeva, P. Katsarov, C. Delattre, E. Apostolova, Alginate from *Ericaria crinita* possesses antioxidant activity and attenuates systemic inflammation via downregulation of pro-inflammatory cytokines, Mar. Drugs 22 (2024) 482, https://doi.org/10.3390/MD22110482.
[198] I. Fajriaty, I. Fidrianny, N.F. Kurniati, N.M. Fauzi, S.H. Mustafa, I.K. Adnyana, In vitro and in silico studies of the potential cytotoxic, antioxidant, and HMG CoA reductase inhibitory effects of chitin from Indonesia mangrove crab (*Scylla serrata*) shells, Saudi J. Biol. Sci. 31 (2024) 103964, https://doi.org/10.1016/J.SJBS.2024.103964.
[199] M. Bai, W. Han, X. Zhao, Q. Wang, Y. Gao, S. Deng, Glycosaminoglycans from a sea snake (*Lapemis curtus*): extraction, structural characterization and antioxidant activity, Mar. Drugs, mdpi.com 16 (2018). doi:https://doi.org/10.3390/md16050170.
[200] Y. Lu, S. He, Z. Zhao, C. Liu, Y. Lei, M. Liu, Q. Zhang, D. Lin, Y. Liu, S. Lin, X. Lu, W. Qin, Structural characteristics, gelling properties, in vitro antioxidant activity and immunomodulatory effects of Rhamnogalacturonan-I rich pectic polysaccharides alkaline-extracted from wax apple (*Syzygium samarangense*), Foods 14 (2025) 1227, https://doi.org/10.3390/FOODS14071227.
[201] P. Dörschmann, S. Apitz, I. Hellige, S. Neupane, S. Alban, G. Kopplin, S. Ptak, X. Fretté, J. Roider, M. Zille, A. Klettner, Evaluation of the effects of fucoidans from fucus species and *Laminaria hyperborea* against oxidative stress and iron-dependent cell death, Mar. Drugs 19 (2021) 557, https://doi.org/10.3390/MD19100557.
[202] M.M. El-Sheekh, F. Ward, M.A. Deyab, M. Al-Zahrani, H.E. Touliabah, Chemical composition, antioxidant, and antitumor activity of fucoidan from the brown alga *Dictyota dichotoma*, Molecules 28 (2023) 7175, https://doi.org/10.3390/MOLECULES28207175.
[203] S. Zhou, H. Qin, Z. Long, L. Kong, J. Ma, Y. Lin, H. Lin, Z. Huang, Z. Li, Effects of laminarin on antioxidant capacity and non-specific immunity of spotted sea bass (*Lateolabrax maculatus*), Aquac. Rep. 40 (2025) 102549, https://doi.org/10.1016/J.AQREP.2024.102549.
[204] M. Fröba, M. Große, C. Setz, P. Rauch, J. Auth, L. Spanaus, J. Münch, N. Ruetalo, M. Schindler, M. Morokutti-Kurz, P. Graf, E. Prieschl-Grassauer, A. Grassauer, U. Schubert, Iota-carrageenan inhibits replication of sars-cov-2 and the respective variants of concern alpha, beta, gamma and delta, Int. J. Mol. Sci. 22 (2021), https://doi.org/10.3390/IJMS222413202.
[205] G.C. Porter, D.R. Schwass, G.R. Tompkins, S.K.R. Bobbala, N.J. Medlicott, C. J. Meledandri, AgNP/Alginate Nanocomposite hydrogel for antimicrobial and antibiofilm applications, Carbohydr. Polym. 251 (2021), https://doi.org/10.1016/J.CARBPOL.2020.117017.
[206] S.H. Shi, W.T. Yang, K.Y. Huang, Y.L. Jiang, G.L. Yang, C.F. Wang, Y. Li, β-glucans from Coriolus versicolor protect mice against *S. typhimurium* challenge by activation of macrophages, Int. J. Biol. Macromol. 86 (2016) 352–361, https://doi.org/10.1016/J.IJBIOMAC.2016.01.058.
[207] M. Alboofetileh, M. Rezaei, M. Tabarsa, M. Rittà, M. Donalisio, F. Mariatti, S. G. You, D. Lembo, G. Cravotto, Effect of different non-conventional extraction methods on the antibacterial and antiviral activity of fucoidans extracted from *Nizamuddinia zanardinii*, Int. J. Biol. Macromol. 124 (2019) 131–137, https://doi.org/10.1016/J.IJBIOMAC.2018.11.201.
[208] N. Oliyaei, M. Moosavi-Nasab, S.M. Mazloomi, Therapeutic activity of fucoidan and carrageenan as marine algal polysaccharides against viruses, 3 Biotech 12 (2022) 1–15, https://doi.org/10.1007/S13205-022-03210-6.

[209] M. Moosavi-Nasab, N. Oliyaei, J.B. Eun, A. Mirzapour-Kouhdasht, Innovation in the Seafood Sector through the Valorization of By-Products, in: Innovation in the Food Sector Through the Valorization of Food and, books.Google.Com, 2020 https://books.google.com/books?hl=en&lr=&id=tJw5EAAAQBAJ&oi=fnd&pg=PA117&ots=-o4fqIddwR&sig=waNOd7HyN-3ziStwk1Xt52maMLA (accessed May 29, 2025).

[210] S.F. Hosseini, M. Rezaei, D.J. McClements, Bioactive functional ingredients from aquatic origin: a review of recent progress in marine-derived nutraceuticals, Crit. Rev. Food Sci. Nutr., Taylor & Francis 62 (2022) 1242–1269. doi:https://doi.org/10.1080/10408398.2020.1839855.

[211] R. Zhao, Z. Qiu, X. Bai, L. Xiang, Y. Qiao, X. Lu, Digestive properties and prebiotic activity of garlic saccharides with different-molecular-weight obtained by acidolysis, Curr. Res. Food Sci. 5 (2022) 2033–2044, https://doi.org/10.1016/J.CRFS.2022.10.022.

[212] J. Li, Z. He, Y. Liang, T. Peng, Z. Hu, Insights into algal polysaccharides: A review of their structure, depolymerases, and metabolic pathways, J. Agric. Food Chem. 70 (2022) 1749–1765, https://doi.org/10.1021/ACS.JAFC.1C05365.

[213] N. Chaiwong, P. Leelapornpisid, K. Jantanasakulwong, P. Rachtanapun, P. Seesuriyachan, V. Sakdatorn, N. Leksawasdi, Y. Phimolsiripol, Antioxidant and moisturizing properties of carboxymethyl chitosan with different molecular weights, Polymers (Basel) 12 (2020) 1–14, https://doi.org/10.3390/POLYM12071445.

[214] X. Liu, S. Xu, X. Ding, D. Yue, J. Bian, X. Zhang, G. Zhang, P. Gao, Structural characteristics of *Medicago Sativa* L. Polysaccharides and Se-modified polysaccharides as well as their antioxidant and neuroprotective activities, Int. J. Biol. Macromol. 147 (2020) 1099–1106, https://doi.org/10.1016/J.IJBIOMAC.2019.10.078.

[215] P. Zou, X. Lu, C. Jing, Y. Yuan, Y. Lu, C. Zhang, L. Meng, H. Zhao, Y. Li, Low-molecular-weightt polysaccharides from *Pyropia yezoensis* enhance tolerance of wheat seedlings (*Triticum aestivum* L.) to salt stress, Front. Plant Sci., frontiersin.org 9 (2018). doi:https://doi.org/10.3389/FPLS.2018.00427.

[216] V.P. Chakka, T. Zhou, Carboxymethylation of polysaccharides: synthesis and bioactivities, Int. J. Biol. Macromol. 165 (2020) 2425–2431, https://doi.org/10.1016/J.IJBIOMAC.2020.10.178.

[217] S. Duan, M. Zhao, B. Wu, S. Wang, Y. Yang, Y. Xu, L. Wang, Preparation, characteristics, and antioxidant activities of carboxymethylated polysaccharides from blackcurrant fruits, Int. J. Biol. Macromol. 155 (2020) 1114–1122, https://doi.org/10.1016/J.IJBIOMAC.2019.11.078.

[218] L. Chen, G. Huang, Antioxidant activities of phosphorylated pumpkin polysaccharide, Int. J. Biol. Macromol. 125 (2019) 256–261, https://doi.org/10.1016/J.IJBIOMAC.2018.12.069.

[219] Z.W. Li, Z.M. Du, Y.W. Wang, Y.X. Feng, R. Zhang, X.B. Yan, Chemical modification, characterization, and activity changes of land plant polysaccharides: a review, Polymers 14 (2022) 4161, https://doi.org/10.3390/POLYM14194161.

[220] L. Şen, S. Okur, Effect of hazelnut type, hydrocolloid concentrations and ultrasound applications on physicochemical and sensory characteristics of hazelnut-based milks, Food Chem. 402 (2023) 134288, https://doi.org/10.1016/J.FOODCHEM.2022.134288.

[221] X.X. Pan, J.H. Tao, S. Jiang, Y. Zhu, D.W. Qian, J.A. Duan, Characterization and immunomodulatory activity of polysaccharides from the stems and leaves of *Abelmoschus manihot* and a sulfated derivative, Int. J. Biol. Macromol. 107 (2018) 9–16, https://doi.org/10.1016/J.IJBIOMAC.2017.08.130.

[222] S. Punia, Barley starch modifications: physical, chemical and enzymatic - a review, Int. J. Biol. Macromol. 144 (2020) 578–585, https://doi.org/10.1016/J.IJBIOMAC.2019.12.088.

[223] H. Rostamabadi, I. Demirkesen, B. Hakgüder Taze, A. Can Karaca, M. Habib, K. Jan, K. Bashir, M.R. Nemţanu, R. Colussi, S. Reza Falsafi, Ionizing and nonionizing radiations can change physicochemical, technofunctional, and nutritional attributes of starch, Food Chem.: X 19 (2023) 100771, https://doi.org/10.1016/J.FOCHX.2023.100771.

[224] N.L. Del Mastro, Polysaccharides and Radiation Technology, in: Radiation-Processed Polysaccharides: Emerging Roles in Agriculture, 2022, pp. 91–106, https://doi.org/10.1016/B978-0-323-85672-0.00015-5.

[225] J. Wang, Y. Wang, L. Xu, Q. Wu, Q. Wang, W. Kong, J. Liang, J. Yao, J. Zhang, Synthesis and structural features of phosphorylated *Artemisia sphaerocephala* polysaccharide, Carbohydr. Polym. 181 (2018) 19–26, https://doi.org/10.1016/J.CARBPOL.2017.10.049.

[226] L. Xie, M. Shen, P. Wen, Y. Hong, X. Liu, J. Xie, Preparation, characterization, antioxidant activity and protective effect against cellular oxidative stress of phosphorylated polysaccharide from *Cyclocarya paliurus*, Food Chem. Toxicol. 145 (2020), https://doi.org/10.1016/J.FCT.2020.111754.

[227] L. Malafronte, S. Yilmaz-Turan, A. Krona, M. Martinez-Sanz, F. Vilaplana, P. Lopez-Sanchez, Macroalgae suspensions prepared by physical treatments: effect of polysaccharide composition and microstructure on the rheological properties, Food Hydrocoll. 120 (2021) 106989, https://doi.org/10.1016/J.FOODHYD.2021.106989.

[228] K. Eha, T. Pehk, I. Heinmaa, A. Kaleda, K. Laos, Impact of short-term heat treatment on the structure and functional properties of commercial furcellaran compared to commercial carrageenans, Heliyon 7 (2021) e06640, https://doi.org/10.1016/j.heliyon.2021.e06640.

[229] T. Zhao, Y. Guo, S. Yan, N. Li, H. Ji, Q. Hu, M. Zhang, Q. Li, H. Gao, L. Yang, X. Wu, Preparation, structure characterization of carboxymethylated schisandra polysaccharides and their intervention in immunotoxicity to polychlorinated biphenyls, Process Biochem. 115 (2022) 30–41, https://doi.org/10.1016/J.PROCBIO.2022.02.005.

[230] H. Cheng, G. Huang, The antioxidant activities of carboxymethylated garlic polysaccharide and its derivatives, Int. J. Biol. Macromol. 140 (2019) 1054–1063, https://doi.org/10.1016/J.IJBIOMAC.2019.08.204.

[231] A.I. Barbosa, A.J. Coutinho, S.A. Costa Lima, S. Reis, Marine polysaccharides in pharmaceutical applications: fucoidan and chitosan as key players in the drug delivery match field, Mar. Drugs 17 (2019), https://doi.org/10.3390/MD17120654.

[232] X. Chen, Y. Wang, Y. Ye, H. Yu, B. Wu, The pre- and post-column derivatization on monosaccharide composition analysis, a review, Chem. Biodivers. 21 (2024) e202400749, https://doi.org/10.1002/CBDV.202400749.

[233] E. Quitério, C. Soares, R. Ferraz, C. Delerue-Matos, C. Grosso, Marine health-promoting compounds: recent trends for their characterization and human applications, Foods 10 (2021) 3100, https://doi.org/10.3390/FOODS10123100.

[234] O. Yildirim-Semerci, R. Onbas, R. Bilginer-Kartal, A. Arslan-Yildiz, Hydrocolloids for tissue engineering and 3D bioprinting, Innov. Emerg. Technol. 11 (2024), https://doi.org/10.1142/S2737599424400073.

[235] D. Knorr, M.A. Augustin, Food systems restoration, Sustain. Food Technol. 2 (2024) 1365–1390, https://doi.org/10.1039/D4FB00108G.

[236] J.B. Moreira, T.D. Santos, C.G. Cruz, J.T.D. Silveira, L.F.D. Carvalho, M.G. D. Morais, J.A.V. Costa, Algal polysaccharides-based nanomaterials: general aspects and potential applications in food and biomedical fields, Polysaccharides 4 (2023) 371–389, https://doi.org/10.3390/POLYSACCHARIDES4040022.

[237] A.P. Lipinska, J. Collén, S.A. Krueger-Hadfield, T. Mora, E. Ficko-Blean, To gel or not to gel: differential expression of carrageenan-related genes between the gametophyte and tetasporophyte life cycle stages of the red alga *Chondrus crispus*, Sci. Rep. 10 (2020) 1–14, https://doi.org/10.1038/s41598-020-67728-6.

[238] L. Reisky, A. Préchoux, M.-K. Zühlke, M. Bäumgen, N. Gerlach, T. Roret, C. Stanetty, R. Larocque, S. Tao, S. Markert, F. Unfried, M.D. Mihovilovic, D. Becher, T. Schweder, U.T. Bornscheuer, A marine bacterial enzymatic cascade degrades the algal polysaccharide ulvan, Nature Chemical Biology nature.com (2019) 15, 803–812. doi:https://doi.org/10.1038/s41589-019-0311-9 (accessed May 30, 2025).

[239] A.G. Hettle, J.K. Hobbs, B. Pluvinage, C. Vickers, K.T. Abe, O. Salama-Alber, B.E. Mcguire, J.-H. Hehemann, J.P.M. Hui, F. Berrue, A. Banskota, J. Zhang, E.M. Bottos, J. Van Hamme, A.B. Boraston, Insights into the κ/ι-carrageenan metabolism pathway of some marine Pseudoalteromonas species, Commun. Biol. nature.com (2019) 2 474. doi:https://doi.org/10.1038/s42003-019-0721-y.

[240] M. Schultz-Johansen, P.K. Bech, R.C. Hennessy, M.A. Glaring, T. Barbeyron, M. Czjzek, P. Stougaard, A novel enzyme portfolio for red algal polysaccharide degradation in the marine bacterium paraglaciecola hydrolytica S66T encoded in a sizeable, Front. Microbiol., frontiersin.org 9 (2018). doi:https://doi.org/10.3389/FMICB.2018.00839.

[241] J. Long, Z. Ye, X. Li, Y. Tian, Y. Bai, L. Chen, C. Qiu, Z. Xie, Z. Jin, B. Svensson, Enzymatic preparation and potential applications of agar oligosaccharides: a review, Crit. Rev. Food Sci. Nutr. 64 (2024) 5818–5834, https://doi.org/10.1080/10408398.2022.2158452.

[242] F. Liu, D.J. McClements, C. Ma, X. Liu, Novel colloidal food ingredients: protein complexes and conjugates, Annu. Rev. Food Sci. Technol. 14 (2023) 35–61, https://doi.org/10.1146/ANNUREV-FOOD-060721-023522.

[243] H. Jafari, C. Delporte, K.V. Bernaerts, H. Alimoradi, L. Nie, D. Podstawczyk, K. C. Tam, A. Shavandi, Synergistic complexation of phenol functionalized polymer induced in situ microfiber formation for 3D printing of marine-based hydrogels, Green Chem. 24 (2022) 2409–2422, https://doi.org/10.1039/D1GC04347A.

[244] S.R. Falsafi, H. Rostamabadi, K. Samborska, S. Mirarab, A. Rashidinejhad, S. M. Jafari, Protein-polysaccharide interactions for the fabrication of bioactive-loaded nanocarriers: chemical conjugates and physical complexes, Pharmacol. Res. 178 (2022) 106164, https://doi.org/10.1016/J.PHRS.2022.106164.

[245] Y. Li, Z. Wan, S. Zhao, H. Lu, D.J. McClements, X. Liu, F. Liu, Development of zein-based complexes and conjugates with enhanced surface hydrophilicity: structure, emulsifying, foaming, and antioxidant properties, Food Hydrocoll. 154 (2024) 110064, https://doi.org/10.1016/J.FOODHYD.2024.110064.

[246] S. Baksi, D. Saha, S. Saha, U. Sarkar, D. Basu, J.C. Kuniyal, Pre-treatment of lignocellulosic biomass: review of various physico-chemical and biological methods influencing the extent of biomass depolymerization, Int. J. Environ. Sci. Technol. 20 (2023) 13895–13922, https://doi.org/10.1007/S13762-023-04838-4.

[247] J.S. Gomes-Dias, J.A. Teixeira, C.M.R. Rocha, Recent advances in the valorization of algae polysaccharides for food and nutraceutical applications: a review on the role of green processing technologies, Food Bioprocess Technol. 15 (2022) 1948–1976, https://doi.org/10.1007/S11947-022-02812-5.

[248] D. Jaison, G. Chandrasekaran, M. Mothilal, pH-sensitive natural almond gum hydrocolloid based magnetic nanocomposites for theragnostic applications, Int. J. Biol. Macromol. 154 (2020) 256–266, https://doi.org/10.1016/J.IJBIOMAC.2020.03.103.

[249] M. Ahmad, P. Mudgil, A. Gani, F. Hamed, F.A. Masoodi, S. Maqsood, Nano-encapsulation of catechin in starch nanoparticles: characterization, release behavior and bioactivity retention during simulated in-vitro digestion, Food Chem. 270 (2019) 95–104, https://doi.org/10.1016/J.FOODCHEM.2018.07.024.

[250] J.J. Ferguson, E. Stojanovski, L. MacDonald-Wicks, M.L. Garg, High molecular weight oat β-glucan enhances lipid-lowering effects of phytosterols. A randomised controlled trial, Clin. Nutr. 39 (2020) 80–89, https://doi.org/10.1016/j.clnu.2019.02.007.

[251] P.O.C. Alencar, G.C. Lima, F.C.N. Barros, L.E.C. Costa, C.V.P.E. Ribeiro, W. M. Sousa, V.G. Sombra, C.M.W.S. Abreu, E.S. Abreu, E.O.B. Pontes, A.C. Oliveira, R.C.M. de Paula, A.L.P. Freitas, A novel antioxidant sulfated polysaccharide from

the algae *Gracilaria caudata*: in vitro and in vivo activities, Food Hydrocoll. 90 (2019) 28–34, https://doi.org/10.1016/J.FOODHYD.2018.12.007.
[252] Y. Luo, Food colloids binary and ternary nanocomplexes: innovations and discoveries, Colloids Surf. B Biointerfaces 196 (2020) 111309, https://doi.org/10.1016/J.COLSURFB.2020.111309.
[253] Y. Luo, Perspectives on important considerations in designing nanoparticles for oral delivery applications in food, J. Agric. Food Res. 2 (2020) 100031, https://doi.org/10.1016/J.JAFR.2020.100031.
[254] B. Qu, Y. Luo, Chitosan-based hydrogel beads: preparations, modifications and applications in food and agriculture sectors – a review, Int. J. Biol. Macromol. 152 (2020) 437–448, https://doi.org/10.1016/J.IJBIOMAC.2020.02.240.
[255] A. George, P.A. Shah, P.S. Shrivastav, Guar gum: versatile natural polymer for drug delivery applications, Eur. Polym. J. 112 (2019) 722–735, https://doi.org/10.1016/J.EURPOLYMJ.2018.10.042.
[256] L. Maldonado, S. Chough, J. Bonilla, K.H. Kim, J. Kokini, Mechanism of fabrication and nano-mechanical properties of α-lactalbumin/chitosan and BSA/κ-carrageenan nanotubes through layer-by-layer assembly for curcumin encapsulation and determination of in vitro cytotoxicity, Food Hydrocoll. 93 (2019) 293–307, https://doi.org/10.1016/J.FOODHYD.2019.02.040.
[257] Y. Zhao, H. Khalesi, J. He, Y. Fang, Application of different hydrocolloids as fat replacer in low-fat dairy products: ice cream, yogurt and cheese, Food Hydrocoll. 138 (2023) 108493, https://doi.org/10.1016/J.FOODHYD.2023.108493.
[258] J. Zang, P. Xiao, Y. Chen, Z. Liu, D. Tang, Y. Liu, J. Chen, Y. Tu, Z. Yin, Hydrocolloid application in yogurt: progress, challenges and future trends, Food Hydrocoll. 153 (2024) 110069, https://doi.org/10.1016/J.FOODHYD.2024.110069.
[259] M. Arab, M. Yousefi, E. Khanniri, M. Azari, V. Ghasemzadeh-Mohammadi, N. Mollakhalili-Meybodi, A comprehensive review on yogurt syneresis: effect of processing conditions and added additives, J. Food Sci. Technol. 60 (2023) 1656–1665, https://doi.org/10.1007/S13197-022-05403-6.
[260] P.R. Mary, S. Mutturi, M. Kapoor, Non-enzymatically hydrolyzed guar gum and orange peel fibre together stabilize the low-fat, set-type yogurt: a techno-functional study, Food Hydrocoll. 122 (2022) 107100, https://doi.org/10.1016/J.FOODHYD.2021.107100.
[261] F. Javidi, S.M.A. Razavi, New hydrocolloids in ice cream, in: Emerging Natural Hydrocolloids: Rheology and Functions, 2019, pp. 525–547, https://doi.org/10.1002/9781119418511.
[262] A. Kurt, I. Atalar, Effects of quince seed on the rheological, structural and sensory characteristics of ice cream, Food Hydrocoll. 82 (2018) 186–195, https://doi.org/10.1016/J.FOODHYD.2018.04.011.
[263] P. Abuengmoh, D. Ahure, N.N. Igoli, Proximate, vitamin and mineral composition of bread produced from wheat, banana and mango flour blends. www.foodsciencejournal.com, 2022 (accessed May 31, 2025).
[264] F. Salehi, Effect of common and new gums on the quality, physical, and textural properties of bakery products: a review, J. Texture Stud. 51 (2020) 361–370, https://doi.org/10.1111/JTXS.12482.
[265] Y. Li, J. Guo, Y. Wang, F. Zhang, S. Chen, Y. Hu, M. Zhou, Effects of hydrocolloids as fat-replacers on the physicochemical and structural properties of salt-soluble protein isolated from water-boiled pork meatballs, Meat Sci. 204 (2023) 109280, https://doi.org/10.1016/J.MEATSCI.2023.109280.
[266] E.A. Irondi, Y.T. Imam, E.O. Ajani, E.O. Alamu, Natural and modified food hydrocolloids as gluten replacement in baked foods: functional benefits, Grain Oil Sci. Technol. 6 (2023) 163–171, https://doi.org/10.1016/J.GAOST.2023.10.001.
[267] S.W. Horstmann, C. Axel, E.K. Arendt, Water absorption as a prediction tool for the application of hydrocolloids in potato starch-based bread, Food Hydrocoll. 81 (2018) 129–138, https://doi.org/10.1016/J.FOODHYD.2018.02.045.
[268] T. Di Renzo, M.C. Trivisonno, S. Nazzaro, A. Reale, M.C. Messia, Effect of different hydrocolloids on the qualitative characteristics of fermented gluten-free quinoa dough and bread, Foods 13 (2024) 1382, https://doi.org/10.3390/FOODS13091382/S1.
[269] S. Saeidy, A. Nasirpour, S. Barekat, Effect of sugar beet fiber and different hydrocolloids on rheological properties and quality of gluten-free muffins, J. Sci. Food Agric. 103 (2023) 1404–1411, https://doi.org/10.1002/JSFA.12234.
[270] M. Krempel, K. Griffin, H. Khouryieh, Hydrocolloids as Emulsifiers and Stabilizers in Beverage Preservation, in: Preservatives and Preservation Approaches in Beverages: Volume 15: The Science of Beverages, 2019, pp. 427–465, https://doi.org/10.1016/B978-0-12-816685-7.00013-6.
[271] L. Staubmann, A. Mistlberger-Reiner, E.M. Raoui, G. Brunner, L. Sinawehl, M. Winter, R. Liska, M. Pignitter, Combinations of hydrocolloids show enhanced stabilizing effects on cloudy orange juice ready-to-drink beverages, Food Hydrocoll. 138 (2023) 108436, https://doi.org/10.1016/J.FOODHYD.2022.108436.
[272] P. Aggarwal, V. Kumar, M. Yaqoob, S. Kaur, N. Babbar, Effect of different levels of hydrocolloids on viscosity and cloud stability of kinnow juice and beverages, J. Food Process. Preserv., Wiley Online Library 44 (2020). doi:https://doi.org/10.1111/JFPP.14802.
[273] Y. Ni, Z. Zhang, L. Fan, J. Li, Evaluation of physical stability of high pressure homogenization treatment cloudy ginkgo beverages, LWT, Elsevier 111 (2019). doi:https://doi.org/10.1016/j.lwt.2019.05.008 (accessed May 31, 2025).
[274] W. Yu, J. Cui, S. Zhao, L. Feng, Y. Wang, J. Liu, J. Zheng, Effects of high-pressure homogenization on pectin structure and cloud stability of not-from-concentrate orange juice, Front. Nutr., frontiersin.org 8 (2021). doi:https://doi.org/10.3389/FNUT.2021.647748.
[275] K.H. Erna, K. Rovina, S. Mantihal, Current detection techniques for monitoring the freshness of meat-based products: a review, J. Packag. Technol. Res. 5 (2021) 127–141, https://doi.org/10.1007/S41783-021-00120-5.
[276] M. Sharma, L. Duizer, Characterizing the dynamic textural properties of hydrocolloids in pureed foods—a comparison between TDS and TCATA, Foods 8 (2019) 184, https://doi.org/10.3390/FOODS8060184.
[277] N. Pematilleke, M. Kaur, B. Adhikari, P.J. Torley, Meat texture modification for dysphagia management and application of hydrocolloids: a review, Crit. Rev. Food Sci. Nutr. 64 (2024) 1764–1779, https://doi.org/10.1080/10408398.2022.2119202.
[278] N. Pematilleke, M. Kaur, B. Adhikari, P.J. Torley, Investigation of the effects of addition of carboxy methyl cellulose (CMC) and tapioca starch (TS) on the beef patties targeted to the needs of people with dysphagia: a mixture design approach, Meat Sci. 191 (2022) 108868, https://doi.org/10.1016/J.MEATSCI.2022.108868.
[279] N. Jommark, S. Chantarathepthimakul, P. Ratana-arporn, Effect of phosphates substitution with carboxymethyl cellulose and konjac glucomannan on quality characteristics of low-fat emulsion sausage, J. Food Process. Preserv. 46 (2022) e16256, https://doi.org/10.1111/JFPP.16256.
[280] B. Ferjančič, S. Kugler, M. Korošec, T. Polak, J. Bertoncelj, Development of low-fat chicken bologna sausages enriched with inulin, oat fibre or psyllium, Int. J. Food Sci. Technol. 56 (2021) 1818–1828, https://doi.org/10.1111/IJFS.14808.
[281] B.A.A. Abdulrahem, I.M.K. Al-Aubadi, M.M.A. Mohamed, Effect of concentrations of basil seed gum on the sensory properties of chicken sausage, Basrah J. Agric. Sci. 35 (2022) 229–242, https://doi.org/10.37077/25200860.2022.35.1.17.
[282] M. Garcia-Vaquero, Advances in hydrocolloids for food applications: natural sources, bioactivity and delivery systems, Food Hydrocoll. Health 4 (2023) 100172, https://doi.org/10.1016/J.FHFH.2023.100172.
[283] S. Pirsa, K. Hafezi, Hydrocolloids: structure, preparation method, and application in food industry, Food Chem. 399 (2023) 133967, https://doi.org/10.1016/J.FOODCHEM.2022.133967.
[284] Sajad Pirsa, K. Hafezi, Hydrocolloids: structure, preparation method, and application in food and pharmaceutical industries, 2022, https://doi.org/10.21203/RS.3.RS-1582020/V1.
[285] M.Y.F. Koko, H.A.M. Hassanin, B. Qi, L. Han, K. Lu, S. Rokayya, Y. Harimana, S. Zhang, Y. Li, Hydrocolloids as promising additives for food formulation consolidation: a short review, Food Rev. Intl. 39 (2023) 1433–1439, https://doi.org/10.1080/87559129.2021.1934004.
[286] L.L. Tan, M. Mahotra, S.Y. Chan, S.C.J. Loo, In situ alginate crosslinking during spray-drying of lactobacilli probiotics promotes gastrointestinal-targeted delivery, Carbohydr. Polym. 286 (2022) 119279, https://doi.org/10.1016/J.CARBPOL.2022.119279.
[287] F. Liu, S. Zhang, K. Chen, Y. Zhang, Fabrication, in-vitro digestion and pH-responsive release behavior of soy protein isolate glycation conjugates-based hydrogels, Food Res. Int. 169 (2023) 112884, https://doi.org/10.1016/J.FOODRES.2023.112884.
[288] M. Semenova, A. Antipova, E. Martirosova, D. Zelikina, N. Palmina, S. Chebotarev, Essential contributions of food hydrocolloids and phospholipid liposomes to the formation of carriers for controlled delivery of biologically active substances via the gastrointestinal tract, Food Hydrocoll. 120 (2021) 106890, https://doi.org/10.1016/J.FOODHYD.2021.106890.
[289] Z. Yang, D.J. McClements, C. Li, S. Sang, L. Chen, J. Long, C. Qiu, Z. Jin, Targeted delivery of hydrogels in human gastrointestinal tract: a review, Food Hydrocoll. 134 (2023) 108013, https://doi.org/10.1016/J.FOODHYD.2022.108013.
[290] M.I. Shaik, S.H.A. Rahman, A.S. Yusri, M.R. Ismail-Fitry, N.S.S. Kumar, N. M. Sarbon, A review on the processing technique, physicochemical, and bioactive properties of marine collagen, J. Food Sci. 89 (2024) 5205–5229, https://doi.org/10.1111/1750-3841.17273.
[291] S. Sid, M. Alam, M. Islam, Y. Kumar, R.S. Mor, A. Kishore, N. Kumar, Characterization and quality attributes of spray-dried Kinnow peel powder using maltodextrin and gum arabic, J. Food Process Eng. 46 (2023) e14488, https://doi.org/10.1111/JFPE.14488.
[292] S.V. Medina-López, C.M. Zuluaga-Domínguez, J.P. Fernández-Trujillo, M. S. Hernández-Gómez, Nonconventional hydrocolloids' technological and functional potential for food applications, Foods 11 (2022) 401, https://doi.org/10.3390/FOODS11030401.
[293] A.C. Cichella Frabetti, J.O. de Moraes, A.S. Porto, R. da S. Simão, J.B. Laurindo, Strawberry-hydrocolloids dried by continuous cast-tape drying to produce leather and powder, Food Hydrocoll. 121 (2021) 107041, https://doi.org/10.1016/J.FOODHYD.2021.107041.
[294] B.U. Aktar, A.K. İshak, D. Ozmen, H.E. Tuna Ağırbaş, O. Atıl, O.S. Toker, Can rheometer be used for determination of baking stability of cocoa based filling creams, J. Food Eng. 387 (2025) 112320, https://doi.org/10.1016/J.JFOODENG.2024.112320.
[295] R.A. Bhure, M. Alam, V. Nanda, V.M. Pawar, S. Saxena, Exploring the impact of thermal processing on the quality attributes of honey: a comprehensive review, J. Food Process. Eng. 48 (2025) e70033, https://doi.org/10.1111/JFPE.70033.
[296] S. Dasgupta, A. Noor, *Citrus sinensis* enriched polyphenols loaded alginate microspheres: characterization, stability, in vitro release, bio-accessibility, and biological activities, Food Biosci. 68 (2025) 106743, https://doi.org/10.1016/J.FBIO.2025.106743.
[297] E.A. Günter, V.V. Martynov, V.S. Belozerov, E.A. Martinson, S.G. Litvinets, Characterization and swelling properties of composite gel microparticles based on the pectin and κ-carrageenan, Int. J. Biol. Macromol. 164 (2020) 2232–2239, https://doi.org/10.1016/J.IJBIOMAC.2020.08.024.
[298] T. Udo, G. Mummaleti, A. Mohan, R.K. Singh, F. Kong, Current and emerging applications of carrageenan in the food industry, Food Res. Int. 173 (2023) 113369, https://doi.org/10.1016/J.FOODRES.2023.113369.

[299] S. Russo Spena, R. Pasquino, N. Grizzuti, K-carrageenan/locust bean gum gels for food applications—A critical study on potential alternatives to animal-based gelatin, Foods 13 (2024) 2575, https://doi.org/10.3390/FOODS13162575/S1.

[300] M. Pateiro, B. Gómez, P.E.S. Munekata, F.J. Barba, P. Putnik, D.B. Kovačević, J. M. Lorenzo, Nanoencapsulation of promising bioactive compounds to improve their absorption, stability, functionality and the appearance of the final food products, Molecules 26 (2021), https://doi.org/10.3390/MOLECULES26061547.

[301] M.H. Ghazali, K.M. Keener, Y. Pan, S. Zou, J.-H. Cheng, Cold plasma-integrated bio-based packaging for meat quality and safety monitoring: a mini review, Food Wellness 1 (2025) 100004, https://doi.org/10.1016/J.FOODW.2025.100004.

[302] A. Prasetyaningrum, B.S. Wicaksono, A. Hakiim, A.D. Ashianti, S.F.C. Manalu, N. Rokhati, D.P. Utomo, M. Djaeni, Ultrasound-assisted encapsulation of citronella oil in alginate/carrageenan beads: characterization and kinetic models, ChemEngineering 7 (2023) 10, https://doi.org/10.3390/CHEMENGINEERING7010010.

[303] T. Ramdhan, S.H. Ching, S. Prakash, B. Bhandari, Physical and mechanical properties of alginate based composite gels, Trends Food Sci. Technol. 106 (2020) 150–159, https://doi.org/10.1016/J.TIFS.2020.10.002.

[304] A. Dick, X. Dong, B. Bhandari, S. Prakash, The role of hydrocolloids on the 3D printability of meat products, Food Hydrocoll. 119 (2021), https://doi.org/10.1016/J.FOODHYD.2021.106879.

[305] M.L. Medeleanu, S.P. Sanchez, G.M. Cătunescu, A.B. Cerezo, Risk assessment of food additives including dietary exposure, EFSA J. 22 (2024) e221110, https://doi.org/10.2903/J.EFSA.2024.E221110.

[306] P. Komisarska, A. Pinyosinwat, M. Saleem, M. Szczuko, Carrageenan as a potential factor of inflammatory bowel diseases, Nutrients 16 (2024) 1367, https://doi.org/10.3390/NU16091367.

[307] T.S. Parreidt, K. Müller, M. Schmid, Alginate-based edible films and coatings for food packaging applications, Foods 7 (2018) 170, https://doi.org/10.3390/FOODS7100170.

[308] M. Younes, P. Aggett, F. Aguilar, R. Crebelli, M. Filipič, M.J. Frutos, P. Galtier, D. Gott, U. Gundert-Remy, G.G. Kuhnle, C. Lambré, J.C. Leblanc, I.T. Lillegaard, P. Moldeus, A. Mortensen, A. Oskarsson, I. Stankovic, I. Waalkens-Berendsen, R. A. Woutersen, M. Wright, L. Brimer, O. Lindtner, P. Mosesso, A. Christodoulidou, S. Ioannidou, F. Lodi, B. Dusemund, Re-evaluation of carrageenan (E 407) and processed Eucheuma seaweed (E 407a) as food additives, EFSA J. 16 (2018) e05238, https://doi.org/10.2903/J.EFSA.2018.5238.

[309] Entering the European market for seaweed hydrocolloids, CBI, 2023. https://www.cbi.eu/market-information/natural-food-additives/seaweed-hydrocolloids/market-entry (accessed May 31, 2025).

[310] L. Zhang, W. Liao, Y. Huang, Y. Wen, Y. Chu, C. Zhao, Global seaweed farming and processing in the past 20 years, Food Prod. Process. Nutr. 4 (2022) 1–29, https://doi.org/10.1186/S43014-022-00103-2.

[311] R. Pravin, G. Baskar, S.L. Rokhum, A. Pugazhendhi, Comprehensive assessment of biorefinery potential for biofuels production from macroalgal biomass: towards a sustainable circular bioeconomy and greener future, Chemosphere 339 (2023), https://doi.org/10.1016/J.CHEMOSPHERE.2023.139724.