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REVIEW ARTICLE

Macroalgae-derived hydrocolloids and their applications in food industry and their health effects

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Abstract

The growing global demand for sustainable food sources has intensified interest in macroalgae as an ecologically efficient and nutrient-rich biomass. Macroalgae are an important industrial source of hydrocolloids such as carrageenan, agar, alginate, ulvan, and fucoidan, which are widely used in the food, pharmaceutical, and cosmetic industries due to their gel-forming, thickening, and stabilizing properties. These polysaccharides exhibit not only outstanding techno-functional capabilities such as gel formation, thickening, stabilization, and viscosity europemodification, but also important biological activities such as antioxidant, anti-inflammatory, antimicrobial, and anticancer effects. Furthermore, the chemical composition and bioactivity of macroalgae vary significantly depending on the species, environment, and extraction conditions, which requires systematic comparisons and optimization. This review summarizes the chemistry of hydrocolloids derived from macroalgae, extraction techniques, structure-function interactions, and recent developments in their practical applications in food processing. Additionally, their bioactive properties, including antioxidant, antimicrobial, immunomodulatory, and metabolism-related effects, are evaluated from a health perspective based on current experimental data. This study specifically compares traditional and newly emerging extraction strategies and relates their technological-functional performance in food systems to their potential roles as health-promoting agents. In contrast to previous studies that typically emphasize technological applications or biological activity separately, this review synthesizes both perspectives to provide a comprehensive understanding of macroalgal hydrocolloids. This synthesis consolidates existing knowledge and establishes a perception-focused integrated framework that can guide future innovations in the development of next-generation food applications and advanced biomaterials.

Keywords Carrageenan · Fucoidan · Ulvan · Agar · Alginate

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Introduction

The global population is expected to reach approximately 9.8 billion by 2050, which will further deepen current challenges related to food security, nutritional adequacy, and sustainable resource use. Traditional agriculture and livestock systems contribute significantly to greenhouse gas emissions, highlighting the need for alternative biomass sources that are compatible with low-impact production strategies [1, 2]. In this regard, macroalgae are gaining increasing attention due to their rapid growth rates, rich biochemical composition, diverse bioactive components, and suitability for integration into future food supply frameworks [3, 4]

Macroalgae (seaweeds) represent an ecologically important and taxonomically diverse group of photosynthetic aquatic organisms [5, 6]. They contain valuable primary nutrients such as proteins, lipids, dietary fiber, carbohydrates, vitamins, and essential minerals, as well as secondary metabolites such as carotenoids, alkaloids, phenolics, terpenes, sulfated polysaccharides, and phytosterols. Most of these compounds show antioxidant, anti-inflammatory, antimicrobial, antifungal, and anticancer properties, making macroalgae an important natural source of nutraceuticals and functional food components [5, 7, 8].

Today, macroalgae are harvested in approximately 50 countries, and around 300 species are commercially exploited. According to the Food and Agriculture Organization (FAO) records, global macroalgae production has increased significantly, rising from 34.7 thousand tons in 1950 to 34.7 million tons in 2019, with 97% of this coming from aquaculture [9]. These are generally classified as Chlorophyta (green), Phaeophyta (brown), and Rhodophyta (red), representing 1%, 46%, and 54% of global production, respectively [5, 9].

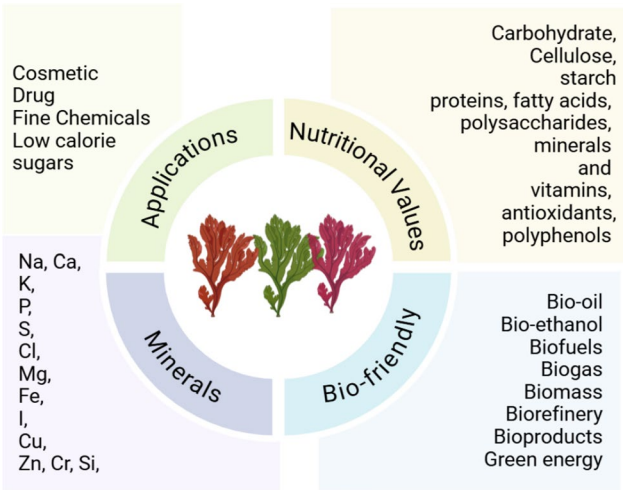

Fig. 1 Macro- and micronutrients composition of macroalgae and their applications (Created from Microsoft PowerPoint)

Significantly, macroalgae constitute the most abundant biological source of hydrocolloids such as agar, alginate, carrageenan, ulvan and fucoidan which are widely used in the food industry as thickeners, stabilizers, emulsifiers and gelling agents [3, 6, 10, 11]. Compared with terrestrial hydrocolloids like pectin and starch, macroalgal hydrocolloids generally exhibit superior functional properties and unique structural characteristics. These properties are primarily attributed to the presence of sulfate ester groups in carrageenan and fucoidan [12, 13]. Such structural characteristics enhance solubility, water-binding capacity, network formation, and gel strength, thereby expanding their applicability not only in food formulations but also in bioactive packaging materials [3, 12, 14].

Although algal polysaccharides have been the subject of numerous studies [15–17], there is still no comprehensive publication that simultaneously examines hydrocolloids obtained from macroalgae, their extraction, technological applications in food systems, and related health effects. This review aims to fill this gap by critically evaluating the current knowledge on the structure, extraction strategies, industrial use, and bioactive properties of carrageenan, agar, alginate, ulvan, and fucoidan, while also highlighting the challenges and future opportunities for large-scale application.

Chemical composition and health effects of macroalgae

Macroalgae, as sessile organisms, are constantly exposed to environmental stress factors such as fluctuations in temperature and salinity, ultraviolet radiation, and anthropogenic pollutants. To withstand these conditions, they synthesize a wide variety of secondary metabolites, including pigments (fucoxanthin, phycobiliproteins, chlorophylls), phenolic compounds, alkaloids, terpenes, sulfated polysaccharides, and phytosterols, most of these exhibit antioxidant, antimicrobial, anti-inflammatory and anticancer activities [5, 7, 8]. In addition, macroalgae are rich in macronutrients such as carbohydrates proteins, lipids, dietary fiber and moisture, as well as essential micronutrients including minerals (Ca, Mg, Na, K, P, Cu, Fe, Mn, Se, Zn) and vitamins (A, C, E), which contribute to their nutritional and commercial value [9, 18–20]. These compounds not only enhance dietary diversity but also provide a basis for novel nutraceutical, pharmaceutical and functional food applications [19–21]. The macro- and micronutrient composition of various macroalgal species is illustrated in Fig. 1.

Seaweeds have a diverse biochemical profile encompassing both nutritional components and bioactive metabolites. In terms of bioactive antioxidant components, these species are particularly rich in polyphenols, tocopherols,

mycosporine-like amino acids, and photosynthetic pigments such as carotenoids, chlorophylls, and phycobilins. Phytochemical screens confirmed the presence of tannins, saponins, alkaloids, and flavonoids in different taxa. *Enteromorpha intestinalis* exhibited the highest chlorophyll content (1.57 mg/g), while *Sargassum asperum* contained the highest carotenoid level (0.19 mg/g). In addition, *Gracilaria tenuistipitata* gave the highest agar content under alkaline extraction with 6% NaOH, and *Hypnea boergesenii* showed moderate antioxidant capacity (IC_{50} = 91.06 ± 6.44 µg/mL). Together, these findings support the potential of seaweeds as pharmacologically important functional food ingredients [21]. However, significant compositional differences among species highlight the need for species-specific assessment. For example, the brown algae *Turbinaria decurrens* exhibited relatively lower antioxidant potential with a phenolic content of 4.62 ± 0.3 mg GAE/g and antioxidant value of 14.75 ± 0.13%. While these patterns are partially consistent with general trends (such as red algae typically exhibiting higher phenolic and flavonoid levels), they do not fully align with all previous reports [20]. Differences in chemical structure, such as the degree of sulfation, branching patterns, and molecular weight of polysaccharides, play a critical role in regulating bioactivity, along with environmental factors and extraction conditions. Therefore, understanding structure–activity relationships is crucial to identifying species with the highest functional food potential.

Macroalgae can contribute to a balanced diet and represent a promising functional food source due to their nutritional composition, bioactive metabolites and sensory attributes, all of which support human well-being [19, 22]. Disruption of cellular redox homeostasis leads to oxidative stress and excessive generation of reactive oxygen species (ROS), resulting in biomolecular damage that drives the development of numerous chronic diseases [23]. Like terrestrial photosynthetic organisms, macroalgae possess antioxidant defense systems capable of neutralizing ROS and protecting macromolecules such as proteins, lipids, enzymes, DNA and RNA from oxidative injury [24]. Previous studies also indicate antiproliferative potential, demonstrating that macroalgal extracts reduce cancer cell viability, induce apoptosis, and limit lipid and glucose accumulation [25]. These biochemical outcomes provide the mechanistic rationale for the health-promoting pathways summarized in Fig. 2.

Figure 2 schematically illustrates the protective and therapeutic roles of macroalgal bioactive compounds in human health. Green, brown and red seaweeds constitute rich sources of polyphenols, carotenoids, chlorophylls, vitamins and sulfated polysaccharides that attenuate oxidative and nitrosative stress by ROS and reactive nitrogen species (RNS). This process contributes to the maintenance of genetic stability at the cellular level by preventing DNA damage. Through these mechanisms, algae exert four primary biological effects: cardioprotective, anticancer, antimicrobial, and antidiabetic activities. The cardioprotective effect is associated with the protection of vascular health by reducing oxidative stress, the suppression of inflammation, and the prevention of lipid oxidation. Anticancer activity is mediated by the prevention of DNA damage, cell cycle regulation, and the induction of apoptosis. The antimicrobial effect is based on the ability of algal compounds to disrupt

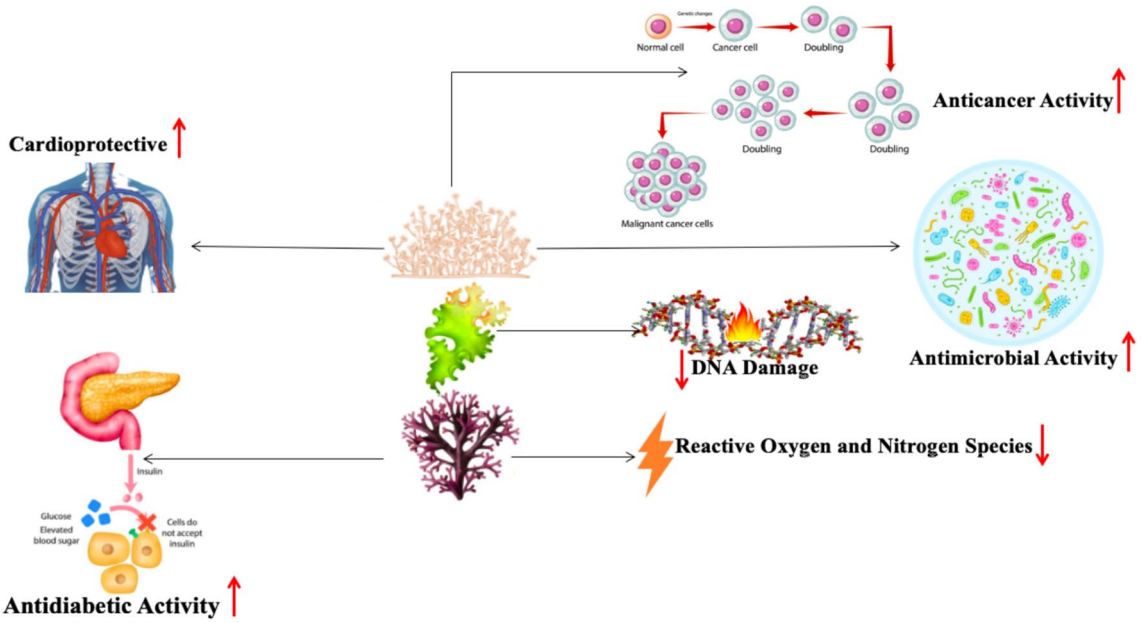

Fig. 2 Health improvement activity of macroalgae (Created from Microsoft PowerPoint and Freepik)

bacterial and fungal cell membranes and inhibit enzymatic processes. Antidiabetic activity, on the other hand, is related to improving insulin sensitivity and glycemic control by inhibiting the α-amylase and α-glucosidase enzymes. The red upward arrows in the diagram indicate an increase in these beneficial effects, while the downward arrows indicate a decrease in harmful processes (e.g., ROS/RNS production). Overall, this figure clearly demonstrates the functional food and nutraceutical potential of seaweeds by providing versatile bioprotection through the reduction of oxidative stress. Overall, these metabolites endow macroalgae with notable multifunctional bioactivities, particularly antioxidant, anticancer, antimicrobial and anti-inflammatory effects, highlighting their relevance as nutraceutical and therapeutic resources [3, 5, 6, 10].

Macroalgae-derived hydrocolloids and their legal regulations

Agar

Agar is a widely utilized hydrocolloid extracted predominantly from red macroalgae (Rhodophyta), and is particularly valued for its strong thermo-reversible gelling capacity. This versatile substance was discovered in the seventeenth century in Japan. It is mainly extracted from red algae species such as *Gracilaria* sp., *Pterocladia* sp., and *Gelidium* sp. [26, 27]. Agar is a linear polysaccharide consisting of alternating units of 1,3-linked β-D-galactopyranose and 1,4-linked 3,6-anhydro-α-L-galactopyranose [28].

Agar yield depends on species, season, environmental factors, extraction method and stages of the growth phase [29]. Roleda et al. [30] examined monthly variation in *Gelidiella acerosa* (Rhodophyta) and reported that biomass and agar yield were highest in the wet season, whereas gels obtained during the dry season exhibited superior textural strength. Consistent with this, Ganesan et al. [31] observed maximum agar yield during the northeast monsoon, which gradually decreased over summer months. A related study by Ogretmen and Kaya (2019) [32] also confirmed seasonal influence, showing that *Gelidium latifolium* collected in January produced the highest extraction yield (36.26%), while July samples yielded the lowest (33.52%). Collectively, these results indicate that seasonal variation significantly alters both agar yield and gel quality, providing insight into optimum harvesting periods for industrial production.

Agar is commonly extracted with hot water, as it becomes colloidally soluble above 90 °C and forms a rigid gel (32–39 °C) without requiring additional gelling agents. There is no supplementary substance necessary for the formation of an agar matrix, and the structural integrity of the gel remains unaffected by the presence of salts or proteins [3, 29]. On the other hand, to increase the extraction yield some pre-treatment methods can be applied. For instance, in Roleda et al.'s [30] study, agar was isolated from *Gelidium acerosa* by applying several pre-extraction treatments and extraction techniques. In the comparative analysis, it was determined that among the extraction methods, the acetic acid pre-treated and autoclaved sample provided the highest agar yield and gel strength with 29.8 ± 2.41% [30]. Ogretmen and Duyar (2018) [33] performed different pre-treatment methods (waiting for 15 h in pure water, washing 80% ethanol and no treatment) and extraction methods (autoclave, water bath, and water bath plus magnetic stirrer) to improve the extraction efficiency of agar from *Gelidium latifolium*. According to the results, the extraction method including water bath and magnetic stirrer extraction (in water was boiled at 95 °C on a magnetic stirrer at for 6 h) provided the highest extraction yield (~46%) with pre-treatment with washing 80% ethanol while the autoclave extraction caused the lowest yield (~37%). Gómez Barrio et al. (2022) [34] applied two different extraction procedures for agar extraction from *Gelidium sesquipedale*: Extraction yield ranged from 1.5–15.85% at conventional extraction conditions (80–110 ºC, 2–6 h, in distilled water) whereas it changed from 8.50 to 16.14% ultrasound-based extraction (85 ºC, 30–60 min in distilled water) [34]. Two different extraction protocols were used to extract agar from *Gelidium sesquipedale* by Li et al. (2021) [35]: ultrasonication combined with a controlled alkali pretreatment followed by enzyme-assisted extraction (EAE), and ultrasonication combined with enzyme-assisted extraction. The results showed that using enzyme (i.e. carbohydrase and proteinase) lead to 2 to sixfold higher extraction yield than that of non-enyzme extraction for extraction time of 2 to 3 h. Novel extraction methods including ultrasound and/or enzyme usage provided higher extraction yield compared to conventional extraction, because ultrasound or enzyme applications disrupt algal cell wall and facilitate the release of agar polysaccharides. Overall, studies consistently demonstrate that ethanol pretreatment, ultrasound-assisted, and enzyme-assisted protocols yield significantly higher agar recovery compared to conventional extraction, mainly due to enhanced cell-wall disruption.

Agar is composed of a mixture of molecules with various physical and chemical characteristics. The main components of agar that play a key role in determining its gelling properties, structural properties and various applications are agarose and agaropectin [27, 36]. Agarose is responsible for the gel-forming properties of agar, through hydrogen bonding. Agarose forms gels when its polysaccharides assume a helical structure, which can combine to form a stable gel arrangement. In contrast, the structure of agaropectin is

more complex with higher levels of sulfation and branching and exhibits less contribution in gel formation. This complexity results in different gelling and non-gelling properties that can be employed for specific applications. The gel-forming capacity of agar is affected by various ecological and genetic factors, as well as the timing of the macroalgae harvest [36, 37]. The extraction methodology and the resulting structural composition of agar play a decisive role in determining its techno-functional behaviour in food systems and packaging applications, particularly through their impact on gel strength, network stability, and thermal resistance.

Agar exhibits diverse applications across multiple fields due to its unique properties. In the food industry, it functions as a strong gelling and thickening agent and is widely used as a vegetarian alternative to gelatine in products such as vegan gels and gummy candies [18]. The gel-forming properties of agar are ten times higher than those of gelatine, so it has a very wide range of uses in various formulations including traditional Asian dishes, confectionery jellies, nougat, toffees, canned meats and bakery fillings, where its high melting temperature provides enhanced thermal stability [3, 36]. Even at low concentrations (0.2%), agar can be used as an effective thickener and stabilizer in dairy, meat, fish, and bakery products [27, 28].

Beyond its conventional uses, agar shows an excellent film-forming capacity and biocompatibility, making it a promising material for biodegradable and edible packaging systems. Agar-based films derived from renewable sources are fully compostable, safe for food contact, and they have been used successfully to extend the shelf life of fresh produce such as cherry tomatoes [38, 39]. Its customizable nature allows fine tuning of thickness, barrier characteristics, and flexibility to meet specific packaging requirements [38]. Although it has strong film-forming properties, it usually requires modification to eliminate brittleness and moisture sensitivity. Blending agar with other biopolymers such as chitosan or starch enhances tensile strength, flexibility, and barrier properties through synergistic interactions [40, 41]. Protein-agar composites, for example pea protein-agar films, further improve mechanical integrity and provide better adhesion to food surfaces [42]. In addition, incorporating active ingredients such as essential oils, antioxidants, or nanoparticles can impart antimicrobial and antioxidant functions, extend shelf life and improve food safety [42–45]. These composite and active agar films therefore represent versatile and sustainable platforms for advanced food packaging applications.

In advanced applications, agar has gained attention in nanotechnology, where it serves as a matrix for nanoparticle reinforced films such as melanin nanoparticle composites, offering improved mechanical strength, UV protection, and antioxidant activity [46, 47]. In biotechnology, agarose, a key component of agar, is crucial for gel formation in microbial culture media and is extensively used for techniques such as electrophoresis, chromatography, and enzyme immobilization. Additionally, agar derivatives find applications in dental prosthetics, plant tissue culture, and various other biotechnological processes. Owing to its natural origin, strong gel-forming capability, and biocompatibility, agar continues to be an important raw material in pharmaceutical applications as well [27].

The safety of agar (E 406) as a food additive was reevaluated by the European Food Safety Authority (EFSA) Panel on Food Additives and Nutrient Sources Applied to Food. At doses up to 4.500 mg/kg bw per day, no genotoxic or carcinogenic effects were observed in animal studies, and oral intake of 4.500 mg per person (~64 mg/kg bw/day) for 12 weeks was considered tolerable in humans without adverse effects. The Scientific Committee for Food (SCF) had previously given agar a "not specified" acceptable daily intake (ADI) in 1989, while the Joint FAO/WHO Expert Committee on Food Additives (JECFA) had given it a "not limited" ADI in 1974 [48]. These evaluations confirm that agar is a safe, non-toxic hydrocolloid approved for unrestricted food use.

Alginates

Alginate, commonly referred to as M and G blocks, is a linear polymer composed of β-D-mannuronic acid and α-L-guluronic acid [49]. Three distinct structures are formed throughout the polymeric chain by covalently bonding these two building components. These structures, also called poly M, poly G, and poly MG, are created by placing sequential G, M, and MG blocks together. Alginates' viscosity and thickening potential have been determined by the two variants: categories of these blocks and the size of alginate [50]. It has been demonstrated that the G blocks accelerate up the formation of hydrogels by forming covalent connections with cations like Ca^{2+}. The mass and length of the G block, the ratio of the M to G blocks, the molecular mass of the alginate, the organization of the monomeric structure, and the functional groups are therefore the most important variations that affect the alginate's physical and chemical characteristics [51]. It is believed that more than 200 alginates have been found and extracted from nature so far [49]. The M/G ratio governs gel stiffness, ion-binding affinity and rheological behaviour, making it a critical determinant of alginate's functional performance.

Alginate is ex

tracted from brown algae such as *Laminaria* sp., *Macrocystis* sp., and *Ascophyllum nodosum*. The extraction process involves using hot sodium carbonate solutions to dissolve

alginic acid salts from the algal biomass. After filtration and purification, sodium alginate is obtained. Further processing of the sodium alginate solution can yield calcium alginate or alginic acid through solid precipitation [29, 36]. Youssouf et al. [52] reported that extraction yield for alginate from *Sargassum binderi* and *Turbinaria ornata* was ~ 54% a pH 12 by using ultrasound-assisted extraction (UAE) with short extraction duration (40 min) while it was 27% for extraction duration of 2 h in conventional extraction. Nogueira et al. [53] obtained alginate extracts from *Sargassum cymosum* by using 2% Na_2CO_3 to adjust pH 10, with a high yield (~ 45.8%). In a different work, Mohammed et al. [54] used harsher conditions (5.5% Na_2CO_3) and determined extraction yield as 21.7% without alginate degradation from *Sargassum* spp. They reported that the alkaline solution's penetration into the algae's cell walls was increased with an increase in temperature, increasing the solubility and extraction of the alginate in the solution. On the other hand, microwave-assisted extraction (MAE) increased extraction yield of alginate from *Saccorhiza polyschides* compared to conventional extraction method [55]. In microwave application, vibrations are produced, and temperature of intracellular fluids increase. Compounds are released into the solvent due to internal heating rupturing the cell wall [56]. Overall, ultrasonic, alkaline and microwave-assisted extractions consistently outperform conventional methods by enhancing cell-wall permeability, thereby increasing alginate solubilization and recovery.

Alginates can be used widely in the food sector to give thickening, stabilizing, and film-forming properties, much like agar [57]. Alginates from potassium, ammonium, calcium, and sodium salts are examples of brown macroalgae. Foods mostly include sodium versions of these alginate salts [3]. Alginate, a biopolymer, placed second after cellulose in terms of availability worldwide and in aquatic environments. They can be used extensively as additives in the food sector, pharmaceutical development, wound dressings, fertilizers, chelating agents to remove heavy metals like lead from blood, and many other industries because they are non-toxic [18, 58]. Alginates are unique among hydrocolloids in that they can dissolve under cold conditions, which allows them to form gels without the need for heat. These gels maintain their structure at low temperatures and remain stable even after freeze–thaw cycles [3].

In addition to their conventional uses, alginates form the basis of diverse structuring and delivery systems. Alginate-based edible films and coatings are widely applied to enhance moisture retention, oxidation delay and to extend the shelf life of fresh products such as chicken, cherry tomatoes, and dried apricots [59–61]. Calcium alginate beads play a key role in encapsulation technologies, where they serve as protective barriers for probiotics, essential oils and antioxidants, improving their stability and controlled release during digestion [62–65]. Moreover, alginate-based nano-emulsion and microencapsulation systems have been developed to incorporate hydrophobic ingredients into food matrices, enhance dispersion, and increase the bioavailability of functional compounds [66]. These systems support alginate's role as a multifunctional agent suitable for modern food formulations. Apart from these applications, alginic acid and its sodium salts also play diverse roles as gelling agents, emulsifiers, and stabilizers in a broad spectrum of foods and beverages [67]. Beyond delivery systems, alginates also play a textural and stabilization role across a range of commercial food matrices. They improve texture and stability in fermented dairy products such as yogurt by maintaining the curd structure, and enhancing overall qualities such as viscosity, and results in a smoother texture in the final product. Alginate is also used to stabilize beer foam and to improve the frozen structure of ice cream by limiting ice-crystal growth [68]. In emulsion-based products such as salad dressings and mayonnaise, it helps disperse oil and water phases and prevents phase separation [22, 67, 69].

Alginic acid (E400) and its sodium, potassium, ammonium and calcium salts (E401-E404) are approved food additives. Sodium alginates have not been associated with adverse effects when used as food additives, and are regarded as biocompatible, biodegradable and Generally Recognized as Safe (GRAS) for the general population [3]. However, EFSA reports that current toxicological data are insufficient to establish a safety assessment for alginic acid and its salts (E400–E404) in infant formulas and foods for special medical purposes (categories 13.1.5.1 and 13.1.5.2). Therefore, their safety remains unconfirmed for infants and young children consuming such products.

Carrageenan

Carrageenan is one of the highly sulfated polysaccharides derived from red algae that belong to a group known as Rhodophyta [70, 71]. Carrageenan is extracted from the members of the families Gigartinaceae and Solieriaceae of the class Florideophyceae (Rhodophyta, red macroalgae) (*Chondrus crispus*, *Chondrus ocellatus*, *Kappaphycopsis cottonii*, *Eucheuma denticulatum*, *Chondracanthus acicularis*, *Gigartina pistillata*, *Sarcothalia radula*, *Mastocarpus stellata* [36, 72]. Most of the macroalgae species evaluated for carrageenan production are cultivated primarily in the coastal areas of the Philippines, Indonesia and Chile [3]. Beyond its industrial role as a gelling and stabilizing agent, recent original research has highlighted carrageenan's potential health benefits. For instance, in vitro and in vivo studies demonstrate that κ-carrageenan exhibits notable antioxidant and anti-inflammatory properties, reducing

reactive oxygen species and modulating cytokine expression [73]. Experimental models further suggest that carrageenan can influence gut microbiota composition, enhance short-chain fatty acid production and support intestinal barrier integrity [74]. Moreover, dietary supplementation with carrageenan has been linked to improved lipid metabolism and reduced markers of metabolic syndrome in animal studies [75]. These findings indicate that carrageenan's bioactivity extends beyond its technological applications, offering promising avenues for functional food development. Nevertheless, it is important to note that carrageenan's health effects are structure-dependent, with κ-, ι-, and λ-carrageenan differing in sulfate content and biological activity. While κ-carrageenan is most frequently associated with beneficial outcomes, some studies caution that high doses or degraded forms may elicit pro-inflammatory responses [76]. This underscores the need for careful consideration of carrageenan type, purity, and dosage in both experimental and applied contexts.

Carrageenan possesses ester sulfate levels ranging from 15 to 40% and based on its algal origin and synthesis processing its molecular weight of carrageenan varies from 20–40 to 200–800 KDa [77, 78]. Carrageenan is composed of repeating β-d-galactose and 3,6-anhydro-α-d galactose molecules joined by α-(1,3) and β-(1,4) glycosidic linkages [79]. Carrageenan's properties are determined by the location and quantity of ester sulphate groups [80]. Carrageenan exists in various forms, but the most common and functionally evaluated types in industrial applications are kappa (κ), lambda (λ), and iota (ι) carrageenans. These types are classified according to their degree of sulfation: κ-carrageenan contains one sulfate group per disaccharide, ι-carrageenan two, and λ-carrageenan three. The choice of carrageenan depends on the desired functional properties; κ- and ι-carrageenans exhibit gel-forming capacity, while λ-carrageenan is more commonly used as a thickener and viscosity-regulating agent [18, 81].

Extraction efficiency varies considerably depending on temperature, pH, solvent system and assistance technologies (ultrasound, enzymes, pressurized-water). These parameters not only modulate yield but also influence sulfate distribution and gel strength. There are different extraction methods like conventional extraction, enzyme-assisted extraction and fungal treatment to extract carrageenan from macroalgae. In classical or conventional extraction of carrageenan from red macroalgae, hot alkali treatments or traditional boiling are performed [82]. Hot water (80 °C) and hot milk (80 °C) are used as the solvent medium in the extraction process of carrageenan [36]. Rudke et al. [83] reported that extraction yield of carrageenan from red algae *Kappaphycus alvarezii* in conventional extraction was higher (50.25%) probably due to the long extraction duration of 2 h (at 80 °C) compared to microwave-assisted extraction (at 60, 80 and 100 °C, ranged from 17.16 to 23.42%) and pressurized-water carrageenan extraction (at 60 and 80 °C, ranged from 29.00 to 34.12%). On the other hand, variables such as temperature, pH, and time during the extraction process significantly affect the chemical composition and gel properties of carrageenan [47, 84]. Although microwave-assisted extraction and pressurized-water carrageenan extraction had lower extraction yield than that of conventional extraction, they provided the same or higher gel strength and viscosity compared to conventional extraction [83]. On the other hand, cellulase-treated extraction produced the highest yield (45%), followed by conventional boiling (37.5%), while fungal treatment produced the lowest yield (37%) [85].

κ-carrageenan produces a firm, rigid, yet fragile gel structure in the presence of potassium ions. Conversely, ι-carrageenan forms a flexible, elastic gel when calcium ions are present. λ-carrageenan functions solely as a thickening agent and lacks the ability to gel. Additionally, κ-carrageenan exhibits limited freeze–thaw stability, whereas ι-carrageenan demonstrates superior freeze–thaw resistance. Consequently, a combination of κ- and ι-carrageenan is frequently employed to achieve specific textural, stability, and water-retention properties [3].

Carrageenan and its related compounds are useful for many uses because of their active and powerful groups as well as unique qualities, such as biodegradability and biocompatibility, which are mainly due to their anionic nature [78, 86]. The food, pharmaceutical, and cosmetics sectors have long used carrageenan because it has anticoagulant, antiviral, antithrombotic, antibacterial, cholesterol-lowering, anticancer, immunomodulatory, and antihyperlipidemic activity [87]. Moreover, carrageenan type and bioactivity are significantly influenced by extraction parameters: alkaline extraction promotes the synthesis of κ-carrageenan, whereas lower pH or enzymatic extraction might increase sulfate content, improving its bioactivity [87]. Carrageenan-based films have been shown to be effective buccal drug delivery systems. In an original study using ibuprofen as a model compound, κ-carrageenan films formulated with poloxamer and polyethylene glycol (PEG) demonstrated faster release than the crystalline drug form, indicating their suitability for oral strip and mucosal delivery applications [88]. This approach may be particularly beneficial for elderly and pediatric patients who have difficulty swallowing traditional solid dosage forms [89]. Carrageenan can replace several synthetic cosmetic additives due to its natural anti-photoaging and anti-melanogenic activity, making it suitable for lotions, shampoos and dermal formulations [90].

Carrageenan is a water-soluble linear biopolymer, and some of its functional properties such as molecular weight,

structure and viscoelastic properties have expanded its utilization area. It is widely used in industries related to food because of its remarkable natural qualities, which include emulsifying, thickening, and stabilizing [80, 91]. Carrageenan has approval from the Food and Drug Administration (FDA) as a safe additive for use in food. It is utilized extensively in many food applications as an emulsifier, thickener, gelatinizer, and stabilizer because of its exceptional functional qualities [92]. Food-grade carrageenan, also known as additives E407 or E407a, is typically chosen in its whole form in the food sector. This adaptable component is crucial for thickening and replacing fat in plant-based and low-fat dairy products. Carrageenan finds application in beverages for stabilization and suspension, while in meat products, it enhances tenderness and acts as a binder in those meats with reduced sodium content. Carrageenan serves as a plant-based substitute for bovine-derived gelatin in confectionery applications, making it suitable for vegetarian and vegan formulations. Collaborating with gums such as konjac or LBG (Locust Bean Gum), carrageenan imparts diverse textures to dessert jellies. Moreover, carrageenan is an effective substitute for emulsifying salts, capable of stabilizing cheese fat without impacting the calcium-to-phosphorus (Ca:P) ratio, resulting in homogeneous cheese products. Additionally, it can be used to provide structural stability in cheese substitutes and can also be used as a substitute for casein in the production of cheese alternatives. Furthermore, when added to various sauces, it plays an important role in regulating the product's viscosity and texture [3, 93].

In recent years, carrageenan-based films, coatings, and nanocomposites have gained significant importance due to their excellent film-forming ability, the ability to incorporate bioactive compounds, and transparent film formation [94]. In a recent research study, κ-carrageenan based nanocomposite films were prepared using konjac glucomannan and TiO_2 nanoparticles. Prepared films showed improved functional properties and have effective photocatalytic antifungal activity for *Penicillium viridicatum*. Films maintained the freshness of strawberries when compared to open storage and plastic packaging [95]. When carrageenan is combined with polymers such as chitosan, cellulose, polylactic acid and alginate, improvements in barrier and mechanical properties are observed, which in turn overcome the brittleness of pure carrageenan films [96].

The general requirements for a food-grade carrageenan are outlined in Commission Regulation (EU) No 231/2012: (i) It should be presented as a nearly odorless, yellowish to colorless powder; (ii) a 1.5% solution at 75 °C should have a minimum viscosity of 5 mPa.s, a sulphate content of 15% to 40% (as SO_4), and an ash content of 15% to 40%; and (iii) refined products should be soluble in hot water and contain no more than 2% acid-insoluble matter. According to the EFSA's report, food-grade carrageenan (E 407) and processed is not absorbed intact and do not exhibit any signs of genotoxicity or carcinogenicity [97]. A high NOAEL range of 3.400–3.900 mg/kg bw/day was established by subchronic and chronic toxicity experiments in rats that showed no negative effects at doses up to 7.500 mg/kg bw/day. According to EFSA, carrageenans should weigh between 200 and 800 kDa on average; however, because of their natural source, samples may contain lower-molecular-weight polymers. Additionally, during extractive processing, hydrolysis may take place, producing a small amount of very-low-molecular-weight polymer chains of 10–20 kDa (known as poligeenan), which do not provide texturizing qualities. At least in rodents, consuming a lot of poligeenan may be linked to ulcerative colitis. The quantity of low-molecular-weight polysaccharide chains in E407 is therefore controlled for safety reasons, and samples shouldn't have more than 5% of the fraction with a molecular weight below 50 kDa [98]. While food-grade carrageenan (E407/E407a) is considered safe for general consumption, regulatory concern primarily arises from low-molecular-weight fractions (poligeenan < 50 kDa), which are restricted due to potential intestinal irritation.

Ulvan

Ulvan, which makes up roughly 9–36% of the dry weight biomass, is the main sulphated polysaccharide present in the cell walls of green algae in the genus *Ulva* [99]. Ulvan is characterized by the content of rhamnose (16.8–45.0%), glucuronic acid (6.5–22.5%), xylose (2.1–12.0%), iduronic acid (0.7–9.1%), glucose (0.5–6.8%) and sulphate (14–32%) [100]. The repeating disaccharide units are identified as type A and type B ulvanobiuronic acid 3-sulfate [101]. Ulvan has a more complicated structure than other algal polysaccharides because of its monosaccharide composition, diversity of glycosidic bonds, and functional group modifications. The chemical composition of ulvan may vary depending on factors such as algae type, harvest time, environmental growth conditions and extraction methods applied [102, 103].

Ulvan extraction efficiency is strongly influenced by solvent conditions, pH, temperature, enzymatic assistance and sonication, which collectively shape not only yield but also sulfation pattern and bioactivity. Various techniques such as hot water, acidic solvents, microwave-assisted, enzyme-assisted methods and chelating agents are used to extract ulvan [104, 105]. Enzyme-assisted extraction is performed with 15–47% efficiency using enzymes such as pectinase, alpha-amylase, and proteinase K to protect sulfate groups [106, 107]. Extraction yield, biological functionality, and physiological properties (such as hydration, polarity,

swelling, and viscosity) vary depending on extraction conditions such as pH, temperature and time. For instance, in Malvis Romero et al. [108]'s study, the highest extraction yield (17.9%) was obtained with a combination of enzymatic and ultrasound-assisted extraction. Kazemi et al. [109] extracted ulvan from *Ulva intestinalis* by using six different methods: 1. Hot water extraction (80 °C, 3 h), 2. Hot acidic extraction (80 °C, 3 h, pH 3), 3. Hot alkaline extraction (80 °C, 3 h, pH 10), 4. Microwave-assisted extraction (80 °C, 30 min), 5. Autoclave-assisted extraction (121 °C, 30 min) and 6. Ultrasonic-assisted extraction (80 °C, 30 min). They found that hot acidic (23.21%) and ultrasonic-assisted extraction (22.73%) provided the highest extraction yield for ulvan among all extraction procedures. Enzyme use increased extraction yields, and the highest yield (26.7%) was achieved by ultrasonic enzyme treatment. Compared to ulvan extracted by hot water extraction and ultrasonic-assisted treatment, ulvan extracted by enzyme-assisted and ultrasonic-enzyme-assisted treatment showed a noticeable DPPH radical scavenging activity, particularly that extracted by enzyme-assisted treatment. According to the rheological analysis, ulvan (4%, w/w) extracted using enzyme-assisted, ultrasound-enzyme-assisted, ultrasound-assisted, and hot water treatment showed stable shear viscosities [110]. Overall, enzyme-ultrasound-assisted extraction consistently delivers superior ulvan yield and antioxidant performance compared to single-step thermal extraction approaches.

The biological activity and potential applications of ulvan are significantly influenced by parameters such as its monosaccharide composition, sulfate content, molecular weight, and structural characteristics. Ulvan exhibits multiple biological functions, including antioxidant, anticoagulant, anti-inflammatory, immunomodulatory, antimicrobial, antiviral, antihyperlipidemic and antitumor activity [106, 111–113]. These effects are largely attributed to its sulfate ester content, uronic acids and glycosidic substitution patterns, which enhance electron transfer, radical scavenging and cell signaling. Bioactivity is strongly structure-dependent; ulvans with higher sulfate substitution demonstrate significantly greater antioxidant and immunostimulatory capacity, as evidenced in Qi et al. (2005) and Yaich et al. (2017) [114, 115].

Ulvan is used in the development of various types of biomaterials such as membranes, films, nano- and microparticles, hydrogels and 3D porous structures [116–118]. Ulvan, which has similar properties to alginate, is particularly useful in hydrogel formulations and in applications such as cartilage tissue engineering in combination with poly (D-lactic acid) [116]. In addition, ulvan is successfully used in food and cosmetic products such as edible films, stabilizers, emulsifiers and prebiotic foods [119, 120]. These diverse applications demonstrate the high commercial and scientific value of ulvan and underscore its strategic importance in areas such as biomaterial development, pharmaceutical formulations, food and cosmetic industries [121].

The increasing popularity of using ulvan is due to its sulfate-rich composition and bioactivity [122]. Ulvan-based films show good antioxidant properties. Don et al. conducted a study in which crosslinked ulvan and chitosan films were prepared. An increase in tensile strength was observed, and films showed antioxidant and whitening ability; hence, they have great potential to be used as a new biomaterial [123]. In another research study, hydrogel films were prepared using ulvan for wound dressing applications. The films had better water vapor transmission rate and swelling behavior, which is good for a potential wound dressing biomaterial. The films also showed antioxidant and antimicrobial properties [124].

To the best of our knowledge, there is not currently specific legal regulation for ulvan. On the other hand, ulvan from *Ulva pertusa* was given to Wistar rats in a subchronic (6-month) toxicity study. High doses (3.000 mg/kg/day) changed blood parameters and liver-related serum markers, but also decreased blood lipids, suggesting both some toxicity and antihyperlipidemic effects [125]. When evaluated in vitro on fibroblast-like cells, ulvan from *Ulva lactuca* exhibited little cytotoxicity and vitality similar to that of hyaluronic acid, a non-toxic control [116]. While ulvan is generally regarded as safe and biocompatible, long-term toxicological validation in humans is still required to establish regulatory admissibility for food and biomedical use.

Fucoidan

Fucoidans are sulfated polysaccharides obtained from brown algae that contain sulphate ester groups consisting mainly of α-L-fucose residues [78]. These negatively charged polysaccharides with a hygroscopic structure are found in the cell walls of brown algae, protecting them from environmental stress and playing functional roles such as preventing water loss [126]. Fucoidan was first isolated in 1913 by Henrik Kylin from species such as *Laminaria digitata*, *Ascophyllum nodosum*, and *Fucus vesiculosus.* The chemical structure of fucoidans is extremely complex and varies depending on the species of algae. Fucoidans typically consist of a backbone composed of α(1→3)-linked L-fucopyranose residues or alternating α(1→3) and α(1→4)-linked L-fucopyranosyl units. Structurally, they contain high amounts of L-fucose and sulfate ester groups, as well as lower levels of D-xylose, glucuronic acid, D-galactose, and D-mannose [127–129].

The physicochemical properties and bioactivity of fucoidan are directly related to the algae species, environmental conditions and extraction methods [130]. Fucoidan extraction

has been performed for over 100 years using dilute acetic acid. However, in recent years, enzyme-assisted extraction, ultrasound-assisted extraction, microwave-assisted extraction, and hot water extraction have been developed. These modern approaches not only increase extraction efficiency but also enable the production of purer and more biologically active fucoidan. For instance, to extract fucoidan from *Ecklonia maximum*, Mapholi and Goosen [131] investigated the possibility of using ultrasound-assisted enzymatic extraction and found that it significantly exceeded both enzyme-assisted extraction and ultrasound-assisted extraction, showing a 20% increase after 240 min. Moreover, parameters such as extraction temperature and time, solvent type, solid/solvent ratio, and applied extraction power significantly affect the process and can lead to significant changes in the molecular weight and chemical structure of fucoidan [130]. For instance, the fucoidan yields from the brown macroalgae *Fucus distichus* ssp. *evanescens* and *Saccharina latissima* obtained by the enzyme-assisted extraction were similar to the yields obtained by conventional extraction. On the other hand, the molecular sizes of the fucoidans were considerably greater with enzyme-assisted extraction [132]. Overall, recent extraction strategies combining enzyme and ultrasound-assisted extraction generally yield higher fucoidan recovery and superior bioactivity compared to traditional acid extraction, mainly due to improved cell-wall disruption and sulphate retention.

Fucoidan exhibits antioxidant, antiviral, antibacterial, anti-inflammatory, anticoagulant, antitumor and anti-obesity activities, largely influenced by sulphate content, monosaccharide ratio and molecular weight [133–136]. Bioactivity is mechanistically linked to electron-scavenging capacity and inhibition of viral attachment, where sulphated chains interact with positively charged viral glycoproteins to block host-cell entry. Fucoidans from *Fucus vesiculosus* inhibited HIV reverse transcriptase even at 0.5–1.0 mg/mL [137], and structural variations continue to be central in determining therapeutic potential.

Fucoidan has a wide range of applications particularly in functional foods, cosmetics, and pharmaceuticals, thanks to its low toxicity profile, limited side effects, and cost-effectiveness [138]. Fucoidan-based products are generally recognized as safe (GRAS) by the FDA up to 250 mg/day and are widely used in dietary supplements and dietary products [139]. It has also gained an important place in biomedical applications such as tissue engineering, drug delivery and magnetic resonance imaging contrast agents [140, 141]. The wide range of applications for fucoidan makes it an attractive ingredient for both scientific research and industrial use [97].

Fucoidan has several biological characteristics it regulates growth factor β receptor I and II (TGFRI/TGFRII), an immunity regulator for anti-cancer treatment [142], and the ability to engage with specific proangiogenic growth factors [143]. Recent studies have increasingly focused on utilising fucoidan in applications like films, nanofibers, and in combination with other natural polymers. Electrospun fucoidan nanofibers are of great interest due to their high surface area, porosity and controlled release of drugs. Overall, they show biomedical potential as they inhibited the growth of cells and caused cell death [144]. Fucoidan-loaded electrospun polyvinyl alcohol/levan nanofibers were developed for wound dressing application. Enhancement in tensile strength was observed, and cell viability increases over time. Fucoidan promotes tissue regeneration and prevents infection [145]. In another research study, fucoidan, chitosan and pullulan were utilised together for fabricating a microneedle patch for differential drug release. The results showed that this microneedle achieved rapid hemostasis/analgesia and sustained bactericidal action, a potential strategy for high-quality wound healing [146]. These findings demonstrate that fucoidan is not only bioactive but also an excellent structural matrix for drug delivery and regenerative materials due to its charge-driven interactions and controlled-release behaviour. In conclusion, fucoidan is a versatile material for advanced pharmaceutical, biomedical, and packaging applications.

European Union legislation on macroalgae-based hydrocolloids

As mentioned previous sections, algae-based hydrocolloids have been used in food industry due to their functions such as gelling, emulsifying, stabilizing, thickening, etc. Even though, functional properties of algae-based hydrocolloids are important for food industry, it is equally essential to evaluate their regulations and legal usage. According to Regulation (EU) 2017/2470, additional specific labelling requirements for "fucoidan extract from the seaweed *Undaria pinnatifida* and *Fucus vesiculosus*" were stated as the designation of the novel food on the labelling of the foodstuffs containing it shall be 'Fucoidan extract from seaweed *Undaria pinnatifida*' or the designation of the novel food on the labelling of the foodstuffs containing it shall be 'Fucoidan extract from seaweed *Fucus vesiculosus*' and maximum level of them is 250 mg/day [147]. As seen in Table 1, agar, alginate, carrageenan, fucoidan, and ulvan exhibit unique gelling behaviors and rheological behaviours due to variations in molecular structure and cross-linking processes. Rheological studies reveal shear-thinning flow and temperature-sensitive viscosity behaviours. Carrageenan, especially the κ- and γ-types, is a very versatile viscoelastic modifier in food systems because it forms gels with changeable elasticity and strength by helix aggregation

Table 1 Compariton of agar, alginate, carrageenan, fulcan, and ulvan in terms of rheological properties, gelling mechanism and application examples in food industry [141, 156, 302–311]

Macroalgae-based hydrocolloids	Source	Rheological properties and gelling mechanism	Applications in food industry
Agar	*Gracilaria* spp. *Gelidinum* spp. (red macroalgae)	Gelling mechanism: The hydrogen atoms in the 3,6-anhydro-L-galactose residues that enable the molecule to form a helix and the formation of a gel as a result of the interaction of these helices Aparent viscosity decreased with an increase in temperature (from 30 to 60 °C). Shear-thinning behavior. Strong and brittle gels. Gelling temperature: 34–38.4 °C, melting temperature: 81.9–94.2 °C	Bakery products, jelly, stabilizers for canned food, jam, dessert, ice-cream, sauces, agar noodles, jam, pudding, ice-cream. It has been also used as culture medium and matrix for electrophoresis
Alginate	*Laminaria* spp., *Macrocystis* spp. (brown macroalgae)	Two methods of gelatinisation: Ionic crosslinking with cations (ionic gels) or acid precipitation (acidic gels). Soft, elastic gels. Melting temperature: MT: >300 °C	Sauces, jam, marmalade, syrups, ice cream toppings and in fruit pies, animal food, ruit drinks and beer Coating and encapsulation
Carragenan	*Kappaphycus* spp. *Eucheuma* spp. (red macroalgae)	Gel mechanism: A coil-to-helix transition followed by self-assembly of the carrageenan helix resulting in a three-dimensional network κ-Carrageenan: Strong, rigid gels, particularly in the presence of potassium ions ι-Carrageenan: Softer, more elastic gels when combined with calcium ions λ-carrageenan: lacks and highly soluble and incapable of forming gels Gelling temperature: 30–50 °C, melting temperature: 50–70 °C	Fruit and vegetable bars, meat and meat products, bakery products and creams, pudding, chocolates, and custards
Fucoidan	*Fucus* spp. *Undaria* spp. *Laminaria* app (brown macroalgae)	A non-gelling polysaccharide. It could interact with κ-carrageenan to form a stable gel blend. Gelling mechanism is unclear but formation of hydrogen bonds between fucoidan and κ-carrageenan chains. Viscoelastic, shear-thinning forms gels in blends	Fucoidan-based nanoparticles, drug delivery, cancer treatments, tissue engineering, antibacterial applications
Ulvan	*Ulva* spp. *Enteromorpha* spp.	Gelation mechanisms form cross-linking interactions (ionic bonding with multivalent cations) and non-cross-linking interactions (electrostatic forces and hydrogen bonding) Both shear-thinning and shear-thickening depends on extraction methods, ionic presence, and species origin. Less firm than agar and alginate. The addition of Ca^{2+} promotes viscosity enhancement	Food additives, innovative packaging solutions, cosmetics formulations, medical materials, and agricultural applications. Development of hydrocolloid particles, cross-linked gels, porous hydrogels, nanofibers, and bioactive materials for potential disease and metabolic disorder treatment

GT: Gelling temperature, MT: Melting temperature

and ionic interactions (e.g., K^+ or Ca^{2+}). On the other hand, fucoidan is mostly a non-gelling polysaccharide, but when combined with other substances (like κ-carrageenan), it can create organized hydrogel networks and display various rheological behaviors. These rheological and gelation variations directly correspond to application sectors in terms of industrial relevance. Agar is perfect for desserts, culture media, and vegetarian gel applications due to its strong, hard gels and good temperature stability. Carrageenan is frequently employed as a stabilizer and gelling agent in dairy, meat substitutes, and processed foods due to its strong interaction with proteins and adjustable flexibility. Alginate is useful for encapsulation, edible films, and biomedical applications. Fucoidan adds functional hydrocolloid formulations with additional health or bioactive properties, despite having less well-known as a pure gelling agent. Ulvan's good rheology and bioactivity make it promising for use in sustainable packaging, biomaterials, and functional foods, even though it is still relatively new in the industry. In general, the optimal hydrocolloid for each industrial setting depends on the gelation mechanism (thermal vs. ionic), network strength, and rheological response (viscosity, modulus, shear behavior).

Extraction of macroalgae-derived hydrocolloids

High levels of polysaccharides in the cell wall of macroalgae play a role in important physiological functions. The polysaccharides in algae vary between species. Macroalgae contain important sulfated hydrocolloids including fucoidan and alginate in brown macroalgae, agar and carrageenan in red macroalgae, and ulvan in green macroalgae [148, 149].

The extraction of polysaccharides from complex algal cell matrices is critical to maintaining their bioactivity and functionality. Hot water extraction, alkali extraction, and diluted acidic extraction methods are widely used methods for hydrocolloid extraction [150, 151]. In the literature, some studies have shown the use of hot water extraction for the extraction of polysaccharides from various algal sources such as *Palisada perforate* (Rhodophyta), *Dicyopteris divartica* (Phaeophyceae), and *Caulerpa racemosa* (Chlorophyta) [152–154]. Moreover, extraction methods affect the structural properties, bioactive properties, and techno-functional properties of polysaccharides [99, 155]. For example, alkaline treatment is required to obtain high-strength agar gel for *Gracilaria* species [156], but alkaline treatment is not required for carrageenan extraction but may be used to increase gel strength [157]. On the other hand, a hybrid sulphated galactan (κ-/β-carrageenan) was obtained from *Betaphycus gelatinus* by cold and hot alkaline extraction methods, followed by alkali treatment to convert the precursor structures into primary carrageenans [158]. Moreover, hot water extracts showed the highest fucoidan content and purity, with the highest fucose concentration, while acidic extracts produced the most uronic acid contamination and lower sulphate content [99]. Industrial extraction of hybrid carrageenan from *C. crispus* (Rhodophyta) wastes was carried out by using microwave extraction technic [159]. The results indicated that the extracted hybrid carrageenan showed thermomechanical properties that were similar to those of their commercial equivalents, such as gelling and melting temperatures or viscoelastic moduli [159]. According to Tuvikene et al. [160], alkali treatment is also a necessary step for the isolation of high-quality gelling hybrid carrageenan. Moreover, Gomes-Dias et al. (2024) [161] used cold water, ethanol and alkaline extraction methods both separately and sequentially to obtain agar and porphyrans from red algae. They reported that the sequential extraction approach increased the gel formation capacity while not having any negative impact on the extraction yield and product purity.

As summarized in Table 2, traditional extraction methods are advantageous due to their low-cost equipment requirements and simple protocols. However, they also present important limitations, including long processing times, high energy and water consumption, and the use of hazardous chemicals [162]. To overcome these limitations, innovative and environmentally friendly extraction technologies have been increasingly adopted. According to the literature, using green extraction techniques to produce hydrocolloids from macroalgae has major benefits in terms of sustainability and efficiency (Table 2). Advanced and green technologies such as enzyme-assisted extraction, microwave-assisted extraction, ultrasound-assisted extraction, and pressurized liquid extraction (PLE) can significantly improve extraction efficiency while reducing processing time, energy demand and solvent usage [163, 164]. For instance, industrial extraction of hybrid carrageenan from *C. crispus* (Rhodophyta) wastes was carried out by using microwave extraction technique [159]. The results indicated that the extracted hybrid carrageenan showed thermomechanical properties that were similar to those of their commercial equivalents, such as gelling and melting temperatures or viscoelastic moduli [159].

MAE typically operates at elevated temperatures (120–170 °C) in mild acidic solutions, enabling very short extraction times (10–30 min) [165, 166]. MAE provides uniform heating, allowing for the disintegration of cell walls, increased porosity of the matrix and release of solutes from the cells [167, 168]. For instance, MAE of carrageenan yields approximately 23% extraction efficiency, while ulvan and fucoidan extractions may reach 40% and 70%, respectively, with minimal solvent use [83, 165]. Similarly, PAE

Table 2 Advantages and disadvantages of extraction methods and comparison of the effects of hydrocolloids on functional and bioactive properties

Methods	Hydrocolloids	Advantages	Disadvantages	Effect of functional properties	Effect of bioactivities	References
Hot water extraction (HWE)	Carregenan (*Kappaphycus*), Agar (*Gracilaria vermiculophylla*) Ulvan (*Ulva rigida*)	Easy to apply, Low cost, Suitable for industry	High temperature, Molecular weight decrease, Long processing time High solvent consumption	Decrease in gel strength and viscosity, High gel strength in some agars	Risk of thermal degradation, Decrease of antioxidant activity	[156, 182, 312]
Enzyme Assisted Extraction (EAE)	Ulvan (*Ulva fenestrata*), Fucoidan (*Ecklonia maxima*) Carragenan	Low temperature Protect the structure High extraction yield Green technology	High enzyme cost, Enzyme selection is critical, Slow extraction process	Protect molecular weight High gel strength and viscosity	High antioxidant and anticoagulant activities High anti-viral activity	[108, 131, 313, 314]
Ultrasound assisted Extraction (UAE)	Ulvan (*Ulva fenestrate*) Carragenan (*Kappaphycus alvarezii)* Fucoidan (*Ecklonia maxima*) (*Sargassum ilicifolium*)	High yield Short treatment time, Increases solvent diffusion Green technology High extraction yield, Inexpensive	Excessive force, Rupture of polymer chain	Maintains functionality if applied intermediate ultrasound, Decrease viscosity, if applied excessive ultrasound High solubility Thermal stability	Increase antioxidant activity, if applied mild degradation High anti-cancer activity	[108, 109, 131, 315, 316]
Microwave assisted extraction (MAE)	Carragenan (*Kappaphycus alvarezii)* Ulvan (*Ulva intestinalis*)	Short treatment time, Protect energy Suitable for thermal-sensitive compounds	If applied high microwave, depredated polymers High capital cost	High gel strength at optimum conditions, Decrease molecular weight, If applied high microwave	Protect bioactivity if applied short time	[83, 315, 317]
Pressured Liquid Extraction (PLE)	Fucoidan *Saccharina japonica*)	High extraction yield, Low solvent consumption Short extraction time	High equipment cost, Some polysaccharides are sensitive to pressure	Protect molecular weight at mild temperature and pressure, Stable gel behavior High emulsifying activity	Protect antioxidant activity	[318]
Supercritical Fluid Extraction (SFE)	Fucoidan Carragenan (*Kappaphycus alvarezii)*	No solvent residue, Green technology Short extraction time Suitable for thermal-sensitive compounds	Need co-solvent for polar polysaccharides, Low yield, High equipment cost	Protect structure	Protect bioactivity	[83, 319]
Hybrid methods (UAE+EAE, MAE+UAE, ultrasound (US)+microwave (MW))	Ulvan (*Ulva fenestrata)* Carragenan (*Kappaphycus alvarezii*) Fucoidan (*Ecklonia maxima*)	Highest extraction yield, Short process time	Complex optimization process	Highest gel strength and viscosity High molecular weight	Highest antioxidant and anticoagulant activities	[108, 131, 315, 317]

of carrageenan at 80 °C for 15 min provides an extraction efficiency of 34%. UAE conditions vary depending on the hydrocolloid type, generally involving moderate temperatures. For example, UAE of carrageenan at 25 °C for 30 min results in an efficiency of 45%, whereas ulvan extraction at 84.75 °C for 30 min provides 22.5% efficiency [169, 170].

EAE offer high efficiency and selectivity by allowing the degradation of structural carbohydrates in macroalgal cell walls with targeted enzymes such as cellulase, pectinase, xylanase, β-glucosidase, and protease [171–173]. It has been successfully applied for the extraction of polysaccharides from the macroalgae such as *Codium fragile* (Chlorophyta) [174], *Sargassum wightii* [175] and *Sirophysalis trinodis* (Phaeophyceae) [176]. Optimization of parameters such as temperature, pH, substrate-enzyme ratio, and solvent type in the extraction process is critical for the efficiency of enzymatic processes [177].

In UAE, macroalgae's cell walls are broken down and polysaccharides are extracted using water and ultrasonic waves [178]. The UAE method was successfully applied to obtain alginate, carrageenan and ulvan from macroalgae species such as *Sargassum aquifolium* (Phaeophyceae), *Kappaphycus alvarezii* (Rhodophyta) and *Ulva intestinalis* (Chlorophyta), respectively [52, 179]. Longer UAE durations have been shown to enhance ulvan functionality, with the best results achieved after 2 h [180].

PLE is an innovative method that enables the extraction of compounds in a shorter time and with less solvent consumption by utilizing high temperature and pressure conditions [181]. It has been applied to extract fucoidan from *Nizamuddinia zanardinii* and *Saccharina japonica* (Phaeophyceae) with high yields [182, 183], and has also been tested for carrageenan extraction from *Kappaphycus alvarezii* [91]. However, Mendes et al. [184] reported that although UAE provided higher yield and viscosity for κ-carrageenan than the conventional alkaline method, PLE was limited due to low viscosity and acidic pH. Furthermore, the UAE–EAE hybrid approach, in which EAE is combined with UAE, is reported to provide the highest hydrocolloid yields and best rheological/technofunctional properties in the literature [131].

Extraction methods performed for agar, carrageenan, alginate, ulvan, fucoidan macroalgal hydrocolloids are given in Table 3. Extraction method, temperature, pH, time, and solvent used have a significant impact on extraction efficiency. For instance, carrageenan exhibited greater extraction yields by both hot water and UAE, while hot water extraction of ulvan provided moderate results. For alginate and carrageenan, MAE and UAE often provided quicker processing, less solvent consumption, and greater extraction yield. On the other hand, EAE caused lower extraction than those of other techniques, as seen with fucoidan and ulvan. Although extraction performance can vary greatly, advanced methods like MAE and UAE for fucoidan showed promise for more environmentally friendly processing and improved structural preservation. However, most of these green methods are still under development, and traditional extraction techniques remain the dominant methods in the industry due to high equipment costs, limited knowledge for process optimization, and difficulties in transitioning to industrial-scale application. Moreover, green extraction approaches align strongly with circular-economy and eco-extraction frameworks, as they minimize solvent and energy consumption, enable biomass valorisation, and reduce environmental load [185–187].

In summary, depending on the type of algae used, the chemical structure of the target polysaccharide, and the intended industrial application, polysaccharide extraction processes vary. Optimization of parameters such as heat, pH and chemical treatments during extraction has a decisive impact on the chemical structures, bioactivities and potential industrial applications of polysaccharides by increasing both product yield and functionality [149, 164, 188].

Health effects of macroalgae-derived polysaccharides

Being immobile in their marine habitats, macroalgae are constantly exposed to environmental pressures such as fluctuations in temperature, changes in salinity, ultraviolet radiation, and the presence of pollutants. To cope with these stressors, they generate a diverse array of secondary metabolites. These include pigments (fucoxanthin, phycobiliproteins, chlorophylls), phenolic derivatives, alkaloids, terpenes, sulfated polysaccharides, and phytosterols, many of which exhibit notable bioactive functions [5, 7, 8]. They are rich in macronutrients like carbohydrates, protein, lipids including omega-3, omega-6 and omega-9 fatty acids, fiber, moisture, and micronutrients such as salts, minerals (Ca, Mg, Na, K, P, Cu, Fe, Mn, Se, Zn) and vitamins (A, C, E) are essential for health [5, 22, 24]. These components have significant potential as sustainable alternatives for enhancing dietary diversity and fulfilling nutritional requirements, and as candidates for developing novel nutraceuticals, pharmaceuticals and functional foods [19–21]. Macro- and micronutrients composition of macroalgae and their applications are given in Fig. 1.

Macroalgae can provide a balanced diet and can be a promising food source with functional, health, and sensory attributes and provide human well-being [19, 22]. In metabolism, disruption of homeostasis due to the disruption of the balance of cellular prooxidant/antioxidant reactions leads to oxidative stress, excessive production of ROS and free

Table 3 Extraction of macroalgal hydrocolloids

Macroalgal hydrocolloids	Extraction technique	Extraction parameters	Extraction efficiency	References
Agar	Hot water extraction	Temperatures above 85 °C and pH between 3.4 and 4.4	29.7% Carrageenan: 76.3% extraction efficiency	[310, 320, 321]
Carrageenan	Ultrasound-assisted extraction	2 h agitation, Temperature: 25 °C, extraction time: 30 min, extraction solvent: Na_2CO_3	45.05% extraction efficiency	[83]
	Pressurized water extraction	Temperature: 60 and 80 °C, extraction time: 15 min	34.12% at 80 °C extraction efficiency	[312]
	Microwave-assisted extraction	Temperature: 60, 80 and 100 °C; extraction time: 15 min	23.42% extraction efficiency at 80 °C	
	Hot water extraction	Temperature: 80 °C, extraction time: 2 h	50.25% extraction efficiency	
Alginate and carrageenan	Microwave-assisted extraction	Short duration, reduced solvent consumption, and optimal frequency	Higher efficiency, shorter extraction time	[163, 322]
	Ultrasound-assisted extraction	High-intensity sonication	A good method for saving time and solvents	[313, 323]
Alginate	Alkaline extraction	Maintaining pH levels above the alginate's pKa value	Excellent yield, but chemically demanding	[322]
		Temperature: 70 °C, extraction time: 3 h, amount of Na_2CO_3: 0.84 mol/L	29.28% extraction efficiency	[324]
		Temperature: 80 °C, extraction time: 90 min and pH: 10	45.79% extraction efficiency	[102]
Ulvan	Microwave-assisted extraction	Optimal temperature between 120–160 °C, mild acidic solution, extraction time within 15–30 min, and using 400–600 W power	36.38–40.4% extraction efficiency, faster processing, and lower solvent use	[107]
	Enzyme-assisted extraction	Cellulysin, 20 h	14.1% extraction efficiency	[315]
	Hot water extraction	Temperature: 120 °C, extraction time: 30 min, precipitate with ethanol	26.73% extraction efficiency	[325]
	Ultrasound-assisted extraction	Temperature 84.75 °C, extraction time 30.51 min, solvent to sample ratio of 60.51 mL/g	22.5% extraction efficiency	[165]
Fucoidan	Microwave-assisted extraction	Temperature range between 120–160 °C Power: 400–800 W and Duration: 10–30 min	30–70% extraction efficiency, short extraction time, and environmentally friendly	[316]
	Ultrasound-assisted extraction	Temperature: 40–80 °C, Power: 20–40 kHz, and Time: 30–90 min	30–65% extraction efficiency, better structural preservation, and less solvent use	
	Subcritical water extraction	Temperature: 120 °C, extraction time: 5 min and solvent to sample ratio of 20 g/L	46 mg/g dw extraction efficiency and antioxidant activity compared with hot water extraction	[326]
	Microwave-assisted extraction	Temperature: 150, 160, and 170 °C for 1, 10, and 30 min, respectively	13.6% extraction efficiency at 150 °C for 30 min	[131]
	Ultrasound-assisted enzymatic extraction	Temperature: 40–65 °C, ultrasound intensity: 0–118 $W.cm^{-2}$, Amount of enzyme (Accellerase): 0–0.05 mL/g and pH 4.5–6	7.9% extraction efficiency at 58.75 °C, 88.75 $W.cm^{-2}$, pH 6 and with no enzyme	[105]
Rhamnan	Microwave-assisted extraction	Temperature range between 100 °C to 180 °C, Duration: 10 min and Frequency; 2.45 GHz, max output; 1 kW	53.1% extraction efficiency at 140 °C, and then drastically decreased above 160 °C	[317]
Laminarin	Ultrasound-assisted extraction	60% ultrasonic power amplitude and 0.1 M hydrochloric acid for 15 min	Highest yield of laminarin, 5.82% and 6.24%	[327]
	Ultrasound-assisted extraction	Ultrasonication was conducted by an ultrasound probe and ultrasound bath. Temperature: 70 °C, and with 0.1 M HCl. Power for ultrasound probe: 20 kHz and power of ultrasound bath:550 W	57.34% extraction efficiency	[328]
	Hot water extraction	pH 1.5, temperature: 99.3 °C and extraction time 30 min	36.8% extraction efficiency	[329]
	Hot water extraction	Temperature 120 °C and extraction time 80.9 min	23.44% extraction efficiency	[330]
	Enzyme assisted extraction	Celluclast®, under conditions of 60 °C, pH 4.0, and an enzyme-to-substrate ratio of 4.0% (v/w)	57% extraction efficiency	[331]
Porphyran	Hot water extraction	Temperature 60- 100 °C and extraction time 30- 240 min	22.15% extraction efficiency at 100 °C and 120 min	[332]

radicals, and consequently, cellular damage, leading to the onset of many diseases [23]. Since macroalgae have antioxidant defence mechanisms like photosynthetic plants, they reduce the formation of ROS that attack molecules such as proteins, lipids, enzymes, DNA and RNA [24]. A study has reported that macroalgae exhibited antiproliferative effects (inactivated in cancer cells) and they induce apoptosis, inhibit cell viability, and reduce glucose and lipid accumulation [25].

As bioactive compounds, macroalgal polysaccharides including hydrocolloids exert diverse health benefits through multiple mechanisms. Their physiological effects are primarily mediated through their interaction with gut microbiota, immunomodulatory pathways, and metabolic processes. Studies have demonstrated their anti-obesity, anti-diabetic, anti-inflammatory, antioxidant, and gut-modulating properties, suggesting their potential application in the prevention and management of metabolic and inflammatory diseases (Fig. 2, Table 4) [189–191]. These compounds, which provide a food source for beneficial intestinal microorganisms thanks to their prebiotic-like properties, increase microbial diversity and promote the production of health-supporting metabolites such as short-chain fatty acids (SCFAs) [192, 193]. Macroalgal polysaccharides act through distinct, structure-dependent mechanisms; they do not share a single pathway of action. Fucoidan (sulfated fucose backbone) primarily attenuates inflammatory signaling via nuclear factor-κB (NF-κB), with upstream phosphoinositide 3-kinase/protein kinase B/nuclear factor erythroid 2–related factor 2 (PI3K/AKT/Nrf2) signaling and context-dependent AMP-activated protein kinase (AMPK) crosstalk in metabolic tissues, whereas alginate (guluronate–mannuronate) exerts anti-obesity effects largely through gastrointestinal viscosity, delayed gastric emptying, and incretin responses (glucagon-like peptide-1 (GLP-1)/peptide YY (PYY)) that reduce energy intake. Carrageenan (κ/ι/λ; red algal sulfated galactans) shows dose- and type-dependent immunomodulation in macrophages and epithelial models, with host-context sensitivity. Ulvan (rhamnose-uronic acid; green algal) is fermented to SCFAs that signal via G-protein-coupled receptor 41 (GPR41) and G-protein-coupled receptor 43 (GPR43), and histone deacetylase (HDAC) inhibition to reinforce barrier integrity and dampen inflammation. Together, these processes influence lipid handling, appetite control, cytokine activity, and the composition of the gut ecosystem; however, the extent of their impact depends on factors such as polymer structure, molecular size, and administered dose [76, 194–199]. In the next sections, the discussion will focus on the metabolic advantages of macroalgal polysaccharides, emphasizing their possible contribution to the prevention and management of obesity, diabetes, and dyslipidaemia.

Anti-obesity effects

Obesity is a complex metabolic disorder marked by abnormal expansion of adipose tissue and disturbances in energy regulation. Evidence from recent studies suggests that macroalgal polysaccharides may counteract obesity through several pathways, including modulation of lipid metabolism [200–202], regulation of appetite [190, 203], and shaping of gut microbial communities [202, 204, 205]. Their prebiotic properties foster beneficial intestinal microbiota and stimulate short-chain fatty acid (SCFA) production, which serve as important mediators of metabolic health [206]. In addition, these polysaccharides have been reported to suppress adipogenesis, improve circulating lipid parameters, and influence inflammatory cascades linked to obesity-associated complications [196].

One of the primary mechanisms by which macroalgal polysaccharides exert anti-obesity effects is through the regulation of lipid metabolism. Studies indicate that these polysaccharides can inhibit lipid absorption, reduce hepatic lipid accumulation, and enhance fatty acid oxidation by modulating key metabolic enzymes such as AMP-activated protein kinase (AMPK) and peroxisome proliferator-activated receptors (PPARs) [207, 208]. Furthermore, they can lower plasma cholesterol and triglyceride levels by promoting bile acid excretion and altering cholesterol metabolism [209]. Another important aspect is their role in appetite regulation; certain macroalgal polysaccharides have been shown to increase satiety hormones, such as glucagon-like peptide-1 (GLP-1) and peptide YY (PYY), while reducing levels of ghrelin, the hunger hormone, thereby contributing to reduced energy intake and weight management [210].

The anti-obesity mechanisms of algal hydrocolloids are different from each other. Fucoidan reduces hepatic lipid accumulation and inflammatory signaling via via nuclear factor-κB (NF-κB) suppression and phosphoinositide 3-kinase/protein kinase B/nuclear factor erythroid 2–related factor 2 (PI3K/AKT/Nrf2) activation in NAFLD-like spheroid models, aligning reduced ROS with in lower tumor necrosis factor-α (TNF-α), interleukin-6 (IL-6), and interleukin-1β (IL-1β) transcription. Fucoidan also reshapes microbial metabolites, but its primary anti-obesity signal in preclinical models is the integration of anti-inflammatory and antioxidant pathways rather than viscosity or primary SCFA stimulation [194, 196]. Carrageenan's metabolic effects are model- and structure-dependent; while macrophage cytokine modulation is robust, epithelial inflammatory amplification in susceptible contexts (e.g., Crohn's-derived cells) cautions against generalization to anti-obesity outcomes without dose/type control [76]. Alginate's anti-obesity potential is driven by viscosity-mediated nutrient diffusion and satiety signalling (GLP-1/PYY), supporting

Table 4 Health effects of macroalgal hydrocolloids

Macroalgea	Bioactive compounds	Health effect	Model (in vitro / in vivo / clinical)	References
Brown Macroalgea				
Saccharina latissima	Fucoidan	Gut microbiota modulation	In vitro, clinical	[333]
Sargassum hemiphyllum, Sargassum horneri	Fucoidan	Anti-cancer effect Used in combination with chemotherapy and radiotherapy Reduction of atopic dermatitis symptoms Anti-inflammatory	In vitro, in vivo, clinical	[172, 334, 335]
Undaria pinnatifida	Fucoidan	Increased antibody production against influenza	Clinical	[336]
Laminaria digitata	Laminarin	Prebiotic effect Gut microbiota Anti-inflammatory Anti-obesity Antioxidant activity Increases immunity	In vitro, in vivo	[337–339]
Laminaria, *Macrocystis*, *Ascophyllum*	Alginate	Maintains glycemic index Antidiabetic activity Gut microbiota	In vitro, in vivo	[336, 340, 341]
Red Macroalgea				
Kappaphycus alvarezii, *Eucheuma spinosum*	Carragenan	Antiviral Immunomodulatory Anti-obesity Antihyperglycemic and antihyperlipidemic effects	In vitro	[342–344]
Porphyra haitanensis	Porphyran	Potential for protection and repair of intestinal epithelium	In vivo	[345, 346]
Gelidum pristoides, *Corallina officinalis*	Sulphated polysaccharides	Antioxidant activity	In vitro	[347, 348]
Green Macroalgea				
Ulva ohnoi *U. rigida* *U. lactula*	Ulvan	Antioxidant activity Anti-cancer Anti-inflammatory Cholesterol-lowering Hypercholesterolemic	In vitro, in vivo	[113, 349, 350]
Monostroma nitidum	Rhamnan	Probiotic effect Lipid-lowering Anti-viral and anti-thrombotic Preventing hyperlipidemia Blood glucose-lowering effect, improvement in insulin resistance	In vitro, in vivo, clinical	[351–353]

reduced energy intake and improved lipid profiles in dietary contexts, as synthesized across recent marine polysaccharide reviews and meta-analyses [195, 196]. Ulvan promotes SCFA production (acetate, propionate, butyrate), which engages GPR41/43 and HDAC inhibition to reduce lipogenesis and enhance fatty acid oxidation-mechanistic nodes that explain downstream anti-obesity outcomes and anti-inflammatory benefits [198].

In vitro, sulfated polysaccharides from brown and red algae reduce adipocyte differentiation and intracellular lipid accumulation, but effects are polymer- and dose-specific; carrageenan's macrophage activation profile warrants careful interpretation in co-culture systems to avoid conflating immunostimulation with anti-adipogenic outcomes [195, 196].

Interactions with the gut microbiota are central to the anti-obesity properties of macroalgal polysaccharides. Acting as fermentable substrates, these compounds support the growth of beneficial genera such as *Bacteroides*, *Bifidobacterium*, and *Lactobacillus*, which in turn elevate SCFA production, notably acetate, propionate, and butyrate [211]. SCFAs function as key signalling molecules, influencing lipid metabolism, limiting lipogenesis, and promoting fatty acid oxidation via activation of G-protein-coupled receptors, especially GPR41 and GPR43 [212]. Beyond metabolic regulation, SCFAs also dampen pro-inflammatory cytokine activity and foster an anti-inflammatory milieu, a mechanism regarded as pivotal in reducing obesity-associated metabolic disturbances [213].

In clinical studies, sulfated polysaccharide (SXRG84) from *Ulva* spp. at doses of 2 and 4 g/day; brown seaweed extract rich in polyphenols 500 mg/day; *Gelidium elegans* (GEE) extract 1000 mg/day; Xanthigen (brown seaweed fucoxanthin + pomegranate seed oil) containing fucoxanthin (1.6–2.4 mg), and sodium alginate at low (9.9 g) and high (15.0 g) volumes have been used. These studies generally reported positive effects on the lipid profile, glucose homeostasis, inflammation, body weight, and feeling of satiety. For example, SXRG84 provided reductions in non-HDL cholesterol, CRP, and proinflammatory cytokines [214]; Brown seaweed extract suppressed the increase in IL-6 and showed improvements in metabolic indicators [215, 216]. GEE extract reduced body weight and fat mass in obese individuals [217]; alginate increased the feeling of satiety [218]; and Xanthigen reduced body fat, liver lipids, triglyceride, and CRP levels, while increasing resting energy expenditure, particularly in women with NAFLD [219].

Evidence from in vitro, animal, and human investigations continues to reinforce the anti-obesity potential of macroalgal polysaccharides. Cell culture experiments demonstrate that polysaccharides obtained from brown and red algae can suppress adipocyte differentiation and lipid deposition in preadipocyte models [220, 221]. In vivo studies using diet-induced obesity models report that supplementation with these polysaccharides consistently attenuates body weight gain, enhances insulin sensitivity, and beneficially alters gut microbial composition [153, 222–224]. Furthermore, a meta-analysis of clinical trials indicates that consumption of macroalgae-derived polysaccharides may lower body mass index, reduce adiposity, and improve circulating lipid parameters, highlighting their promise as functional components in obesity management [225]. Although these outcomes point to positive metabolic effects of seaweed and its derivatives, results are not universally consistent and may differ depending on algal species, dosage, and study population. Consequently, future research should clarify the long-term impacts of seaweed intake and delineate the biological pathways responsible for these benefits.

Antidiabetic and hypoglycemic effects

Type 2 diabetes mellitus is a prevalent metabolic disorder, marked by persistent hyperglycemia, insulin resistance, and impaired glucose regulation [226]. With its rising incidence, there is growing interest in dietary strategies that may provide hypoglycemic benefits. Evidence indicates that polysaccharides derived from macroalgae contribute to glucose homeostasis through several mechanisms, such as enhancing insulin sensitivity, inhibiting carbohydrate-digesting enzymes, and modulating gut microbial activity [196, 227, 228]. These compounds have been associated with reductions in fasting blood glucose, improved pancreatic β-cell performance, and greater glucose uptake in peripheral tissues [229–231].

A central pathway underlying the antidiabetic action of macroalgal polysaccharides involves improved insulin responsiveness and regulation of glucose metabolism. Research shows that these polysaccharides can stimulate metabolic regulators including AMP-activated protein kinase (AMPK), which promotes glucose uptake and suppresses hepatic gluconeogenesis [210]. They also enhance insulin signalling by upregulating Glucose Transporter Type 4 (GLUT4) in skeletal muscle [210]. Moreover, specific polysaccharides such as sulfated fucoidans and alginates inhibit α-glucosidase and α-amylase, thereby slowing carbohydrate breakdown and attenuating postprandial glucose elevations [210].

Modulation of the gut microbiota represents an important pathway through which macroalgal polysaccharides support glycemic regulation. Acting as prebiotics, these compounds stimulate the growth of beneficial microbes such as *Bifidobacterium* and *Akkermansia muciniphila*, both linked to improved insulin sensitivity and reduced inflammation in metabolic disorders [203, 204, 210]. Microbial fermentation

of these polysaccharides generates SCFAs, particularly propionate and butyrate, which enhance insulin signaling, influence lipid metabolism, and suppress pro-inflammatory cytokines associated with insulin resistance [191, 203, 212]. SCFAs also engage free fatty acid receptors (FFAR2 and FFAR3), thereby modulating hormone release from enteroendocrine cells and contributing to glucose homeostasis [212]. In vitro work has shown that brown algal polysaccharides such as fucoidan and laminarin safeguard insulin secretion by protecting pancreatic β-cells from oxidative stress [232]. Consistent with these findings, animal studies demonstrate that supplementation with macroalgal polysaccharides reduces fasting glucose, improves glucose tolerance, and lowers glycosylated hemoglobin (HbA1c) in diabetic models [233]

Anti-inflammatory and immunomodulatory properties

Chronic inflammation is is widely recognized as a major contributor to the development of metabolic, autoimmune, and gastrointestinal diseases. Disorders such as inflammatory bowel disease (IBD) are marked by exaggerated immune responses and impaired immune regulation [234]. The increasing incidence of these conditions has intensified interest in natural bioactive compounds capable of modulating immunity and attenuating inflammation. Among them, macroalgal polysaccharides stand out for their strong anti-inflammatory and immunoregulatory activities, offering therapeutic promise in managing chronic inflammatory states and immune dysfunction [228, 235].

The anti-inflammatory potential of these polysaccharides is largely linked to their influence on signaling cascades and cytokine production. They have been shown to interfere with central pro-inflammatory pathways, particularly nuclear factor kappa B (NF-κB), which governs immune cell activation and the synthesis of inflammatory mediators [193, 208]. For instance, fucoidan has been reported to suppress NF-κB activity, thereby reducing the expression of cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and interleukin-1β (IL-1β) [191, 210]. Since these cytokines drive inflammation both locally in the gut and systemically, their inhibition helps mitigate the harmful effects of chronic inflammatory processes.

Macroalgal polysaccharides also interact with innate immune receptors, including Toll-like receptors (TLRs), which detect pathogen-associated and danger-associated molecular patterns to initiate immune responses [236]. Experimental studies demonstrate that brown algal polysaccharides, especially fucoidan, can temper excessive immune activation by modulating TLR4-mediated signaling [237–239]. Through receptor binding, these compounds regulate the activity of macrophages, dendritic cells, and neutrophils, fostering a more balanced immune profile [190, 206, 238]. Such modulation of TLR pathways is particularly relevant in IBD, where dysregulated immune activation perpetuates chronic intestinal inflammation [235, 239].

Polysaccharides derived from macroalgae exhibit notable immunomodulatory properties by dampening pro-inflammatory signaling pathways (such as NF-κB), strengthening epithelial barrier integrity, and reshaping microbial metabolism. These effects are influenced by structural features including sulphation patterns, molecular size, and backbone configuration. Fucoidan has repeatedly been shown to suppress NF-κB-driven transcription of cytokines (TNF-α, IL-6, IL-1β) and oxidative stress, with supporting evidence from hepatic models, macrophages, and three-dimensional organoid/spheroid systems. In a free-fatty-acid-induced NAFLD spheroid model, fucoidan reduced lipid deposition and NF-κB activity through PI3K/AKT/Nrf2 signaling, pointing to upstream regulation of redox and inflammatory networks [194]. Complementary studies demonstrate that fucoidan limits macrophage activation and apoptotic pathways, consistent with AMPK-mediated metabolic reprogramming that lowers inflammatory tone and promotes resolution [240]. Collectively, these findings indicate that fucoidan interferes with inflammation at multiple levels-directly via NF-κB and indirectly through metabolic sensors (AMPK/Nrf2)- with context-specific benefits across immune and metabolic tissues [194, 240].

Carrageenan's immune effects depend strongly on structural type (κ, ι, λ), with low-molecular-weight fractions eliciting distinct cytokine responses in macrophages through pattern-recognition receptor and inflammasome signaling. Experiments in RAW264.7 macrophages revealed dose- and type-specific cytokine programs, highlighting the importance of purity and chain length in study design [241]. At the intestinal interface, food-grade carrageenan modified microbial composition and epithelial inflammatory responses in mice without increasing permeability. These findings suggest immunomodulatory activity that may amplify inflammation in susceptible contexts (e.g., Crohn's disease-derived epithelial cells) but does not universally impair barrier function [76, 242]. Ulvan functions as a fermentable substrate that enhances SCFA production, which is known to regulate immune tone, strengthen epithelial barriers, and reduce inflammation via G-protein–coupled receptor (GPCR) signaling (GPR41/43) and HDAC inhibition. More broadly, SCFAs contribute to Treg induction and epithelial resilience; ulvan's ability to shift the microbial metabolome toward SCFA generation provides a plausible explanation for its anti-inflammatory activity and supports its inclusion in functional formulations aimed at maintaining gut-immune homeostasis [243, 244].

Antioxidant and anti-aging effects

In addition to acting directly as antioxidants, macroalgal polysaccharides contribute to the regulation of endogenous defence systems. Fucoidan, a polysaccharide obtained from brown algae, has been reported to enhance the activity of major antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) [208]. These enzymes are essential for sustaining cellular redox homeostasis, detoxifying ROS, and protecting cells from oxidative injury. By stimulating their activity, macroalgal polysaccharides not only facilitate ROS neutralization but also strengthen the overall capacity of organisms to resist oxidative stress [245].

Insights from model organisms, particularly *Caenorhabditis elegans*, further suggest that these polysaccharides may exert anti-aging effects through modulation of longevity-related pathways [134]. A central mechanism involves the insulin/IGF-1 signalling (IIS) cascade, in which DAF-16, a FOXO transcription factor, serves as a pivotal regulator. Nuclear translocation of DAF-16 activates genes associated with stress resistance, metabolic regulation, and lifespan extension, thereby supporting cellular stability and delaying age-related decline [134]. Moreover, macroalgal polysaccharides have been shown to influence proteostasis by reducing polyglutamine aggregation, a hallmark of neurodegenerative disorders, pointing to their potential role in mitigating protein misfolding diseases [134]. Although the precise molecular mechanisms remain under investigation, current evidence underscores the ability of macroalgal bioactives to modulate aging pathways and highlights their promise as functional ingredients for extending health span and preventing age-associated conditions [246].

The antioxidant activity of macroalgal polysaccharides is primarily attributed to their chemical structure, which enables them to effectively interact with and neutralize free radicals. For example, polysaccharides such as fucoidan and carrageenan have demonstrated potent radical-scavenging properties, significantly reducing oxidative stress in cellular models [36, 247, 248]. These polysaccharides contain sulphated glycosaminoglycan chains, which contribute to their ability to bind and neutralize ROS, preventing damage to cellular membranes and biomolecules. By reducing oxidative damage, these polysaccharides help maintain cellular integrity and function, which is essential for delaying the aging process and preventing the development of age related diseases [249].

Integrative summary and mechanistic context

To enhance accessibility while retaining mechanistic depth, we synthesize recent original evidence on macroalgae-derived polysaccharides across immune and metabolic axes. Fucoidan consistently attenuates NF-κB-driven cytokine expression and oxidative stress, with upstream modulation of PI3K/AKT/Nrf2 and context-dependent AMPK crosstalk in metabolic and immune models [194, 240]. Carrageenan shows structure-dependent immunomodulation, shaping macrophage cytokine profiles and modulating epithelial inflammatory responses; notably, food-grade carrageenan altered gut microbiota and epithelial responses without uniformly increasing permeability, while epithelial cells from Crohn's disease patients exhibited heightened inflammatory profiles, highlighting host-context sensitivity [76, 242]. Ulvan enhances gut barrier integrity and leverages microbiota-derived SCFAs-engaging epithelial and immune GPCR pathways (GPR41/43) and HDAC inhibition-to reduce inflammatory drive and support mucosal resilience [243, 250]. Together, these findings demonstrate that polysaccharide chemistry (sulfation pattern, molecular weight) and dose determine pathway engagement and outcomes, underscoring the need for standardized characterization and translational designs that capture digestion, fermentation, and epithelial exposure. The key mechanistic insights and experimental outcomes of macroalgae-derived hydrocolloids are summarized in Table 5, which links each hydrocolloid type with its primary mechanism of action, experimental model, and main health-related outcome.

Challenges in developing macroalgal polysaccharides-based health solutions

Although numerous studies have investigated the health-promoting properties of macroalgal polysaccharides, the exact molecular mechanisms underlying their actions remain incompletely defined. For instance, the anti-tumor activity of fucoidan in breast cancer models requires further clarification to determine how it modulates immune responses and induces apoptosis in cancer cells [251].

Most current evidence is derived from in vitro experiments and animal models, which provide valuable mechanistic insights but may not accurately represent human physiology. To enable translation into clinical practice, well-designed human trials are urgently needed. For example, the reported anti-obesity effects of macroalgal polysaccharides, along with their roles in Type 2 diabetes and gut health, have largely been demonstrated in animal systems. Verification in human cohorts is essential to confirm these benefits and establish their therapeutic relevance [190, 234].

The prebiotic capacity of certain polysaccharides, including fucoidan and carrageenan, remains controversial. While some reports indicate positive modulation of gut microbiota and stimulation of beneficial bacterial growth, other studies raise concerns regarding safety, citing risks of intestinal

Table 5 Summary table linking hydrocolloid, mechanism, model, and outcome

Hydrocolloid	Primary mechanism	Pathway/target	Experimental model	Main outcome
Fucoidan	Suppresses inflammatory transcription; reduces oxidative stress	NF-κB↓; PI3K/AKT/Nrf2↑; AMPK-linked metabolic reprogramming	FFA-induced NAFLD 3D spheroids; macrophage/immune models	↓TNF-α/IL-6/IL-1β, ↓lipid accumulation, ↓ROS, improved redox signalling [3, 4]
Carrageenan (food-grade; structure-dependent)	Modulates macrophage cytokines; shapes epithelial inflammatory tone and microbiota	PRR signaling; epithelial inflammatory profile; microbiota composition	RAW264.7 macrophages; mouse diet studies; patient-derived intestinal epithelial cells	Context-dependent immunomodulation; microbiota shifts; amplified epithelial inflammation in Crohn's cells without increased permeability [5, 6]
Ulvan (including ulvan-Na)	Reinforces tight junctions; increases SCFAs; dampens inflammation	Barrier proteins↑; SCFA→GPR41/43; HDAC inhibition	Aging/leaky gut mouse models; mechanistic SCFA literature	Improved barrier integrity; reduced inflammatory drive; mechanistic rationale via SCFA signalling [272]

inflammation or dysbiosis [192, 224]. These conflicting outcomes highlight the need for further research to clarify their microbiota-modulating properties, evaluate efficacy, and assess long-term safety in human diets.

A major limitation is their poor oral bioavailability, attributed to high molecular weight, extensive sulfation, and limited intestinal permeability. These compounds are often degraded in the gastrointestinal tract, restricting systemic absorption and diminishing therapeutic potential. For example, fucoidan and carrageenan undergo partial breakdown in the gut, reducing bioactivity [252, 253]. Approaches such as nanoparticle encapsulation, enzymatic modification, or co-administration with probiotics have been proposed to improve absorption, though most remain at the preclinical stage [254]. Another challenge is the lack of robust human validation. Long-term clinical studies are needed to determine efficacy and safety, particularly in chronic conditions such as obesity, diabetes, and IBD. Optimal dosing strategies also remain undefined yet will be critical for clinical application [255].

Despite extensive in vitro and animal data demonstrating anti-inflammatory, metabolic, and gut-modulatory effects, only limited controlled human trials exist. For example, fucoidan has shown immunomodulatory and anti-fatigue activity in cancer patients, but broader evidence across metabolic and gastrointestinal disorders is lacking. Similarly, carrageenan's immune effects are well established in cell and animal models, yet human findings remain inconsistent, with some suggesting pro-inflammatory responses in susceptible individuals [76]. Ulvan, although promising for enhancing gut barrier integrity and stimulating short-chain fatty acid production, has not yet been validated in human populations [250]. Structural heterogeneity of hydrocolloids-driven by species differences, extraction methods, and processing-further complicates reproducibility and regulatory approval. Without standardized characterization, comparisons across studies and translation into functional food applications remain difficult [256]. Addressing these challenges will require integrated strategies that combine advanced delivery systems, harmonized extraction protocols, and rigorously designed clinical trials.

In summary, macroalgal polysaccharides have shown beneficial effects in obesity, diabetes, and IBD, but their impact on other health conditions is less well explored. Potential cardiovascular benefits, such as modulation of lipid metabolism and reduction of risk factors, remain under-studied. Likewise, their possible roles in neurodegenerative diseases, including Alzheimer's and Parkinson's, are only beginning to be investigated. Expanding research into these areas could substantially broaden the therapeutic applications of macroalgal polysaccharides [257].

Potential applications of macroalgal polysaccharides

Macroalgal polysaccharides represent a unique class of biomaterials whose relevance spans both applied and fundamental domains, but coherence requires distinguishing these facets. Their non-toxicity, biocompatibility, water solubility, and easy availability make macroalgal polysaccharides valuable candidates for a wide range of industrial applications, particularly in the food, cosmetics, and pharmaceutical sectors [152, 258–260].

In food industry applications, their importance lies in physicochemical properties such as gelation, viscosity, emulsification, and film formation, which enable diverse technological functions. For instance, carrageenan is widely used in dairy systems where κ- and ι-fractions stabilize proteins and improve texture under ionic and thermal stress [261]. Alginate's calcium-mediated ionotropic gelation supports restructured foods and encapsulation systems, while agar's strong gel and film-forming capacity has been exploited in edible coatings and biodegradable packaging [262]. Recent advances also highlight macroalgae-derived polysaccharides as precursors for bioplastics and sustainable packaging materials, linking their rheological and barrier properties to industrial innovation [263]. These applied outcomes are evaluated in terms of rheological performance, shelf-life extension, and consumer sensory acceptance, underscoring their role as functional ingredients in modern food systems. By contrast, the health effects of macroalgal polysaccharides are rooted in fundamental biological mechanisms, which differ across polymer types. Fucoidan has been shown to suppress NF-κB signalling and reduce oxidative stress, thereby attenuating inflammatory cytokine production [264]. Ulvan enhances SCFA production during microbial fermentation, which signals through GPR41/43 to reinforce gut barrier integrity and modulate immune responses [265]. Carrageenan exhibits immunomodulatory activity in macrophage and epithelial models, though its effects are structure- and dose-dependent, highlighting the need for careful characterization [76].

Applications in food formulation

The primary utilization of macroalgal polysaccharides is attributed to their hydrocolloid properties, which enable thickening, gelling, stabilizing, emulsifying, fat replacement, and water binding functionality. These techno-functional roles contribute to product structuring and quality improvement in a variety of food matrices (Fig. 3). For instance, carrageenan, alginate and agar agar are widely used in the food industry in many products ranging from fresh fruit and vegetables, ice cream and plant-based meats to gummy candies and functional beverages (Table 6). Carrageenan is mostly utilized in the forms such as κ-carrageenan and/or l-carrageenan as a textural modifier in diverse food products including fruit leathers [266], meat and meat-substitutes [267–269], or as an active packaging agent for coatings and/or sensors [270–273]. Alginate, on the other hand, is commonly used in products requiring encapsulation or as an edible coating agent to extend the shelf life of food products. It is used to encapsulate various food components to produce functional products such as whey and soy protein

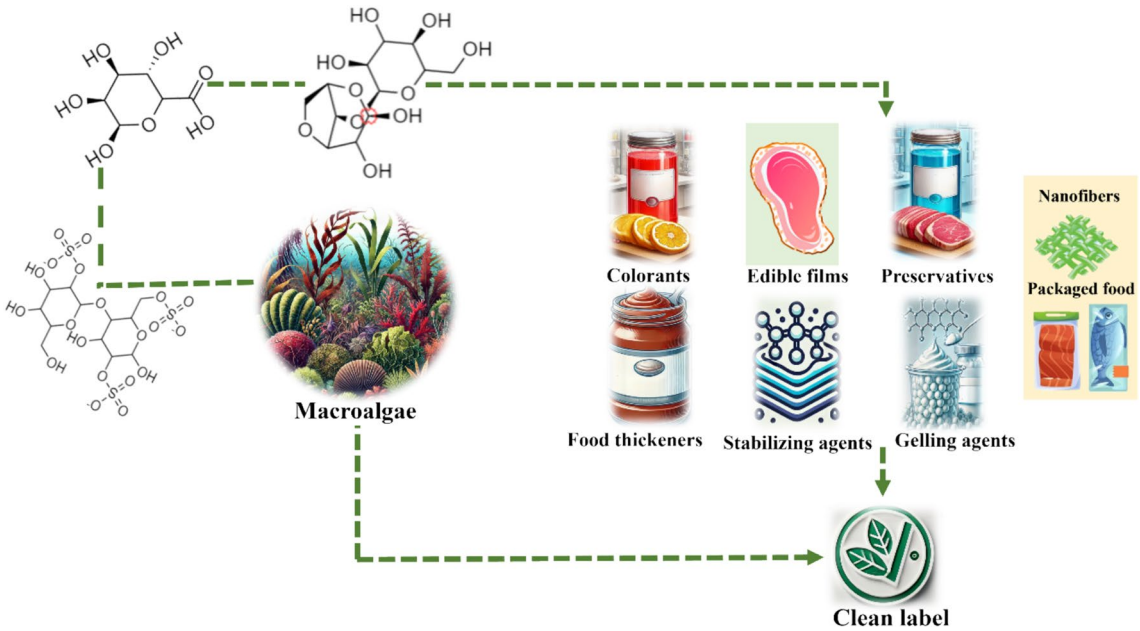

Fig. 3 Macroalgae-derived polysaccharides function as techno-functional ingredients in the food industry (Created from Microsoft PowerPoint and DALLE)

Table 6 Specific food applications of the hydrocolloids

Hydrocolloid type	Designed food product/ Application	Concentrations	Remarks	Key findings	References
Carrageenan	Strawberries (Edible coating)	0.5%	Strawberry storage with the addition of lemon grass essential oil (1%) in refrigerator for 12 days	Coating effectively reduced weight loss and decay in strawberries, resulting in only about 8% weight loss and 14% decay after 12 days, whereas the uncoated control samples showed about 10% weight loss and 78% decay Reduced cellulase, pectin methylesterase, polygalacturonase, and ß-galactosidase activity Maintained antioxidant activity Successfully preserved anthocyanins and phenolic compounds	[344]
	Muffin (Egg replacer)	0.5%, 1%, 2% based on egg (50 g)	Eggless muffin by using super mealworm protein isolate and carrageenan as egg replacer	Higher concentration of carrageenan increased chewiness and cohesiveness but caused no significant changes in hardness Eggless muffins exhibited higher protein digestibility Acceptable sensory properties were observed Baking loss was reduced with an increase in carrageenan concentration Mealworm protein isolate and carrageenan mixture increased the chewiness and cohesiveness Formation of a darker crust and crumb was noted	[354]
	Papaya (Intelligent colorimetric sensor)	n.d	An intelligent label was produced using carrageenan and sodium carboxymethyl cellulose, with the addition of bromothymol blue as a pH- indicator, to monitor the freshness of fresh-cut papaya	Addition of carrageenan enhanced mechanical properties and decreased water solubility and water vapor permeability of the intelligent label Successful color change of the label was observed at different CO_2 concentration levels	[345]
	Chicken wings (Antioxidant and pH-sensitive film)	0.9%	Arrowhead starch was incorporated with κ-carrageenan and black chokeberry extract to monitor freshness of chicken wings	Decreased light transmittance of the film Carrageenan itself was not effective to decrease water vapour permeability of films The addition of carrageenan increased elongation at break values Carrageenan increased apparent viscosity of films Increased antioxidant activity (DPPH free radical) Successfully monitored visible color change of the film during chicken wing spoilage	[355]
	Shrimps (Active food packaging)	2%	Active packaging films of κ-carrageenan with anthocyanin and Zn-carbon doped were prepared by purple Kohlrabi peels to extend quality and shelf life of shrimps	Enabled pH-responsive active and intelligent food packaging Extended the shelf life and quality of shrimps for 15 days of storage Exhibited strong UV blocking ability for both UV-A (85.2%) and UV-B (99.4%) Demonstrated high antioxidant effect Inhibited the growth of G (+) and G (-) bacteria Showed excellent antibacterial properties, particularly against *L. monocytogenes* and *E.coli* Reduced spoilage effectively	[47]
	High protein ice cream (Stabilizer)	0.3% total stabilizer combination	The addition of κ-carrageenan to a stabilizer combination of guar gum and locust bean gum was used in the production of high-protein ice cream made with whey protein isolate	Reduced flow behavior index and hardness value (from 47.2 N to 8 N) Increased consistency coefficient, viscosity and overrun Lower concentration of κ-carrageenan resulted in a high melting rate (from 0.75 g/min to 0.32 g/min) A strong crosslinked gel network was formed Higher concentration of κ-carrageenan led to the destabilization of fat globules and the formation of clumps Acceptable sensorial properties were achieved	[266]

Table 6 (continued)

Hydrocolloid type	Designed food product/ Application	Concentrations	Remarks	Key findings	References
	Guava-banana fruit leather (Textural modifier)	0.3%	An addition of κ-carrageenan and gum Arabic to guava-banana fruit leather for improving product quality	No significant changes in water content of the products Addition of κ-carrageenan increased the tensile strength of the leather Addition of κ-carrageenan enhanced the antioxidant capacity Products showed higher sensorial acceptance	[267]
	Plant-based meat (Textural modifier)	2%	ι-carrageenan addition to pea protein isolate and wheat gluten protein blends at different stages	The addition of ι-carrageenan increased the browning index, water holding capacity, tensile stress and air bubble numbers The most visible fibers were observed after the addition of ι-carrageenan to pea protein isolate ι-Carrageenan caused heterogeneity in the microstructure	[346]
	Shrimp myofibrillar protein (Textural modifier)	0.01%, 0.02%, 0.03%, 0.04%	Improvement in the gelling capacity of shrimp myofibrillar protein by comparing different types of carrageenan (κ-/ι-carrageenan)	Increased gel strength and water holding capacity Improved storage modulus and loss modulus during heat-induced gelation Excessive carrageenan concentration decreased the water-binding capacity of the gel ι-Carrageenan retained more moisture in the texture Increased carrageenan concentration disrupted the gel network	[356]
	Reduced-fat chicken patties (Textural modifier)	1%	The effects of chia flour and κ-carrageenan addition on the physicochemical, textural and sensory properties of chicken patties	Increased pH to 5.54 Increased cooking yield (from 85.6% to 89.4–90.51%), moisture retention (from 79.8% to 84.6–86.0%) and hardness Reduced shrinkage (from 7.3% to 4.7–3.7%), adhesiveness and cohesiveness Acceptable sensorial properties with the use of 1% κ-carrageenan	[347]
	Ready-to-eat *Antarctic Krill* surimi gel (Textural modifier)	1%, 2%, 3%, 4% and 5%	The impact of κ-carrageenan on the quality of surimi gels	Reduced cooking loss (from 27.3 to 6.2%) Increased water holding capacity Helped to prevent protein gel network breakdown Decreased hardness (from 30 N to about 20 N) and chewiness (from 1800 to about 1200) Increased pore size and a more organized microstructure Enhanced product quality	[357]
	Chicken liver pate (Textural modifier)	0.25%, 0.5%, 0.75% and 1%	The use of κ-carrageenan, ι-carrageenan and furcellaran to improve the quality of spreadable chicken liver pate	The addition of κ-carrageenan increases the spreadability of the product more effectively than ι-carrageenan No significant difference in carrageenan type on moisture, fat, protein content, pH and water activity Increased hardness value κ-Carrageenan was shown to be a more effective thickening agent than ι-carrageenan	[62]
Alginate	Dark chocolate (Encapsulation)	10% microspheres including 5:3 ratio of alginate to SPI	Alginate and soy protein isolate (SPI) were used to encapsulate chia seed as an omega-3 source and encapsulates were used in dark chocolate fortification	Increased moisture content (from 1.65 to 1.92%) and water activity (0.33 to 0.37), remaining within acceptable ranges Fortification resulted in a change in color values of chocolate Reduced hardness and adhesiveness (from 24.19 N to 21.73 N) Achieved acceptable sensorial properties	[64]
	Functional beverage (Encapsulation)	n.d	Alginate beads were produced with whey protein isolate and soy protein concentrate to create a functional beverage with *Ziziphus jujube* extract	Decreased acidity of beverage after 14 days of storage in the refrigerator No significant effects on the brix of the beverage (brix value is 11 from the first day to 14 days of storage) Increased turbidity over 14 days of storage Achieved acceptable sensory properties	[348]

Table 6 (continued)

Hydrocolloid type	Designed food product/ Application	Concentrations	Remarks	Key findings	References
	Functional meatballs (Encapsulation)	2.35%	Alginate and lupin were used to encapsulate cod liver oil to create functional meatballs	Had the lowest pH of meatballs after 16 days of storage at 4 °C (from pH 6.6 to 6) Decreased the lipid oxidation, peroxide value, conjugated dienes and carbonyl content Achieved acceptable sensory properties	[358]
	Low cholesterol butter (Encapsulation)	2%	Encapsulation of *Lactica-seibacillus paracasei* strains into calcium-alginate beads to create low cholesterol butter	Achieved 23% reduction in cholesterol of cream and 44% reduction in cholesterol of butter No change observed in the fatty acid profile Improved fatty acid composition Achieved acceptable sensory properties	[359]
	Frozen Fatty Fish Mince (Cryoprotectant)	2%	Medium fatty fish mince was treated with alginate, calcium and sodium salts to extend the shelf life under frozen storage	Reduced levels of free fatty acid and secondary oxidation products compared to control samples The visual color value was better in the alginate-treated sample Achieved higher water holding capacity (80%) Decreased microbial load after 120 days of storage	[59]
	Chicken meat (Edible coating)	1.5%	Alginate, bayberry extract, cinnamaldehyde, and nisin were used to produce an edible coating that extended the shelf life of chicken meat during 9 days of storage at 4 °C	Increased antimicrobial effects were shown by reductions in total mesophilic bacteria, lactic acid bacteria, and yeasts/molds Achieved decreased total volatile nitrogen, indicating the chemical freshness of the product Achieved acceptable sensory properties	[60]
	Cherry tomatoes (Edible coating)	1%	Alginate was used with *Helichrysum italicum* essential oil to produce edible coatings for cherry tomatoes to preserve them at 25 °C, 60% relative humidity for 18 days	No spoilage after 18 days of storage Decreased weight loss (from 1.51% to 1.32%) Tomatoes maintained higher firmness (from 8.28 N to 8.53 N) Decreased color change during storage	[274]
	Orange (Edible coating)	1%	Alginate, cocoa and the combination of both were applied as edible coatings to increase the shelf life of fresh oranges	The highest moisture content was achieved by alginate coating (860 g/kg) Increased firmness and fracturability Although the alginate coating demonstrated superior performance in preserving microbial and textural quality, its effectiveness in maintaining sensory properties was limited; however, the incorporation of cocoa into the alginate coating successfully addressed this issue	[61]
	Dried apricot (Edible coating)	2%	Alginate was used to produce edible coating to increase the shelf life of dried apricots at 25 °C	Improved retention of vitamin C and carotenoid content after 4 months of storage Reduced moisture loss Decreased the rate of change in total soluble solids for 4 months of storage Effective delay in the increase of hardness up to 2 months of storage Reduced microbial growth Achieved acceptable sensory properties	[275]

Table 6 (continued)

Hydrocolloid type	Designed food product/ Application	Concentrations	Remarks	Key findings	References
	Chili peppers (Edible films)	1.5% and 2%	Alginate was used with zein and glycerol to produce edible films for the preservation of chili peppers	The shelf life of chilli peppers increased to 15 days at 20 °C The increase of alginate concentration decreased water vapor permeability of edible films The firmness of coated chili peppers did not change at 10 °C, however, the firmness increased on day 7 at 20 °C Unacceptable sensorial properties	[65]
	Sweet sorghum fermentation (Yeast immobilization)	2%	Dried Baker's yeast (*S. cerevisiae*) was immobilized onto calcium alginate beads	The immobilized yeast had 10 reuse cycles Although the optimum fermentation period was higher for the immobilized yeast, a higher ethanol concentration (from 10 to 12%) and percent conversion were achieved	[232]
	Bayberry Juice (Clarification agent)	1%	Alginate-chitosan composite was used as a clarifier for bayberry juice clarification	Increased transmittance Reduced reduction of anthocyanins when alginate-chitosan composite clarifier was used Improved color and aroma Achieved acceptable sensory properties	[277]
Agar–agar	Carrot juice extraction (Enzyme encapsulation)	1%, 2%, 3%	Cellulase enzyme was immobilized by entrapment into calcium alginate and agar–agar cubes	Increased optimum temperature of enzymes with agar–agar entrapment (from 50 ºC to 60 ºC) Immobilized enzyme was effective in carrot juice extraction Achieved 97.63% immobilization efficiency with agar–agar entrapment, compared to 92.11% with alginate	[279]
	Vegan gels (Gelling agent)	2%	Different monosaccharides were tested in different concentrations for the gelation ability of agar–agar	Decreased moisture content (from 70.56% to 33.45%) Increased viscosity from 0.65 mPa.s to 8.58 mPa.s Increased hardness Different concentration of sugar caused different gelling, hydration and textural properties of agar–agar	[281]
	Vegan gummy candies (Textural modifier)	0.5% and 1%	Agar–agar was used with citric acid and Jaban watermelon exocarp (JWE) powder to produce gummy candies	No significant change in moisture content with varying concentrations of agar–agar Increased concentration of agar–agar increased the viscosity from 0.457 Pa.s to 1.550 Pa.s Color acceptability of candies decreased as the concentration of JWE and agar–agar increased Agar–agar improved the texture and chewiness values in sensory analyses	[280]
	Surimi gels (Textural modifier)	0.125% to 1% (raw materials)	Agar–agar and fucoidan was added to surimi formulation as phosphate replacers to produce surimi gels	Enhanced water holding capacity and maintained gel strength Increased agar–agar concentration after 0.25% caused a decrease in gel strength Increased agar agar concentration caused a decrease in the L* color value in the refrigerator after 24 h, but no change was observed at the frozen stage after 1 year	[284]
	Fermented coconut jelly (Stabilizer)	0.25%, 0.5% and 1%	Agar–agar was used to produce coconut jelly and helped stabilize probiotics, phenolic compounds, and antioxidant compounds during in vitro digestion	Increased agar–agar concentration resulted in a higher retention of antioxidant and phenolic compounds during digestion The survival of probiotics remained above the recommended levels after digestion	[283]
	Solid rapeseed oil (Organogelator)	1% and 3%	Different types of rapeseed oil were solidified by oleogelation method using agar–agar hydrogel	Decreased agar–agar concentration increased weight loss and decreased oil retention capacity (from 98.3% to 64.4%) Lower agar–agar concentration made oleogel softer to the touch Increased oil binding capacity (<90%) with the increase of agar–agar concentration	[282]

Table 6 (continued)

Hydrocolloid type	Designed food product/ Application	Concentrations	Remarks	Key findings	References
	Short-bread cookies (Organogelator)	3%	Agar-canola oleogels were used as an alternative to solid fats in shortbread-type cookies	Increased crispness and decreased hardness Increased baking loss and decreased cookie diameter (from 8 cm to ~ 6 cm when compared to butter) Decreased L* color value of dough Increased water activity	[285]
	Frankfurter sausages (Fat replacer)	16 mg/mL agar for emulsion gel preparation	Emulsion gels were produced using agar–agar and carrageenan to replace 50% and 100% of pork back fat in Frankfurter sausages	No effect on textural properties at 50% substitution Total fat reduction from 25.37 to 17.07 g/g and caloric content reduction of 25% Achieved acceptable sensory properties Reduced a* and increased b* color values	[278]
	Fortified bubble tea (Encapsulation)	5.6% for agar-based bead production	Tributyrin was encapsulated into alginate beads, and then the alginate beads were encapsulated into agar–agar-based beads to produce fortified bubble tea	Lower degree of swelling of beads (around 5%) Increased resistance to digestion of tributyrin oil after encapsulation Maintained structural integrity through the simulated gastrointestinal tract Harder, more resilient and chewier beads were obtained Decreased hardness with the increase in temperature (at 20 ºC the hardness value is 980 g, which decreased to 650 g at 60 ºC)	[38]
	Cherry tomatoes (Food packaging)	2%	Iron-based metal organic framework with quantum dots (CD@MOF) was incorporated into agar–agar/gelatin matrices to produce packaging for cherry tomatoes, which were stored at 4 °C for 24 days	For the cherry tomatoes packed with agar–agar/gelatin films: -Moderately decreased degradation speed -Moderate decrease in firmness -Increased pH from 5.5 to 6 Increased shelf life of cherry tomatoes packed with agar–agar/gelatin/CD@MOF films Microbial growth was controlled by the implementation of CD@MOF into agar–agar/gelatin films (for *E.coli* Control: 9 CFU/mL CD@MOF: 2 CFU/mL after 12 h of storage)	[286]
	Beef (Shelf-life extender)	n.d	Agar–agar and sodium alginate were used to produce a bilayer film, combined with ginger essential oil for the storage of beef under refrigeration	The increase in pH was reduced by the film The accumulation of lipid oxidation products was decreased Microbial growth, particularly of pathogenic bacteria, was reduced in beef products during storage	[350]
Fucoidan	Pasta (Textural modifier)	1%, 5.5% and 10%	The use of fucoidan to improve the textural quality of pasta	Increase bioactive properties No effect of sensory properties until 10% concentration Increase water holding capacity Decrease textural integrity	[360]
	Yoghurt (Functional food)	0.25% and 0.5%	The use of fucoidan to improve shelf life, antioxidant activity and sensory properties	Decrease lipid oxidation Increase quality during shelf life Increase antioxidant activity Good sensory properties (colour, texture and taste)	[361]
	Edible biofilm	alginate/fucoidann ratio 2:1	Alginate and alginate-fucoidan blend films are produced with or without Ca-crosslinking	Decrease in water solubility Decrease of water and oxygen permeability with increase in fucoidan content Increase antioxidant activity Protect polyphenol release	[352]

Table 6 (continued)

Hydrocolloid type	Designed food product/ Application	Concentrations	Remarks	Key findings	References
	Bread (Functional foods)	0.0%, 1.5%, 2.0%, 2.5%, and 3.0%	The use of fucoidan to improve the nutritional value	Decrease glycemic index Decrease in starch digestion rate High bioaccessibility but low bioavailability of Fucoidan	[362]
	Mango (Edible coating)	1%, 3% and 5%	Fucoidan was used to produce an edible coating to increase the shelf life of mango at 20 °C and humidity of ~ 80% for 35 days	Increase shelf life Slowed down the ripening process Showed antibacterial effect Protect C vitamin and antioxidant activity	[363]
	Meat (functional food)	Solvent contained 9.3% laminarin and 7.8% fucoidan	Fucoidan was used to protect the meat and increase antioxidant activity	Increase antioxidant activity Increase shelf life Prevent lipid oxidation	[364]
Ulvan	Yoghurt (Functional food)	1%, 2% and 4%	Ulvan was used to increase functional, sensory and textural properties	Increase probiotic activity Protect quality for 9 days Occur undesirable taste Show prebiotic effect Decrease textural properties at high concentration	[106]
	Active films	3% dried extract	Ulvan was used to produce edible film for food products	Suitable for edible active packaging Decrease antioxidant activity and thermal stability with high concentration	[355]
	Edible films	ulvan concentration of 0.12, 0.24, and 0.48 g/g cellulose	Ulvan and cellulose were used to produce an edible film coating for packaging	Increase oxygen permeability Decrease water vapor permeability Protect the food from oxidative deterioration Increase antioxidant activity of food Increase thermal stability Protect from UV rays	[365]

isolates for functional beverages [64], chia seeds for dark chocolate [63], and cod liver oil for meatballs. Furthermore, it is extensively used as an edible coating for fruits and vegetables such as cherry tomatoes [60], oranges [274], dried apricots [61], and chili peppers [275]. Additional techno-functional applications include its use as a cryoprotectant in frozen foods [276], as a medium for yeast immobilization in fermented products [65], and as a clarification agent in combination with chitosan for fruit juices [232]. Agar–agar also plays multiple techno-functional roles, including use in encapsulation for juice products [277, 278], as a gelling agent and texture modifier in gels [279, 280], and gummy candies [281]. It also serves as organogelator and fat replacer in jellies, oils, cookies and sausages [282–285]. Additionally, agar–agar has been applied to extend shelf life when combined with gelatin or sodium alginate in foods such as cherry tomatoes [38] and fresh beef [286].

Applications in food packaging

In contrast to their roles in food formulation, macroalgal polysaccharides are also extensively utilized in biodegradable packaging materials, addressing the environmental concerns associated with traditional plastic based packaging [287]. Their good gas barrier properties, mechanical strength, and film-forming capacity make them suitable for producing active, intelligent and edible packaging films [17]. However, their inherent water solubility limits water barrier performance, a challenge that can be reduced by incorporating bioactive compounds or fillers [288].

There are numerous studies on the use of macroalgae-derived polysaccharides in the development of innovative and biodegradable packaging materials. Agar-based films reinforced with nano-bacterial cellulose showed improved mechanical and barrier properties through hydrogen bonding [289]. Sodium alginate films for fruit preservation demonstrated increased water contact angle, reduced water vapor permeability, and strong antioxidant and antimicrobial activity, effectively extending strawberry shelf life [290]. Similarly, kappa-carrageenan films infused with mulberry polyphenol extract produced pH-sensitive and antioxidant packaging, enabling freshness monitoring of milk [291].

Ulvan-based films were developed from *Ulva* genus macroalgae, in which carnauba (*Copernicia prunifera*) wax at different concentrations was blended to modify the hydrophilic nature of the films. The results showed that when higher concentrations of carnauba wax were added, the hydrophobicity increased [292]. In the study of Gomaa et al. (2018) [293], fucoidan and alginate were blended to form films. The results showed that the films showed antioxidant properties and a decrease in water solubility and the thickness, oxygen, and water permeability were increased [293].

Combining different polymers is becoming an important step for improving the performance in industrial applications [294]. Blends such as carrageenan-gelatin, alginate-chitosan will enable the creation of polyelectrolyte complex materials, which will in turn enhance physical properties like mechanical strength, barrier properties like moisture and gas resistance [295, 296]. The internal structures of polymers contribute to improving performance because the interaction of sulphates, amino, and carboxyl groups will form stable matrices [297]. The functional matrices will allow macroalgal polysaccharides to be utilised in a wide range of applications like packaging, coatings and drug-delivery systems as discussed earlier.

When these materials are manufactured commercially, they still face several obstacles. The composition of polysaccharides is variable, the reason is seasonal changes, and the method and conditions of extraction species differ [14]. Due to these reasons, standardisation of materials becomes difficult. During production, the material faces different variety of challenges, like water resistance is low, humidity, and inconsistency when producing different batches [298, 299]. Another challenge is the cost-effectiveness of extracting and purification [300]. When these challenges are addressed, the materials can be utilised for real-world applications rather than being a laboratory-based innovation [301].

Conclusions and future perspectives

It is necessary that more biodegradable materials derived from a variety of plant-based resources replace the current resources and materials utilized for food purposes, including harsh chemicals. At this point, macroalgae are seen as an effective alternative to traditional food sources due to their lack of need for arable land, low resource requirements and environmentally friendly production characteristics. For instance, great structural diversity of algal polysaccharides, including carrageenan, agar, alginate, ulvan, and fucoidan, supports a variety of biological and functional characteristics and is used in food applications and other industries. These hydrocolloids have great potential as bioactive substances with medicinal potential as well as sustainable food additives. However, macroalgae-derived hydrocolloids have not yet been thoroughly investigated for their possible uses in food, despite their enormous potential to enhance food functionality and health. Moreover, comprehensive studies are needed to delineate the molecular interactions underlying health effects of macroalgae-derived polysaccharides, which will help optimize their use in targeted therapies. Furthermore, standardized extraction and purification procedures are urgently needed to guarantee reproducibility and comparability across investigations to fully realize their

application. In-depth mechanistic studies are also necessary to clarify the specific molecular connections underlying their immunomodulatory, antiviral, and antibacterial properties. Most significantly, human clinical validation is still scarce and ought to be given top priority to verify the effectiveness and safety of these substances in practical settings. In conclusion, macroalgal hydrocolloids are important natural resources to promote innovations in food and human health because they combine sustainability with bioactivity.

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Declarations

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