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REVIEW **Open Access**

Marine macroalgae polysaccharides-based nanomaterials: an overview with respect to nanoscience applications

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Abstract

Background: Exploration of marine macroalgae poly-saccharide-based nanomaterials is emerging in the nanotechnology field, such as wound dressing, water treatment, environmental engineering, biosensor, and food technology.

Main body: In this article, the current innovation and encroachments of marine macroalgae polysaccharide-based nanoparticles (NPs), and their promising opportunities, for future prospect in different industries are briefly reviewed. The extraction and advancement of various natural sources from marine polysaccharides, including carrageenan, agarose, fucoidan, and ulvan, are highlighted in order to provide a wide range of impacts on the nanofood technology. Further, seaweed or marine macroalgae is an unexploited natural source of polysaccharides, which involves numerous different phytonutrients in the outermost layer of the cell and is rich in sulphated polysaccharides (SP), SP-based nanomaterial which has an enhanced potential value in the nanotechnology field.

Conclusion: At the end of this article, the promising prospect of SP-based NPs and their applications in the food sector is briefly addressed.

Keywords: Macroalgae, Polysaccharides, Nanotechnology, Nanoparticles, Food industry

1 Background

Over the last few years, there has been increasing attentiveness in the pursuit of new functional and bioactive compounds, especially polysaccharides, from marine genesis for wide application in various medical and food industries [1, 2]. The earth is occupied with approximately 70% of water (aqua) bulks consisting of diversified aquatic species (spp.), for instance, benthos, planktons, and nektons. The aqua covered nearly one-half of the overall existing worldwide diversity [3]. Marine plants such as seaweeds called macroalgae are abundant geneses of sulphate-containing polysaccharides mostly, which people consumed as their regular daily diet [2, 4]. The marine species persist in free-floating in the water or bound with the rock forms furthermore in the sands or lands. Some aquatic plants are grown below the littoral zone which is not exposed to sunlight and air but present in dark photosynthesis reactions to prepare their foods [5–7]. In traditional experts, marine plants were used to control various diseases, especially in agriculture pesticides [7].

Seaweed or marine SP-based nanomaterials have an excessive promise for application in nano-biotechnology, biomedical engineering, and modern medicine mainly used as wound dressing, tissue engineering, gene delivery, and drug delivery [8, 9]. Now a day, marine SP-based nanomaterials have fascinated consideration as one of the most essential examinations, mainly in, chemical and biomedical research because of their low cost, abundance, nontoxicity, biodegradability, and biocompatibility

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[10]. In recent years, marine bio-nano-particles of polymers, metal oxides, or metals, liposomes, dendrimers, or micelles are keenly being used for various diseases such as bacteriological infection and tumour side [11]. Marine poly-sugars are easily converted into nanomaterials, nanotubes, nanofibres, micro-particles, membranes, gel, sponge forms, scaffolds, and beads, which are used for food application, nano-biotechnology, and biomedical applications [12, 13].

Marine seaweed or macroalgae is an unfathomed natural source of polysaccharides, which consists of numerous different phytonutrients whose cells are enriched with sulphate poly-sugar. In seaweed algae, cells consist of specific macromolecules or carbohydrates called sulphated polysaccharides (SP) condensing sulphate moieties in their structural poly-sugar backbone [14, 15]. The outermost layer of marine macroalgae is consists of a negative charge due to the presence of cross-linkage sulphate ion groups with multifaceted molecules of polysaccharide. The cell wall constituted of seaweed algae is mostly hemicellulose and cellulose with high contents of carbohydrate macromolecules [15, 16]. The high constituents of sulphate poly-sugar present in marine macroalgae, but also commonly in some mammals such as fish's outermost layers and a few saline condition plants, while it is absent in terrestrial plants [15, 17].

The current review is focused on the brief descriptions of sulphate polysaccharide, and SP-based nanomaterials with a side of biological and commercial applications.

2 Main body

2.1 Marine macroalgae source of sulphated polysaccharide

In the base of pigments that assist in photosynthesis reactions, aquatic macroalgae are classified into three main groups, such as red, green, and brown, which are mentioned as *Phaeophyceae, Chlorophyceae*, and *Rediophyceae.* Some sulphate poly-sugar is carrageenan from red algae, ulvans from green algae, and fucoidans in brown algae. The classified marine algae red, brown, and green species' total poly-sugar contents range from 4 to 76%, whereas green macroalgae lonely yields almost 65% of dry weight [18–20]. The extraction of marine macroalgae was classified into two main categories; these algae are further divided into subcategories, which are shown in Fig. 1.

However, nowadays food scientists are pursuing better-quality approaches for manufacturing, packing, stuffing, and distributing or dispensing safe, healthy (in a good physical shape), tasty, and delicious food products for a varied group of consumers [21, 22]. Novel processing techniques, containing antioxidants or aroma, encapsulation, controlled collections of products, such as dynamic, preserving, well stuffing, or packing yields and enhanced utilizing properties of health benefits which is improved food quality and self-life of items [23, 24].

Recently, sulphate polysaccharides-based nanomaterial of marine macroalgae have been extensively studied due to their enormous nano-technological, biomedical, and food industrial functions having use in oceanic food contents, such as beneficial use in biopolymers Khedri et al. [25], biorefineries, Balina et al. [26], bioremediation Wu et al. [27], pollution controls Son et al. [28], manure Kiraci [29], weather forecasts, Piñeiro-Corbeira et al. [30], medicine, anti-tumour, anti-viral, anti-coagulant, anti-inflammatory, Mouritsen et al. [31], the industrial sector it's used to edible, cheap, nontoxic, food packing or biodegradable packing, and easy culturing properties [32].

3 Constituent of macroalgae

Marine seaweeds consist of various contents of biomolecules in their cell and are classified based on pigments such as red algae, green algae, brown algae, and their subspecies. In marine algae, carbohydrates, proteins, lipids, and dry matter of the cell composition are mostly present [33, 34], as given in Table 1.

4 Marine polysaccharide-based nanomaterials

Seaweeds or aquatic macroalgae SP-based nanomaterials have received significant attention from nanoscience researchers currently, due to their exclusive physicochemical properties as well as simple, inexpensive, stable, nontoxic, safe, hydrophilic, highly biodegradable, and good biocompatibility [35, 36]. These features are of distinctive attention in the field of nano-biotechnology and have an exclusive prospect as biomaterials. Currently, numerous scientists have studied polysaccharides SP-based nanomaterials for biomedical applications, for instance, wound dressing, cancer treatment, tissue engineering, drug delivery, gene delivery, and antimicrobial activities [35, 37, 38].

4.1 *Rediophyceae*: sulphate polysaccharides carrageenan and agar of red algae

The outermost layer of red macroalgae consists of microfibrils (β-1, 3-xylans and cellulose) and a thin matrix, these matrices are comprises 38% of sulphate poly-sugar in the form of carrageen [39]. The higher level refined yield of carrageenan was extracted from *Kappalvarzii sp.*, whose refined production ranges from 20.4 to 28.4% [40]. The average relative molecular weight of carrageenan exists of 100 kDa or more, carrageenan is contained approximately 15–40% of ester sulphate contents, and other units such as D-galactose and 3,6-anhydrous-galactose are cross-linked by a- 1,3 and b- 1,4-glycosidic

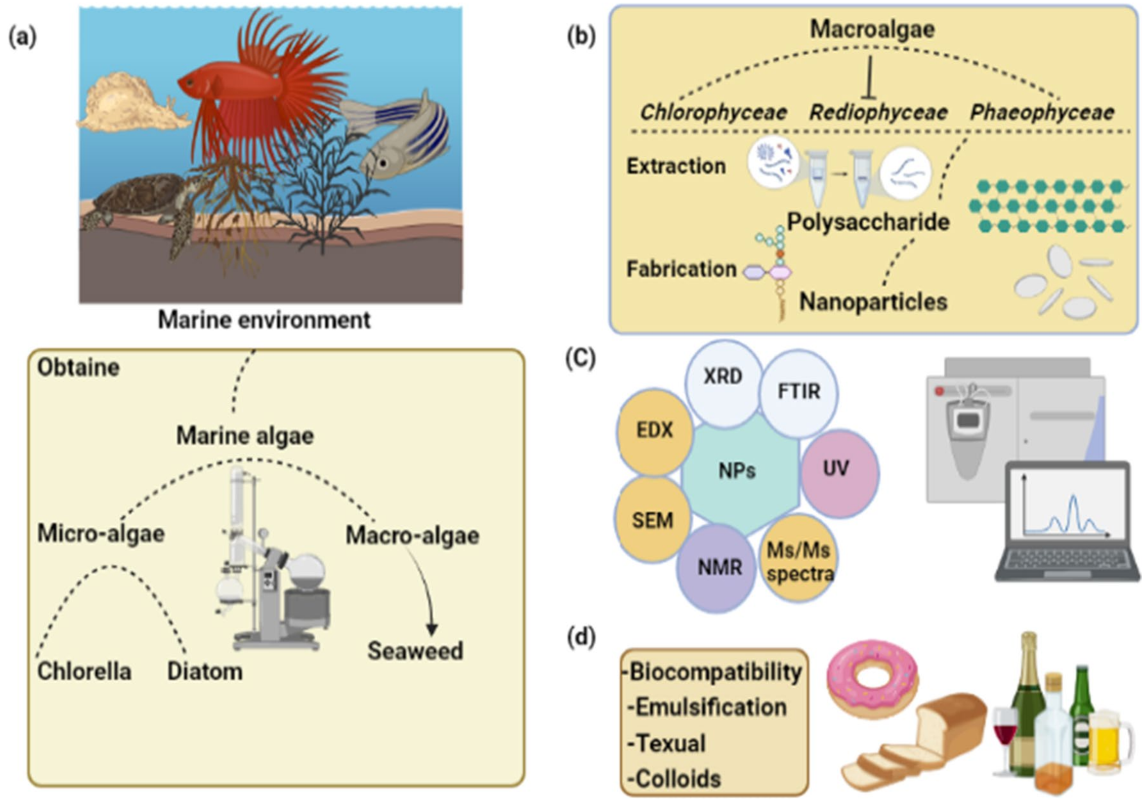

Fig. 1 **a** Whole diagram illustration of the origin of polysaccharides from algae, **b** synthesis of nanoparticles, **c** characterization of polysaccharides-based NPs, **d** and its application in different fields

Table 1 Different constituents of marine algae (Kim et al. [33])

Contents	Brown algae	Green algae	Red algae
Species	*Undaria pinnatifida, Laminaria, Hizikia fusiform, Sargassum fulvellum*	*Enteromorpha, Codium fragile*	*Porphyta tenera, Gelidium amansii*
Lipids%	1–5	1–5	1–5
Protein%	38–51	10–15	7–15
Cellulose%	5–9	5	3–16
Dry matters%	5–10	20	30–40
Carbohydrates%	45–60	48–55	53–70

linkage from red algae carrageenan. Carrageenan is classified into subgroups based on the solubility level in potassium chloride (Kcl), such as, λ, κ, ι, ε, and μ where sulphate groups consist of 22–35% [39–41].

The ester sulphate contains in subgroups of carrageenan such as Kappa carrageenan 25–30% and 28–35% of 3,6-AG contents, Iota carrageenan containing 28–30% ester sulphate and 25–30% of 3,6-AG contents, and Lambda λ carrageenan contains 32–39% of ester sulphate range and 3,6-AG contents is not presents in lambda λ carrageenan [40]. The sums of ester sulphate are inverse proportion to the temperature stability, gel strength, and solubility such as enhanced ester sulphate level than less mechanical properties of sulphate polysaccharides [42]. The carrageenan and agarose NPs obtain from marine macroalgae, synthesis, characterization, and applied in the food industry as shown in Fig. 2.

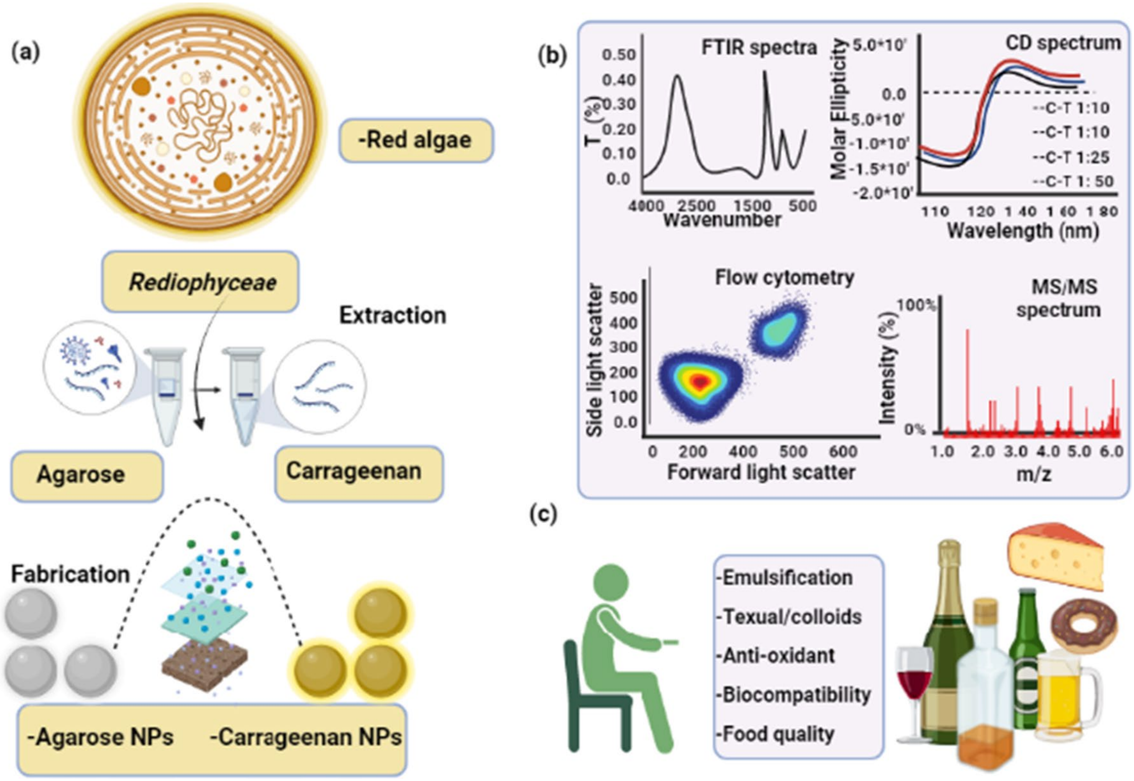

Fig. 2 **a** Complete diagram sketch of the derivation of polysaccharide from *Rediophyceae*/red algae, synthesis of agarose and carrageenan NPs, **b** characterization of carrageenan and agarose NPs with different parameters, **c** and its application in food industries

4.2 Carrageenan Nanoparticles

The carrageenan and tri-polyphosphate nanoparticles (NPs) with nano range size, strong positive (+ive) surface, and stable mostly used in mucosal delivery of macromolecules Rodrigues, Torres et al. [43]. Maciel et al. [44] and Saluri et al. [45] stated the effect of metallic nanomaterials on gastrointestinal (GI) release from altered κ-carrageenan hydrogels; they have also find out the effect of *genipin* cross-linkage and loaded nanoparticles on drug delivery; Fig. 2 shows carrageenan nanoparticles preparation and use in different fields. The novel synthesis of carrageenan and CS nanoparticles is more suitable for biomedical fields, especially drug delivery systems [46, 47]. The production of such nanomaterials of carrageenan in hydrophilic conditions, performing of experiment with very mild technique, to avoid the usage of organic solvents and another aggressive environment. The carrageenan-based NPs were stated as suitable carriers that can offer continuous control for drug delivery. The carrageenan NPs showed high safety, good biocompatibility, low toxicity, and against fibroblast cell lines [44, 47, 48].

4.3 Agarose Nanoparticles

Rediophyceae or red marine algae's outermost layer (cell wall) presents in a compound called agar which is responsible for constructing their cell structure [12]. Agar is a combination of two polysaccharides, namely agaropectin the non-gelling part resides in sulphated galactan, containing sulphuric esters, D-glucuronic acid, and agarose is the gelling portion which is involved in D galactose and 3,6-anhydro-L-galactose sugar; they are bonded with each other by α and β bonds [49]. The main source of agar is *Gracilaria* and *Gelidium spp.* which are commonly present on the rocks beside shorelines, agar is obtained at 100–130 °C temperature and pressure with a pH range of 5.0–6.0 [12, 49].

Furthermore, agarose is normally used for its gel-forming features to synthesize semiconductor and metal NPs. Agarose nanomaterials have shown antibacterial activity besides E. coli. Moreover, the agarose compound films can be rapidly rehabilitated to carbon–metal complex composites by carbonizing the films in the nitrogen atmosphere [50, 51]. Manivasagan and Oh [52] and Sun et al. [53] described the usage of agarose-stabilized gold nanoparticles for the detection of micromolar nucleosides concentration of DNA, the agarose-stabilized gold NPs yield detection by spectroscopic. The agarose nanoparticles are used in industrial nano-biotechnology and biomedical especially chip biosensing applications.

4.4 *Phaeophyceae*: sulphate polysaccharide fucoidan NPs

The fucoidan was produced by sea cucumbers and sea urchins, the more bioactive property and higher yield of fucoidan were obtained by brown algae. The molecular weight range of fucoidan is from 20 to 200 kDa and sulphate polysaccharide present in the cell wall at approximately 40% w/v dry weight. Fucoidan was obtained by various species such as *Turbinaria ornate*, *T. ornate*, *T. decurrens*, *Sargassum ilicifolium*, *S. wightii*, *S. myriocystum*, *S. marginatum*, *Padina boergesenii*, *P. gymnospora*, and *Dictyota dichotoma.* The brown seaweeds cell wall is compressed of cellulose, sulphate fucan, and align in the ratio of 1:1:3… [54, 55]. Jang et al. [56] and Lira et al. [57] described the synthesis and characterization of fucoidan coated poly-(isobutyl cynoacrylate) NPs.

Nanomaterials were synthesized by anionic emulsion polymerization and by redox radical emulsion polymerization with fucoidan as a novel coating biomaterial; fucoidan nanoparticles were synthesized on a nanoscale, as shown in Fig. 3. Leung et al. [58] and Rao et al. [59] stated the biosynthesis of silver nanoparticles (Ag NPs) by carboxy-methylated curdlan or fucoidan as stabilizing and reducing agents. Fucoidan bioactive molecule was extracted from marine brown algae *Cladosiphon okamuranus* which is coated or loaded by NPs using liposomes as nano-carriers. The fucoidan NPs are used against osteosarcoma and anti-cancer activity which have effective results [60, 61].

The synthesis of fucoidan nanoparticles by acetylation of fucoidan which is slightly modified by hydrophobic region, it's mostly used in cancer treatment, especially for chemotherapeutic agent-loaded nanoparticles. Doxorubicin was used as a model chemotherapeutic agent, and the biomedical application acetylated fucoidan nanoparticles were used for drug delivery purposes (Fig. 2). The characterization of fucoidan nanoparticles used by various techniques such as SEM, EDX, XRD, TEM, NMR, UV, by their morphology and drug release properties [62, 63].

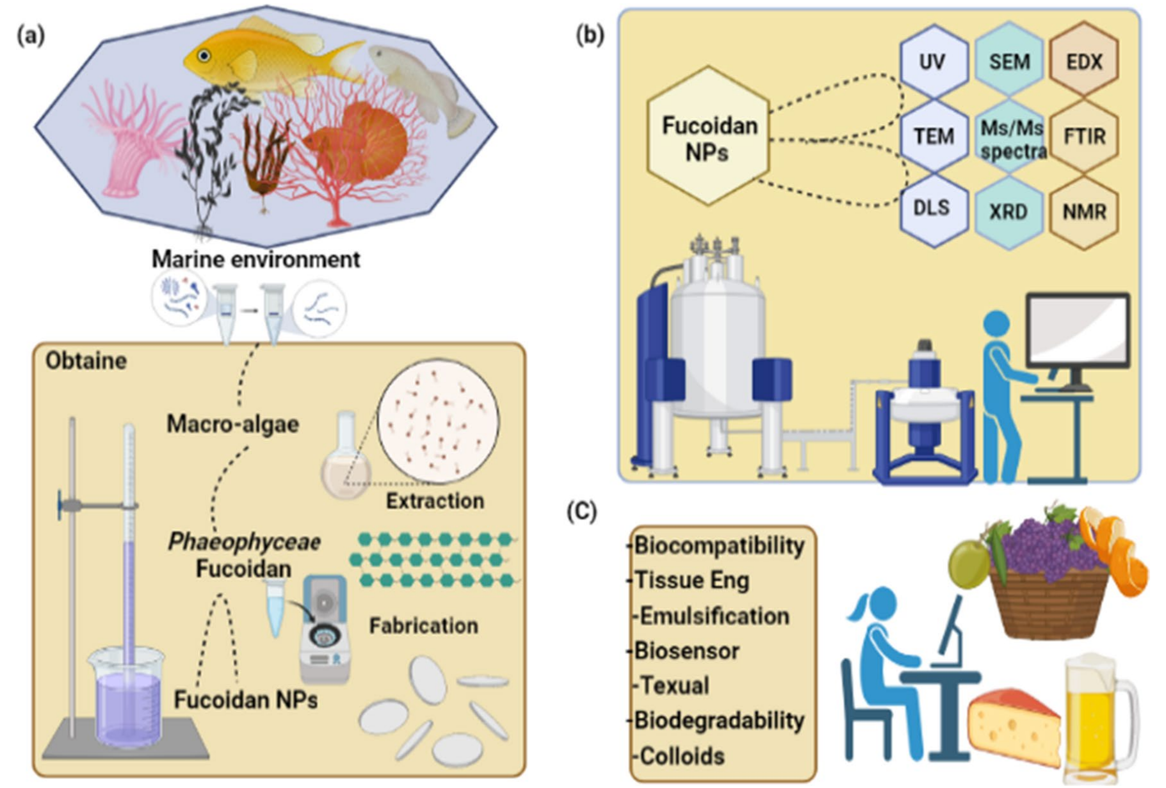

Fig. 3 **a** Extraction of sulphate poly-sugar from marine macroalgae to make SP-based fucoidan NPs, **b** characterization of fucoidan NPs with various aspects, **c** and its application with different fields

4.5 *Chlorophyceae:* sulphate polysaccharides ulvan nanofibres

Ulvan or green seaweed is the family of sulphate polysaccharide (SP), sulphate poly-sugar contents existing in the cell wall of green macroalgae as 9–36% in the form of Ulvan. Ulvan is a polyanionic heteropolysaccharide involved in enormous quantities of rhamnose and glucuronic acid. In the green algae, the cell wall consists of various quantities of monosaccharides for instance iduronic acid 5%, xylose 9.6%, glucuronic acid 22.5%, and rhamnose 45% these monosaccharides are linked to gathering a form of α- and β- (1, 4) glycosidic linkage to make disaccharides units. Different kinds of di-sugar, ulvan are classified into four main types, for instance, A3s, B3s, U3s, and U2s, 3 s. The outermost layer of marine algae has various functions and biological properties and is classified into different subgroups of species [64, 65], which are illustrated in Table 2 in detail. Currently, ulvan extraction from marine macro-green algae, *Ulv rigida*, has been used for the synthesis of nanofibres as shown in Fig. 4; these nanofibres present a unique character in such a way that they are highly used in different fields such as wound dressing, gene delivery, tissue engineering, and drug delivery purpose.

Ulvan is an interesting candidate for nanofibres synthesis and has been magnificently introduced into industrial nano-biotechnology (Toskas et al. [66] and Weiner et al. [67]) for the isolation of polysaccharide from marine green algae which is rich in ulvan bioactive molecules that examine the spinnability property; this ulvan was fabricated to make nanofibres, which have exclusive application in physiochemical, biological, and biomedical fields, for instance, cancer treatment, wound dressing, gene delivery, tissue engineering, and drug delivery.

5 Features and industrial usages of marine macroalgae polysaccharide degrading enzyme

The trickiest thing in the processing step with the extraction of valuable components of intercellular polysaccharide from seaweed, because all compounds are compacted and filled in the cell it is so challenging to do, and even if those substances are extracted, it needs a lot of costs [77, 78]. Now a day, food scientists are interested to find out new functional components derived from high-value seaweed algae. The optimization steps are must need for conceivable extraction methods and low molecular weight of marine macroalgae poly-sugar. Hence, an analysis of the procedure of attracting the functionality of marine macroalgae polysaccharides has been actively conducted. The various components obtained, such as polymannuronate, alginic, and low molecular weight polyguluronate, which are responsible for different biological control functions are remarkable [79, 80], as presented in Table 3.

6 Application of sulphate polysaccharides in food industries

Sulphate poly-sugar is significantly exploited in the food industries due to its viscosity-enhancing assets, stabilizing, emulsifying, and gelling. Considering it enhances and stabilizes the food structure, they are widely active in food preparations for instance jams, jellies, and ice creams, further use in milk products as a flavour. Red algae, carrageenan sulphated galactans is

Table 2 Sulphate polysaccharide (SP)-based nanomaterial and their functions and biological properties

SP macroalgae	Sub-form of SP	Pigments of the macroalgae	SP functional properties	Biological properties	References
Carrageenan NPs	κ, j, i, e, and μ	Red-phycocyanin, phycoerythrin	Gelling binding Thickening Emulsion Viscosity controller Suspending agents	Lipid barrier properties, anti-cancer, anti-inflammatory, anti-coagulant, antioxidant, and antimicrobials	[68–70]
Agar NPs	–	Red-phycocyanin, phycoerthrin	Excellent gelling Emulsifying agent Thickening Clarifying, Texturizing	Antioxidant, anti-tumour, anti-viral, anti-diabetic, anti-coagulant, alpha-glucosidase inhibitor, and laxative properties	[71, 72]
Ulvan NPs	A3s, B3s, U3s, U2s, 3s	Green chlorophyll a and b, carotene	Adhesion, Caking Viscosity and thickening, encapsulation, suspension	Anti-inflammatory, anti-septic, anti-viral, anti-cancer, and antimicrobial properties	[73, 74]
Fucoidan NPs	F, L, U, G, GA	Brown Fucoxanthin	Gelling, Foaming Suspension Improving quality, Chemical reactivity Controlling moisture	Immunoregulatory, anti-complementary, anti-inflammatory, anti-viral, anti-neoplastic, antioxidant, blood thinners, mucosal shielding agent	[75, 76]

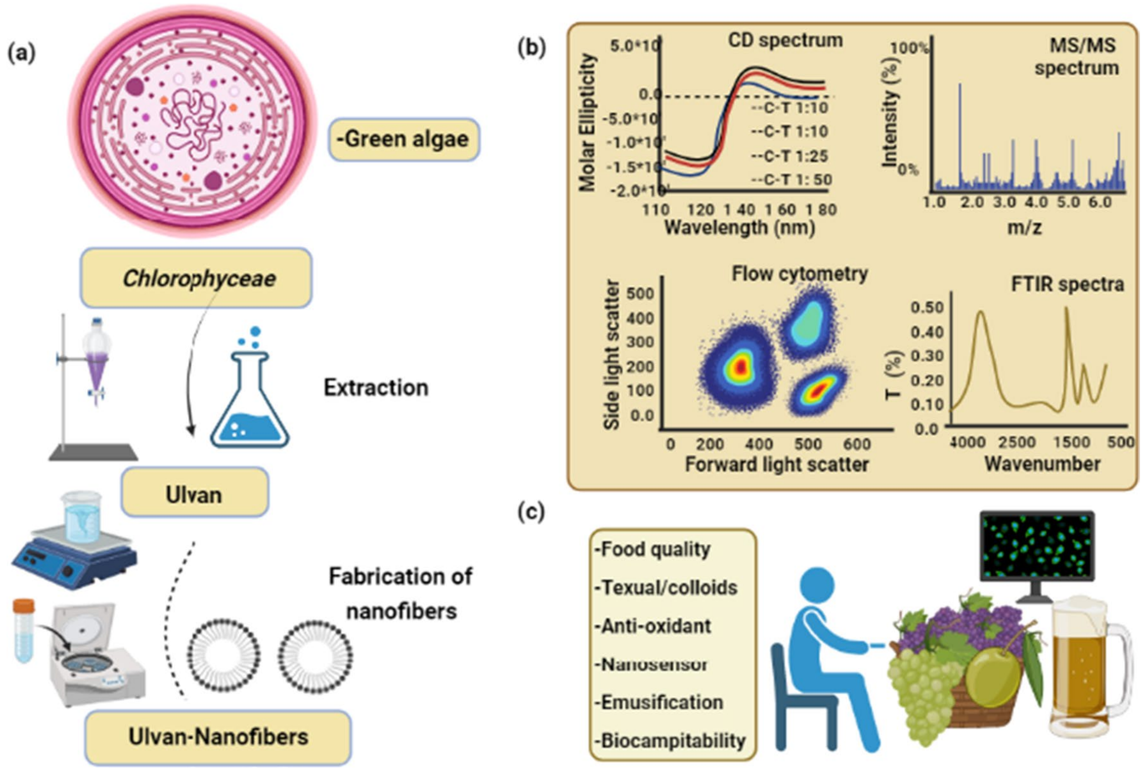

Fig. 4 **a** Extraction of ulvan from *chlorophyceae* marine green algae to make ulvan nanofibres, **b** characterization of ulvan nanofibres with different techniques, **c** and its application with various sectors

Table 3 Major sources of macroalgae that are responsible for degrading enzyme

Macroalgae	Major sugar constituents	Degrading enzyme	Sources	References
Brown algae	Alginate: D-glucuronic acid plus D-mannuronic	Alginate lyase	*Pseudomonas* sp. *Alginovibrio aquatilis*, *Azotobacter*	[81, 82]
	Fucoidan: sulphated L-fructose, galactose, xylose, glucuronic acid	Endo and Exo 1, 3-β-glucanase	*Neurospora crassa*, *Thermotoga neapolitana*, *Candida albicans*	
	Laminaran: beta 1, 3-glucan, beta 1, 6-glucan	Laminarinase	*Trichoderma viride*	
Green algae	Cellulose, xylane, mannose	Cellulase	*Penicillium* sp., *Nectria catalinensis*	[81, 83]
		Xylanases	*Bacillus* sp., *Aspergillus niger*	
Red algae	Agar: agarose plus agarofectin	Arylsufatase	*Klebsiella pneumonia*, *Salmonella typhimuriumm*, *Pseudomonase* sp.	[81, 84]
		α-Agarase	*Thalassomonas* sp. *Vibrio* sp.	
	Carrageenan: D-galactose-sulphated galatan	β-Agarase	*Pseudomonas* sp, *Bacillus* sp, *Streptomyces* sp, *Vibrio* sp.	
		Carrageenase	*Pseudomonas alcaligenes@Cytophaga drobachiensis*	

the prominent commercially beneficial, sulphate polysugar used in fermentation industries for the preparation of various products. In food industries, SP is used for different purposes like adjustment of colloids, declining fate contents, an increase in shelf life, and so on [15, 85, 86]. The important and most preferable uses of macro marine algae are hydrocolloids, nutraceuticals, and food packaging which are briefly discussed below.

6.1 Hydrocolloids properties

The term hydrocolloid has come from the Greek words hydro means aqua and kola means gum. They are mostly presented in hydrophilic poly-sugar long chains having OH groups responsible for operative water binding and help to gel formations. The constituents which form viscous dispersions and gelatinous, as soon as they are dispersed in aqua are terms as hydrocolloids. The marine macroalgae extraction of sulphate polysaccharides such as brown and red species like agar, and carrageenan are commercially available hydrocolloids. They assist as stabilizers, thickeners, emulsifiers, and fillers in cosmetics, pharmaceuticals, foods, and numerous other industries, with unbelievably distinctive physicochemical properties [87–89]. Their main functions and properties are enlisted in Table 2.

The oldest demoralized commercial hydrocolloid has been used as agar since the sixteenth century. Agar is the first hydrocolloid endorsed by the Drug Administration as generally recognized as safe (GRAS) and food that utilized it as nutrition supplements additives. The red macroalgae species such as *Gracilaria* and *Gelidium* production of admirable quality agar, because they have the best gelling feature with a resistance to high temperatures. Agar has inclusive application in the processing (fermentation) of food items for instance milkshakes, nutritional milk drinks, jellies, dry food powder, jams, pastry fillings, soups, spreads, chocolate milk, organic products, brew, creams, flavours, sauces mixes, beverages, puddings, garnishes, poultry products, canned food, pet nourishment, tofu, frozen yogurt, and ice cream. The seaweed algae agar utilized in the food industries (baking) has more dominant properties than other hydrocolloid macroalgae. Besides all these food properties, agar is used in microbial and biotechnological laboratories for large-scale preparation for culture media for microorganism growth [90–92].

6.2 Food packing and nutraceutical properties

Sulphated polysaccharide (SP) such as ulvan, carrageenan, fucoidan, and agar are biopolymers they have reasonable significance in pharmaceutical, biomedical, microbiology, nourishment, and biotechnological fields somewhere it is utilized as exemplifying specialists, balancing out, and gelling. SP biopolymers molecules can create both non-edible as well as edible wraps or film, covers, and bags with improved restriction properties by avoiding the exchange of oxygen (O_2), enhancer, moisture, and lipid content existent in food products, the different substances exist in mixed nutrition and microbial culture mediums [93–95]. They could be combined with commercial biopolymers for instance butyrate, polyhydroxy, polyolefins, polylactic acid with nanomaterials (nanocrystals and nanoparticles) resulting in the creation of biocomposite nanofood packing, they also have other properties of biodegradable ability and toxic free nature. The sulphated polysaccharide together with nano-formulations such as various metal nanomaterials silver, iron oxide, and magnesium oxide which is enhanced antimicrobial activity even at small ppm. Sulphated poly-sugar is used to confine the function of foodborne pathogens, for instance, *Escherichia coli*, *Salmonella enterica*, *Enterococcus faecalis*, and *Listeria monocytogenes.* Now a day highly appreciated biodegradable packing is due to reducing the daily usage of pollution and plastics, in such a way sulphated poly-sugar SP biopolymers have preferred in biofood packing [96–98]. Overall sketch of extraction of SP and its usage in food industries is shown in Fig. 5.

Nutraceuticals are the deliquesced form of the words food and pharmaceutical highly significant nutrition and its additives with benefits for food, industrial microbial, or biotechnological and biomedical fields. Nowadays, nutraceutical properties of food are attracted significant desire in the suitable application of health benefits, recently numerous research has disclosed the pharmacological assistances of sulphate polysaccharide achieved from seaweed macroalgae spp. [99, 100]. The brown- and red-coloured seaweed sp. have augmented nutrient content and well quality employed as nutritious supplements beside the regular diet because they are a rich source of soluble fibbers comprising more supplements of a biomolecule. The major constituents of sulphate are demonstrated in Table 1, while minor constituents include vitamins, fatty acids, terpenoids, minerals, polyphenols, lipoproteins, polyether, carotenoids, etc. The sulphate sugar (SP) is enriched with omega 3 fatty acids (unsaturated omega), e.g. palmitic myristic acid, arachidonic acid, and linoleic, which are saturated fatty acids. The red macroalgae contain negative charge sulphate polysaccharide which is used for different purposes in daily life for instance anti-viral, anticoagulation, antimicrobial, anti-inflammatory, antioxidant, anti-cancer, and anti-tumours applications [101–103].

7 Emerging application of marine macroalgae polysaccharides

Explorations on marine macroalgae polysaccharide-based bio-products are responsible for a foundation for evolving new strategies and advanced processes for developing sustainable products. Studies have been innovative from the addition of new methods for investigating glycan structure and envisaging how it interacts with various microbiomes of the human gut. Currently, advanced scientific technologies should provide a virtuous understanding of how bacteria selectively consume

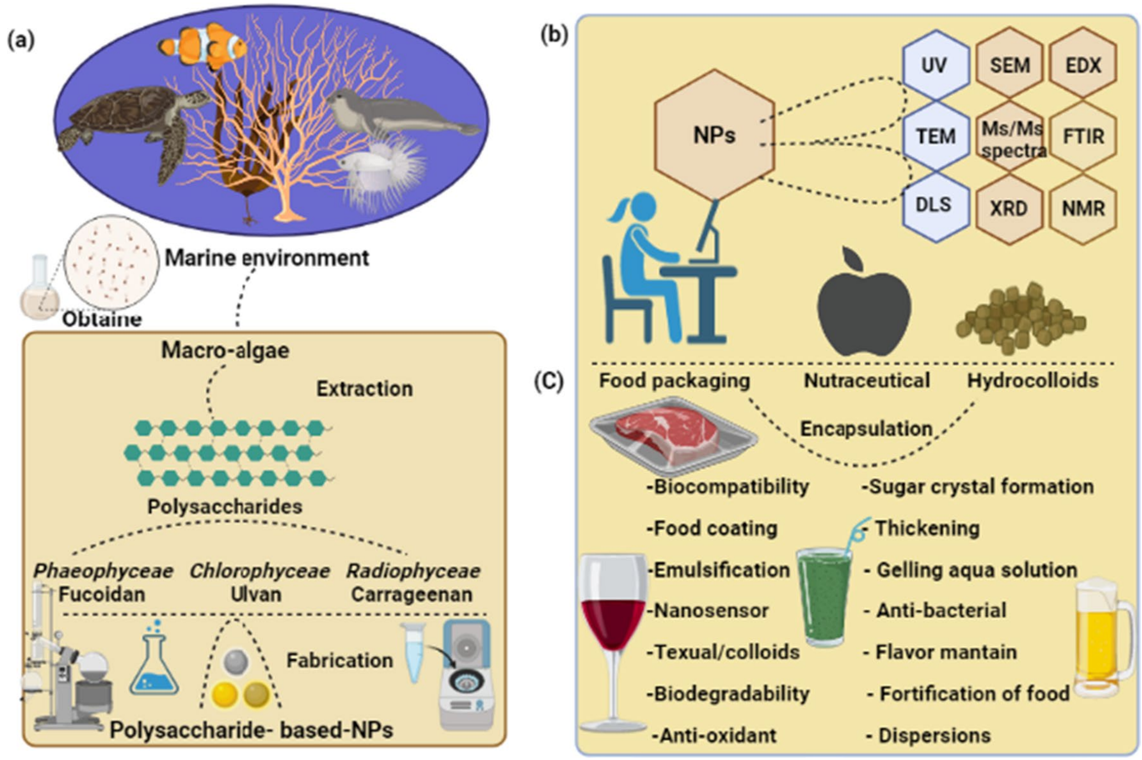

Fig. 5 Marine macroalgae polysaccharides extraction and its application in food industries

glycan in complex bacteriological communities [104, 105]. Furthermore, glycomics, chemical probes, unravel sequence database, associating CAZyme, and computational analysis will be important to unlock next-generation compositional approaches and make a sensational innovative frontier for microbiome function [104, 106]. Several enzymes like 1, 3-β glucanase, chitinase, peroxidase, and phenylalanine ammonia-lyase were definitely improved by polysaccharides treatment from algae in tomato leaves through *P. tricornutum* polysaccharides have revealed admirable improvement (i.e. 238.26) amid confirmed marine macroalgae polysaccharides. The extraction of polysaccharides from marine sources is currently tested for AgO NPs fabrication as well as plant growth stimulations. AgO NPs positively trialled for antibacterial effects. Yet, as far as we know, there are recently no examines on recombinant technology of marine macroalgae to increase polysaccharide production [104, 107].

8 Market prospective and scope

Marine macroalgae-based market perspective falls in numerous food classifications such as polysaccharides, natural pigments, carotenoids, fatty acid derivatives, and single-cell proteins. Further, the small scale non-centralized manufacturing of microalgae products, consistent with established supplies, might be confining market invasion [104, 108]. Marine macroalgae-based bio-products have industrialized over the years, more substantial value to the market. Marine macroalgae biomass is recently being sold for approximately € 1000 t^{-1}. Additionally, techno-economic exploration on the selling price of marine macroalgae polysaccharides applications assessed for moisturizers, immune stimulants, plant growth stimulants, and biofuel production, respectively. According to Eurostat data, the market for biopolymers bioactive compounds, of which marine algae-based merchandise are part, contains nearly €16.71 Billiton, and by this 2023, the global algae final products is estimated to be worth US $44.6 billion [109, 110]. A large number of aspects are finding out the structure of polysaccharides with macroalgae spp, via geographical location, harvest season, extraction, and purification approaches, difficult to commercialize. One of the potential aspects, the enzyme is used to modify the compound's structure important to accomplish bioactive compounds for the human being. So, it is significant to appreciate the structure and enzyme activity as well as marine macroalgae polysaccharides for their superior commercial prospects [111, 112].

9 Future aspects

In the future research can be attentive to the fabrication of NPs from marine macroalgae poly-sugar-based biomaterials, such as chitosan, carrageenan, fucoidan, agarose, and ulvan. Different seaweed/marine macroalgae sulphated polysaccharide have their application and intrinsic worth. The marine source algae, i.e. *radiophyceae, phaeophyceae, and chlorophyceae*, are anionic polysaccharides and so easily synthesize NPs with cationic polymers such as ulvan, chitosan, and agarose, which indicates its perspective as food quality, processing, coating, and biocompatible drug delivery [113, 114]. The marine macroalgae polysaccharide NPs' fabrications in this review were mostly based on *radiophyceae, chlorophyceae, and phaeophyceae,* (e.g. carrageenan, fucoidan, ulvan, and agarose). The main intention of the ulvan, fucoidan, agarose, and carrageenan is to produce stable polymeric NPs, which can be attained by the opposed charge interaction of polysaccharide. Synthesized NPs have been revealed to protect food items, coating, encapsulation, biocompatibility, and sustainably. Furthermore, the benefits of marine macroalgae polysaccharides include biodegradability, nontoxic, emulsification, and encapsulation [115, 116].

10 Conclusion

The marine environment consists of numerous species where oceanic phytoplanktons, for instance seaweeds, have their metabolic and structural alteration to withstand the precarious environment for existence purposes. Marine seaweed has extensive applications in different industries, especially on the food side to boost the nutrition, food quality, and retaining characteristics of supplements and biomedical applications. The sulphate polysaccharide-based nanoparticles' extraction from macroalgae is an extensive application in various fields of daily life, such as a synthetic polymer, by-products in nutrition, cosmetics, medicine, gene delivery, drug delivery, cancer treatment, tissue engineering, wound dressing, water treatment, and biosensor. Hence, moreover nowadays, food scientists and researchers fully focused on SP sugar conventional synthetic and animal's derived nutritional substances in food industries, enhancing health products and eco-friendly. The isolated marine poly-sugar is inexpensive, nontoxic, abundant, biodegradable, biocompatible, and safe and has high stability. Seaweed polysaccharides-based nanomaterials have great potential in the fabric, biomedicine, pharmaceutical, and food industries for the future. For the enhancement of marine macroalgae polysaccharide-based bio-economy, it is highly domineering to study the function-structural activities and their particular mechanisms for the advanced application of marine macroalgae polysaccharides. However, cost-effective and efficient extraction and purification approaches pay the manner for viable growth of marine macroalgae poly-sugar-based industrial applications such as pharmaceutical, functional food, and food safety, also nano-cellulose, biofuels, biostimulation as well as other innovative incipient applications. This article compiles the newest advances in marine macroalgae polysaccharides, which are used in industrial applications. It also scrutinized the growing market scope for marine macroalgae polysaccharides-based nanomaterial products together with advanced products after defined health attributes.

Abbreviations

NPs: Nanoparticles; SP: Sulphated polysaccharide; C-NPs: Carrageenan nanoparticles; A-NPs: Agar nanoparticles; U-NPs: Ulvan nanoparticles; F-NPs: Fucoidan nanoparticles; SEM: Scanning electron microscopy; EDX: Energy-dispersive X-ray; XRD: X-ray diffraction; TEM: Transmission electron microscopy; NMR: Nuclear magnetic resonance; FTIR: Fourier transform infrared; CD: Circular dichroism; MS/MS: Tandem mass spectrometry.

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KA contributed to methodology, validation, writing investigation, research investigation, and writing—review and editing. HR, KA, MA, RA, and HI contributed to conceptualization and writing—review and editing. SA, AH, and MMS contributed to supervision, conceptualization, resources, investigation, and writing—review and editing. All authors read and approved the final manuscript.

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