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Red Sea macroalgae as a source of sulfated polysaccharides: biomedical, and cosmeceutical perspectives

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Review Article

ABSTRACT: Seaweeds are naturally found along Egypt's shoreline, particularly in the Red Sea. Seaweed is notable for its rich content of polysaccharides. These seaweeds can contain as much as 70% polysaccharides within their cell walls, which play a vital role in various biological activities such as moisturizing, skin whitening, anticancer effects, immunomodulation, antibacterial activity, antioxidant capabilities, anticoagulation, antidiabetic effects, and anti-inflammatory actions. This positions them as highly promising candidates in both biomedical and cosmeceutical fields. This review highlights the importance of algal sulfated polysaccharides in medicine, and their rising significance in the cosmetic and pharmaceutical sectors.

Keywords: Seaweed, Red Sea, Polysaccharides, pharmacological activities, cosmetics, and medicine

INTRODUCTION

Algae are non-vascular organisms, devoid of roots, stems, leaves, and conducting tissues. They also share with plants the presence of chlorophyll (Pereira, 2018). Algae utilize light to produce sustenance and inhabit nearly all regions; however, this article concentrates on macroalgae or seaweed. Seaweed inhabits both shallow coastal waters and the depths of the ocean, but coastal areas constitute its primary home. There are over 300,000 kinds of algae, with 6,500 residing in the ocean (Hassan *et al.,* 2024). These are categorized by color as Phaeophyta (brown algae), Rhodophyta (red algae), and Chlorophyta (green algae). Fucoxanthin, a xanthophyll pigment, conceals chlorophyll a, c, and beta-carotene, resulting in the brown coloration of the Ochrophyta, Phycoerythrin, and phycocyanin obscure chlorophyll a, beta-carotene, and other xanthophylls in the red pigmentation of Rhodophyta. Chlorophyll a, and b conceal beta-carotene and other xanthophylls, imparting agreen hue to Chlorophyta. Their coloration corresponds with that of vascular plants (Pereira, 2021).

As a member of a class of organisms that contribute significantly to biodiversity on Earth, seaweed plays an essential role in maintaining a healthy ecosystem. In marine ecosystems, these diverse organisms play a crucial role. According to Dawczynski *et al*. (2007), they study these additions are beneficial to human health; these seaweeds play a crucial role in aquatic food webs. According to Ghallab *et al.* (2024), and Ahmed *et al.* (2024), they find extensive use in the cosmetics, pharmaceutical, and food sectors.

DIVERSITY OF SEAWEEDS IN THE RED SEA

In the 18th century, Forsskål (1775) gathered a few macroalgae species from the northern Red Sea to conduct botanical investigations. Since then, marine phycological studies in the Red Sea have progressed. When Papenfuss (1968) cataloged benthic algae from various sections of the Red Sea, forty-five scholarly papers had been published and reviewed. Following this, other papers have addressed the taxonomic diversity of macroalgae in the northern Red Sea (Aleem, 1978; Rasser & Piller, 1997; El-Manawy,2008; El-Manawy & Shafik, 2000; Issa *et al*., 2014). Einav *et al.* (2021) revised checklist of macroalgae of the Red Sea from 1756 to 2020 revealed the presence of 576 taxa, including 286 Rhodophyta, 157 Ochrophyta (class Phaeophyceae), and 133 Chlorophyta, while the global variety of all algae (micro and macro) consists of over 164,000 species, with approximately 9,800 of them being seaweeds, 0.17% of which have been cultivated for commercial use (Duarte *et al.,* 2007; Sultana *et al.,* 2023).

SEAWEED AS A SOURCE OF BIOACTIVE COMPOUNDS

Seaweed produces many secondary bioactive chemicals that destroy bacteria and cells. This group includes polyketides, cyclic peptides, polysaccharides, phlorotannins, diterpenoids, sterols, quinones, and glycerol lipids. These bioactive chemicals are used for food and medication production (Hamed *et al.,* 2018). Red algae contain gelling agents such as agar, and carrageenans, while brown algae contain alginate (Flores-Contreras *et al.,* 2023). Seaweed also includes heart-healthy polyunsaturated fatty acids (PUFAs), including Docosahexaenoic acid (DHA), and Eicosapentaenoic acid (EPA) (Pereira *et al.,* 2012). They also include vitamins A, C, and E, and minerals like calcium, iron, and iodine (Arora & Philippidis, 2023). Famous secondary metabolites include sulfated polysaccharides, phlorotannins, carotenoids, polyphenols, and fucoxanthin. Several have been studied for their ability to reduce oxidative stress (Menaa *et al.,* 2021). Medical benefits of marine macroalgae are claimed. Omega-3 fatty acids lower lipids, blood pressure, and heart disease risk (Khan *et al.,* 2021).

Macroalgae may include compounds that could address industrial challenges. Consumer apprehensions regarding synthetic substances have escalated, leading to a preference for natural alternatives with beneficial health effects. Biomolecules in macroalgae extracts demonstrate anti-inflammatory, antimicrobial, antidiabetic, anticancer, neuroprotective, anti-aging, photoprotective, lipolytic, moisturizing, and whitening properties. Consequently, components of macroalgae may appeal to cosmetic corporations (Hamed *et al.,* 2015; Vuong *et al.,* 2018). Quality standards, contaminant surveillance, and algal biochemistry research are essential for safety and efficacy. Improving extraction, characterization, and sustainable cultivation techniques will establish macroalgae as a dependable source of bioactive compounds (Monroy-García *et al.,* 2025).

POLYSACCHARIDES

Natural polysaccharides come from plants, animals, microbes, and algae (Rajalekshmy, 2019). Polysaccharides, comprised of monosaccharides and sulfate groups, distinguish marine macroalgae from other algae. These compounds have biological impacts (Moreira *et al.,* 2023). Macroalgae have structural and storage polysaccharides like cellulose and starch, which provide physical structure and stability. Glycosaminoglycans (GAGs), found in connective tissues, play key roles in cell support, blood clotting, and inflammation regulation (D'Ayala *et al.*, 2008; Boddohi & Kipper, 2010) (Figure 2).

CLASSIFICATION, AND CHEMICAL STRUCTURE OF POLYSACCHARIDES

Polysaccharides are sugar molecules linked by glycosidic linkages or covalently to peptides, amino acids, and lipids (Muhamad *et al.,* 2019). Mizrahy and Peer (2012) defined homopolysaccharides as homoglycans with identical monosaccharides. Different monosaccharides make up heteropolysaccharides (Figure 3).

THE CHEMISTRY OF POLYSACCHARIDES OF MARINE ALGAE IS APPROPRIATE FOR COSMECEUTICAL APPLICATIONS.

Researchers are interested in the bioactive qualities of algal polysaccharides such as alginate, agar, carrageenan, and red and brown algae fucoidan. Other polysaccharides include ulvan, laminarin, angelan, porphyran, spirulan, agarose, and rhodymenan. These polysaccharides are useful in cosmetics, health, and industry due to their unique structure and function. (Michaud, 2018; Lourenço-Lopes *et al.,* 2020). Carbohydrate polysaccharides form hydrogels or hydrocolloids, which are essential in cosmetics. Cosmetics use active and functional polysaccharides (PS). Functional PS are those with applications in formulation technology and stabilization, whereas active PS moisturize and fight free radicals in cosmetics (Pereira, 2018). Seaweed includes a diverse range of structural and functional PS, such as fucoidans, laminarins, alginates, carrageenans, galactans, agar, porphyran, glucans, and ulvans. Most PS derived from macroalgae are used for their physicochemical properties, including skin-protective properties (anti-wrinkle, lightning, moisturizing, UV-protective, antioxidant, anti-inflammatory, etc.), and emulsifier, stabilizer, and viscosity-controlling properties (Fernando *et al.,* 2018).

Brown seaweed polysaccharides

Brown algae (Phaeophyceae) contain unique polysaccharides that comprise a large portion of their cell wall and contribute to their biological functions. Alginic acids, fucoidans, and laminarans are the three most valuable physiologically active polysaccharides found in brown algae (Usoltseva et al., 2017).

Alginates: One of the most serious problems in the cosmetics industry today is the shortage of natural emulsifiers with safe features. Alginates provide a long-awaited solution as an emulsifier, gel-forming polymer, thickening agent, and bioactive material. (Qin, 2018). Alginate is a gelling polysaccharide composed of -L-guluronic acid and 1,4-linked β-D-mannuronic acid, which are randomly dispersed along the chain. This hydrophilic colloidal polysaccharide is used to build cell walls and intracellular components (Guo *et al.,* 2020). In the presence of divalent cations like Ca^2, Sr^2, and Ba^2, alginates rapidly produce hydrogels (Jiang *et al.,* 2016).

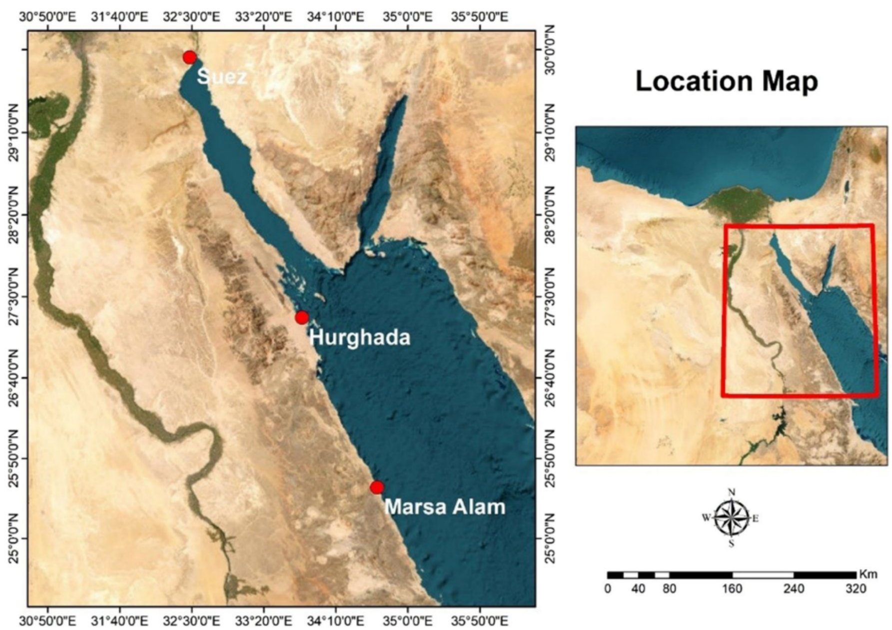

Figure 1. Geographical location of the western coast of the Egyptian Red Sea (Sami *et al.,* 2025).

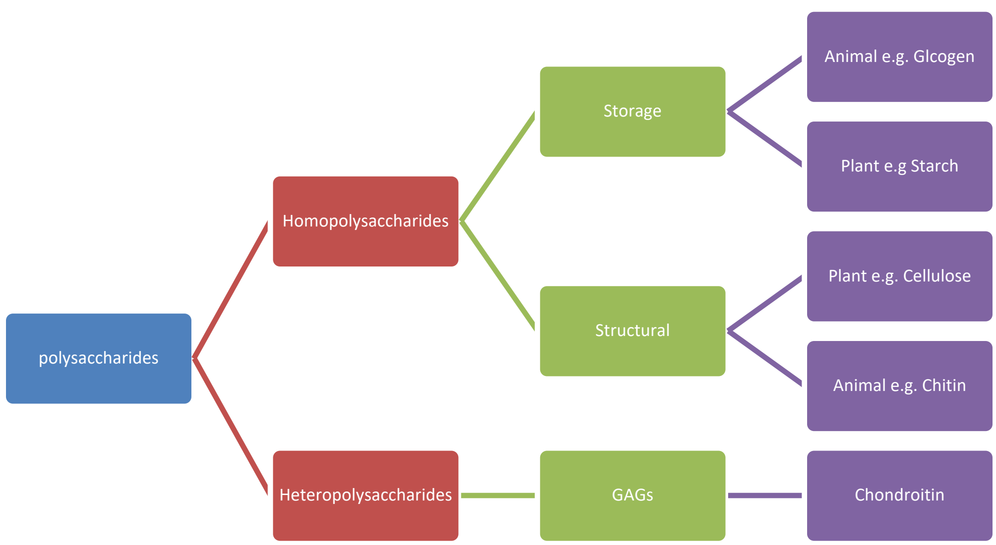

Figure 2. Polysaccharide classification based on monosaccharide building blocks and physiological attributes.

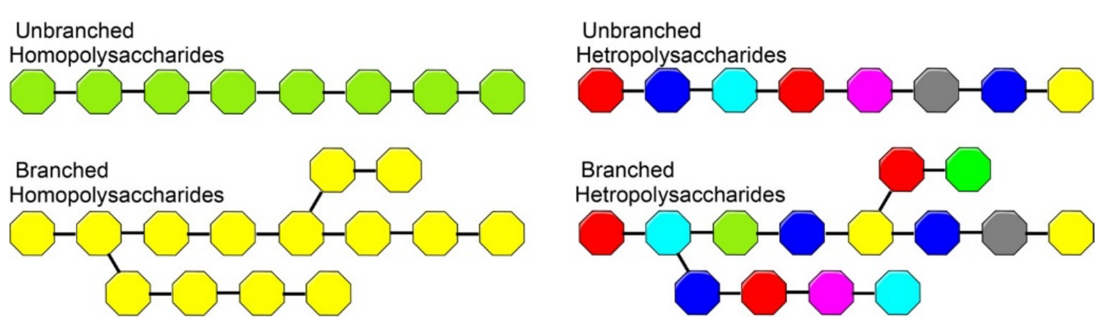

Figure 3. Branched and unbranched homopolysaccharides, and heteropolysaccharides, with different monosaccharides represented by different colors (Mohammed *et al.,* 2021).

In addition to divalent cations, acidic circumstances (low pH) make it insoluble, resulting in gel-like properties. However, both the sodium and potassium salts of alginic acid are water-soluble; hence, alginates are extracted by converting insoluble alginic acid and its salts to water-soluble sodium and potassium alginate (Fernando *et al.,* 2018). To investigate the alginate yield and qualities, five prominent brown seaweed species were collected in the Red Sea (*Padina boergesenii, Turbinaria triquetra, Hormophysa cuneiformis, Dictyota ciliolata, and Sargassum aquifolium*). The investigation showed variances in alginate yield among seaweeds (Rashedy *et al.,* 2021). Alginic acid, which makes up the majority of the polysaccharides in the cell wall structure of brown algae, is a common ingredient used in pharmaceutical formulations, cosmetics, and the food industry as a useful thickener for jellies, drinks, and ice creams because of their biocompatible properties, such as biodegradability, muco-adhesiveness, hemocompatibility, , and non-accumulation in biological systems (Qin, 2018; Fatma & Özdemir, 2024). Alginates may create hydrogels with stiffer, more flexible, and more recoverable cations. Significant water retention and adsorption are its strengths, which help to preserve moisture and increase viscosity; it is suitable in cosmetics (Michalak *et al.,* 2020).

Fucoidans: Brown seaweeds' cell walls, such as *Dictyota menstrualis*, *Padina boryana*, *Kjellmaniella crassifolia*, and *Fucus vesiculosus* contain fucoidans, which contain a fucose-containing sulfated polysaccharides (Usoltseva *et al.,* 2018). Sulfate ester groups, glucose, mannose, galactose, xylose, acetyl groups, and uronic acids form fucoidans (Cunha & Grenha, 2016). Fucoidans kept seaweed moist at low tides and helped them avoid drying. The fucoidan concentrations of brown seaweed normally range from 10 to 20%, with the greatest concentration documented so far being 46.6% in *Laminaria digitata*. (Tanna, and Mishra,2019; Zhang, and Thomsen,2021). The amount of fucoidan depends on the algae, season, tissue location, and environment. They are not highly correlated with seawater salinity, temperature, oxygen, or biogenic components (Shao & Duan, 2022). Researchers have largely focused on its anticoagulant qualities, although its antioxidant advantages are emerging. Fucoidan from *Laminaria japonica* lowers lipid peroxidation (LPO) in diabetic mice's serum, liver, and spleen (Li *et al.,* 2002). When the skin is attacked by UVB (ultraviolet B) radiation, fucoidan enhances the synthesis of procollagen type I and suppresses the production of metalloproteinase matrix. So, this polysaccharide can be utilized as a therapeutic agent, aiming to prevent skin premature aging. Furthermore, studies have found that administering fucoidans to human leukocytes can reduce elastase activity, hence protecting the skin's elastic properties. Fucoidans also inhibit tyrosinase, which can reduce pigmentation of skin (Wijesinghe & Jeon, 2012; Thomas & Kim, 2013). Fucoidan can also help to protect hair and skin by removing free radicals, lowering inflammation, wrinkles, allergies, and sensitive skin reactions. This polysaccharide can also increase skin elasticity, firmness, and brightness, as well as hair protection, growth, stiffness, and gloss (Usov & Zelinsky, 2013).

Laminarins: Laminaran, also known as laminarin or leucosin, is a glucan that can exist in either soluble or insoluble forms. The soluble form dissolves entirely in cold water, whereas the insoluble form is soluble only in hot water (Usman *et al.,* 2017). Laminarins are key carbohydrates in brown algae, characterized by their low molecular weight. It is prevalent in *Saccharina* and *Laminaria* but scarce in *Fucus*, *Undaria,* and *Ascophyllum*. The species, harvest date, and culture site determine seaweed laminarin content (Li *et al.*, 2021). Laminarin sulfate, known for its wound healing properties, has led to the development of a novel hydrogel, and the maximum amount of it reaches 35% of the algal dry weight (Kadam *et al.,* 2015). Although laminarin cannot gel or increase the viscosity of an aqueous solution, its use for medical and pharmaceutical purposes is of significant interest because laminarin inhibits blood coagulation, free radicals, cancer, and inflammation (Choi, 2012), and cosmetics with laminarin fight cellulite (Fabrowska *et al.,* 2015). Irradiation-induced degradation can enhance radical scavenging capabilities while limiting melanin synthesis in melanoma cells. (Pangestuti *et al.,*2021).

Red seaweed polysaccharides

Red algae have around 6500 species, making them the most diversified taxonomic group (Rawiwan *et al.,* 2022). Galactan is the main structural component of seaweed intercellular matrix, and cell walls (Khongthong, 2021). Red algae generate carrageenan, sulfated galactans, and agars, which are important, and distinctive polysaccharides (Kraan, 2012). Also, porphyrins, xylans, and floridean starch are found (Otero *et al.,* 2023).

Carrageenans: Carrageenophytes are Gigartinales red seaweeds. They produce a refined polymer called "carrageenin," which is unstable, hard to remove from seaweed, and binds to cations to generate various salts (carrageenan). Seaweed salts make up 30%–75% of its dry weight. Cardoso *et al.* (2014) , and Pacheco-Quito *et al.* (2020) describe carrageenan, which is a linear sulfated polygalactan, as alternating galactose residues with α(1–3) and β(1–4) linkages. The three main carrageenan types are kappa (κ), iota (ι), and lambda (λ). Iota, and kappa carrageenan may merge, whereas lambda may thicken (Trindade, 2022). Seaweeds do not synthesize this pure carrageenan, but hybrid structures are more typical. For example, theta (θ), xi (ε), beta (β), mu (μ) , and nu (v) can develop. When exposed to an alkali treatment, they can be changed into kappa, and iota, respectively, by the creation of 3,6-anhydrogalactose bridges. (Pereira, 2018). Red seaweed, including *Chondrus crispus, Betaphycus gelatinum*, and *Eucheuma denticulatum,* provides carrageenan. From a commercial point of view, Business and regulatory organizations (FDA, EFSA) considered it safe after toxicological testing showed low or no side effects. Cosmetics and medicines use nearly 20% of carrageenan, making this important for many companies. Shampoos, conditioners, moisturizers, medicines, sunblock, grooming creams, deodorants, mists, and foams contain carrageenan. Due to their hydrogel production, they can fight viruses and bacteria, and control pathophysiological processes like hyperlipidemia (Pacheco-Quito *et al.,* 2020).

Agar: Agars are linear polysaccharides containing alternating α-(1→3)-D-galactopyranose and β-(1→4)-linked 3,6-anhydro-L-galactopyranose residues, and C-6 sulfate groups. Gelatinous hydrocolloid agar is primarily agarose and agaropectin, and typically made from red seaweed like *Gracilaria*, and *Gelidium* (Nishinari *et al.,* 2017). Hydrocolloid characteristics substantially impact agar polymeric structures. Including α-(1→4)-linked 3,6-anhydro-D-galactopyranose residues in polymer chains may boost agar's hydrocolloid content. Agar and carrageenans are sulfated galactans due to their backbone structure. How much sulfation of agar polymers affects their anionic charges. Therefore, it may create more neutral agarose or agaropectin with more sulfur. Thicker agarose gel is caused by α-(1→4)-linked 3,6-anhydro-D-galactopyranose residues (Otero *et al.,* 2023). Agar can keep its properties at 250 °C, and impending boiling. This makes it suitable for jellied confections, which may be heated, and cooled (Ouyang *et al.* 2018). Agar thickens and is used in medication delivery tablets and capsules in the pharmaceutical and cosmetic industries (Aziz *et al.,* 2020). Agar has been widely used in creams for its emulsifier, and stabilizer properties, and it has also been demonstrated to be capable of controlling the moisture content in h, and lotions, deodorants, foundation, exfoliant, scrub, cleanser, shaving cream, anti-aging treatments, facial moisturizer/lotion, liquid soap, acne treatments, body wash, and facial powder. (Fertah *et al*.,2017).

Green seaweed polysaccharides: Green seaweed is rich in proteins, fibers, lipids, phenols, and flavonoids, but they have less polysaccharide than other seaweeds (Otero *et al.,* 2023). Ulvans are sulfated polysaccharides found only in the green seaweed *Ulva* genus, and have strong antioxidant properties (Gomaa *et al.,* 2022).

Ulvan: Ulvan comprises 8%–29% of the algae's dry weight. The polysaccharide contains rhamnose, xylose, glucose, mannose, galactose, and uronic acids (Pereira, 2018). Ulvan forms gels with divalent cations such as Ca^{2+}, Cu^{2+}, and Zn^{2+}. This is possible at temperatures up to 180 °C, and pH levels of 7.5 to 8.0. Ulvans' bio-functional and rheological qualities make them good cosmetic raw materials (Yaich *et al.,* 2017). Ulvan generates complicated gels by creating spherical structures in boric acid and calcium ions. Ulvans protect, moisturize, fight cancer, and fight free radicals, according to Fabrowska (2015) and Bai (2022). Ulvan is used to flavor drinks, cloud cosmetics, and stabilize them. In vitro studies have shown that ulvan may protect against hydrogen peroxide-induced oxidative stress, which intrigues the cosmetics sector. The beauty industry uses ulvan because it contains moisturizing glucuronic acid and rhamnosyl residues, which are being studied for their ability to promote cell growth and collagen production (Lakshmi *et al.,* 2020).

PHARMACOLOGICAL ACTIVITIES

Sulfated polysaccharides (SPs) are the primary bioactive polymers found in many seaweed species. Because of the complicated chemical compositions and varied functional groups, SPs can interact with a variety of textures, chemical substances, lipids, cellular proteins, and microbial species. These interactions enable SPs to exhibit a wide range of bioactivities, including antioxidants, anti-inflammatory, anticoagulants, anticancer, antibacterial, and wound healing characteristics (Jegadeshwari & Rajaram, 2024) (Figure 4).

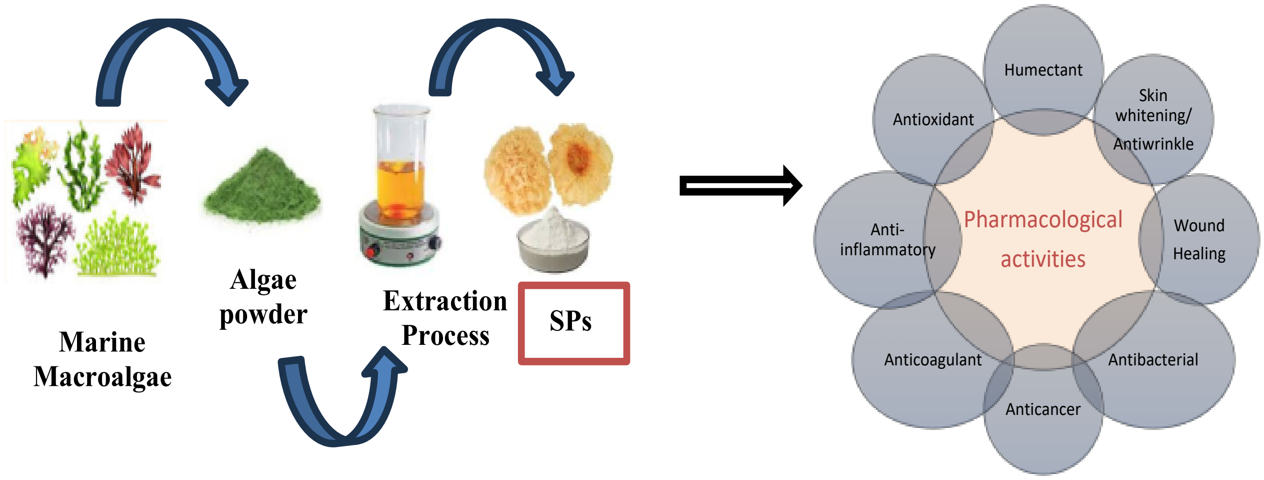

Figure 4. Pharmacological activities of sulfated polysaccharides from marine macroalgae.

Humectant Activity

Moisturizing agents enhance the skin's barrier function against hazardous environmental factors by preserving its elasticity and appearance. Jesumani *et al.* (2019) reported that skin moisture levels indicate health, so skincare products are very important. All polysaccharides and glycerol enhanced moisture absorption over time. Hydrogen interactions between water and polysaccharide hydroxyl groups are essential for moisture retention and absorption, according to Li *et al.* (2017). Propylene glycol (1:1) extracts of *Laminaria japonica* may hydrate human skin (Wang *et al.,* 2015).

Skin whitening and anti-wrinkle activity

Tyrosinase enzyme plays a crucial role in the production of melanin, the pigment responsible for skin, as it catalyzes the oxidation of tyrosine to dopaquinone. Increased sun exposure causes melanin overproduction causes hyperpigmentation (Liang *et al.,* 2012). Compounds that inhibit tyrosinase activity can be used to reduce melanin production, potentially leading to skin lightening or treating hyperpigmentation. According to Xie *et al.* (2020), polysaccharides from *Pyropia haitanensis, Gracilaria chouae*, and *Gracilaria blodgettii* may lighten skin and inhibit tyrosinase. Jesumani *et al.* (2019) found that crude polysaccharides from *Sargassum* sp. may lighten skin by inhibiting tyrosinase, slow aging by blocking elastase, protect against free radicals, hydrate skin, and increase water retention. Chen *et al.* (2019) mentioned that *S. fusiforme* polysaccharides inhibited tyrosinase with a maximal inhibition of 14.3% at 1000 µg/ml. Fernando *et al.* (2018) examined how *Chnoospora minima* and *S. polycystum* polysaccharides inhibit tyrosinase. They found that, with a concentration of 200 µg/ml. *Ecklonia maxima* marine algal sulfated polysaccharides for cosmetic use. This species has antioxidant, anti-melanogenesis, and photoprotective qualities that might be used in medicine and cosmetics (Wang *et al.,* 2020).

Antioxidant Activity

Antioxidants are substances that protect cells from the harmful effects of reactive oxygen species (ROS), which include singlet oxygen, superoxide, peroxyl radicals, and hydroxyl radicals. An imbalance between antioxidants and ROS causes oxidative stress, which leads to cellular damage. Oxidative stress has been associated with cancer, aging, and inflammation (Wijesinghe & Jeon, 2011). Antioxidants protect the skin from the harmful effects of ROS (Weber *et al.* 1997). Another study discovered that *Porphyra yezoensis* polysaccharides effectively scavenge ROS in HK-2 cells (Human kidney-2 cells), prevent Ca. Oxalate crystal adhesion restores mitochondrial membrane potential, unblocks the cell cycle, prevents cell death, upregulates antioxidant proteins (Nrf2, HO-1, SOD, and CAT), and downregulates keap-1 expression to activate the Keap1/Nrf2 signaling cascade (Deng *et al.,* 2024). Algal polysaccharides have strong antioxidant effects, which protect against oxidative stress and cellular damage. These findings emphasize the potential of seaweed polysaccharides as natural antioxidants with prospective uses in boosting health and treating oxidative stress-related illnesses (Jegadeshwari & Rajaram, 2024). *Halimeda* is widely dispersed in the Mediterranean and Red Sea (Galal &

Rashedy, 2023 a; Galal & Rashedy,2023 b). It has a high economic importance since it can create hydrocolloids, which are used in the food and pharmaceutical industries. It is a rich source of natural antioxidants such as carotenoids, unique bis-indole alkaloids, various sugars, high phenolic contents, high total flavonoid content, terpenoids, and it has many biomedical applications. (Mani *et al.,* 2024).

Anti-inflammatory Activity

Inflammation is vascular tissues' complicated biological reaction to damaging stimuli and the organism's effort to eliminate the stimuli and start tissue repair. Macrophages drive inflammation (Kazlowska *et al.,* 2010). According to Wang *et al.* (2022), SPs from *Codium fragile* effectively reduced inflammatory markers such as prostaglandin E2, NO, IL-1β, TNF-α, and IL-6 in Lipopolysaccharide (LPS) stimulated RAW264.7 macrophages. Previous research found that these polysaccharides reduced ROS, apoptosis, and NO in LPS-stimulated zebrafish. SPs from the red seaweed *Spyrida sp.* prevent protein denaturation and reduce inflammation, according to Reddy *et al.* (2023). Sulfated polysaccharides from *Sargassum horneri* inhibited RAW 264.7 cell production of nitric oxide, prostaglandin E2, and pro-inflammatory cytokines (Sanjeewa *et al.,* 2018). *Codium elongatum* polysaccharides inhibited the cyclooxygenase 2 pathway in the carrageenan-induced rat paw edema model, demonstrating their anti-inflammatory actions (Gupta, 2024). In another vivo investigation, Manikandan *et al.* (2020) found strong anti-inflammatory efficacy in brown algae fucoidan. Premarathna *et al.* (2024) examined the immunomodulatory effects of Carrageenan and Xylan from *Chondrus crispus*, *Ahnfeltiopsis devoniensis*, *Sarcodiotheca gaudichaudii*, and *Palmaria palmata* algae species. Ulvan, derived from *Ulva lactuca* algae, has immunoregulatory and anti-inflammatory characteristics (Kidgell *et al.,* 2020). A polymer's anti-inflammatory efficacy depends on its sulfate group density and sugar content (Lee, 2022). Previous research has demonstrated that SPs' anti-inflammatory effects depend on their molecular weight, that smaller particles may interact with inflammatory mediators better due to increased bioavailability, and tissue penetration (Nagahawatta *et al.,* 2022).

Anticoagulant Activity

Thromboembolic illness is the production of blood clots (thrombi) that can restrict blood vessels, which could contribute to major problems such as a stroke, coronary artery disease, or an embolism of the lungs (Lichota *et al.,* 2020). Oxidative stress leads to this illness by causing endothelial dysfunction, which enhances platelet adhesion and activity. High ROS levels can directly trigger platelets to assemble into clots, and oxidative stress may influence platelet receptor expression, which promotes the production of clots (Li *et al.,* 2024). Heparin, an anticoagulant medication, is widely used in the treatment and prevention of thrombosis. However, heparin has some adverse effects, like thrombocytopenia, hemorrhagic problems, and inherited or obtained anticoagulants shortage invalidation (Pomin, 2009). Thus, it is necessary to look for alternative sources of anticoagulant agents. According to research on marine algae, certain macroalgae create sulfated polysaccharides that can reduce these processes. Polysaccharide fractions of *Ahnfeltiopsis devoniensis* had the best anti-coagulation activity (Premarathna *et al.,* 2024). The *Chaetomorpha aerea* polysaccharide strongly inhibited intrinsic coagulation factors XII, XI, IX, and VIII. It also inhibited coagulation factor Xa via antithrombin III (Qin *et al.,* 2023). The *Cladophora oligoclada* sulfated polysaccharide has high antithrombin-III (AT-III) and heparin cofactor II-enhancing activities (He *et al.,* 2021). A 100 mg/kg dosage of sulfated polysaccharide isolate from the brown algae *Sargassum polycistum* showed anticoagulant effects, according to Manggau *et al.* (2022). Polysaccharides' anticoagulant effect depends on their sugar concentration, molecular weight, sulfation level, and sulfate group location on the sugar backbone (Chagas *et al.,* 2020). These results imply that sulfated polysaccharides might be used to produce new anticoagulants with lower bleeding risks.

Anticancer Activity

Food experts are interested in algal polysaccharides because they may prevent cancer. The anticancer properties are dependent on the composition of sugars, molecular weight, water solubility, glucose linkage, tertiary structure, branching rate and form, the presence of other ligands, and chemical modification of polysaccharides. *In vivo* and *in vitro* studies have revealed that polysaccharides decrease tumor development and trigger apoptosis (Lemieszek & Rzeski, 2012). Vaikundamoorthy *et al.* (2018) show that *Sargassum wightii* polysaccharide fractions increase ROS, disrupt mitochondrial membranes, and trigger apoptosis in breast cancer cells. Caspase 3-9 activity rises. SP fractions from *Codium edule* green seaweed suppressed MCF-7 human breast cancer cell growth with an IC_{50} of 5.54 µg/ml. Bayro *et al.* (2019) accomplished this by triggering apoptosis in MCF-7, changing membrane integrity, and increasing caspase 3/7 activity at 62.5 µg/ml. In vitro, *Porphyra Haitanensis* polysaccharides suppress human gastric cancer SGC-7901 tumor cell growth and causes apoptosis (Chen & Xue, 2019). Brown seaweed produces sulfated polysaccharides called fucoidan. Fucoidans reduce cancer cell growth by regulating nuclear factor kappa-light-chain enhancer of activated B cells (NF-κB) signaling pathways (Hsu *et al.,* 2020). Carrageenan is important in pharmaceutical formulation; it fights respiratory illnesses, tumor growth, and immune system regulation (Pradhan & Ki, 2023). Fucoidan from the brown algae *Turbinaria decurrens* showed anticancer activity against HT29 human cancer of the colon cell lines. The inhibitory concentration ranged from 5.41 ± 0.36 to 73.52 ± 2.54 µg/ml. (Nguyen *et al.,* 2024).

Antibacterial Activity

Since Polysaccharides are repeated monosaccharide units connected by glycosidic linkages. Sulfated polysaccharides work in pharmaceuticals and diets. Glycoprotein receptors on polysaccharides bind with substances in the bacterial cell wall, cytoplasmic membrane, and DNA, causing their antibacterial effect. This increases cytoplasmic membrane permeability, protein leakage, and bacterial DNA binding (Pierre *et al.,* 2011; Amorim, 2012). Polysaccharides such as fucoidan and laminarin have been utilized as oral antibiotics to suppress *Staphylococcus aureus*, *Escherichia coli* growth, and *Helicobacter pylori* biofilm adherence in the gastric mucosa. They have also been added to food as a supplement to boost farmed fish immunity and minimize *Piscirickettsia salmonis*. Khosravi *et al.* (2018) discovered that *Gracilariopsis persica* polysaccharides inhibited *Salmonella typhimurium*, *Aeromonas hydrophila*, *Pseudomonas aeruginosa*, and *E. coli.* Silver nanoparticles conjugated with sodium alginate from *Sargassum latifolium* had the best antibacterial activity against *P. aeruginosa, S. aureus, K. pneumoniae, E. coli, B. subtilis*, and *B. cereus* compared to alginate alone (El-Sheekh *et al.,* 2022). Elangovan *et al.* (2022) found that polysaccharides from the seaweed *Portieria hornemannii* had the highest antibacterial activity against *Vibrio cholerae* (21 mm at 600 µg/ml), followed by *S. aureus* (18 mm), and *P. aeruginosa* (15 mm) at the same amount taken. All these results suggest that seaweed-derived sulfated polysaccharides may be excellent pathogen fighters.

Wound Healing Activity

Lesions harm tissues, organs, and the integumentary system. Wounds are classified by origin, location, kind of damage, depth, complexity, infection, etc. The type and genesis of the injury, its timing, whether it is acute or chronic, and the degree of skin and underlying tissue damage are most important in wound assessment. Wound repair, or healing, is a complicated series of overlapping processes that restore skin structure and function. Collagenation, epithelialization, and tissue remodeling are coordinated in this biological process (Aderibigbe & Buyana, 2018; Pozharitskaya *et al.,* 2019).

Due to their high biological activity, biocompatibility, biodegradability, nontoxicity, immunogenicity, high absorption capacity, hydrogel formation capabilities, and low production costs, alginates are expected to succeed in modern biotechnologies, including wound dressings. Alginate-based dressings can absorb fluids 20 times their weight and treat sick and non-infected wounds (Sudarsan *et al.,* 2015; Ching *et al.,* 2017). The ability of alginates to form hydrogels in aqueous solutions after adding bivalent metal compounds is particularly important in wound treatment. Mannuronic acid makes softer gels than guluronic acid (Murakami *et al.,* 2010). Alginates, gel-forming biopolymers, are widely used in tissue engineering, wound dressings, and drug delivery systems (Rupérez *et al.,* 2013). Mixtures of alginate with other biopolymers, such as natural (chitosan, hyaluronic acid, collagen, fibrin, gelatin, and cellulose), and synthetic alternatives, may increase the biological activity of the hydrogel polymer matrix. Some researchers developed hydrogels from different sources as Murakami *et al.* (2010) from chitin/chitosan, fucoidan, and alginate, Saarai *et al.* (2012) from sodium alginate/gelatin, Singh *et al.* (2012) from polyvinylpyrrolidone/alginate with nano-silver, and Xing *et al.* (2012) from alginate-chitosan. All alginate-based wound dressings were designed to promote autolysis and moisten partial-and full-thickness wounds with substantial drainage, whether infected or not. Carrageenan-based hydrogels absorb wound exudate and moisten wounds to stimulate cell migration, and they're water-soluble. Due to their low cytotoxicity, antibacterial, and antioxidant capabilities, Liu *et al.* (2020) found that these hydrogels may treat acute and chronic lesions. Ulagesan *et al.* (2023) created a composite hydrogel using κ-carrageenan and phycobiliprotein from *Porphyra yezoensis,* which improved fibroblast migration and wound healing. Ulvan-based hydrogels have garnered interest in their wound-healing capabilities. Their beneficial qualities, acquired from marine sources like *Ulva sp.*, let these hydrogels heal a range of lesions (Jiang *et al.,* 2022).

OTHER USES

Thickening agent

Due to the need to manage viscosity for cosmetic product fluidity, hydrocolloids like alginic acids and polysaccharides are used to thicken and stabilize emulsions (Priyadarshani & Rath, 2012). Alginic acid is composed of two monosaccharides, β-d-(1,4)-mannuronic acid, and a-l-(1,4)-guluronic acid, and may be processed with alkali and mineral acids. Alginic acids are used in cosmetics because they absorb water fast and give biological support to prevent brown algae and bacterial cells from bursting, which is the basis of their application in cosmetic formulations (Wijesinghe & Jeon, 2011). Other SPs may thicken cosmetic products to manage viscosity, and emollience like agar (Fertah *et al.,* 2017), and carrageenans (Stengel *et al.,* 2011).

Gelling agent

Polysaccharides contain hydrophilic hydroxyl groups, which allow them to form physically crosslinked hydrogels. Chemical alterations can also introduce new functional molecules, allowing the development of chemically cross-linked hydrogels. Thus, sulfated polysaccharides from seaweed can produce hydrogels (Cui *et al.,* 2024). Physicochemical characteristics of carrageenan can be improved, and new features introduced by crosslinking its hydroxyl and sulfate groups (Campo *et al.,* 2009). According to Liu *et al.* (2019), κ-and ι-carrageenan have substantial commercial potential owing to their viscoelastic and gel characteristics. Hydrogels and three-dimensional double helix networks are made by crosslinking adjacent sulfate groups. However, the lack of the cross-linking sulfate group in λ-carrageenan prevents hydrogel formation. Researchers use carrageenan hydrogels for drug delivery, wound dressing, and tissue engineering (Lester *et al.,* 2020; Zhong *et al.,* 2020).

CONCLUSION

Hence, studies focused on bioactive compounds of macroalgae, while basic chemical composition and comprehensive structural elucidation are still lacking, hence most of the research relies on detailed bioactivity-structure correlations of polysaccharides. Future research on Red Sea seaweed should confirm their medical and industrial value through more detailed studies and clinical trials. Sustainable farming and safe harvesting methods are needed to protect the environment and increase yield. Improved extraction and processing techniques will support wider applications in food, health, and biotechnology.

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