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Polysaccharides from Macro and Microalgae: A Review of Biological Activities, Structural Features, and Some Extraction Techniques

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Abstract

Polysaccharides derived from various natural sources have long been investigated and employed in a variety of industries, including food, feed, and biological activities as antioxidants, antivirals, anti-inflammatory, antimicrobial, anticancer and anticoagulants. In recent decades, micro and macroalgae have been used as sources of different active ingredients, especially because of their biocompatibility, biodegradability, non-toxicity, and specialized medicinal properties. Polysaccharides have sparked considerable interest in their use, particularly bioactive polysaccharides. The main purpose of this article was to review macro and microalgae as main sources, native biological activities, isolation, characterization, and the structural features of bioactive polysaccharides. Moreover, the review has also been focused on the chemical and functions of polysaccharide derivatives from different algal groups.

Key words:macroalgae; microalgae; polysaccharides; chemical structure; biological functions; applications.

1.Introduction

Algae are classified as microalgae or macroalgae depending on their size and shape. Furthermore, they live in various habitats, including freshwater and marine environments, which contribute to their diversity, such as freshwater microalgae and marine macroalgae.

Unicellular microorganisms known as microalgae can develop in fresh or salt water. and exhibit morphological structures ranging from 3–10 μm in diameter or length. Microalgae are prokaryotic and eukaryotic organisms that grow quickly and have high productivity [1,2].

Bioactive components, including proteins with essential amino acids, vitamins, polysaccharides, fatty acids, minerals, photosynthetic pigments, enzymes, and fiber, are widely distributed in microalgae and cyanobacteria, which are important natural sources of substances with great nutritional and therapeutic properties [3].

Most of the bioactive compounds were produced through specially conditioned secondary metabolic pathways. These compounds possess antibacterial, antiviral, antifungal, and antialgal activities [4].

Cyanobacteria are a phylogenetically old group of prokaryotic phototrophic microorganisms. Their existence in the biosphere since the early Precambrian and wide diversity up to the present time indicate their extraordinary and continual biologically and ecologically successful life strategies, with repeated rapid adaptations to various environmental conditions in different ecosystems [5].

The only prokaryotes that carry out oxygenic photosynthesis in a manner like plants are

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cyanobacteria, which are widespread gram-negative bacteria with a complicated evolutionary history. Cyanobacteria possess several advantages as hosts for biotechnological applications, including simple growth requirements, ease of genetic manipulation, and attractive platforms for carbon neutral production processes [6].

Cyanobacteria are used as a promising alternative for bioactive compounds because of their fast growth, diversity, and simple genetic background, which can be easily manipulated to form cell factories [7]. They produce bioactive compounds that are remarkably effective against both gram-negative and gram-positive bacteria and are considered new drugs that are essentially needed to combat and treat bacterial infections [8].

Algae is a rich source of bioactive compounds known as polysaccharides, which are natural resources that can be renewed and represent a significant class of polymeric materials with applications in biotechnology. They offer a wide selection of goods that are useful to people. Exopolysaccharides (EPSs) of microbial origin have replaced polysaccharides of algal origin as a better option because they have unique functionality, repeatable physicochemical features, and steady cost and availability [9].

Polysaccharides are large molecules made up of numerous smaller monosaccharides, each of which often contains more than ten. These small monomers are joined by specialized enzymes to form large sugar polymers, also known as polysaccharides [10].

Due to the discovery of several biological activities, including immunomodulatory, antibacterial, anticoagulant, antimutagenic, radioprotective, anti-oxidative, and anticancer properties, polysaccharides have recently attracted a lot of attention. So, this review showed the role of algal polysaccharides and their derivatives in these biological activities which Figure 1 illustrates the extraction, purification, and biological properties of polysaccharides from algal species

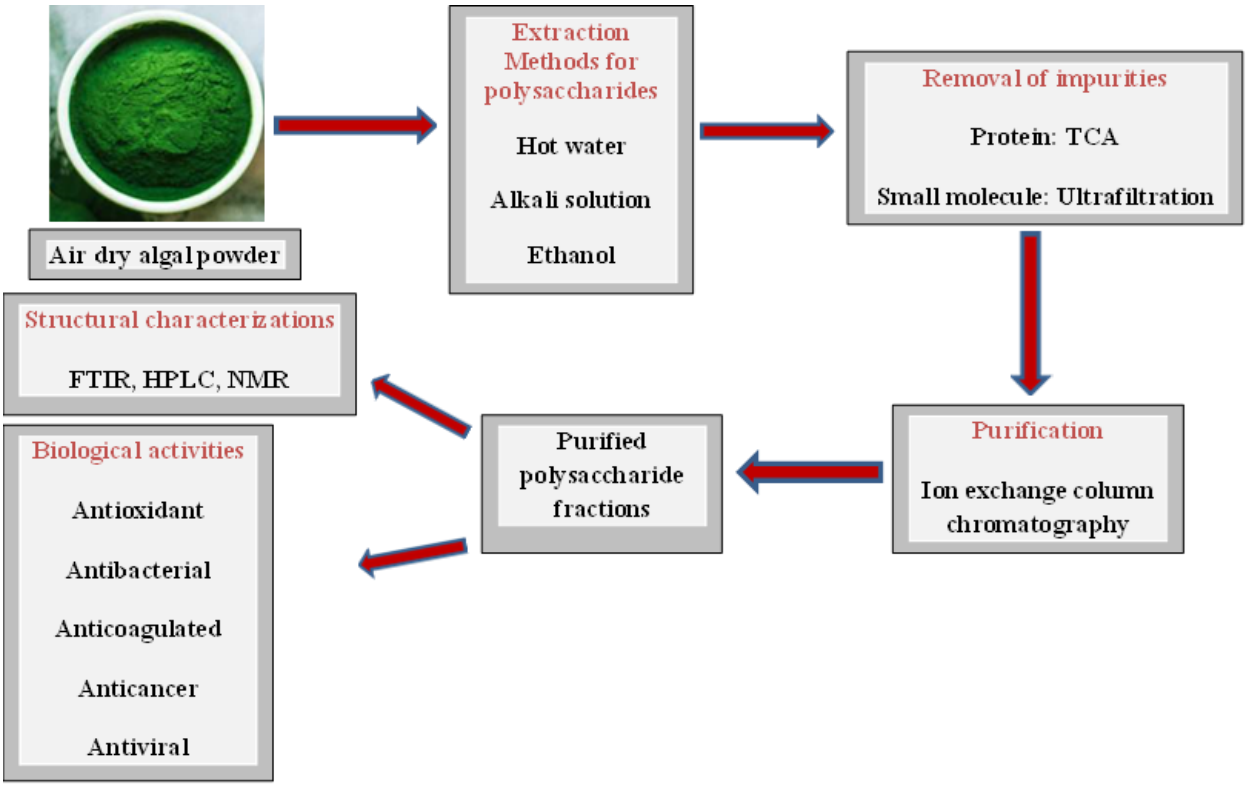


Fig. 1. Schematic diagram of Extraction, purification, and biological properties of polysaccharides from algal species.

As shown in Table 1, the extraction methods of polysaccharides from some different macroalgal species and their bioactivities.main components of marine algae, plants, animals, insects, and microorganisms [16].

All organisms contain polysaccharides, which have a wide variety of biochemical structures based on combinations of up to 40–50 different monosaccharides (hexoses and pentoses), many of which are complex sugars. Various polysaccharides with unique structural and practical entities have

1- Polysaccharides

gained special attention in the current biomedical zone

Table: 1 Extraction methods of polysaccharides from some different macroalgal species and their bioactivities

Macroalgal species (Brown algae)	Macroalgal polysaccharides	Extraction	Biological activities	Methods	References
Sargassum vulgare	Fucoidan	Filtration, precipitation with acetone (0.3, 0.5, 1 and 1.5 volumes), and collection of the various precipitates produced by the various volumes to freeze-dry the proteolytic enzyme in NaCl (0.25 M, pH 8, 60 °C, 24 h).	Anticoagulant	APT (activated partial thromboplastin time), thrombin time (TT), and prothrombin time (PT). APTT coagulation tests.	[11,12]
Sargassum vulgare	Fucoidan		Antitumor	DPPH radical scavenging.	[11,13]
Sargassum vulgare	Fucoidan		Antioxidant	DPPH and ABTS radical scavenging, total antioxidant, ferric reducing, and hydroxyl radical scavenging activities.	[14,15]
Ascophyllum nodosum	Laminarin	Centrifugation (16,887 g, 20 min) was performed after $CaCl_2$ (1%, 85 °C, 4 hours). Using ethanol, the supernatant was first precipitated (1 hour) and then reprecipitated (20 °C, 48 hours). The pellets were freeze-dried and dialyzed (15 kDa).	Antioxidant	radical scavenging activity by FRAP and DPPH.	
Laminaria cichorioides	Fucoidan	Concentration, dialysis, and freeze-drying are performed after HCl (60 °C, pH 2-3, 3 h, 2 times).	Anticoagulant	Thrombin time (TT), prothrombin time (PT)	[11]
Coccophoral angsdorfii	Laminarin	Concentration, dialysis, and freeze-drying was conducted after HCl (0.1 M, room temperature, twice) and the supernatant was neutralized to pH 5.7-6.1 using $NaHCO_3$ (3%) and the subsequent steps.	Anti-inflammatory	Colon and liver *in vivo* inflammatory cytokine reduction.	[16]

Marine algae, plants, animals, insects, and microbes are primarily composed of polysaccharides [10].

A polysaccharide, also known as a glycan, is an enormously large molecule made up of numerous smaller monosaccharides, typically with a content of more than ten. These small monomers are joined by specialized enzymes to form significantly larger sugar polymers, or polysaccharides, as shown in Figure 2 [10].

2- Cyanobacterial Exopolysaccharides (EPS)

Cyanobacterial EPS can perform as adhesion, structural support, defence against abiotic stress, bioweathering processes, gliding motility, and nutrition repositories in phototrophic biofilms or biological soil crusts [17].

In contrast to other natural polysaccharides derived from plants and macroalgae, microbial-

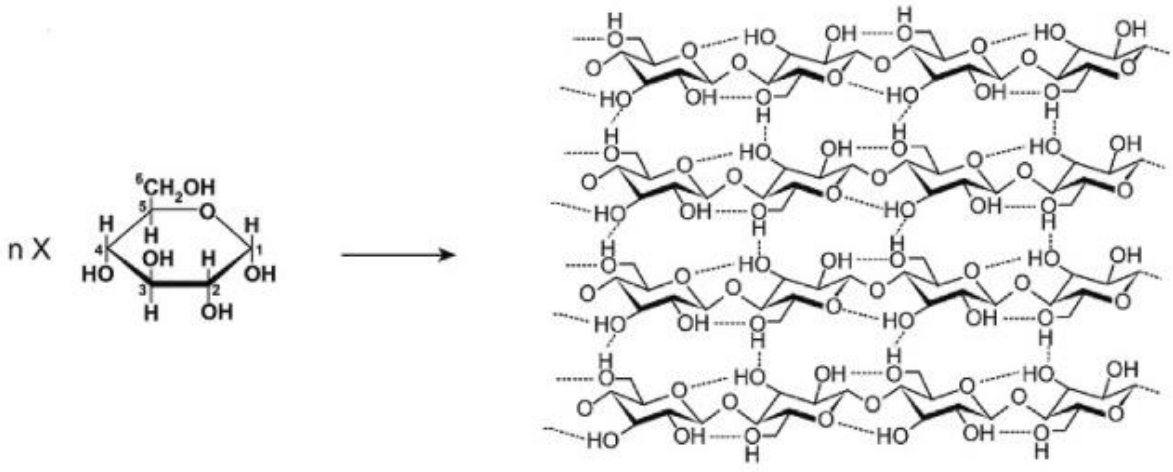


Fig. 2. Chemical structure of mono and polysaccharides

polysaccharides may find use in the food, cosmetic, and pharmaceutical industries. Extracellular polymeric substances (EPSs) produced by cyanobacteria are polysaccharidic in composition and exhibit distinctive biochemical characteristics that intrigue them from a biotechnological standpoint. Complex exopolysaccharides made up of at least ten distinct monosaccharides can be produced by cyanobacteria [18].

For suspending or stabilizing the aqueous phase, EPSs are mostly utilized in industry as thickening and gelling agents. Due to the differences in the qualities of the EPS produced by various organisms, they have varied industrial uses [19].

3- Endopolysaccharides

Glycogen is the major storage polysaccharide in blue-green algae, and its production is highly reliant on algal growth conditions, nitrate concentration, and light intensity. Nitrate shortages may cause increased glycogen synthesis. The accumulation of glycogen is aided by a low nitrate content [20].

4- polysaccharides derivatives

Sulfated polysaccharides are microalgal polysaccharides that contain sulphate esters and have specific medical applications. The basic therapeutic mechanism is based on the stimulation and regulation of macrophages. The sugar content, position, anddegree of sulfation of sulfate polysaccharides are all linked to their biological activity [14]. Table 2 shows the biological activities of sulfated polysaccharides.

Sulfated galactans, carrageenans, and agarans, as well as fucoidans and ulvans, are examples of polysaccharides with various structural variations found in red, brown, and green seaweeds, respectively. They are extremely soluble in water and possess several important biological traits, including those of antiviral, anticancer, anticoagulant, antioxidant, antitumoral, prebiotic, immunomodulatory, and anti-inflammatory substances. In the field of medication delivery systems, researchers are now utilizing SPs because of their excellent reactivity to environmental conditions, including pH and temperature [10].

Table 2: Biological activities of sulfated polysaccharides from different algal species

Sources	Sulfated polysaccharides	Monomer units	Bioactivities	References
Green algae	Ulvan	Iduronic, glucuronic, rhamnose, and xylose	Antitumor, anti-inflammatory, antiviral, anti-coagulant, and antioxidant	[21]
Red algae	Carrageenan	3,6 anhydrogalactose& galactose units	Antithrombotic, antioxidant, antiviral, anticancer, and anticoagulant	[22]
Brown algae	Fucan/fucoidan	Mainly fucose	Antithrombic, antiviral, anticancer, immunostimulatory, anti-coagulant, antithrombic, antioxidant, and anti-complementary	[23]
Blue green algae (*Spirulina platensis*)	Calcium spirulan (Ca-sp)	O-hexuronsyl-rhamnose (aldobiurnic acid) and O-Rhamnose-acofriose	Antibiotics and antiviral	[24]

4.1- Sulphated polysaccharides (SPs)

Microalgal polysaccharides are primarily heteropolysaccharides with a variety of additional components, such as sulphates [25].

Sulphated polysaccharides (SPs) are sulphate esters in carbohydrate macromolecules found in marine algae, seagrasses, mangroves, and a few terrestrial plants [26]. As shown in Figure 3, the chemical structure of several types of sulfated polysaccharides and some derivatives.

All SPs have the potential to be highly effective anticancer, immunomodulatory, vaccine adjuvant, anti-inflammatory, anticoagulant, antiviral, anti-antiprotozoal, antibacterial, and antilipemic agents [10].

Anionic polysaccharides include sulfated galactans and fucans in marine species. Although structural differences among species exist, all phyla share their core traits. Brown algae and echinoderms in the ocean contain sulfated fucans, while red and green algae include sulfated galactans. A potential source of chemicals for antithrombotic therapy is the family of polysaccharides found in algae and invertebrates, which are also powerful mammalian blood anticoagulants. [27].

According to tests using DPPH, ABTS, Nitric oxide (NO), superoxide, and hydroxyl radicals, SPs such as fucoidan, porphyran, carrageenans, and ulvan have been reported to have antioxidant activity. The presence of sulfated polysaccharides with glucose subunits in the algae was verified by GC-MS. It exhibits higher effective antioxidant activity (between 65 and 75%) as compared to non-sulfated polysaccharides. Higher SP concentrations and the presence of sulphate groups improved the effectiveness of scavenging activity [28].

4.2- Fucoidan

Natural sulfated polysaccharides from natural seaweeds, fucoidans (FUC), have a variety of organic functions. which investigated the anti-inflammatory, antioxidant, and chemoprotective properties of FUC from Laminaria japonica [10].

In Laminaria japonica, a key economic algae species in China, a sulfated heteropolysaccharide group called fucoidan was isolated. Fucoidan and its derivatives (including sulfated, phosphorylated, and aminated fucoidan) were evaluated for their anticoagulant action using in-vitro anticoagulant systems. [29].

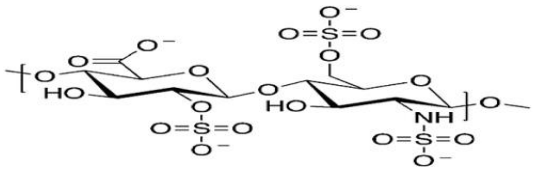
Fucoidan may be able to suppress thrombin activity or fibrin polymerization, according to the method by which it can prolong the thrombin time spent [30]. The inhibitory effect of fibrin polymerization was one area where FPS showed notable activities. The prolongation of thrombin time activity was

unaffected by fucoidan, though. The phosphorylation events may have resulted in the loss of sulphate groups and molecular weight, which may have decreased the activity on thrombin time [31].

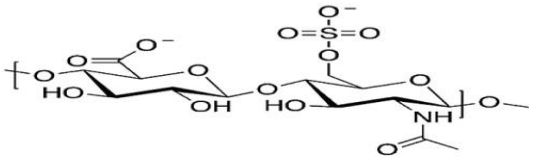
4.3- Calcium spirulan (Ca-SP)

The blue-green alga Spirulina platensis is used to extract the sulfated polysaccharide known as calcium spirulan (Ca-SP). According to reports, Ca-SP has anticoagulant effect through a putative suppression of thrombin that may be mediated by heparin cofactor II (HCII), although via a different mechanism than heparin [32].

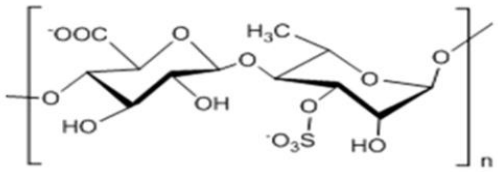
Multiple viruses' replication was blocked in vitro by calcium-spirulan, an intracellular polysaccharide that worked by inhibiting virus entry into the different host cells [33].



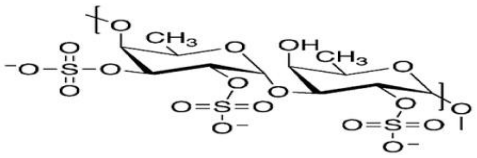
Heparin Sulphate



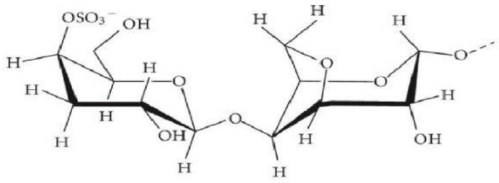
Chondroitin Sulphate



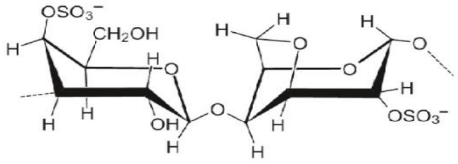
Ulvan



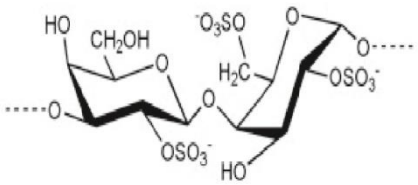
Fucoidan



Kappa - Carrageenan



Iota - Carrageenan



Lamda - Carrageenan

Fig. 3. Chemical structure of several types of sulfated polysaccharides and some derivatives [10]

5- Biological activities of polysaccharides

5.1- Antioxidant activity

There are several possible uses for microalgal biomass in food, medicine, and cosmetics. It is thought to be a rich natural source of antioxidants [34]. Moreover, microalgal biomass may contain numerous substances with significant antioxidant potential, including lipids, pigments, and polysaccharides.

In liver homogenates and mouse erythrocyte hemolysis, EPS has better antioxidant activity in scavenging free radicals and has inhibitory effects on lipid peroxidation. Mice tissues and cells are therefore more shielded against oxidative damage as a result [35]. It can protect systems from oxidative and radical stress agents by preventing the buildup and activities of free radicals and reactive chemical species [36].

Marine SPs provided evidence of their antioxidant activities by their potent metal chelating ability, hydrogen-giving ability, and efficiency as free radical and superoxide foragers [37]. The action of SPs' antioxidants is generally accepted to have a beneficial relationship with the rate of sulphate clusters. For instance, marine SP showed an enhanced radical rummaging movement over the neutral frame, which was probably caused by the electrophile sulphate bunch portion that advanced intramolecular hydrogen reflection and the radical-inhibiting effect of chelating particles like Fe^{2+} and Cu^{2+} [38].

Marine SPs function as antioxidants by increasing the activity of antioxidant enzymes and reducing lipid metabolites, which can be added to the antioxidant framework enhancement by increasing catalase activity. By reducing lipid peroxidation and advancing antioxidant status, the SPs showed an astonishing dose-dependent increase in antioxidant capacity and dramatically reduced the isoproterenol-induced cardiac damage [39].

Marine SPs can prevent cell death and ensure organelles to produce an antioxidant effect. The green growth-extracted SPs may improve the antioxidant state, in this manner avoiding layer injury. That the SPs are of might secure against responsive oxygen species-mediated cell damage and restrain oxidative stretch [40].

5.2- Anticancer activity

In cancer cell lines, EPS inhibited tumor progression (*in vivo*) and had antiproliferative characteristics (*in vitro*). The EPS are also highly effective at enhancing the tumoricidal activity of macrophages and Natural killer cells (NK cells), which in turn inhibits the growth of tumor cells by triggering NO generation, which in turn activates the innate immune system and enhances the production of cytokines like interleukin [41,42].

The EPS may also control cell signalling pathways, promote tumor cell differentiation and death, and prevent cancer cells and host cells from interacting or adhering to one another [33].

The calcium-Spirulan of *Arthrospira* (*Spirulina*) has been shown to inhibit tumor cell adhesion and proliferation in addition to pulmonary metastasis. It functions as matrices for stem cell cultures and shows promise in the treatment of spinal cord damage [43].
Marine SPs' anticancer mechanisms are described as being involved in controlling the cell cycle, which includes capturing the movement of the cell cycle and activating apoptosis [44].

Additionally, human leukemic monocyte lymphoma cell line-derived SPs isolated from microalgae induce apoptosis *in vitro* and may have an antiproliferative impact (U 937) [45].

5.3- Antimicrobial activity

A systematic search for physiologically active components in microalgae started in the 1950s. Microalgae have long been employed for medicinal purposes. However, during the past ten years, substantial research has turned its attention to microalgae with the goal of identifying new chemicals that may one day become therapeutically effective medicines. In the interim, microalgae have been found to have antibiotics. In a wide range of microalgal extracts and extracellular products, antibacterial, antifungal, antiprotozoal, and anti-plasmodial capabilities have been shown [46].

Phenols, fatty acids, polysaccharides, indoles, terpenes, and volatile halogenated hydrocarbons are just a few of the chemical groups whose components have been linked to the antibacterial action of microalgae against several human infections [47].

Sulfated polysaccharides, however, have not yet been proven to have a clear antibacterial effect. Sulfated polysaccharides (carrageenans) serve as antibiotics, according to two theories. Although SP enteritidis did not adhere to 3H-carrageenan in an experiment utilizing the substance, one believes that the sulfated polysaccharides bind to the bacterial surface. The opposing view contends that the bioavailability of nutrients may be decreased by cationic ions or by nutrients being trapped by sulfated polysaccharides [48].

5.4- Antiviral activity

Sulfated polysaccharides have one of their most important natural functions as an antiviral agent. Natural polysaccharides either lack or have a very weak antiviral effect. Similar tests were conducted on *Sargassummcclurei*, *Sargassumpolycystum*, and *Turbinariaornata*, which also showed that they have antiviral activity against HIV and did not cause any damage to normal cells.

Normally, the presence of the sulphate group will aid in the SPs' activity while they develop a mechanism of action on the initial blockage of viral entry into the host cell [49].

The mechanism by which these sulfated polysaccharides inhibit the various phases of viral infection inside the host cell has also been demonstrated [50].

Polysaccharides can prevent viruses from reproducing by interfering with a few steps in the virus's life cycle or by enhancing the host's antiviral immune responses, which can speed up the viral clearance process [51].

The viral cycle has six stages, as depicted in Figure 4: cell adsorption or attachment, entry, uncoating, syntheses (replication and translation of viral genomes), collection, and release[50].

The majority of studies have looked at how carrageenans affect the first two steps in various viruses and cell lines, but it has also been noted that carrageenans have an inhibitory influence on viral production. Below is a summary of the research that looked at preventing each step of viral propagation.

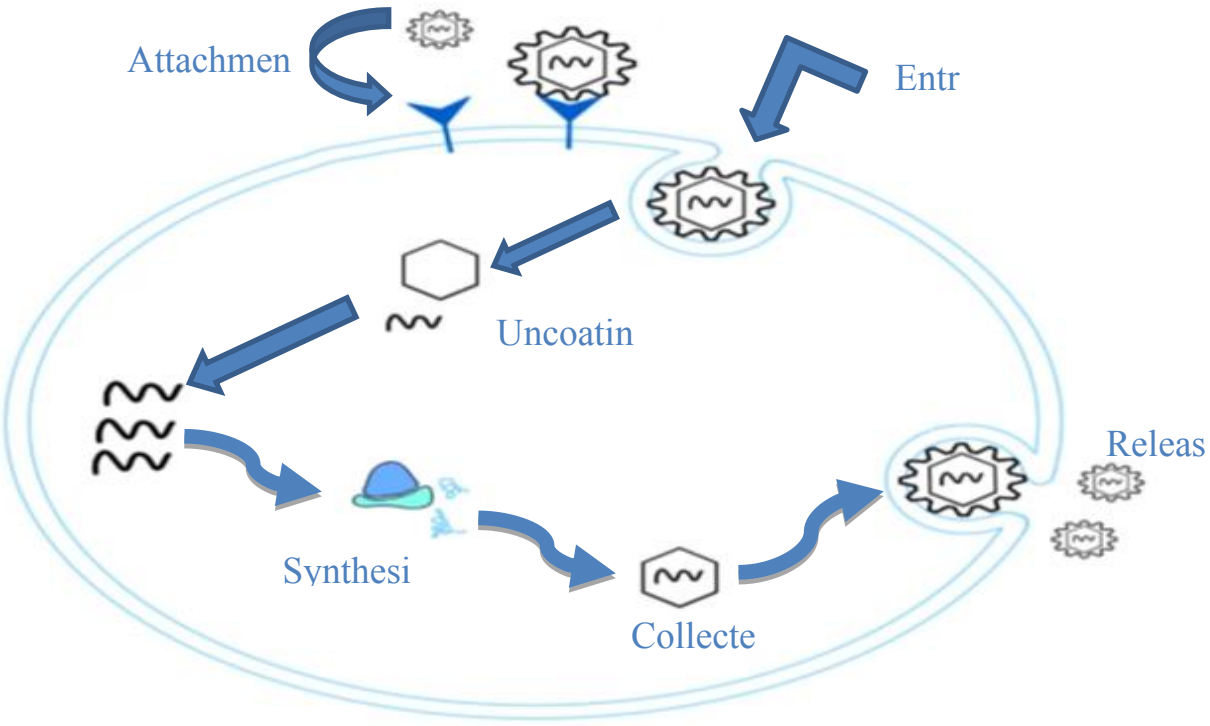


Fig.4. The process of viral infection and seaweed polysaccharides' antiviral properties [50].

The use of EPS from red algae, particularly *Porphyridium sp*., in antiviral may be the medicinal use that has received the most research. To clarify this antiviral activity, several potential pathways have been proposed [14,52]. (1) the anionic nature of EPS against viruses; (2) inhibition of attachment or adsorption; (3) inhibition of viral particle penetration into host cells; (4) inhibition of virus replication during the initial stages of the virus infection; and (5) prevention of the formation of various retroviral reverse transcriptase without cytotoxic effects against the host cells. Since it was first thought that numerous mechanisms might be engaged in antivirus activities, it has not been entirely obvious which

mechanism (or mechanisms) is the most effective against viruses.

Additionally, the antiviral effect of marine SPs may be achieved by blocking viral translation and replication by carefully targeting viral replication proteins or by impeding other intracellular targets [53].

The main reason that these branching SPs were able to restrict the replication of the virus was because they blocked some of the infection's later stages, such as DNA replication and translation, by downregulating the herpes simplex infection protein mix [54].

5.5- Anticoagulant

Anticoagulant treatment is necessary for most thromboembolic processes. This explains ongoing initiatives to create targeted and effective antithrombotic and anticoagulant medications [55]. The main medication for the treatment and prevention of venous thrombosis and thromboembolism has been heparin, a sulfated polysaccharide, since the 1940s. But hemorrhagic side effects are a clear consequence of heparin use. It is widely known that sulfated l-fucans with anticoagulant activities can be found in a wide range of anticoagulant polysaccharides, which are common in marine brown algae [56].

The health of patients with cerebral thrombosis, aspiratory embolism, and stroke has been maintained thanks to the major attention that Marine SPs have received for developing safe anticoagulant medication and anticipating thrombus formation [57].

The main mechanism by which marine SPs exert their anticoagulant effect is through the potentiation of common plasma protease inhibitors. Actuated protein II (IIa, often known as thrombin) and actuated protein X (Xa) are two examples of plasma proteases. Antithrombin (AT) and Heparin Cofactor II (HCII) are the two main serpins that serve as inhibitors. Tests for activated partial thromboplastin time (APTT), prothrombin time (PT), and thrombin time (TT) can determine the anticoagulant activity of SPs [58]. While using serpin-free plasmas, it has been demonstrated that some marine SPs can inhibit coagulation. By preventing the synthesis of factor Xa and/or thrombin via the procoagulant tense and prothrombinase complexes, respectively, cucumber fucosylated chondroitin sulphate and red algal sulfated galactan have been demonstrated to exhibit a distinctive serpin-independent anticoagulant action. [59].

5.6- Anti-inflammatory and Immunomodulatory Activities

Porphyridium sp. and *chlorella sp*. are two examples of marine microalgae whose polysaccharides have been discovered to have pharmacological properties, including anti-inflammatory and immunomodulatory drugs.

Nitric oxide (NO) can be produced more actively by macrophages when EPS is present, and cytokine production is also immunostimulant [41]. the EPS's ability to reduce inflammation in human skin, [60]. There was a positive association between the sulphate content and the immunomodulatory action, and it was discovered that the anti-inflammatory function of *Porphyridium* EPS was caused by the suppression of polymorphonuclear leukocytes' (PMNs) migration/adhesion and the development of erythema by the EPS [35].

However, since leukocyte migration to the site of damage promotes the release of more cytokines and nitric oxide, treatments must be effective in preventing this excessive inflammation [60].

5.7- Other biological activities

Marine SPs offer a wider range of applications in the pharmaceutical and cosmetics industries thanks to their unique functional and physiological characteristics. A growing number of SP items have arisen in the showcase because of a deep grasp of the nutritional value and wellness advantages of marine SPs. Marine SPs can be utilized in cosmetics because of their thickening, moisturizing, and antioxidant-movement properties. Ulvan may initiate cell proliferation and collagen biosynthesis due to the high rate of rhamnose in its atoms. In expansion, the presence of glucuronic acid confers moisturizing properties, which are crucial for skin assurance and harm prevention in dry situations [61].

SPs have been widely used to advance and stabilize the surface of goods in confectionery, jelly, and other foods as nutrient-added ingredients. Additionally, it has strong application value and advancement potential and can be used as a coating film or food film for packaging food [62].

The overall look of the medication delivery system incorporates the SPs of red algae in a significant way. Both bioactive nanocomplexes and nanocarriers can be created by SPs. Due to their bioactive qualities as antiviral agents, immunological boosters, diabetic medicines, etc., marine SPs may also be employed to make functional foods or medications [63].

Additionally, fluid fertilizers have been made using marine SPs [64].

In addition, to induce nitrite generation, SPs taken from the sea green alga *Ulva rigida* have increased the expression of several chemokines and interleukins by a factor of more than 2. Additionally, the ability of *U. rigida* SPs to increase cyclooxygenase-2 (COX-2) and nitric oxide synthase-2 (NOS-2) expression and stimulate prostaglandin secretion from macrophages in diseases where macrophage function is compromised or needs to be boosted suggests their potential in clinical applications for altering specific macrophage activities. [65]. Most EPS bioactivities come from various microalgae and cyanobacteria, and their compositional monosaccharides have sparked a lot of interest in using these polysaccharides, as summarized in Table 3.

Table 3. Summary of monosaccharides of EPS from different microalgae and cyanobacteria and their bioactivities.

Algal species (Microalgae)	Compositional Monosaccharides	EPS bioactivities	References
Nostoc sphaeroids	Man, Glc, Xyl, Gal, GlcA	Immunological activity	[66]
Nostoc flflagelliforme	Glc, Gal, Xyl, Man, GlcA	Antiviral activity, antithrombin activity	[67]
Spirulina platensis	GalA, Fru, Man, Gal, Xyl, Glc, GlcA, Rha	Antiviral activity	[68]
Porphyridium purpureum	Gal, Xyl, Glc, GlcA, Fuc	Antiviral, antimicrosporidian activity	[69,70]
Rhodella maculate	Gal, Xyl, GlcA, Rha, Ara, Glc	n.a.	[70]
Rhodophyta Porphyridium	Xyl, Gal, Glc, GlcA	Anti-inflammatory, antioxidant, hypocholesterolemic, bio lubricant	[71]
Porphyridium cruentum	Gal, Glc, Ara, Man, Fuc, Xyl, Rha	Antibacterial, antiviral, antiglycemic	[72]
Cochlodinium polykrikoides	Man, Gal, Glc	Antiviral	[73]
Synechocystis aquatilis	GalA, GlcA, Rha, Fuc, Xyl, Man, GalA, Glc	n.a.	[74]
Aphanothece halophytica	Glc, Fuc, Man, Ara, GlcA	Adjuvant activity, antiviral, anticancer	[75,76]
Arthrospira platensis	Rha, Gal, Glc, Fuc, Xyl	Antiviral, antibacterial, antioxidant, anticoagulant, skin repairs	[69,77,78]
Gyrodinium impudicum	Gal	Immunomodulatory and antitumor activity	[73,79]
Phormidium autumnale	Rha, Rib, Man, Glc, Fuc, Gal, Ara, GalA, GlcA	n.a.	[74]
Chlamydomonas reinhardtii	GalA, Rib, Ara, Xyl, Glc, Gal, Rha	Antioxidant	[80]

Algal species (Microalgae)	Compositional Monosaccharides	EPS bioactivities	References
Chlorella stigmatophora	Glc, GlcA, Xyl, Rib, Fuc	Anti-inflammatory, immunomodulatory (immunosuppressant)	[81]
Dictyosphaerium chlorelloides	Gal, Rha, Man, Glc, Xyl, Ara	Antiproliferative, immunostimulant of pro- and anti-inflammatory cytokines	[82]
Anabaena augstmalis	Glc, Gal, Man, Xyl, Fuc, Rha, GalA, GlcA	n.a.	[74]
Graesiella sp.	Man, Xyl, Rib, Rha, Fuc, Gal, Ara, Glc, Xyl	Antioxidant, antiproliferative	[36]
Dunaliella salina	Glc, Gal, Fru, Xyl	n.a.	[83]
Haematococcus pluvialis	Rib, Ara, Man, Glc	Antiaging, immunomodulatory	[84]
Naviculadirecta	Gal, Man, Rha, Glc, GlcA, Xyl, Fuc	Antiviral	[85]
Phaeodactylum tricornutum	Glc, GlcA, Man	Anti-inflammatory, immunomodulatory (immunostimulatory)	[81]
Rhodella sp.	Rha, Ara, GlcA, Xyl, Gal, Glc	n.a.	[86]
Rhodella reticulata	n.a.	Antioxidant	[87]
Rhodellaviolacea	Gal, Xyl, Glc, GlcA, Rha, Ara	n.a.	[70]
Cyanobacterium aponinum	GalA, Fuc, Glc, Ara, Gal, Man, Rha, GlcA	Immunomodulatory	[82]
Dunaliella tertiolecta	Glc	n.a.	[88]
Parachlorella kessleri	Ara, Rha, Xyl, Man, Gal	Antitumor, immunomodulatory	[89]
Aphanothece sacrum	Man, Xyl, Rha, Fuc, GalA, GlcA, Glc, Gal	Adsorption of metal ions, liquid crystallization, anti-allergic, anti-inflammatory	[90]
Nostoc sphaeroids	Man, Glc, Xyl, Gal, GlcA	Immunological activity	[66]
Codium divaricatum	Gal, Glc	Anticoagulant activity	[91]
Ulva prolifera	Rha, Glc, GlcA, Xyl	Iron supplement	[92]
Ulva fasciata	Rha, Xyl, Glc	Antioxidant activity	[93]
Monostroma latissimum	Rha, Glc, Xyl	Anticoagulant activity	[94]
Enteromorpha clathrata	Ara, Rha, Gal, GlcA	Anticoagulant activity	[95]
Sargassum aquifolium	Fuc, Gal, Man, GlcA, Xyl	Anticoagulant and anti-tumor activities	[96]
Sargassum plagiophyllum	Fuc, Gal, Xyl, Man	Anticancer activity	[97]
Sargassum horneri	Fuc, Gal, Man, Xyl, Rha	Inflammatory activity	[98]
Undaria pinnatifida	Fuc, Glc, Gal	Anticancer activity	[99]
Dictyopteris divaricata	Fuc, Xyl, Man, Glc, Gal	Antioxidant and immunomodulatory activities	[100]
Dictyota dichotoma	Pure glucan	Anticancer	[101]

Algal species (Microalgae)	Compositional Monosaccharides	EPS bioactivities	References
Ascophyllum nodosum	GlcA, Fuc	Antioxidant activity	[102]
Gracilariacorticata	Glc, Xyl, Man	Antioxidant activity	[103]
Gracilaria rubra	Gal, Fuc	Immunostimulate and antioxidant activities	[104]
Gelidium pacificum	Xyl, Gal, GalA	Anti-inflammatory activity	[105]
Grateloupialivida	Gal	Anticoagulant and antioxidant activities	[106]
Phaeodactylum tricornutum	Ara, Rha, Fuc, Rib, Xyl, Man, Gal, Glc	Anti-inflammatory, immunomodulatory activities	[81]
Chlorella stigmatophora	Ara, Rha, Fuc, Rib, Xyl, Gal	Anti-inflammatory, immunomodulatory activities	[81]
Arthrospira platensis	Ara, Rha, Fuc, Xyl, Man, Gal, Glc, GalA, GlcA	Antiviral, anti-tumor activities	[43]
Porphyridiumcruentum	Glc, Gal	Antioxidant, antiviral, hypoglycaemic, anti-tumor activities	[33]
Porphyridiummarinum	Fuc, Xyl, Gal, Glc, GlcA	Anti-microsporidian activity	[70]
Porphyridium purpureum	Fuc, Xyl, Gal, Glc, GlcA	Antiviral, anti-microsporidian activities	[33]
Rhodellamaculata	Ara, Rha, Gal, Glc, Xyl, GlcA	Anti-microsporidian activity	[70]
Rhodella reticulata	GlcA, Gal	Antioxidant, antiviral, hypoglycaemic, anti-tumor activities	[87]
Rhodellaviolacea	Ara, Rha, Gal, Xyl, Glc, GlcA	Anti-microsporidian activity	[70]

n.a., not available; Gal, galactose, GalA, galacturonic acid, Glu, glucose, GlcA, glucuronic acid; Ara, arabinose; Fuc, fucose; Fru, fructose; Rib, ribose; Man, mannose; Rha, rhamnose; and Xyl, xylose.

Conclusion and future perspectives

Algal polysaccharides play a significant role on a large scale in biological activities because of their useful properties. This review exhibits PS with macro- and microalgal structural features, biological functions, and component parts, such as cyanobacteria. Besides, the correlations between the structure, particularly sulfate bunches, and biological activity.

Consent for publication

All authors read and approved the final manuscript.

Conflicts of interest

The authors declare there are no conflicts of interest.

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