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Microalgal polysaccharides: Structural diversity, bioactive potential, and challenges for sustainable commercialization

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Abstract

Microalgae are recognized as a promising source of bioactive compounds with potential applications in food, pharmaceutical, cosmetic, and biotechnology industries. Among these compounds, polysaccharides have attracted increasing attention due to their unique structural characteristics and diverse biological activities. This review examines the chemical composition, structural diversity, biological functions, and commercial production prospects of microalgal polysaccharides. Unlike most terrestrial plant polysaccharides, microalgal polysaccharides are often characterized by complex heteropolymeric structures, high sulfate content, and diverse monosaccharide compositions, which contribute to their distinctive physicochemical and biological properties. Numerous studies have demonstrated their antibacterial, antiviral, antioxidant, immunomodulatory, and anticancer activities, highlighting their potential for high-value industrial applications. Despite these promising attributes, large-scale commercialization remains constrained by challenges related to cultivation efficiency, extraction and purification technologies, production costs, and product standardization. Advances in strain selection, bioprocess optimization, and downstream processing are expected to improve production efficiency and economic feasibility. Overall, microalgal polysaccharides represent a valuable and sustainable resource with considerable potential for future commercial development.

Keywords: Microalgae, Polysaccharides, Sulfated Polysaccharides, Chemical Structure, Biological Activities, Commercial Production, Bioprocessing

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Review of the biological potential of marine microalgae and their competitive advantages relative to terrestrial plants

The exponential growth of the global population, the increasing demand for food security and public health, and the emergence of drug resistance and environmental pollution have exerted substantial pressure on traditional sources of bioactive compounds. Although terrestrial plant resources offer certain advantages, their cultivation is constrained by fundamental challenges such as the need for arable land, high freshwater consumption, and seasonal and climatic effects on the quantity and quality of produced compounds. These limitations have necessitated exploration of alternative sources, particularly aquatic environments. The oceans, which cover more than 70% of the Earth's surface, represent a vast repository of largely untapped biodiversity, encompassing an estimated ~800,000 species of microalgae and cyanobacteria (Kumar *et al*., 2020; Ravindran *et al*., 2021; Silvello *et al*., 2022; Sousa *et al*., 2026). Microalgae, as efficient biological factories, are capable of producing a unique suite of metabolites including polysaccharides, pigments, unsaturated fatty acids, and proteins and therefore constitute a valuable resource for pharmaceutical, food, cosmetic, biofuel, and bioremediation applications. The global microalgae market was estimated at approximately USD 3.4 billion in 2020 and is projected to reach USD 4.6 billion by 2027, a growth attributed to increasing awareness of the environmental benefits and economic applications of microalgae (Sasaki *et al*, 2020; Koçer *et al*., 2021; Li *et al*., 2022; Vasilakis *et al*., 2025).

Microalgae, as unicellular photoautotrophic organisms, offer unparalleled potential to address environmental and industrial challenges. Among the bioactive metabolites produced by microalgae, their polysaccharide derivatives characterized by unique chemical structures and biological activities are of particular interest. The following sections present a detailed examination of the structural diversity and biological properties of microalgal polysaccharides (Chamizo *et al*, 2020; Deamici *et al*., 2021; Gouda *et al*., 2022).

Structural characteristics of microalgal polysaccharides

Polysaccharides are polymers composed of long chains of monosaccharides and are classified into homopolysaccharides (composed of a single type of monosaccharide) and heteropolysaccharides (containing two or more types of monomeric units). The structure and composition of the polysaccharide are determined by the types of monosaccharides present in the chain and the nature of the linkages between them. Microalgal polysaccharides are primarily heteropolymers consisting of galactose, xylose, and glucose in varying ratios, which are connected through glycosidic bonds. Other sugars, such as rhamnose, fucose, arabinose, mannose, orthomethylated sugars, and acidic residues of glucuronic acid and galacturonic acid, may also be components of the polysaccharides found in microalgae and cyanobacteria (Akter *et al*., 2025; Pan-Utai *et al*., 2025). Glucose is the most commonly encountered sugar. Fructose is generally not found in microalgal exopolysaccharides but is often a component of exopolysaccharides produced by cyanobacteria (Morales-Jiménez *et al*., 2020; Morais *et al*., 2020; Morais *et al*., 2021).

Polysaccharides extracted from microalgae exhibit significant structural and molecular differences from those derived from other sources such as plants and animals. These polysaccharides often have a highly heterogeneous structure, meaning that the types of monosaccharides, the degree of branching, and the nature of glycosidic linkages can vary, exhibiting greater diversity than plant polysaccharides like starch or cellulose. A notable feature of microalgal polysaccharides is the presence of sulfate groups in their structure, which are rarely found in plant or animal sources. Microalgal polysaccharides typically have variable molecular weights and specific branching patterns. The structural features of microalgal polysaccharides are influenced by the taxonomy of the algae and the cultivation conditions. Overall, these structural differences make microalgal polysaccharides exhibit unique biological and pharmaceutical functions compared to plant or animal polysaccharides. Microalgal polysaccharides can be categorized into intracellular polysaccharides and extracellular polysaccharides (Medina-Cabrera *et al*., 2020)

Bioactivities of microalgal polysaccharides and their relationship with chemical structure

Polysaccharides are natural macromolecules that participate in numerous biological processes such as cell adhesion, cell-to-cell communication, and the immune response. Furthermore, these bioactive compounds possess antioxidant, immunomodulatory, anticancer, antimicrobial, anti-inflammatory, and antiviral properties. Microalgal polysaccharides can be intracellular or extracellular (Exopolysaccharides EPS). Microalgal EPS are typically heteropolysaccharides with a high diversity of sugars (including xylose, rhamnose, and galactose) and often contain sulfated groups and uronic acids. The chemical characteristics of microalgal polysaccharides have a significant effect on their biological activity. The functional properties of polysaccharides vary based on their monosaccharide composition, molecular weight, sulfate and uronic acid content, linkage types, and distribution within the molecule (Li *et al*., 2020). The presence of rare monosaccharide constituents and oligosaccharides in microalgae, such as rhamnose or fucose, often confers biological activities. The presence of sulfate groups or acidic monosaccharides (such as uronic acids) also has a significant effect on their biological activity. For example, the increased net charge of the EPS from the alga *Porphyridium cruentum* (resulting from sulfate and acidic monosaccharides) has led to enhanced antitumor and antiviral activities (Levasseur *et al*., 2020; Prybylski *et al*., 2020; Kazachenko *et al*., 2021; Yi *et al*., 2021).

In addition, chain size, spatial conformation, and the presence of other chemical groups (e.g., amino acids, proteins, or nucleic acids) are factors influencing their properties. For example, the antioxidant potential of the *Porphyridium cruentum* exopolysaccharide is associated with its sulfate content (4.5%) and/or the presence of a 66 kDa glycoprotein. Furthermore, the antioxidant property of polysaccharides can be inversely proportional to their molecular weight; a study revealed that the 6.5 kDa fragment exhibited higher radical scavenging activity than the 256 kDa and 60.6 kDa fragments. In a study, the polysaccharide from *Porphyridium* sp. exhibited antibacterial activity against *Escherichia coli* (72%) and *Bacillus subtilis* (35% reduction). The authors attributed this capacity to the different cell wall composition and structure of the bacteria. Regarding the antiviral potential of microalgal polysaccharides, strains with higher sulfation and uronic acid levels showed greater activity. Uronic acid constituents, sulfate half-ester groups, and carboxyl groups confer anionic properties to exopolysaccharides, ultimately enabling them to act as protective agents against viruses (Costa *et al*., 2020; Alvarez *et al*., 2021; Madadi *et al*., 2021).

Prospects for economic production of polysaccharides from microalgae

According to various reports, the global market size for algae (including microalgae and macroalgae) in 2022 was estimated at approximately 1.5 to 2 billion dollars. The compound annual growth rate for this market is projected to be between 6% and 10% for the period 2023 to 2030 or 2023 to 2032. This growth rate indicates a positive outlook, driven by the increasing demand for natural, sustainable, and environmentally friendly products. However, the path to commercialization is confronted with numerous challenges. The first hurdle is the high cost of industrial-scale production, ranging from cultivation and harvesting to extraction and purification. A second challenge is the competition from cheaper alternative sources, such as vegetable oils or synthetic compounds. Furthermore, stringent regulations in the food and pharmaceutical safety sectors can impede the market entry process for new products (Colusse *et al*., 2021; Guo *et al*., 2021).

In the industrial-scale production of the primary feedstock, the type of cultivation system and production efficiency play a decisive role. Temperature and oxygen management, equipment sanitation, and biomass separation from the culture medium are among the key technical challenges in this industry. The choice between open systems (such as raceway ponds) and closed systems (tubular or flat-panel photobioreactors) directly impacts cost and efficiency. Open ponds, owing to their lower capital investment and ease of operation, are suitable for the mass production of low-value-added biomass (such as animal feed or biofertilizers); however, controlling cultivation conditions is difficult, and they are prone to contamination and fluctuations in product quality. In contrast, photobioreactors enable more precise control over growth conditions, increased biomass density, and the production of high-value compounds such as bioactive polysaccharides, although their capital and energy costs are higher (Parwani *et al.*, 2021; Chen *et al.*, 2025). An appropriate system design must maximize light and carbon dioxide utilization while minimizing mass transfer limitations. Furthermore, the scalability of these systems is critical; many technologies that are successful at the laboratory scale face challenges such as efficiency losses and increased costs at the industrial scale. Therefore, the choice of a cultivation system must be based on the type of target product, its economic value, and regional conditions (access to land, water, and energy). The optimal balance among capital investment, production efficiency, and product quality is the key to achieving economically viable and sustainable microalgal production (Kusmayadi *et al.*, 2021; Sathyanarayanan *et al.*, 2026). In terms of the technologies required for industrial production, the downstream processes of harvesting, drying, and extraction are determinants of the final cost following biomass production. Microalgal harvesting is considered the most cost-intensive step due to the minute size of the cells and low biomass concentration. Drying also impacts quality and cost; freeze-drying preserves the quality of sensitive compounds but is costly, whereas spray-drying is more economical but is accompanied by the risk of degrading bioactive metabolites. In the extraction stage, the use of green solvents such as ethanol or supercritical carbon dioxide, and novel technologies (ultrasound, microwave), can enhance process efficiency and sustainability. The biorefinery approach, in which multiple products (proteins, lipids, pigments) are extracted from a single biomass, is the primary key to reducing costs and increasing value addition. Conversely, significant economic opportunities also exist. The development of novel harvesting and extraction technologies, the application of biorefinery systems for the co-production of multiple products, and the utilization of wastewaters or low-cost carbon sources can reduce costs. Furthermore, increasing consumer awareness regarding health and environmental sustainability will bolster the market for these products. In summary, the economic future for producing bioactive compounds from microalgae is promising, but its realization will require technological innovation, supportive policies, and sustainable business models (Costa *et al.*, 2021).

A precise understanding of the target market, market size, competitive pricing, and the needs of end customers is essential for determining product profitability. Does the product in question have a position in the current market, or does it necessitate the creation of a new one? Determining the product's value-added and its differentiation from competing products is also important. The greatest economic challenge arises when microalgal products must compete with similar products produced from conventional or chemical sources. The utilization of microalgae as a source for specific active compounds is often not economically justifiable in comparison to conventional or synthetic alternatives, owing to the high costs of biomass production and purification (Moreira *et al.*, 2022) (Tables 1 and 2).

Table 1: Commercial production of microalgal pigments.

Production Capacity (ton/year)	Year Established	Location /Country	Company Name	Product	Microalgae
n.a.	1990	Kailua-Kona, Hawaii	Nutrex Hawaii	Hawaiian *Spirulina*, BioAstin Hawaiian Astaxanthin	*Spirulina*, *Haematococcs pluvialis*
18	2003	China	Jingzhou Natural Astaxanthin Inc.	Astaxanthin powder (1.5 to 3.0%), natural astaxanthin oleoresin, natural astaxanthin softgels (5 to 10%)	*Haematococcs pluvialis*
n.a.	n.a.	n.a.	Algatech	n.a.	*Haematococcus pluvialis*, *Phaeodactylum tricornutum*, *Porphyridium cruentum*, *Nannochloropsis* sp.
n.a.	1969	Osaka, Japan	Sun *Chlorella*	*Chlorella* tablets and drinks	*Chlorella*
Chlorella 1000, *Spirulina* 200	1967	Taiwan	Far East Microalgae Ind. Co., Ltd.	Organic *Spirulina* and *Chlorella* tablets, food supplements, and aquaculture feed	*Chlorella* and *Spirulina*
0.9	1995	China	Beijing Gingko Group	Astaxanthin	*Haematococcus pluvialis*
1.2	n.a.	China	Stone Forest Astaxanthin Biotech Co., Ltd.	Astaxanthin	*Haematococcus pluvialis*
0.6	n.a.	China	Yunnan Alphy Biotech Co., Ltd.	Astaxanthin	*Haematococcus pluvialis*
0.4	n.a.	China	Yunnan SGYJ Biotech Co., Ltd	Astaxanthin	*Haematococcus pluvialis*

Table 2: Market size and potential market for microalgal products (Patel *et al*., 2022).

Market Size (2009) (Million US$)	Potential Market (2020) (Million US$)	Sectors/ Market Fields
300	800	Colorants
30	300	Nutraceuticals
Developing	500	Pharmaceuticals/Chemicals
Emerging/rising	30	Cosmetics/Personal care

Currently, markets are segmented into three categories: 1. High-value products such as pigments and supplements; these are profitable and suitable for current investment. 2. Food and chemical products, for which competitiveness requires that production costs be lowered, a goal achievable within the next decade. 3. Biofuels; this sector is not currently profitable and requires further progress in cost reduction ().

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