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Microalgal Polysaccharides: A Review of Chemical Structure, Biological **Activities, and Prospects for Commercial Production**

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Abstract:

Microalgae have attracted significant attention from researchers in recent decades due to their rich bioactive compounds. Characteristics such as high growth rates, the ability to be cultivated in diverse environments, and the lack of direct competition with human food sources make them an attractive option for sustainable production. However, achieving economic and commercial viability for microalgal-derived products requires a thorough examination of biological, technological, and economic factors. This review explores the structural features, biological activities, and economic aspects of microalgalderived polysaccharides. Polysaccharides extracted from microalgae exhibit considerable differentiation from land plant polysaccharides due to the heteropolymeric nature of their constituent monosaccharides and their high sulfate content. Moreover, numerous studies have shown that the diversity and specificity of the chemical structures of these compounds result in a range of bioactivities, including antibacterial, antiviral, and anticancer properties. Despite the significant biological advantages of these compounds, the largescale and commercial production of microalgal polysaccharides faces technical and economic challenges that must be addressed.

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1.1. 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, emergence of drug resistance and environmental pollution have substantial pressure on traditional sources 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). Microalgae, as efficient biological factories, are capable of producing a unique suite of metabolites polysaccharides, including 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 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).

Microalgae, unicellular as photoautotrophic organisms. offer unparalleled potential address environmental and industrial challenges. Among the bioactive metabolites produced microalgae, their polysaccharide derivatives characterized bv 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).

2.1. Structural Characteristics of Microalgal Polysaccharides

Polysaccharides are polymers composed of long chains of monosaccharides and are classified homopolysaccharides into single (composed of a type monosaccharide) heteropolysaccharides (containing two or more types of monomeric units). The structure composition of and 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, orthomethylated arabinose. mannose. sugars, and acidic residues of glucuronic acid and galacturonic acid, may also be components of the polysaccharides found in microalgae and cyanobacteria. Glucose is the most commonly encountered sugar. Fructose is generally not found in microalgal exopolysaccharides but is often component of exopolysaccharides produced by cyanobacteria (Morales-Jiménez et al., 2020 Rachidi 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 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 polysaccharides intracellular and polysaccharides extracellular (Medina-Cabrera et al., 2020)

3.1. Bioactivities of Microalgal Polysaccharides and Their Relationship with Chemical Structure

Polysaccharides natural are macromolecules participate that 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 properties. antiviral Microalgal polysaccharides can be intracellular or extracellular (Exopolysaccharides EPS). **EPS** Microalgal are typically heteropolysaccharides with a high diversity of sugars (including xylose, rhamnose, and galactose) and often contain sulfated groups chemical and uronic acids. The characteristics of microalgal polysaccharides have a significant effect on their biological activity. The functional properties of polysaccharides vary based on monosaccharide their composition, molecular weight, sulfate and uronic acid content, linkage types, and distribution within the molecule (Li et al., 2020). The presence of rare monosaccharide and oligosaccharides constituents 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).

spatial In addition. chain size, conformation, and the presence of other (e.g., chemical groups amino acids, proteins, or nucleic acids) are factors influencing their properties. For example, potential antioxidant 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 inversely proportional to their molecular weight; a study revealed that the 6.5 kDa exhibited higher fragment 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 composition and structure of the bacteria. Regarding the antiviral potential 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).

4.1. 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 sustainable, natural, for and environmentally friendly products. However, the path to commercialization is confronted with numerous challenges. The first hurdle is the high cost of industrialscale production, ranging from cultivation extraction harvesting to 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 (Guo et al., 2021; Colusse 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 flatpanel 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 difficult, and they are prone to contamination and fluctuations in product quality. In contrast, photobioreactors enable precise control over 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). 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).

In terms of the technologies required for industrial production, the downstream of harvesting, drying, processes extraction are determinants of the final cost following biomass production. Microalgal harvesting is considered the most costintensive 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 technologies (ultrasound, microwave), can enhance process sustainability. efficiency and The biorefinery approach, in which multiple products (proteins, lipids, pigments) are extracted from a single biomass, is the primary key to reducing costs 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, sustainable business models (Costa et al., 2021).

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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).

Table 1: Commercial production of microalgal pigments

	1 abie	1: Commerci	ial production of mi	icroalgal pigments	
Production Capacity (ton/year)	Year Established	Location/ Country	Company Name	Product	Microalgae
n.a.	1990	Kailua- Kona, Hawaii	Nutrex Hawaii	Hawaiian <i>Spirulina</i> , 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 <i>Spirulina</i> and <i>Chlorella</i> 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

Tuble 2: Warket size and potential market for interoalgul products (1 ator et al., 2022)						
Market Size (2009)	Potential Market (2020)	Sectors/Market Fields				
(Million US\$)	(Million US\$)					
300	800	Colorants				
30	300	Nutraceuticals				
Developing	500	Pharmaceuticals/Chemicals				
Emerging/rising	30	Cosmetics/Personal care				

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

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 (Patel et al., 2022).

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