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MARINE MICROALGAE AND DIATOMS: BIOTECHNOLOGICAL APPLICATIONS AND ENVIRONMENTAL SIGNIFICANCE

M. FAIROZ BASHA¹, DAVEEDU.T¹ AND K.V.L. SHRIKANYA RAO^{1*}

¹Department of Biotechnology, Vikrama Simhapuri University, Kakatur, Nellore-524 324,
Andhra Pradesh, India

*Corresponding Author: Dr. KVL Shrikanya Rao: E Mail: fairozbasham@vsu.ac.in

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ABSTRACT

Marine microalgae, particularly diatoms, represent a significant group of photosynthetic organisms contributing approximately 50% of marine primary production. These unicellular eukaryotes possess ornate silicified shells and demonstrate exceptional potential for biotechnological applications. Microalgae produce diverse high-value compounds including single-cell proteins (lectins), pigments (xanthophylls), bioactive compounds (phlorotannins, fatty acids, polysaccharides, peptides, terpenes), and pharmaceuticals with antimicrobial properties. Due to the global emergence of antibiotic-resistant pathogens, microalgae-derived compounds offer promising alternatives for pharmaceutical, cosmetic, nutritional supplement, and biofuel industries. Advanced biotechnological processes enable enhanced yields of specialized bioproducts including organic acids, alcohols, and biomaterials. Diatoms serve dual roles in industrial biotechnology for recombinant protein production and as rich sources of natural lipids and carotenoids, while supporting cellular rejuvenation and immune responses. This review examines fatty acid metabolism, biosynthetic pathways, and catalytic enzymes involved in bioactive compound production.

**Keywords: Microalgae, Diatoms, Biotechnology, Pharmaceuticals, Pigments,
Environmental Applications**

1. INTRODUCTION

Microalgae, predominantly diatoms (Bacillariophyceae), are ubiquitous eukaryotic organisms inhabiting oceanic photic zones where light penetration supports photosynthesis. These microscopic organisms, characterized by intricate silicified shells, demonstrate remarkable morphological diversity and occupy marine ecosystems globally. As photoautotrophs, diatoms convert solar energy into ATP while synthesizing organic compounds from CO₂ and water, contributing substantially to global oxygen production through photosynthesis [1]. Diatoms exhibit several advantageous characteristics for biotechnological applications: (i) ubiquitous distribution with excellent environmental adaptability, (ii) rapid reproduction and biomass accumulation within hours, (iii) controlled growth facilitated by silica requirements, and (iv) profitable biomass utilization [2]. The increasing global demand for sustainable protein sources has positioned aquaculture as the fastest-growing food sector, requiring omega-3 long-chain polyunsaturated fatty acids (LC-PUFAs), including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), essential for marine fish nutrition and stress tolerance [3]. Microalgal lipids comprise polar and non-polar categories. Non-polar

lipids include sterols, acylglycerols, free fatty acids, steryl esters, and waxes, while polar lipids encompass phosphoglycerides and glycolipids. These lipids serve structural functions in cellular membranes and energy storage. Third-generation biofuels derived from marine biomass overcome limitations associated with first and second-generation biofuels by eliminating competition with food crops and reducing land requirements [4].

Industrial production

The worldwide demand for carotenoids market by type (astaxanthin, betacarotene, lutein, lycopene, canthaxanthin, and zeaxanthin), application (feed, food and beverages, dietary supplements, cosmetics and pharmaceuticals) global wise forecast. Biotechnological sources of carotenoids account for a growing proportion; As a result, demand for β -carotene, xanthophylls like astaxanthin, canthaxanthin, and lutein has increased [5]. *Dunaliella*, *Chlorella*, *Haematococcus* spp., *Muriellopsis*, and *Chlamydomonas*, all members of the Chlorophyceae family, are the most significant source for the microalgae [6]. The majority of industries concentrate on and consider of their whole carotenoids concentrated in an accumulating technique as an essential component of their biomass,

which may provide an economical standard for chemical synthesis [7]. *Dunaliella* has the highest concentration of 9-cis β -carotene in natural sources examined to date using improved methods of study [8, 9], with levels up to 100 g/kgDW [10, 11]. However, *Muriellopsis* sp. has been used to produce lutein for commercial purposes because of its high lutein contents (up to 35 mg L⁻¹) and development.

2. ENVIRONMENTAL PARAMETERS AND CULTIVATION

2.1 Critical Growth Factors: Microalgal cultivation requires optimization of multiple environmental parameters including light intensity, temperature, pH, salinity, and dissolved oxygen levels. **Light Requirements:** Optimal light intensity ranges from 100-200 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (approximately 5-10% of full sunlight). Blue and redlight spectra prove most effective for photosynthesis. Light/dark cycles enable cells to synthesize and accumulate photosynthetic components during illumination while conducting essential metabolic processes during dark periods [16]. **Temperature Tolerance:** Marine microalgae tolerate temperatures from 1.9°C to 31°C, with optimal growth occurring between 15-25°C. Temperature variations affect frustule ornamentation and cellular morphology [17]. **pH and Salinity:** pH levels

significantly influence chemical and biological processes. Natural waters typically exhibit alkaline conditions due to carbonate presence. Optimal salinity ranges between 20-24 g L⁻¹, with many species thriving in slightly diluted seawater. Salinity stress increases saturated fatty acid content and overall lipid production [18]. **Dissolved Oxygen:** Adequate gas exchange prevents thermal stratification and ensures uniform light and nutrient distribution. CO₂ supplementation (1% v/v) overcomes atmospheric limitations and maintains pH stability through CO₂/HCO₃⁻ buffering.

2.2 Biodiversity and Taxonomic Significance: Microalgal diversity encompasses numerous taxonomic groups with varying biomass production capabilities. Diatoms and dinoflagellates produce short-lived blooms, while picoeukaryotic species like *Emiliania huxleyi* receive extensive research attention. Stramenopiles, characterized by flagellated cells with unequal flagella, include important groups such as pelagophyceae and dictyophyceae. Harmful algal bloom species like *Aureococcus anophagefferens* demonstrate the ecological impact of microalgal populations [19].

3. BIOCHEMICAL COMPONENTS AND BIOACTIVE COMPOUNDS

The list of bioactive compounds production and their source is shown in **Table 1**.

Table 1: The list of bioactive compounds production and their source

Microalgae Name	Dunaliella salina	Haematococcus pluvialis	Chlorella vulgaris	Coelastrella striolata var. multistriata	Scenedesmus almeriensis
Active compound	β -carotene [12]	Lutein, Cantaxanthin [12], Astaxanthin [13]	Cantaxanthin, astaxanthin [12]	β -carotene, Canthaxanthin, astaxanthin [14]	β -carotene, Lutein [15]

3.1 Primary Metabolites

Proteins: Microalgal protein content ranges from 42-70% dry weight in cyanobacteria and 58% in *Chlorella vulgaris*. These proteins contain essential amino acids comparable to traditional

sources including eggs and soy. However, applications remain limited due to chlorophyll-induced color changes and rigid cell walls affecting digestibility.

Carbohydrates: Structural and metabolic carbohydrates include monosaccharides, oligosaccharides, and polysaccharides. Different microalgal groups produce specific polysaccharide types: cyanophytes synthesize semi-amylopectin, Chlorophyta produce starch (amylose and amylopectin), Rhodophyta generate floridean starch, and diatoms create chrysolaminarin. Storage capacity reaches 30-80% dry weight under nutrient-limiting conditions.

Lipids: The most commercially significant components, lipids comprise 20-50% dry weight in numerous species. Neutral lipids

(triacylglycerols) accumulate under stress conditions, while polar lipids maintain membrane integrity. Microalgae produce diverse C16-C18 fatty acids with various degrees of saturation and omega fatty acid profiles.

3.2 High-Value Natural Products Pigments: Microalgae produce commercially valuable carotenoids including β -carotene, astaxanthin, lutein, and fucoxanthin. *Dunaliella salina* generates approximately 1200 tons of β -carotene annually, while *Haematococcus pluvialis* produces astaxanthin valued at \$140 USD per kilogram. These compounds demonstrate superior antioxidant properties compared to synthetic alternatives.

Polyunsaturated Fatty Acids (PUFAs): Microalgae-derived PUFAs offer advantages over fish oils by containing lower levels of contaminants including mercury, dioxins, and polychlorinated biphenyls. DHA production through heterotrophic cultivation of *Cryptothecodinium cohnii* and *Schizochytrium limacinum* supports a \$9

billion global market for infant formula applications.

4. EXTRACTION AND PURIFICATION TECHNOLOGIES

4.1 Bioactive Compound Recovery: Lipid Extraction: Cell disruption through physical, chemical, or biological pretreatment facilitates lipid recovery. Solvent-based extraction using chloroform-methanol or hexane-isopropyl alcohol, combined with advanced techniques including supercritical fluid extraction, ultrasound-assisted extraction, and enzyme-assisted extraction, enhances yield and quality Polysaccharide Purification: Traditional hot water extraction has been supplemented by microwave-assisted, ultrasonic-assisted, and enzyme-assisted methods. Purification requires removal of low molecular weight compounds, lipids, and pigments through membrane separation, ion-exchange, size-exclusion, and affinity chromatography. Peptide Production: Enzymatic hydrolysis using proteases (papain, alcalase, trypsin) provides optimal bioactive peptide generation. Purification employs size-exclusion, reversed-phase, and ion-exchange chromatography, with RP-HPLC offering superior separation efficiency.

5. ECOLOGICAL IMPORTANCE AND ENVIRONMENTAL APPLICATIONS

5.1 Marine Ecosystem Contributions: Diatoms contribute 20-40% of global oxygen production and support marine food webs from microorganisms to commercially important fish species. Their silicified frustules preserve well in sediments, serving as paleoenvironmental indicators and fossil research tools. Seasonal diatom blooms sustain marine biodiversity in global oceanic systems.

5.2 Environmental Stress Response

Diatoms respond to various environmental stressors including trace metal contamination, organic loading, physical stress, and pH variations. Trace metal stress activates detoxification mechanisms through phytochelatin and glutathione production. Multiple stress conditions provide insights into adaptation mechanisms and bioremediation potential [20].

5.3 Biotechnological Applications: Diatom frustule structures inspire nanotechnology applications due to their intricate pore arrangements ranging from nano- to micrometer scales. Silaffins, silacidins, and long-chain polyamines (LCPAs) regulate frustule formation, offering templates for materials science applications [21].

6. INDUSTRIAL PRODUCTION AND COMMERCIAL APPLICATIONS

6.1 Cultivation Systems

Commercial microalgae production utilizes open pond systems and closed photobioreactors. Open raceways (2-10 m width, 15-30 cm depth) provide cost-effective cultivation but limited environmental control. Closed systems offer contamination protection and precise parameter control, supporting higher-value product cultivation.

6.2 Pigment Production Optimization
β-Carotene: *Dunaliella salina* cultivation at 25°C generates 80 g m⁻³ d⁻¹ biomass with 1.25 mg L⁻¹ β-carotene recovery. Continuous biphasic bioreactors achieve 2.45 mg m⁻³ d⁻¹ production rates. **Lutein:** *Scenedesmus almeriensis* produces 4.9 mg L⁻¹ d⁻¹ lutein under optimal conditions (30°C, pH 8.0). Nitrogen availability, temperature, irradiation, and pH significantly influence lutein accumulation. **Astaxanthin:** *Haematococcus pluvialis* employs two-stage cultivation: green biomass production followed by astaxanthin induction under stress conditions. Optimal iron supplementation (18 μmol L⁻¹ Fe²⁺-EDTA) enhances astaxanthin synthesis to 30.7 mg g⁻¹.

6.3 Market Applications

Microalgal carotenoids serve multiple industries including food coloring, dietary supplements, cosmetics, and pharmaceuticals. Global carotenoid demand encompasses astaxanthin, β-carotene, lutein, lycopene,

canthaxanthin, and zeaxanthin across feed, food and beverage, dietary supplement, cosmetic, and pharmaceutical applications.

7. HEALTH BENEFITS AND THERAPEUTIC APPLICATIONS

Industrial applications

The main areas of actual or potential industrial application, in terms of carotenoids from microalgal sources, food consumption and health that class of compounds is in high demand on the markets because of its antioxidant qualities, which are presently its main value in the microalgae biomass field. Carotenoids derived from microalgal sources have been the subject of numerous research papers [22].

Anti-Oxidant, Anti-Inflammatory and Anti-Mutagenic Activities

Microalgae and cyanobacteria pigments have been shown to have strong anti-oxidant properties in animal studies, according to previous research. A important factor in the cardiovascular disease prevention is the circulation of antioxidants. C-vitamin and phenolic plasmatic concentrations are correlated with C-reactive proteins, anti-oxidized low-density lipoprotein, and cholesterol concentrations [23, 24]. Compared to other carotenoids including vitamin C and E, astaxanthin is a more powerful antioxidant. A non-vitamin is astaxanthin [25, 26]. Even

though it contains antioxidants and membrane-preserving abilities, astaxanthin has such a large number of possibilities for the cancer treatment and prevention, metabolic syndrome, gastrointestinal, rheumatoid arthritis, diabetes, diabetic nephropathy, liver, and neurodegenerative diseases that are chronically inflammatory. It may also be advantageous for other inflammatory diseases in addition to the cardiovascular system. According to the findings, nonprovitamin. Retinoids might be replaced with and ought to be taken into consideration as a viable method of enhancing skin condition. However, it is necessary to use human trials to confirm the numerous examples of health advantages brought about by Asta [27].

Anti-cancer

Given that dietary carotene intake is limited and blood carotenoid levels are within normal ranges, epidemiologic studies have shown an unusual relationship between cancer incidence and these factors. For instance, studies focused on pigments extracted of the marine diatom *Odontella aurita* that shown an anti-proliferative effects on culturing of bronchopulmonary and epithelial cells whenever extracted were introduced to cell conditions [28, 29]. The immune system's cells produce intercellular communications work very well, therefore they might be

impacted by how carotenoids manage DNA. As a result that several microalgae pigments inhibit or inhibit the activity of drug efflux pumps, they may be useful in restoring reverse-ing MDR in cancer cells or drug sensitivity.

Anti-Allergic

The results of some outstanding mice experiment clearly showed that carotenoids can significantly lower the production of immunoglobulin E. For instance, animals sensitive to ovalbumine showed a decrease in food allergy [30]. Another research found that combining vitamin E and β -carotene had a similar impact on splenocytes [31]. A rodent mast cell model was recently used to demonstrate the anti-allergic activity of fuco [32, 33].

Anti-obesity

Obesity risk is reduced by fucoxanthin and its metabolite fucoxanthinol [34-36]. Actually, the gastrointestinal lumen's lipase activity is reduced by these two marine carotenoids, which also prevents the absorption of triglycerides [36]. Fucoxanthin affects a number of enzymes involved in fat metabolism during normal metabolism, increasing the release of energy from fat and resulting in an increase in thermogenesis [37].

Uses for food and feed supplements at earlier larval species:

The production of carotenoids from microalgae through a microbiological process requires further research and development in the field of alimentary aquaculture, which is increasingly and especially focused at improving consumer awareness of environmental and health concerns [7]. The use of natural pigments is now widespread. A great example of this use of *Dunaliella spp* to produce large quantities of carotenoids with a preservation purpose [13].

Industrial production

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8. FUTURE PERSPECTIVES AND CHALLENGES

Genome engineering techniques enable metabolic pathway optimization for enhanced bioactive compound production. Advanced cultivation systems, harvesting technologies, and downstream processing methods continue improving production efficiency and cost-effectiveness. Environmental Applications. Diatoms offer potential solutions for environmental remediation, including heavy metal removal and coastal pollution control. Their role as primary producers supports ecosystem restoration and climate change mitigation through carbon sequestration. However, critical research/ advanced studies like comprehensive genomic, proteomic, and metabolomic databases are need to be setup. Similarly scalable cultivation and harvesting technologies need to be improved finally cost-effective extraction and purification methods,

and regulatory frameworks supporting commercial development is to be come into the force.

CONCLUSION

Microalgae, particularly diatoms, represent a sustainable biotechnological resource with diverse applications spanning pharmaceuticals, nutraceuticals, cosmetics, and biofuels. Their exceptional biochemical diversity, rapid growth rates, and environmental adaptability position them as key organisms for addressing global challenges including food security, antibiotic resistance, and climate change. Successful commercial implementation requires continued advancement in cultivation technologies, extraction methods, and regulatory frameworks. The integration of genetic engineering, systems biology, and process optimization will unlock the full potential of microalgal biotechnology. Diatoms contribute fundamentally to marine ecosystems as primary producers, supporting food webs from microorganisms to marine mammals. Their silicified cell walls provide valuable environmental support, while their photosynthetic activity generates 20-40% of global oxygen production. Climate change sensitivity makes diatoms as important indicators for environmental monitoring and ecosystem management.

Future research should focus on developing sustainable production systems, expanding bioactive compound applications, and implementing environmental remediation strategies. The convergence of academic research, industrial development, and policy support will determine the success of microalgal biotechnology in addressing 21st-century challenges while maintaining marine ecosystem integrity.

Conflict of Interest: None

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