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Biotechnological Applications of Marine Microalgae from Biofuels to Biopharmaceuticals

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ABSTRACT

Marine microalgae represent a versatile and sustainable resource for biotechnology owing to their rapid growth, high metabolic plasticity, and ability to synthesize diverse bioactive compounds. This review examines the state-of-the-art in the biotechnological applications of marine microalgae, focusing on three major arenas: (1) biofuel and energy production, (2) high-value bioproducts for food, nutraceutical, pharmaceutical and cosmetic uses, and (3) environmental applications including bioremediation and waste-to-worth valorization. The cultivation strategies, strain improvement, downstream processing, techno-economic and life-cycle considerations, and regulatory and commercial challenges. Emerging trends such as synthetic biology, co-cultivation systems, integrated biorefineries, and circular economy models are highlighted. Finally, the present perspectives on how marine microalgae can contribute to global sustainability goals and identify important future research directions for unlocking their full potential.

Keywords: *marine microalgae; biotechnology; biofuels; biopharmaceuticals; bioremediation; biorefinery.*

1. Introduction

Marine microalgae are photosynthetic microorganisms that play a vital role in global ecosystems and biogeochemical cycles. They convert sunlight, carbon dioxide, and inorganic nutrients into valuable organic matter, contributing significantly to primary production and oxygen generation. In recent years, marine microalgae have emerged as promising renewable resources for biotechnology due to their high photosynthetic efficiency, rapid growth, and ability to thrive in diverse and extreme marine environments. Unlike terrestrial crops, they can be cultivated in non-arable lands and saline waters, offering sustainable alternatives for bioresource production without competing with agriculture [1]. The increasing demand for sustainable raw materials has accelerated research into the biotechnological potential of marine microalgae. These organisms are rich in lipids, proteins, polysaccharides, pigments, and bioactive metabolites, making them useful in multiple sectors including energy, food, pharmaceuticals, cosmetics, and environmental management. Microalgal lipids can be converted into biodiesel, while their proteins and pigments have applications in nutrition and health. Moreover, the unique secondary metabolites produced by marine microalgae—such as carotenoids, polyunsaturated fatty acids (PUFAs), and sulfated polysaccharides—possess antioxidant, anti-inflammatory, antimicrobial, and anticancer properties, establishing them as potential sources for new drug leads and therapeutic agents [2].

Recent advancements in cultivation systems, metabolic engineering, and biorefinery approaches have enhanced the commercial viability of marine microalgae. Integrated biorefinery models allow the extraction of multiple value-added products from a single biomass source, maximizing economic returns and minimizing waste, coupling microalgae cultivation with carbon capture and wastewater treatment supports global sustainability goals by reducing greenhouse gas emissions and recycling nutrients. Such combined benefits highlight the dual role of marine microalgae in both environmental remediation and industrial innovation [3], these advantages, challenges remain in scaling up production, optimizing harvesting, and reducing processing costs. The interdisciplinary research—integrating biotechnology, marine biology, chemical engineering, and environmental sciences—is essential to unlock the full potential of these microscopic powerhouses. This review aims to explore the current state and future prospects of marine microalgae in biotechnology, emphasizing their applications from renewable biofuels to high-value biopharmaceuticals [4].

2. Cultivation and Strain Improvement

2.1 Cultivation Systems

Marine microalgae can be grown in open pond systems or closed photobioreactors (PBRs). Closed systems offer better control over environmental parameters (light, temperature, salinity, nutrients), lower contamination risk, and often higher productivity per unit area. However, they also incur higher capital and operational costs.

Optimising light harvesting, mixing, gas exchange (CO_2 supply, O_2 removal), and nutrient delivery are important for maximizing productivity [5]. Radiative and scattering properties of microalgae are dynamic and change during growth phases, influencing light availability and culture design.

2.2 Strain Selection and Genetic Improvement

Selecting marine microalgal strains with desirable traits (high lipid content, high pigment yield, robust growth under high salinity/temperature) is critical. Advances in omics (genomics, transcriptomics, proteomics, metabolomics) enable system-level understanding of microalgal metabolism. Genetic engineering and synthetic biology are increasingly used to enhance production of target molecules, redirect metabolic fluxes, and adapt strains to industrial conditions. For example, engineered microalgae have been developed to accumulate higher amounts of polyhydroxyalkanoates (PHAs) or to degrade plastics via heterologous enzyme expression [6].

2.3 Co-Cultivation and Consortia

Recent work shows that microalgae grown in co-cultures with bacteria, fungi, or other algae can enhance nutrient recycling, improve biomass productivity, and trigger novel metabolite synthesis. For instance, *Nannochloropsis* sp. co-cultured with other microorganisms demonstrated improved lipid accumulation and nutrient removal efficiency [7].

2.4 Downstream Processing and Biorefinery Model

After cultivation, harvesting, dewatering, extraction, purification, and product formulation pose major technological challenges. Efficient downstream processes are required to make microalgal products economically viable. Novel techniques such as supercritical CO_2 extraction, membrane filtration, and enzymatic cell disruption are being developed. Integration of downstream processing into a biorefinery approach—where biomass is fractionated into multiple product streams (biofuels, nutraceuticals, feed, fertilizer)—is considered essential to reduce processing costs and increase overall value [8].

Table 1: Marine Microalgae, Their Products, Applications, and Cultivation Notes

Microalga Species	Main Bioactive Compounds	Applications	Cultivation Notes / Challenges
Nannochloropsis	EPA, Lipids	Biofuels, Nutritional supplements, Aquaculture feed	High lipid content, scalable in photobioreactors
Haematococcus pluvialis	Astaxanthin	Antioxidants, Cosmetics, Pharmaceuticals	Sensitive to light stress; high-value compound
Spirulina / Arthrospira	Phycocyanin, Proteins	Nutraceuticals, Food colorants, Antioxidants	Robust growth, open pond cultivation possible
Phaeodactylum tricornutum	EPA, Fucoxanthin	Nutraceuticals, Pharmaceuticals, Biofuels	Requires controlled photobioreactor conditions
Chlorella vulgaris	Proteins, Vitamins, Carotenoids	Food supplements, Biofertilizers, Wastewater remediation	Fast-growing, tolerates variable conditions
Dunaliella salina	β-Carotene, Glycerol	Cosmetics, Nutraceuticals	Halotolerant, thrives in high-salinity environments
Isochrysis galbana	DHA, Lipids	Aquaculture feed, Nutraceuticals	Low biomass productivity; co-cultivation improves yields
Tetraselmis suecica	Proteins, Lipids, Carotenoids	Biofuels, Aquaculture feed, Nutraceuticals	High growth rate; robust under varying light regimes

3. Biofuel and Energy Applications

3.1 Lipid-Based Biofuels

Microalgae are a promising source of biodiesel because many species accumulate large amounts of lipids (triacylglycerols, TAGs). Lipids can be converted via transesterification into biodiesel. Marine microalgae offer advantages over terrestrial oilseed crops by higher areal productivity and no requirement for fertile land [9], these advantages, commercial biodiesel production from marine microalgae remains limited due to high cultivation and harvesting costs, low extraction efficiencies, and competition with cheaper feedstocks [10].

3.2 Bioethanol, Biohydrogen and Methane

Beyond biodiesel, microalgal biomass carbohydrates can be fermented into bioethanol or anaerobically digested into methane. Photobiological hydrogen production is also explored using microalgae [11].

3.3 Integration with Wastewater Treatment

Cultivating marine microalgae in wastewater or industrial effluents allows nutrient removal (nitrogen, phosphorus) while generating biomass for biofuel production—this "waste-to-biofuel" concept helps lower costs and enhances sustainability [12].

3.4 Techno-Economic and Life-Cycle Considerations

Important hurdles for commercial microalgal biofuels include energy input vs. output ratio, harvesting/dewatering costs, lipid extraction yield, and market price of the fuel. Life-Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) are increasingly used to evaluate viability [13].

4. High-Value Bioproducts: Nutraceuticals, Pharmaceuticals & Cosmetics

4.1 Polyunsaturated Fatty Acids (PUFAs) and Lipids

Marine microalgae produce essential PUFAs (e.g., EPA, DHA), which are valuable for human health (cardiovascular, neuroprotective). These compounds are increasingly sourced from microalgae rather than fish oil, offering sustainability and purity benefits [14].

4.2 Pigments and Carotenoids

Microalgal pigments (e.g., astaxanthin, β-carotene, fucoxanthin, phycobiliproteins) display antioxidant, anti-inflammatory, and photoprotective activities. These make them useful for nutraceuticals, functional foods and cosmetics [15].

4.3 Polysaccharides and Glycoconjugates

Algal polysaccharides and glycoproteins exhibit bioactivities including anticoagulant, antiviral, immunomodulatory, and wound-healing properties. These compounds hold promise for pharmaceutical and biomedical applications [16].

4.4 Proteins, Peptides and Microalgal Biomass

Microalgae provide high-quality proteins, bioactive peptides, vitamins and other micronutrients. Their biomass and extracts can be used in functional foods, dietary supplements and animal feed [17].

4.5 Cosmetic and Skincare Applications

Marine microalgae derived ingredients (e.g., MAAs – mycosporine-like amino acids, microalgal extracts) show photoprotective, anti-ageing and skin-moisturising effects, making them appealing for cosmeceutical formulation [18].

5. Environmental and Other Industrial Applications

5.1 Bioremediation and Waste-Valorization

Marine microalgae can remediate pollutants via biosorption, bioaccumulation and biodegradation pathways. They can treat heavy metals, dyes, pharmaceuticals, nutrients and even plastics [19].

5.2 Carbon Sequestration and CO_2 Mitigation

Microalgae fix CO_2 rapidly during photosynthesis and can be integrated into carbon capture systems, thus contributing to climate change mitigation [20].

5.3 Bioplastics and Bio-materials

Microalgal biomass can be used to produce bioplastics (e.g., PHB) or as reinforcement in composite materials, thus offering a sustainable alternative to petroleum-based plastics [21].

5.4 Animal Feed and Aquaculture

Marine microalgae are used as feed or feed supplements (e.g., in aquaculture), providing essential nutrients, enhancing growth, immune response and coloration in farmed species [22].

6. Challenges and Bottlenecks

The tremendous potential, marine microalgal biotechnology faces several significant challenges. Cultivation and harvesting, particularly at large scales, remain expensive, while downstream processing suffers from inefficiencies and high energy demands during dewatering, extraction, and purification. Strain instability and difficulties in scaling up further limit productivity, as laboratory-level yields often fall short in commercial systems. Additionally, regulatory barriers, safety concerns, and market acceptance pose challenges, especially for food and pharmaceutical applications. Finally, microalgae face strong competition from established microbial and plant-based production platforms, requiring improvements in both yield and cost-effectiveness to become commercially viable. Future developments in marine microalgal biotechnology are being shaped by several emerging trends. Advances in synthetic biology, metabolic engineering, gene editing, and adaptive laboratory evolution are enabling the development of microalgal strains with higher yields of target compounds [23]. The concept of integrated biorefineries is gaining momentum, where microalgae are used to co-produce biofuels, high-value bioproducts, and environmental remediation services, often leveraging waste streams to improve sustainability and economic feasibility. Co-cultivation strategies and consortia engineering, involving bacteria or fungi, are being explored to enhance growth, productivity, and metabolic outputs. At the same time, digitalization, automation, and AI-based process optimization—including digital twin modeling of cultivation systems—offer opportunities to reduce costs and improve operational control. Supportive policy frameworks, streamlined regulatory approval processes, and strategies to boost consumer acceptance are essential to transition microalgal innovations from the lab to the market. Collectively, these advancements contribute to global sustainability goals, supporting multiple UN Sustainable Development Goals such as SDG 2 (Zero Hunger through biomass and feed production), SDG 3 (Good Health via nutraceuticals and pharmaceuticals), SDG 12 (Responsible Production), and SDG 13 (Climate Action through CO_2 fixation).

7. Conclusion

Marine microalgae are emerging as a pivotal resource for biotechnology, spanning applications from renewable biofuels to high-value pharmaceuticals and environmental remediation. Their unique combination of rapid growth, metabolic flexibility and minimal competition for land or freshwater make them particularly attractive in the context of sustainability and the bio-economy. Nevertheless, to fully realise their promise, industry-scale implementation must overcome challenges in cultivation, harvesting, downstream processing, strain engineering, and regulatory frameworks. Advances in synthetic biology, biorefinery concepts, automation, and circular economy models hold the important to unlocking microalgal biotechnology's potential. With coherent collaboration among scientists, engineers, policy-makers and industry stakeholders, marine microalgae may become integral to future biotechnological innovation and global sustainability efforts.

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