Microalgal Biorefineries: Co-producing Biofuels, Proteins, and High-Value Carotenoids

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Abstract: *The increasing demand for sustainable energy, nutritious food, and bio-based chemicals has accelerated the development of integrated microalgal biorefineries as an environmentally friendly alternative to fossil-based industries. Microalgae possess exceptional photosynthetic efficiency, rapid growth rates, and the ability to accumulate a wide spectrum of commercially valuable biomolecules, including lipids, carbohydrates, proteins, pigments, antioxidants, vitamins, and polyunsaturated fatty acids, making them one of the most versatile renewable feedstocks for the emerging bioeconomy.*

Unlike conventional single-product processing, the microalgal biorefinery concept aims to maximize biomass utilization through the simultaneous production of biofuels, protein-rich ingredients, and high-value compounds such as carotenoids, thereby improving economic feasibility and minimizing waste generation. Such integrated processing strategies support the principles of circular bioeconomy by coupling renewable energy production with the manufacture of nutraceuticals, pharmaceuticals, animal feed, cosmetics, and specialty chemicals.

Microalgal biomass can be converted into multiple forms of renewable energy, including biodiesel, bioethanol, biogas, and biohydrogen, while residual biomass serves as an excellent source of proteins and bioactive metabolites with significant industrial applications. Furthermore, commercially important carotenoids such as astaxanthin, β-carotene, lutein, and fucoxanthin exhibit potent antioxidant, anti-inflammatory, and anticancer activities, contributing substantially to the overall economic value of microalgal biorefineries. Recent advances in strain improvement, metabolic engineering, cultivation technologies, harvesting methods, downstream processing, and integrated extraction techniques have significantly enhanced biomass productivity and product recovery efficiencies. However, challenges including high cultivation costs, energy-intensive harvesting, scalability limitations, contamination risks, and process integration continue to restrict large-scale commercialization.

Keywords: *Microalgae; Biorefinery; Biodiesel; Bioethanol; Biogas; Biohydrogen; Carotenoids; Proteins; Circular Bioeconomy; Renewable Energy.*

1. Introduction

The rapid depletion of fossil fuel reserves, increasing greenhouse gas emissions, and growing global demand for sustainable food and energy have intensified the search for renewable biological resources capable of supporting future bio-based industries [1,2]. Conventional petroleum-derived fuels have significantly contributed to economic development but are associated with severe environmental consequences, including climate change, air pollution, and ecological degradation [5,6]. Simultaneously, increasing global population and industrialization have placed unprecedented pressure on agricultural land, freshwater resources, and food production systems, necessitating innovative approaches that simultaneously address energy security, environmental protection, and sustainable resource utilization [7, 10].

Early research on microalgae primarily focused on single-product applications such as biodiesel production because many species accumulate substantial quantities of triacylglycerols under nutrient-stressed conditions [26, 27]. However, economic assessments revealed that producing only biofuel from microalgae remains financially challenging due to the high costs associated with cultivation, harvesting, drying, cell disruption, and downstream processing [30, 31]. Consequently, researchers introduced the concept of integrated microalgal biorefineries, where every biomass fraction is efficiently utilized to generate multiple products with different market values, thereby improving process economics and minimizing waste generation [32, 33, 35].

The biorefinery concept follows principles similar to petroleum refineries, where a single feedstock is fractionated into multiple valuable products rather than producing only one commodity [36,37]. In microalgal biorefineries, lipids are converted into biodiesel or aviation biofuels, carbohydrates are processed into bioethanol or biogas, proteins are recovered for food and feed applications, while pigments and carotenoids are extracted for nutraceutical, pharmaceutical, and cosmetic industries [42]. Such integrated utilization significantly enhances biomass valorization and supports the development of sustainable circular bioeconomies [44, 45].

Recent technological advances have accelerated the commercial potential of microalgal biorefineries. Improvements in photobioreactor design, open pond cultivation, wastewater-based cultivation systems, genetic engineering, metabolic pathway optimization, artificial intelligence-assisted cultivation management, and environmentally friendly extraction technologies have collectively increased biomass productivity and reduced operational costs [46, 47]. Moreover, advances in omics technologies, synthetic biology, and systems biotechnology are enabling the development of genetically improved microalgal strains capable of producing higher concentrations of lipids, proteins, and valuable pigments under optimized cultivation conditions [51,52].

Despite remarkable progress, several scientific and technological challenges remain before large-scale commercialization becomes economically viable. High cultivation costs, contamination during open pond cultivation, energy-intensive harvesting and variability in biomass composition, seasonal productivity fluctuations, and inefficient downstream processing continue to limit industrial implementation [59-63]. Nevertheless, continuous advances in process integration, strain improvement, carbon capture technologies, wastewater utilization, and life-cycle optimization are steadily addressing these limitations and moving microalgal biorefineries toward commercial reality [39,64, 65].

2. Microalgal Biorefineries

Microalgal biorefineries have emerged as one of the most promising sustainable production platforms capable of simultaneously generating renewable biofuels, food ingredients, animal feed, pharmaceuticals, nutraceuticals, cosmetics, fertilizers, and other high-value bioproducts from a single biomass source [5–9].

The biorefinery concept is founded on the principles of complete biomass valorization, circular economy, resource efficiency, and environmental sustainability [12, 13]. Instead of targeting only lipid extraction for biodiesel production, modern microalgal biorefineries recover multiple biochemical fractions in a cascading manner. Lipids are converted into biodiesel, sustainable aviation fuel, or renewable diesel; carbohydrates are fermented to produce bioethanol or anaerobically digested for biogas production; proteins are purified for food, feed, and nutraceutical applications; while pigments and carotenoids are extracted for pharmaceutical and cosmetic industries [15, 18].

Another important characteristic of integrated microalgal biorefineries is their compatibility with carbon capture and wastewater treatment technologies [16, 24-26]. Microalgae efficiently utilize carbon dioxide emitted from industrial flue gases during photosynthesis, thereby reducing greenhouse gas emissions while simultaneously producing valuable biomass [25]. Furthermore, cultivation in municipal, agricultural, and industrial wastewater enables simultaneous nutrient removal and biomass generation, reducing freshwater consumption and fertilizer requirements [24]. These integrated systems contribute significantly to achieving the Sustainable Development Goals (SDGs), particularly those related to clean energy, climate action, sustainable industry, and responsible production and consumption [9,28, 29].Recent technological developments have further strengthened the feasibility of microalgal biorefineries through improvements in cultivation systems, harvesting technologies, biomass fractionation, and downstream processing [32, 33]. Advanced photobioreactors, membrane harvesting systems, supercritical fluid extraction, ultrasound-assisted extraction, microwave-assisted extraction, enzymatic hydrolysis, and green solvent technologies have substantially increased product recovery while reducing processing costs and environmental impacts [31–35].

2.1 Concept and Principles

The concept of a microalgal biorefinery is based on the comprehensive utilization of microalgal biomass through integrated physical, chemical, biological, and thermochemical processing technologies to generate multiple valuable products from a single cultivation process [7, 8]. This strategy mirrors the operational principles of petroleum refineries, where every fraction of crude oil is converted into marketable products. In microalgal systems, every biochemical component of the biomass is similarly exploited to maximize profitability and sustainability [34, 35, 36].

Microalgal biomass primarily consists of lipids, proteins, carbohydrates, pigments, nucleic acids, vitamins, minerals, and numerous secondary metabolites, with their relative proportions depending on species, cultivation conditions, and nutrient availability [23, 24]. Under nitrogen limitation, many species accumulate lipids suitable for biodiesel production, whereas protein synthesis predominates under nutrient-replete conditions [14, 21, 22].

2.2 Microalgal Species Used

The success of an integrated microalgal biorefinery largely depends on selecting suitable microalgal species capable of producing high biomass yields together with substantial quantities of lipids, proteins, carbohydrates, and high-value secondary metabolites [12].

The green microalga **Nannochloropsis** has attracted considerable attention because of its high lipid productivity and abundance of omega-3 polyunsaturated fatty acids, particularly eicosapentaenoic acid (EPA) [16, 17].

Increasingly, advances in metabolic engineering, adaptive laboratory evolution, genome editing, and synthetic biology are enabling the development of improved strains with enhanced biomass productivity, stress tolerance, lipid accumulation, and carotenoid biosynthesis [48].

3. Biofuel Production from Microalgae

Microalgae have emerged as one of the most promising renewable feedstocks for next-generation biofuel production because of their rapid growth rates, high photosynthetic efficiency, remarkable carbon dioxide fixation capacity, and ability to accumulate substantial amounts of lipids and carbohydrates under controlled cultivation conditions [11–15].

3.1 Biodiesel

Biodiesel represents the most extensively investigated biofuel derived from microalgae owing to the ability of numerous species to accumulate high concentrations of neutral lipids, primarily triacylglycerols (TAGs), under nutrient-stress conditions [16, 17]. These lipids can be extracted and converted into fatty acid methyl esters (FAMEs) through transesterification using methanol or ethanol in the presence of alkaline, acidic, or enzymatic catalysts [14, 15]. The resulting biodiesel possesses physicochemical properties comparable to petroleum diesel while exhibiting lower sulphur content, reduced particulate emissions, and improved biodegradability [3, 4].

Several cultivation strategies have been developed to maximize lipid production, including two-stage cultivation systems, heterotrophic and mixotrophic growth, carbon dioxide supplementation, wastewater cultivation, and metabolic engineering [27, 28]. Advanced harvesting techniques such as membrane filtration, magnetic separation, electrocoagulation, and bio flocculation have also improved biomass recovery while reducing operational costs [30].

3.2 Bioethanol

Bioethanol production from microalgae primarily utilizes carbohydrate-rich biomass composed of starch, cellulose, glycogen, and other fermentable polysaccharides [14, 15]. The production process generally involves biomass pretreatment, enzymatic or acid hydrolysis to release fermentable sugars, followed by microbial fermentation using organisms such as **Saccharomyces cerevisiae**, **Zymomonas mobilis**, or genetically engineered bacterial strains [15].

3.3 Biogas

Anaerobic digestion represents one of the most efficient approaches for converting residual microalgal biomass into renewable methane-rich biogas [13, 14].

3.4 Biohydrogen

Biohydrogen has emerged as one of the cleanest renewable energy carriers because its combustion produces only water without greenhouse gas emissions [16, 17]. To overcome this limitation, researchers are developing genetically engineered strains, advanced photobioreactors, metabolic pathway modifications, and hybrid cultivation systems that improve hydrogen yield and process stability [46–55].

4. Protein Production from Microalgae

Microalgae have attracted considerable attention as sustainable alternative protein sources owing to their rapid biomass productivity, balanced amino acid composition, and comparatively lower environmental footprint than conventional plant and animal proteins [40, 41].

5. High-Value Carotenoids

Among the numerous valuable metabolites synthesized by microalgae, carotenoids represent one of the most economically important product groups because of their extensive applications in nutraceuticals, pharmaceuticals, cosmetics, food colouring, aquaculture, and animal nutrition [18, 19].

5.1 Astaxanthin

Astaxanthin is regarded as one of the most valuable natural carotenoids because of its exceptionally strong antioxidant activity, which is estimated to be substantially greater than that of vitamin E, vitamin C, and β-carotene [21, 22].

5.2 β-Carotene

β-Carotene is a provitamin A carotenoid extensively used in food, pharmaceutical, cosmetic, and nutraceutical industries because of its antioxidant activity and its role as a precursor of vitamin A [19, 21].

5.3 Lutein

Lutein is a xanthophyll carotenoid recognized for its beneficial effects on human eye health, particularly in preventing age-related macular degeneration and cataracts [21, 22]. Species such as **Chlorella vulgaris**, **Scenedesmus obliquus**, and **Muriellopsis** are among the most productive natural sources of lutein [24].Several cultivation strategies, including nitrogen optimization, light intensity regulation, and carbon dioxide supplementation, have been developed to maximize lutein accumulation [27, 28].

5.4 Fucoxanthin

Fucoxanthin is a unique marine carotenoid predominantly synthesized by brown algae and marine diatoms such as **Phaeodactylum tricornutum**, **Odontella aurita**, and **Chaetoceros** species [23, 24].

Commercial production of fucoxanthin relies primarily on controlled photobioreactor cultivation of marine diatoms followed by environmentally friendly extraction and chromatographic purification [34, 35].

6. Integrated Biorefinery Technologies

The economic feasibility of microalgal biorefineries depends largely on integrated processing technologies that enable the recovery of multiple valuable products from a single biomass source while minimizing waste generation and energy consumption [9]. An integrated microalgal biorefinery generally consists of five interconnected stages: cultivation, harvesting and dewatering, biomass pretreatment, fractionation of valuable biomolecules, and conversion of residual biomass into renewable energy products [32, 33].

7. Techno-economic and Environmental Sustainability

The commercial success of microalgal biorefineries depends not only on biological productivity but also on their techno-economic feasibility and environmental sustainability [38, 39].

Integrated biomass utilization also contributes significantly to waste minimization and resource efficiency [9–13]. Recovery of high-value carotenoids, proteins, and polyunsaturated fatty acids before biofuel production maximizes biomass valorization, while residual biomass can be converted into bioethanol, methane-rich biogas, biochar, or biofertilizers [19, 20].

Recent advances in automation, artificial intelligence, metabolic engineering, renewable energy integration, and process intensification are steadily improving the commercial outlook for microalgal biorefineries [46–55]. AI-assisted process control enables real-time optimization of cultivation parameters, reducing energy consumption while maximizing biomass productivity [49, 50]. Meanwhile, synthetic biology and genome editing technologies facilitate the development of improved microalgal strains with enhanced lipid accumulation, carotenoid biosynthesis, stress tolerance, and protein productivity [53, 54, 55].

8. Challenges and Future Perspectives

Despite remarkable progress in microalgal biotechnology, several scientific, technological, and economic challenges continue to hinder the widespread commercialization of integrated microalgal biorefineries [29, 30]. Although laboratory-scale investigations have consistently demonstrated the feasibility of producing biofuels, proteins, carotenoids, and other high-value compounds from microalgae, translating these processes into economically viable industrial operations remains a major challenge [38, 39]. Future research should therefore focus on improving cultivation efficiency, reducing production costs, integrating advanced bioprocessing technologies, and developing sustainable commercialization strategies.

One of the primary challenges is the **high cost of biomass cultivation** [32, 33]. Closed photobioreactors provide excellent control over environmental conditions and minimize contamination; however, they require substantial capital investment and high operating expenses [30, 32]. The development of cost-effective hybrid cultivation systems capable of combining the advantages of both cultivation methods remains an important research priority [27, 28].

Integration of microalgal cultivation with municipal wastewater treatment, industrial wastewater remediation, and carbon dioxide capture from flue gases provides a practical strategy for simultaneously addressing environmental pollution and biomass production [29].

Economic sustainability remains one of the most critical determinants of commercialization [34, 35]. Techno-economic studies consistently demonstrate that microalgal biorefineries become financially attractive when multiple high-value products are simultaneously recovered rather than relying solely on renewable biofuel production [12].

Future research should also emphasize **life-cycle assessment (LCA)** and **techno-economic analysis (TEA)** to evaluate commercial feasibility under realistic industrial conditions [36, 37]. Standardized sustainability assessment frameworks will facilitate comparison among cultivation systems, extraction technologies, and biomass utilization pathways while supporting regulatory approval and industrial investment. International collaboration between academic institutions, government agencies, and biotechnology industries will further accelerate the commercialization of sustainable microalgal biorefineries.

9. Conclusion

Microalgal biorefineries represent one of the most promising technological approaches for achieving sustainable production of renewable energy, high-quality proteins, and commercially valuable carotenoids within a single integrated production system [11, 12]. Their exceptional photosynthetic efficiency, rapid biomass productivity, high carbon dioxide fixation capacity, and ability to synthesize a broad spectrum of bioactive compounds distinguish microalgae from conventional terrestrial feedstocks and position them as key contributors to the emerging circular bioeconomy [11, 18, 19]. Unlike traditional biofuel production systems that utilize only a single biomass fraction, integrated microalgal biorefineries maximize biomass valorization by sequentially recovering carotenoids, proteins, lipids, carbohydrates, and other valuable metabolites before converting residual biomass into renewable biofuels and biofertilizers [38, 39].

Recent advances in photobioreactor engineering, wastewater-based cultivation, carbon dioxide sequestration, green extraction technologies, artificial intelligence, metabolic engineering, and synthetic biology have substantially improved biomass productivity, metabolite accumulation, and downstream processing efficiency [56, 57, 58]. Nevertheless, challenges related to cultivation costs, harvesting efficiency, downstream processing, strain optimization, and industrial scalability continue to limit widespread commercialization [29–39]. Addressing these constraints through multidisciplinary research and integrated process optimization will be essential for achieving economically competitive large-scale production [61, 62].

Future commercial microalgal biorefineries are expected to function as highly integrated, zero-waste production systems that simultaneously generate renewable fuels, food ingredients, pharmaceuticals, nutraceuticals, specialty chemicals, and environmental services such as wastewater remediation and carbon capture [13, 26, 28, 29]. Continued investment in biotechnology, systems biology, renewable energy integration, and sustainable process engineering will further enhance commercial viability and accelerate industrial adoption.

In conclusion, integrated microalgal biorefineries offer a transformative platform capable of addressing several global challenges simultaneously, including renewable energy production, food security, environmental sustainability, climate change mitigation, and resource conservation [34–39]. Their ability to co-produce biofuels, proteins, and high-value carotenoids from renewable biomass positions microalgae as one of the most strategically important biological resources for developing resilient, sustainable, and economically viable bio-based industries in the twenty-first century [5–12,34–39].

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