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Review Article

BIOFUEL PRODUCTION FROM MICROALGAE AND MACROALGAE: A CONCISE REVIEW

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Abstract

The increasing global demand for renewable energy has positioned algae-based biofuels as a promising alternative to fossil fuels. Microalgae and macroalgae offer unique advantages due to their rapid growth rates, high lipid and carbohydrate content, and ability to thrive in diverse aquatic environments without competing with food crops for arable land. This concise review highlights recent advances in biofuel production from both microalgae and macroalgae, focusing on cultivation techniques, harvesting strategies, and conversion pathways such as transesterification, anaerobic digestion, and thermochemical processes. The environmental benefits of algal biofuels, including carbon sequestration and wastewater remediation, are discussed alongside economic challenges related to large-scale commercialization. Comparative insights between microalgae and macroalgae are provided to illustrate their respective strengths and limitations in biofuel applications. The review concludes that while significant progress has been made in optimizing algal biofuel systems, further innovations in cost reduction, integrated biorefinery approaches, and policy support are essential to realize their full potential as sustainable energy sources.

Keywords: Microalgae, Macroalgae, Algal biofuels, Renewable energy, Biodiesel, Bioethanol, Biorefinery.

INTRODUCTION

The global energy sector is undergoing a paradigm shift as nations seek sustainable alternatives to fossil fuels in response to climate change, energy insecurity, and environmental degradation. Among various renewable energy sources, biofuels derived from algae have attracted considerable attention due to their high productivity, versatility, and environmental benefits. Unlike terrestrial biofuel crops, algae do not compete directly with food production and can be cultivated in non-arable land using saline or wastewater, making them an attractive feedstock for sustainable energy generation. Microalgae, microscopic photosynthetic organisms, are particularly valued for their high lipid content, which can be converted into biodiesel through transesterification. They also produce carbohydrates suitable for bioethanol and biogas production. Macroalgae, or seaweeds, on the other hand, are rich in polysaccharides such as alginate, carrageenan, and cellulose, which can be fermented into bioethanol or subjected to thermochemical conversion for bio-oil and syngas. Both groups of algae contribute to carbon dioxide mitigation, nutrient recycling, and wastewater treatment, thereby offering environmental co-benefits alongside energy production.

Microalgae have been extensively studied for their high lipid content and rapid growth rates, making them suitable for biodiesel production. Singh *et al*. (2021) provided a comprehensive review of advances in microalgal biofuel production, highlighting cultivation techniques and conversion pathways. Lee *et al*. (2023) discussed recent

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progress in microalgae cultivation for biodiesel, emphasizing challenges in large-scale implementation. Sundaram *et al*. (2023) explored bioengineering strategies to enhance biomass yield and lipid accumulation, while Wang *et al*. (2023) examined genetic engineering approaches to improve biofuel productivity. Nguyen *et al*. (2023) further reviewed microalgae-based biogas production, demonstrating their versatility in multiple energy pathways.

Macroalgae, or seaweeds, are rich in polysaccharides that can be converted into bioethanol and bio-oil. Khan *et al*. (2022) highlighted macroalgae as a sustainable source for bioethanol production, while Rao and Reddy (2022) discussed prospects and challenges of seaweed biomass utilization. Chen *et al*. (2022) investigated thermochemical conversion of macroalgae for bio-oil production, demonstrating its potential as a renewable energy source. Samal and Sukla (2025) emphasized the dual potential of microalgae and seaweed biomass for sustainable biofuel production, underscoring the complementary roles of both groups. Integrated biorefinery models are increasingly recognized as essential for economic feasibility. Li *et al*. (2023) reviewed biorefinery approaches that combine biofuel production with co-products such as nutraceuticals and animal feed. Phillip and Goyal (2024) provided a comprehensive analysis of algal biofuels, stressing the importance of integrated systems. Ahmed and Chowdhury (2023) discussed biosecurity measures in sustainable algal biofuel production, which are critical for maintaining system efficiency and preventing contamination. Environmental impacts of algal biofuels have been widely studied. Das and Roy (2023) conducted a life cycle assessment of algal biofuel systems, identifying key sustainability challenges. Chatterjee and Ghosh (2023) assessed carbon footprints, while Sharma and Singh (2022) examined broader environmental sustainability aspects. Das and Roy (2022) analyzed climate change impacts on algal biofuel systems, highlighting vulnerabilities and adaptation strategies. Kumar and Patel (2022) linked algal biofuels to Sustainable Development Goals, reinforcing their role in global sustainability agendas.

Economic feasibility remains a central concern. Rahman and Karim (2024) analyzed prospects of algae-based biofuels in Asia, while Tanaka *et al*. (2023) provided an economic analysis for Southeast Asia. Li *et al*. (2023) compared economic prospects of microalgae versus macroalgae biofuels, and Chen *et al*. (2022) examined production economics in China. Singh and Verma (2022) focused on India, while Zhang and Liu (2022) provided a broader Asian perspective. Rahman *et al*. (2023) discussed sustainable algal biofuel production in Bangladesh, emphasizing socio-economic impacts. Beyond energy, algae contribute to food security and rural development. Islam and Kabir (2023) explored the role of algal biofuels in South Asia's food security, while Rahman *et al*. (2023) highlighted their contribution to sustainable development in Bangladesh. These studies suggest that algae-based biofuels can simultaneously address energy needs and socio-economic challenges in developing regions.

MATERIALS AND METHODS

This review was conducted by systematically collecting and analyzing recent literature on biofuel production from microalgae and macroalgae. Studies were screened based on relevance to cultivation techniques, harvesting methods, conversion technologies, environmental impacts, and economic feasibility. Selected articles were categorized into thematic clusters: (i) cultivation and biomass production, (ii) conversion pathways, (iii) environmental benefits, and (iv) economic and policy perspectives. Comparative analysis was performed to highlight the strengths and limitations of microalgae and macroalgae in biofuel applications.

RESULTS AND DISCUSSION

The review revealed that microalgae are highly efficient in lipid accumulation, making them suitable for biodiesel production through transesterification. Their rapid growth rates and ability to utilize wastewater enhance sustainability. However, challenges remain in large-scale cultivation and harvesting due to high energy inputs. Macroalgae**,** in contrast, are rich in polysaccharides such as alginate and cellulose, which are ideal for bioethanol and biogas production via fermentation and anaerobic digestion. Thermochemical conversion of macroalgal biomass also yields bio-oil and syngas, expanding their utility. Environmental benefits include carbon sequestration, nutrient recycling, and wastewater remediation, positioning algae as a dual-purpose resource for energy and environmental management. Economically, integrated biorefinery approaches that combine biofuel production with co-products (nutraceuticals, animal feed, pharmaceuticals) are emerging as viable strategies to offset costs. Despite these advances, commercialization is hindered by high capital investment, energy-intensive harvesting, and limited policy support. Comparative analysis suggests that microalgae are more promising for biodiesel, while macroalgae excel in bioethanol and biogas production, highlighting the complementary roles of both groups in sustainable energy systems.

Table 1. Comparison between Microalgae vs. Macroalgae in Biofuel Production.

Aspect	Microalgae	Macroalgae
Feedstock properties	High lipid content; rapid growth; can use wastewater (Singh *et al*., 2021; Sundaram *et al*.,	Rich in polysaccharides (alginate, cellulose, carrageenan) (Khan *et al*., 2022; Rao & Reddy,

	2023).	2022).
Main conversion pathways	Biodiesel via transesterification; Biogas via anaerobic digestion (Lee *et al*., 2023; Nguyen *et al*., 2023).	Bioethanol via fermentation; Bio-oil via thermochemical conversion (Chen *et al*., 2022; Samal & Sukla, 2025).
Advantages	High productivity; CO_2 mitigation; wastewater remediation (Chatterjee & Ghosh, 2023; Wang *et al*., 2023).	Abundant biomass; non-competition with food crops; potential in coastal regions (Khan *et al*., 2022; Chen *et al*., 2022).
Challenges	High cultivation and harvesting costs; energy-intensive processes (Das & Roy, 2023; Lee *et al*., 2023).	Seasonal availability; lower lipid content; pretreatment required (Rao & Reddy, 2022; Samal & Sukla, 2025).
Economic prospects	Promising for biodiesel markets but costly; requires integrated biorefineries (Rahman & Karim, 2024; Tanaka *et al*., 2023).	Strong potential for bioethanol/biogas in Asia; region-specific viability (Li *et al*., 2023; Zhang & Liu, 2022).
Environmental impact	Carbon footprint reduction; aligns with SDGs (Das & Roy, 2022; Kumar & Patel, 2022).	Coastal ecosystem integration; supports circular economy (Rahman *et al*., 2023; Islam & Kabir, 2023).

CONCLUSION

Biofuel production from microalgae and macroalgae represents a promising pathway toward sustainable energy. Microalgae offer high lipid yields suitable for biodiesel, while macroalgae provide carbohydrate-rich biomass for bioethanol and biogas. Both contribute to environmental benefits such as carbon mitigation and wastewater treatment. However, economic feasibility remains a major barrier, requiring innovations in cultivation, harvesting, and conversion technologies. Integrated biorefinery models and supportive policies are essential to bridge the gap between laboratory success and industrial-scale implementation. Future research should focus on: Genetic engineering of algal strains to enhance lipid and carbohydrate yields. Low-cost harvesting technologies such as flocculation and membrane filtration. Integration with wastewater treatment plants to reduce costs and improve sustainability**.** Hybrid conversion pathways combining biochemical and thermochemical methods for higher efficiency. Policy frameworks and subsidies to encourage industrial adoption of algal biofuels. Life cycle assessments (LCA) to evaluate environmental and economic impacts comprehensively.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

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Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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