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Microalgae-Based Technologies for Carbon Capture, Wastewater Treatment and Bioenergy

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Abstract
Microalgae are increasingly being investigated as multifunctional biological resources for sustainable environmental management because they can convert carbon dioxide (CO_2) and nutrients into biomass while producing renewable products. This review examines the integration of three applications—CO_2 capture, wastewater treatment and bioenergy production—within a microalgal biorefinery framework. Microalgae such as Chlorella, Scenedesmus and related taxa use photosynthesis to assimilate inorganic carbon and can simultaneously remove nitrogen and phosphorus from municipal, agricultural and selected industrial wastewaters. The resulting biomass contains lipids, carbohydrates and proteins that can be directed toward biodiesel, biogas, bioethanol, biohydrogen and other value-added products. Recent studies also highlight closed photobioreactors, high-rate algal ponds, algal–bacterial consortia, membrane systems, micro-nano-bubbles, artificial intelligence, predictive modelling and life-cycle assessment as important areas of technological development. However, large-scale application remains constrained by light limitation, contamination, variable wastewater composition, biomass harvesting costs, downstream energy demand and uncertain economic performance. A sustainable system therefore requires integration of wastewater characteristics, reactor design, carbon supply, biomass recovery and safe end-use. Overall, microalgal technology offers a promising route toward a circular bioeconomy in which carbon, water and nutrients are recovered rather than treated only as wastes.

***Keywords**: Microalgae; carbon capture; wastewater treatment; bioenergy; biorefinery; circular bioeconomy; nutrient recovery; sustainability*

1. Introduction

The simultaneous growth of greenhouse-gas emissions, wastewater generation and energy demand has created a need for technologies that address more than one environmental problem at a time. Conventional wastewater treatment is effective for contaminant removal, but it can require substantial energy and may treat nitrogen and phosphorus as wastes rather than recoverable resources. Similarly, engineered carbon-capture systems can reduce emissions but may involve significant energy, infrastructure and operating requirements. Microalgae offer a biological route that can link carbon capture, wastewater remediation and biomass production in one system.

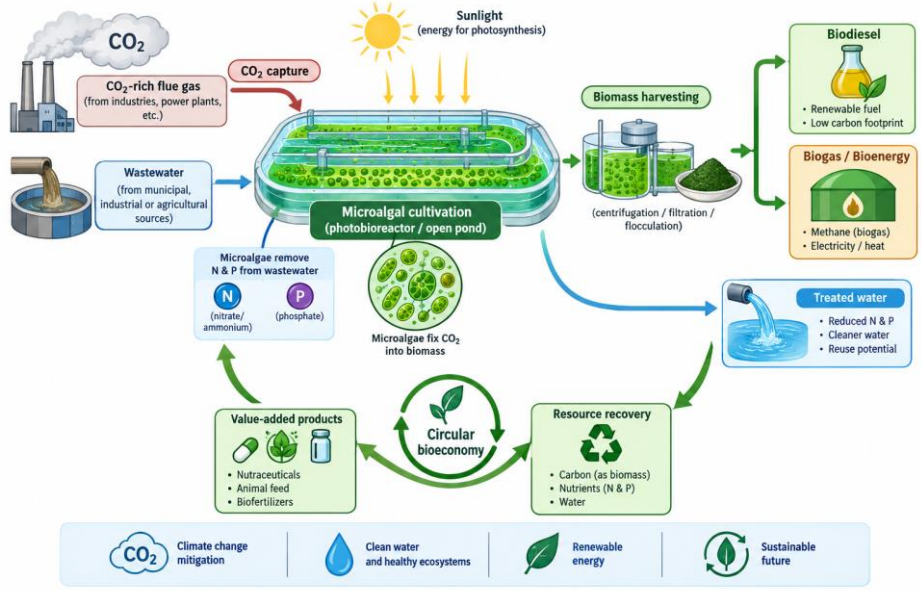


Figure 1. Integrated microalgal pathway linking CO_2 capture, wastewater treatment, biomass recovery and circular resource use. Original schematic prepared for this paper.

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Microalgae are oxygenic photosynthetic microorganisms that use light energy to convert inorganic carbon into organic matter. During cultivation, carbon dioxide is incorporated into cellular biomass while nitrogen and phosphorus can be assimilated for growth. This creates an opportunity to use nutrient-rich wastewater as a cultivation medium and carbon-rich gas streams as a carbon source. Recent reviews describe this integration as a developing circular-bioeconomy pathway because the wastewater supplies nutrients, CO_2 is converted into biomass, and the biomass can subsequently be converted into energy or other products (Bora et al., 2024; Kumar et al., 2024).

The research interest in this area is expanding rapidly. A 2024 scientometric review identified a large and growing body of research on microalgae-based wastewater treatment, with increasing attention to carbon sequestration, cultivation systems and emerging technologies (Kumar et al., 2024; Sharma et al., 2022). More recent work has moved toward integrated systems, including closed-loop carbon capture, algal–bacterial systems, advanced photobioreactors, artificial intelligence and resource recovery (Singh et al., 2026; Thanigaivel et al., 2022).

The objective of this review is to synthesize current knowledge on microalgae-based technologies for CO_2 capture, wastewater treatment and bioenergy, and to identify major technological opportunities and limitations relevant to sustainable environmental management.

2. Literature Review

2.1 Microalgae as a multifunctional bio-resource

Microalgal biomass contains variable proportions of lipids, carbohydrates, proteins, pigments and other metabolites. The biochemical composition depends on species, light intensity, temperature, nutrient availability, salinity, pH and cultivation strategy. This flexibility allows microalgae to be directed toward different products rather than a single fuel pathway. Chlorella and Scenedesmus are frequently studied because of their growth characteristics and ability to tolerate a range of cultivation conditions. The literature also emphasizes that strain selection should be matched to the intended wastewater and final product rather than based only on maximum laboratory growth (Bora et al., 2024; Maurya et al., 2022).

2.2 Carbon capture by microalgae

Microalgal carbon capture is based mainly on photosynthetic fixation. CO_2 from ambient air, concentrated CO_2 streams or industrial flue gas can be transferred into the culture and converted into biomass. Carbon fixation depends strongly on CO_2 concentration, pH, temperature, light availability, gas–liquid mass transfer, nutrient status and physiological condition of the culture. Excessively high CO_2 concentrations can inhibit some strains, while insufficient carbon availability can limit productivity. Recent research therefore emphasizes dynamic CO_2 management rather than assuming that a constant high CO_2 concentration is always beneficial (Basu et al., 2013; Singh et al., 2026).

Recent studies are also exploring the use of industrial emissions as a carbon source. Flue-gas integration can reduce the need for purified CO_2, but gas impurities, temperature, mass transfer and pretreatment requirements must be considered. A 2025 review specifically examined microalgal flue-gas sequestration and its relationship with biofuel-feedstock production, highlighting both the potential and the engineering challenges (Yadav et al., 2019).

2.3 Microalgae-based wastewater treatment

Wastewater can provide water and nutrients for microalgal growth. Nitrogen may be assimilated as ammonium or nitrate, while phosphorus can be incorporated into cellular material. Microalgae can also interact with bacteria: algae produce oxygen through photosynthesis, while bacteria can degrade organic matter and release inorganic nutrients that support algal growth. This symbiotic relationship can improve the performance of algal–bacterial systems (Gupta et al., 2019; Sharma et al., 2022).

Municipal, agricultural, food-processing and selected industrial wastewaters have been investigated as cultivation media. However, wastewater quality varies substantially. Turbidity can reduce light penetration, toxic compounds can inhibit growth, and heavy metals, pathogens or emerging contaminants may accumulate in biomass. Consequently, wastewater-derived biomass should not automatically be considered suitable for food or feed. Recent system-level research stresses the importance of matching the final biomass application with contamination risk and regulatory requirements (Kumar et al., 2024).

2.4 Bioenergy production

The main bioenergy routes from microalgal biomass include biodiesel from lipids, biogas from anaerobic digestion, bioethanol from carbohydrates and biohydrogen under specialized conditions. Biodiesel production generally requires harvesting, dewatering, lipid extraction and transesterification. These downstream steps can be energy-intensive and are major considerations in assessing sustainability. For this reason, recent research increasingly favors integrated biorefineries in which several fractions of biomass are used instead of extracting only lipids (Bora et al., 2024).

Anaerobic digestion is particularly relevant for wet biomass because it can reduce the need for complete drying. The resulting biogas can be used for heat or electricity, while digestate may retain nutrients that can potentially be recovered, subject to safety and regulatory considerations. Thus, the most sustainable pathway may depend on local energy prices, wastewater composition, biomass characteristics and available infrastructure rather than on a single universally optimal fuel.

3. Research Work

3.1 Review approach

This paper is a structured narrative review based on recent peer-reviewed literature concerning microalgal CO_2 capture, wastewater treatment, biomass recovery, bioenergy and circular-bioeconomy integration. Emphasis was placed on recent reviews and research reports published mainly during 2024–2026, supplemented by established literature where necessary. The literature was synthesized under four themes: (i) biological carbon fixation, (ii) nutrient and pollutant removal, (iii) biomass harvesting and conversion, and (iv) system-level sustainability.

3.2 Integrated microalgal technology

An integrated system can be represented as a sequence in which wastewater and a carbon source enter a cultivation unit, microalgae grow under illumination, nutrients and CO_2 are converted into biomass, and the treated water is separated from harvested biomass. The biomass can then be processed into energy products or other materials. Figure 1 illustrates the overall concept.

The most important advantage of this configuration is functional integration. Wastewater is not simply treated; its nitrogen, phosphorus and water content can support biomass production. Likewise, CO_2 is not only captured but converted into a potentially useful biological product. This is the basis of a circular carbon and nutrient pathway described in recent literature (Kumar et al., 2024; Yadav et al., 2019).

3.3 Cultivation technologies

Open high-rate algal ponds are comparatively simple and can be suitable for large areas, but they provide less control over contamination, evaporation, weather and light conditions. Closed photobioreactors provide greater control over contamination, gas transfer and operating conditions but generally involve higher capital and operational complexity. Hybrid systems can combine the advantages of both approaches.

Biofilm-based and attached-growth systems are also attracting interest because biomass can sometimes be recovered with lower water content than suspended cultures. Membrane-based systems can improve separation and treatment performance but introduce membrane fouling and additional cost. Micro-nano-bubble technologies are being explored to improve gas transfer and microalgal cultivation, including CO_2 delivery and biomass separation (Maurya et al., 2022).

3.4 Nutrient recovery and wastewater polishing

Microalgal treatment can reduce dissolved nitrogen and phosphorus through assimilation and other biological mechanisms. Oxygen generated during photosynthesis can support bacterial oxidation of organic compounds, creating a coupled algal–bacterial treatment process. However, removal efficiency is highly dependent on the starting wastewater, retention time, light availability, culture density and operating conditions. Therefore, published removal percentages should not be treated as universal values.

In addition to conventional nutrients, researchers are investigating the removal of selected heavy metals, organic contaminants and emerging pollutants. These applications are promising but require careful monitoring because pollutant removal from water may result in accumulation in

biomass. For this reason, environmental remediation and biomass valorization must be considered together rather than as independent steps.

3.5 Carbon capture and process optimization

Carbon capture efficiency can be improved by selecting strains with suitable carbon-concentrating mechanisms, optimizing pH and gas transfer, controlling light exposure and using suitable reactor geometry. Recent research has also explored bicarbonate utilization, improved photobioreactors, molecular modelling and genetic approaches for handling variable CO_2 availability (Wu et al., 2025; Wu et al., 2025).

Artificial intelligence and predictive modelling represent an emerging trend. These tools can be used to model growth, predict nutrient removal, optimize gas supply, estimate biomass productivity and support process control. A 2024 review of energy-informatics approaches concluded that AI, predictive systems and life-cycle assessment can help optimize microalgal wastewater-to-bioenergy systems (Kumar et al., 2024). These tools are best viewed as decision-support methods that complement biological and engineering knowledge.

3.6 Biomass harvesting and bioenergy conversion

Harvesting is a major bottleneck because microalgal cultures are dilute and cells are small. Common approaches include centrifugation, filtration, sedimentation and flocculation. The selection of method affects energy demand, cost and the quality of recovered biomass. Recent literature reports improved recovery through combinations of flocculation, dissolved-air flotation and centrifugation, but the most suitable approach remains system-dependent (Bora et al., 2024).

For biodiesel, lipid-rich biomass is processed through extraction and transesterification. For biogas, whole or residual biomass can be subjected to anaerobic digestion. Carbohydrate-rich fractions can be considered for fermentation, while protein-rich residues may have applications in non-food products depending on contamination and processing. A biorefinery approach therefore seeks to maximize total resource recovery rather than maximize a single product.

3.7 Sustainability and techno-economic considerations

The environmental promise of microalgae should not be interpreted as proof that every algal system is automatically sustainable. Energy used for pumping, mixing, aeration, lighting, harvesting, drying and downstream conversion can substantially influence the overall environmental balance. Similarly, the source of CO_2, wastewater pretreatment, land requirement and biomass disposal affect life-cycle performance.

Techno-economic assessment and life-cycle assessment are therefore essential before commercial deployment. Recent reviews emphasize that wastewater integration can reduce freshwater and nutrient requirements, while biorefinery strategies can improve product recovery; nevertheless, harvesting, downstream processing and operational stability remain important barriers (Thanigaivel et al., 2022; Yadav et al., 2019). System boundaries must also be defined carefully when reporting carbon capture because carbon fixed into short-lived fuel products is different from carbon stored in durable materials.

3.8 Current challenges and future research directions

The principal challenges include contamination, variable wastewater composition, low light penetration, seasonal temperature variation, culture crashes, harvesting cost and inconsistent biomass quality. Another challenge is the gap between laboratory performance and field-scale operation. Laboratory cultures are often operated under carefully controlled conditions that cannot be maintained economically at large scale.

Future research should therefore emphasize real wastewater, outdoor pilot systems, long-term operation, mixed cultures, robust strains and integrated process control. Dynamic CO_2 conditions are especially important because industrial emissions and renewable energy systems may not provide a constant gas supply. Research on strain selection and adaptive cultivation should consider fluctuating carbon concentration rather than only fixed laboratory conditions (Wu et al., 2025).

AI-assisted monitoring, digital twins, automated control and life-cycle modelling could help improve reliability. However, these technologies should be validated against real operating data. Another priority is safe biomass valorization. Where wastewater-derived biomass contains

contaminants, energy recovery routes such as anaerobic digestion may be more appropriate than direct food or feed applications (Kumar et al., 2024).

Finally, integrated systems should be designed around local resources. A wastewater plant located near an industrial CO_2 source and a heat or electricity demand centre may have different optimal technology choices from a rural facility using agricultural wastewater. Future research should therefore move from "one technology fits all" models toward site-specific circular bioeconomy design.

4. Conclusion

Microalgae-based technology provides a promising biological platform for connecting three major sustainability challenges: carbon emissions, wastewater pollution and renewable-energy demand. Through photosynthesis, microalgae can convert CO_2 into biomass while assimilating nutrients from wastewater. The recovered biomass can then serve as a feedstock for biodiesel, biogas, bioethanol, biohydrogen and other products. This integrated approach has the potential to reduce resource consumption and support a circular bioeconomy.

The evidence reviewed here also shows that technological integration is more important than any single performance metric. Open ponds, photobioreactors, algal–bacterial systems, biofilms, membrane systems, improved gas transfer and AI-assisted control each offer specific advantages and limitations. Sustainable deployment requires consideration of the complete system, including wastewater characteristics, carbon source, energy demand, harvesting, product safety, life-cycle impacts and economics.

Microalgae should therefore be regarded not simply as a source of biofuel but as a multifunctional bio-resource for carbon, water and nutrient recovery. Future progress will depend on long-term pilot-scale validation, robust strains, lower-energy harvesting, improved process control, safe biomass utilization and rigorous techno-economic and life-cycle assessment. With these developments, integrated microalgal systems could contribute significantly to sustainable environmental management and circular resource recovery.

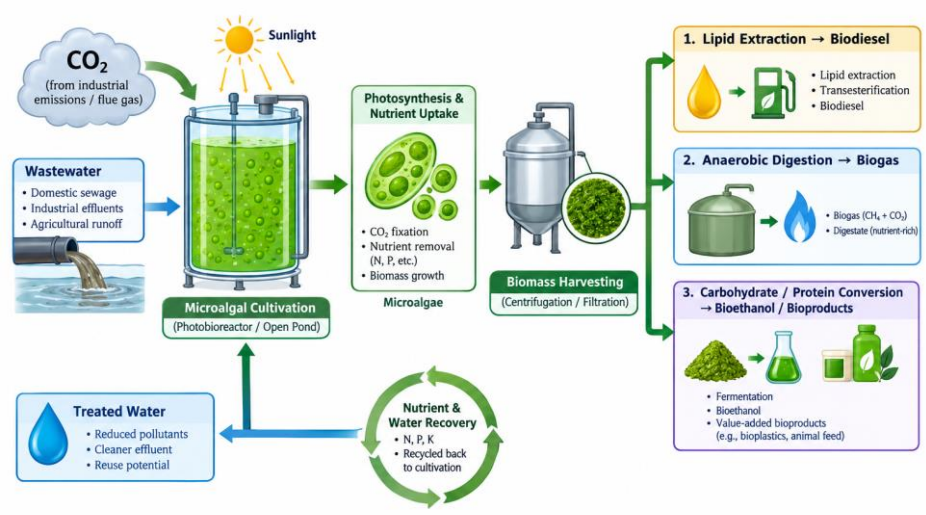


Figure 2. Overview of microalgal-based integrated system for carbon capture, wastewater treatment and bioenergy production.

Figure 2. Overview of microalgal-based integrated system for carbon capture, wastewater treatment and bioenergy production. Original schematic prepared for this paper.

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