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The Role of Algae in Climate Change Mitigation through Carbon Capture, Biomass Production, and Sustainable Biorefinery Development

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Abstract

The increasing atmospheric concentration of greenhouse gases, particularly carbon dioxide (CO_2), has intensified the need for effective, scalable, and environmentally sustainable climate mitigation strategies. Algae, particularly microalgae and cyanobacteria, have attracted considerable attention because of their photosynthetic capacity, rapid growth, high biomass productivity, and ability to utilize CO_2 as a carbon source. Unlike conventional terrestrial bioenergy crops, algae can potentially be cultivated on non-arable land and integrated with industrial carbon dioxide sources, wastewater streams, and nutrient-recovery systems. This makes algal cultivation a promising component of carbon capture and utilization (CCU) and circular bioeconomy strategies. During photosynthesis, algal cells convert inorganic carbon into organic biomass while releasing oxygen, thereby providing a biological pathway for carbon capture. The resulting biomass contains proteins, lipids, carbohydrates, pigments, polyunsaturated fatty acids, vitamins, and other bioactive compounds that can be converted into biofuels, biochemicals, food and feed ingredients, fertilizers, bioplastics, and other value-added products. Consequently, the integration of carbon capture with algal biorefineries offers an opportunity to generate economic value while reducing resource wastage. However, the climate benefits of algae cannot be assumed solely from high photosynthetic productivity. Energy-intensive harvesting and dewatering, nutrient requirements, water consumption, contamination, cultivation stability, infrastructure costs, and downstream processing can substantially influence the overall environmental performance. Recent research therefore emphasizes integrated biorefineries, wastewater-based cultivation, flue-gas utilization, strain improvement, advanced photobioreactors, artificial intelligence-assisted process control, low-energy harvesting, and cascade valorization of biomass. This review examines the biological basis of algal carbon capture, cultivation systems, biomass production, carbon utilization pathways, biorefinery development, major products, environmental and economic considerations, current challenges, and future opportunities. A systems-based approach integrating carbon capture, wastewater treatment, renewable energy, and multi-product biorefineries is proposed as a promising pathway for maximizing the climate-mitigation potential of algae.

Keywords: *algae; microalgae; carbon capture; carbon dioxide fixation; biomass; climate change; biorefinery; biofuels; circular bioeconomy; wastewater treatment.*

1. Introduction

Climate change is closely associated with the continued accumulation of greenhouse gases in the atmosphere, with carbon dioxide being one of the principal contributors to long-term anthropogenic warming. The transition away from fossil-fuel-dependent production systems therefore requires not only rapid reductions in greenhouse-gas emissions but also complementary approaches for carbon capture, utilization, and, where appropriate, durable carbon storage. Biological systems have received increasing attention within this broader climate-mitigation landscape because they can use solar energy to convert inorganic carbon into organic matter.

Algae represent one of the most promising biological platforms for this purpose. Microalgae and cyanobacteria perform photosynthesis and can assimilate dissolved or gaseous inorganic carbon into cellular biomass. Their relatively rapid growth and ability to accumulate substantial quantities of lipids, proteins, carbohydrates, pigments, and other metabolites distinguish them from many conventional terrestrial crops. Microalgal cultivation has consequently been investigated for CO_2 capture, bioenergy generation, wastewater treatment, and production of high-value bioproducts [1–3].

The fundamental advantage of algal systems is that carbon capture can be linked directly to biomass production.

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Instead of treating captured CO_2 exclusively as a waste stream, algal biotechnology attempts to transform carbon into a useful biological resource. Recent reviews have highlighted the potential of microalgae to combine CO_2 fixation with biofuel and biochemical production, particularly when cultivation is integrated with industrial emissions or wastewater streams [4,5]. Such integration can improve resource efficiency by simultaneously addressing carbon, nutrient, and waste-management challenges.

The concept of an algal biorefinery extends this approach further. In a conventional single-product system, algal biomass may be produced primarily for biodiesel or another commodity. However, the economics of such systems can be constrained because cultivation, harvesting, dewatering, drying, extraction, and conversion can be expensive. A biorefinery instead fractionates biomass into multiple product streams so that high-value compounds can subsidize lower-value products such as fuels. Current research increasingly supports this multi-product model as a more realistic route toward commercial algal biotechnology [6,7]. Algae can also contribute to circular-economy strategies. Nutrient-rich municipal, agricultural, and industrial wastewater can provide nitrogen and phosphorus required for algal growth, while CO_2-rich industrial gases can provide inorganic carbon. The harvested biomass can subsequently be processed into fuels, fertilizers, feedstocks, chemicals, or biomaterials. Such integrated systems potentially reduce freshwater consumption, recycle nutrients, and reduce waste disposal requirements [8,9]. Nevertheless, algae should not be considered an inherently carbon-negative technology. The net climate benefit depends on the complete life cycle of the system. Electricity requirements for mixing, pumping, aeration, harvesting, drying, and processing can generate indirect emissions. Nutrient production and transportation can also contribute to the carbon footprint. Furthermore, if algal biomass is converted into fuels and subsequently combusted, much of its biogenic carbon is returned to the atmosphere. Therefore, the strongest climate-mitigation strategies require careful assessment of carbon flows, energy inputs, product lifetime, and the final fate of captured carbon. This review examines the role of algae in climate change mitigation through three interconnected pathways: biological CO_2 capture, sustainable biomass production, and integrated biorefinery development. Particular emphasis is placed on recent technological advances, circular-resource integration, environmental limitations, and strategies required to move algal systems from laboratory-scale research toward economically and environmentally credible large-scale applications.

2. Biological Basis of Algal Carbon Capture

2.1 Photosynthetic carbon fixation

Algal carbon capture is fundamentally based on photosynthesis. During photosynthesis, light energy is used to convert carbon dioxide and water into organic compounds, with oxygen released as a by-product.

The simplified overall reaction can be represented as:

$$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

Although this equation provides a simplified representation, actual carbon assimilation involves a complex sequence of reactions involving carbon-concentrating mechanisms, photosynthetic electron transport, the Calvin–Benson cycle, and subsequent biosynthetic pathways. The captured inorganic carbon is ultimately incorporated into cellular carbohydrates, lipids, proteins, nucleic acids, and other metabolites. Consequently, algal growth represents a biological route for converting gaseous or dissolved carbon into biomass. The effectiveness of this process depends strongly on algal species, carbon concentration, temperature, light availability, pH, nutrient supply, mixing, and reactor configuration [2,10].

2.2 Carbon-concentrating mechanisms

Many microalgae possess carbon-concentrating mechanisms that enhance the availability of CO_2 around the carbon-fixing enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO). These mechanisms may involve active transport of inorganic carbon, conversion between bicarbonate and CO_2, and intracellular accumulation of carbon near photosynthetic sites. Species of *Chlorella*, *Scenedesmus*, *Nannochloropsis*, *Chlamydomonas*, *Spirulina* and other microalgal groups have been extensively investigated for their ability to grow under elevated CO_2 conditions. Recent research emphasizes the importance of selecting strains not merely for maximum laboratory growth but also for tolerance to industrial flue-gas contaminants, temperature fluctuations, salinity, variable light, and large-scale cultivation conditions [3,10].

2.3 Factors influencing carbon fixation

Carbon fixation efficiency is influenced by several interacting parameters. Light intensity controls photosynthetic energy availability, although excessive irradiation can cause photoinhibition. Temperature affects enzymatic activity and cellular metabolism, while pH determines the equilibrium among CO_2, bicarbonate, and carbonate in the culture medium. Carbon concentration affects growth until physiological or mass-transfer limitations occur. Nutrient availability is equally important. Nitrogen and phosphorus are essential for cellular synthesis and biomass formation. Deficiency may reduce biomass productivity even when carbon and light are abundant. Conversely, nutrient limitation can sometimes stimulate accumulation of specific compounds such as lipids or carbohydrates. Therefore, cultivation conditions must be optimized according to the desired product rather than simply maximizing total biomass [11].

3. Sources of Carbon for Algal Cultivation

3.1 Atmospheric CO_2

Algae can assimilate atmospheric CO_2, but direct capture from ambient air presents a major mass-transfer challenge because atmospheric CO_2 occurs at relatively low concentration.

Conventional industrial systems may therefore require substantial cultivation area and efficient gas–liquid transfer to supply adequate carbon. For this reason, direct-air carbon capture using algae is scientifically interesting but generally more demanding than utilization of concentrated CO_2 streams. Recent studies have nevertheless explored novel systems for delivering captured atmospheric CO_2 directly to algal cultures, indicating the potential for integration with emerging direct-air-capture technologies.

3.2 Industrial flue gas

Flue gas from power generation, cement production, steel manufacturing, and other industrial processes contains substantially higher CO_2 concentrations than ambient air. Microalgae can potentially utilize this carbon directly, reducing the need for separate CO_2 purification and compression. Flue-gas integration is therefore one of the most studied applications of algal carbon capture. However, industrial gases may contain nitrogen oxides, sulfur oxides, particulate matter, heavy metals, and other contaminants. Strain tolerance, gas pretreatment, and controlled delivery are therefore necessary to avoid growth inhibition or contamination of biomass intended for sensitive applications [12].

3.3 Industrial and agricultural waste streams

The coupling of algal cultivation with waste streams can provide both carbon and nutrients. Anaerobic digestion facilities, food-processing industries, livestock operations, wastewater-treatment plants, and fermentation facilities can generate CO_2-rich gases and nutrient-containing effluents suitable for algal cultivation. Such integration is particularly attractive because it addresses multiple environmental problems simultaneously. Instead of treating CO_2 and nutrients as waste, they can become inputs for biomass production.

4. Algal Cultivation Systems

4.1 Open raceway ponds

Open raceway ponds are among the simplest and least expensive systems for large-scale algal cultivation. They generally consist of shallow ponds in which water and biomass are continuously circulated using paddle wheels. Their relatively simple construction makes them attractive for bulk biomass production. However, open systems are exposed to environmental fluctuations and contamination. Evaporation, rain, temperature changes, competing microorganisms, predators, and uncontrolled nutrient conditions can reduce productivity. Consequently, open ponds are generally more suitable for robust strains and applications where extremely high culture purity is not essential.

4.2 Closed photobioreactors

Closed photobioreactors provide greater control over environmental conditions. Tubular, flat-panel, column, and other reactor designs can regulate light exposure, temperature, gas transfer, pH, and nutrient availability. Photobioreactors can achieve high productivity and reduce contamination compared with open systems. However, construction and operating costs are generally higher. Biofouling, oxygen accumulation, heat management, gas transfer, and scale-up remain important engineering problems.

4.3 Hybrid cultivation

Hybrid systems combine the advantages of open ponds and closed photobioreactors. Biomass may initially be produced in a controlled photobioreactor and subsequently transferred to a lower-cost open cultivation system. Alternatively, specific stages of cultivation can be operated under different conditions to maximize biomass production followed by product accumulation. The appropriate configuration depends on the target product, climate, available resources, land cost, water availability, and desired degree of contamination control.

Table 1. Major algal cultivation systems and their characteristics

Cultivation system	Major advantages	Major limitations	Suitable applications
Open raceway pond	Low capital cost; simple operation; suitable for large volumes	Contamination; evaporation; environmental variability	Bulk biomass, wastewater treatment
Tubular photobioreactor	High productivity; improved contamination control	High capital and energy requirements	High-value products, controlled CO_2 utilization
Flat-panel photobioreactor	Good light utilization; high surface-to-volume ratio	Scaling and temperature management	Specialty biomass and metabolites
Vertical column reactor	Efficient gas transfer; compact design	Construction complexity	Research and high-value products
Hybrid system	Combines controlled growth with low-cost production	More complex process management	Integrated biorefineries

5. Biomass Production and Composition

The value of algal biomass extends well beyond its role as a carbon sink. Depending on species and cultivation conditions, biomass can contain significant quantities of proteins, carbohydrates, lipids, pigments, minerals, vitamins, polyunsaturated fatty acids, and bioactive compounds. Protein-rich biomass can be considered for animal and aquaculture feed, while selected species may provide compounds of interest for food and nutraceutical applications. Lipid-rich biomass can serve as a feedstock for biodiesel, renewable diesel, or other lipid-derived products.

Carbohydrate-rich fractions can be converted through fermentation or thermochemical processes into bioethanol, biogas, organic acids, and other chemicals. Pigments such as chlorophylls, carotenoids, phycocyanin, and other specialized compounds represent higher-value product opportunities. This diversity is central to the biorefinery concept because different fractions of the same biomass can be directed toward different markets [6,7].

6. Algal Biomass as a Platform for Climate Mitigation

6.1 Biofuels

One of the earliest major motivations for algal biotechnology was the production of renewable fuels. Algae can accumulate lipids that can be converted into biodiesel through transesterification. Other conversion routes include hydrothermal liquefaction for bio-crude production, anaerobic digestion for biomethane, fermentation for ethanol, and biological or photobiological approaches for hydrogen. Microalgal biofuels can potentially avoid direct competition with food crops because algae do not necessarily require fertile agricultural soil. However, high biomass productivity alone does not guarantee economic or environmental sustainability. Harvesting and downstream processing can consume substantial energy, and fuel production must be assessed through full life-cycle analysis [1,6].

6.2 Biohydrogen

Some algae and cyanobacteria can produce hydrogen under specific physiological conditions. Hydrogen is attractive as a low-carbon energy carrier, although biological hydrogen production remains technically challenging because of low productivity, oxygen sensitivity of hydrogen-producing enzymes, and difficulties in maintaining stable production. Future integration of genetic engineering, photobiological systems, and biorefinery concepts may improve the feasibility of algal hydrogen production.

6.3 Biogas

Anaerobic digestion of algal biomass produces methane-rich biogas. This pathway is particularly useful for residual biomass remaining after extraction of high-value compounds. Instead of discarding biomass residues, the material can be converted into energy, improving overall resource efficiency.

Digestate generated during anaerobic digestion can potentially be recovered as a nutrient source for subsequent cultivation after suitable treatment, creating a partial nutrient-recycling loop.

6.4 Biochar and durable carbon products

For climate mitigation, converting a fraction of algal biomass into relatively stable carbon materials may provide greater carbon-retention potential than short-lived fuels. Pyrolysis and related thermochemical processes can generate biochar or carbon-rich materials. The climate value of such pathways depends on process energy, carbon stability, contaminant content, application environment, and long-term carbon retention. Further research is therefore required to establish standardized methods for quantifying the permanence of carbon stored in algal-derived materials.

7. Sustainable Algal Biorefinery

The algal biorefinery is a central concept for improving the economic and environmental performance of algal biotechnology. Rather than relying on a single product, biomass is fractionated so that multiple products are generated sequentially or simultaneously.

A typical process may involve:

CO_2 and nutrients → algal cultivation → biomass harvesting → cell disruption/fractionation → protein + pigments + lipids + carbohydrates → fuels, food/feed ingredients, chemicals, biomaterials and fertilizers.

The multi-product approach improves resource utilization because different biochemical fractions have different market values. High-value compounds can potentially compensate for the lower margins associated with bulk products. Recent systematic analysis of microalgal biorefineries emphasizes the importance of integrating cultivation, low-energy harvesting, cascade processing, techno-economic analysis, and life-cycle assessment rather than optimizing individual process stages in isolation [6].

Table 2. Major products obtainable from algal biomass

Biomass fraction/product	Potential products	Climate/circular-economy relevance
Lipids	Biodiesel, bio-oil, oleochemicals	Renewable carbon utilization
Proteins	Feed, food ingredients, peptides	Replaces resource-intensive protein sources in selected applications
Carbohydrates	Bioethanol, organic acids, biogas	Renewable energy and chemical production
Pigments	Carotenoids, chlorophylls, phycobiliproteins	High-value product generation
Polyunsaturated fatty acids	Nutraceuticals, feed ingredients	High-value biomass valorization
Residual biomass	Biogas, fertilizer, biochar	Minimizes waste
Polysaccharides	Biomaterials, hydrogels, bioplastics	Fossil-material substitution
Mineral-rich residues	Biofertilizers/soil amendments after appropriate assessment	Nutrient recycling

8. Integration with Wastewater Treatment

Wastewater-based algal cultivation is particularly attractive because nitrogen and phosphorus required for algal growth can be recovered from waste streams. At the same time, algae can remove nutrients and contribute to wastewater polishing. Municipal, agricultural, aquaculture, and selected industrial wastewaters have therefore been investigated as cultivation media. The approach can reduce the demand for synthetic fertilizers and freshwater while producing biomass. However, wastewater-grown biomass is not automatically suitable for food or feed. Pathogens, heavy metals, pharmaceuticals, microplastics, and other contaminants must be evaluated according to the intended end use. Biomass generated from contaminated streams may instead be directed toward non-food applications such as bioenergy, biochemicals, or environmental materials after appropriate safety assessment [8,9].

9. Integration of Carbon Capture and Wastewater Treatment

Combining CO_2 capture with wastewater treatment offers a particularly attractive systems approach.

In such systems, an industrial facility can provide CO_2, a wastewater-treatment plant can provide nutrients and water, and the algal facility can generate biomass and oxygen. This integrated configuration can potentially reduce the costs of separate carbon capture and nutrient removal processes. It also supports the circular use of carbon, nitrogen, phosphorus, and water.

For example:
Industrial CO_2 → algal cultivation → biomass production
Wastewater nitrogen + phosphorus → algal biomass
Algal biomass → biorefinery products
Residual biomass → anaerobic digestion → biogas + nutrient-rich digestate
Recovered nutrients → subsequent algal cultivation
Such closed-loop systems are consistent with the principles of the circular bioeconomy and have become an important research direction in contemporary algal biotechnology [7,9].

10. Carbon Capture Enhancement Strategies

10.1 Strain selection

Selecting appropriate algal strains is one of the most important steps in developing efficient carbon-capture systems. Desirable characteristics include rapid growth, high carbon-fixation capacity, tolerance to elevated CO_2, resistance to temperature variation, stable productivity, and resistance to contamination. Strain selection should also consider downstream processing characteristics. For example, a strain that grows rapidly but forms very dilute cultures may impose greater harvesting costs than a slightly slower strain that reaches higher biomass concentrations.

10.2 Genetic and metabolic engineering

Genetic engineering can potentially improve carbon fixation, photosynthetic efficiency, lipid accumulation, stress tolerance, and production of specific metabolites. CRISPR-based technologies have expanded the possibilities for targeted modification of algal genomes. Recent reviews identify strain engineering as a promising route toward improved CO_2 utilization and production of carbon-neutral or low-carbon products [13]. Nevertheless, engineered strains introduce regulatory, ecological, biosafety, and intellectual-property considerations that must be addressed before environmental deployment.

10.3 Artificial intelligence and process optimization

Algal cultivation involves numerous interacting variables, including light, temperature, pH, nutrient concentrations, dissolved oxygen, CO_2 supply, mixing, and harvesting time. Artificial intelligence and machine-learning methods can assist in predicting biomass productivity and identifying operating conditions. Sensor networks and Internet of Things technologies may also enable real-time monitoring of large-scale cultivation systems. Combining digital monitoring with automated control could improve productivity while reducing unnecessary energy and nutrient inputs [6].

11. Harvesting and Downstream Processing

Harvesting is one of the major bottlenecks in algal biotechnology because algal cultures are often dilute. Conventional centrifugation can be effective but may require substantial energy. Alternative approaches include sedimentation, flotation, filtration, membrane separation, bioflocculation, electrocoagulation, and combinations of these methods. After concentration, biomass may require drying or wet-processing depending on the desired product. Drying can be particularly energy intensive. Therefore, modern biorefineries increasingly seek wet extraction and cascade-processing methods that minimize unnecessary drying. Cell disruption may be achieved using mechanical, chemical, enzymatic, thermal, or combined methods. The optimal approach depends on the target compound and should preserve product quality while minimizing energy and chemical consumption.

12. Environmental Benefits

Algal systems can provide several environmental benefits when appropriately designed. First, they can utilize CO_2 as a carbon feedstock. Second, algae can recover nutrients from wastewater, potentially reducing nutrient discharge. Third, algae can produce renewable biomass without necessarily occupying productive agricultural land. Fourth, biomass can replace selected fossil-derived materials and chemicals. Algal systems can also contribute to oxygen production and environmental remediation. However, these benefits should be evaluated within a full life-cycle framework. Recent research emphasizes that system boundaries, energy sources, nutrient inputs, harvesting methods, and product allocation can substantially change the environmental outcome of an algal process [6,14].

13. Economic Considerations

The economic feasibility of algae-based climate technologies remains a major challenge. The cost of infrastructure, cultivation, CO_2 delivery, nutrients, mixing, harvesting, dewatering, extraction, and product purification can be considerable. Single-product systems are particularly vulnerable to economic limitations. For example, producing only biodiesel requires large quantities of biomass while the resulting fuel has relatively low unit value. A multi-product biorefinery can improve economic performance by recovering high-value compounds before converting residual biomass into energy or bulk products. Recent reviews indicate that commercialization is strongly dependent on co-product valorization, process optimization, infrastructure development, and reliable markets [6,15]. Therefore, future systems should be designed around integrated value chains rather than treating biofuel as the only target product.

14. Life-Cycle Assessment and Carbon Accounting

A central requirement for climate-oriented algal biotechnology is rigorous carbon accounting. The quantity of CO_2 absorbed during photosynthesis should not be equated automatically with permanent atmospheric CO_2 removal.

A complete assessment should consider:

1. CO_2 supplied to the culture.
2. Carbon incorporated into biomass.
3. Energy used for cultivation and mixing.
4. Energy required for harvesting and drying.
5. Nutrient production and transportation.
6. Infrastructure and reactor construction.
7. Carbon released during biomass conversion.
8. Carbon retained in durable products.
9. Carbon released through biomass decomposition.
10. Transportation and final product use.

The net climate benefit can therefore be conceptualized as:

Net climate benefit = CO_2 captured − process-related greenhouse-gas emissions − CO_2 released during product use and decomposition + durable carbon retained.

This framework is particularly important for distinguishing carbon utilization from carbon removal. If algal biomass is converted into a fuel and burned, the captured carbon is largely returned to the atmosphere. By contrast, long-lived materials or stable carbon products may retain carbon for substantially longer periods.

15. Major Challenges

Despite considerable progress, several barriers remain.

15.1 High energy requirements

Mixing, aeration, pumping, harvesting, drying, and extraction can consume substantial energy. If this energy is generated from fossil fuels, the resulting emissions may offset part of the carbon benefit.

15.2 Water requirements

Although algae can grow in saline or wastewater systems, large-scale cultivation may still require substantial water management. Evaporation in open ponds can be particularly important in warm climates.

15.3 Nutrient requirements

Nitrogen and phosphorus are essential for biomass production. Reliance on synthetic fertilizers can reduce sustainability. Nutrient recycling through wastewater and anaerobic-digestion systems is therefore increasingly important.

15.4 Contamination and culture stability

Open systems can be affected by competing algae, bacteria, fungi, protozoa, zooplankton, and environmental fluctuations. Maintaining stable high-productivity cultures at industrial scale remains challenging.

15.5 Harvesting costs

Because algal cells are small and suspended at low concentrations, biomass recovery can represent a major fraction of total processing costs. Low-energy harvesting technologies remain a major research priority.

15.6 Product-market limitations

High-value compounds may improve economics but are often produced in limited quantities. Conversely, fuels are produced in large volumes but generally have lower market value. Successful biorefineries must balance these two categories.

15.7 Carbon permanence

The climate benefit of algal carbon capture depends on what happens to the captured carbon after biomass production. Temporary storage in biomass followed by rapid decomposition or combustion provides limited long-term removal.

16. Future Perspectives

The future of algal climate technology is likely to depend on integration rather than deployment of isolated processes. The most promising systems will connect carbon capture with wastewater treatment, nutrient recovery, renewable electricity, biomass valorization, and durable carbon products. Advanced photobioreactors may improve productivity and carbon-transfer efficiency, while optimized open systems may remain important for low-cost bulk biomass. Hybrid systems could combine controlled inoculum production with inexpensive large-scale cultivation. Synthetic biology may enable strains with improved carbon fixation, stress tolerance, and product formation. CRISPR-based engineering and metabolic pathway optimization are already being explored for developing strains tailored to particular biorefinery objectives [13]. AI-assisted process management may further improve performance by dynamically adjusting light, CO_2 delivery, nutrient supply, temperature, and harvesting. Digital twins and sensor networks could facilitate predictive control and early detection of culture instability. Another promising direction is the use of industrial waste CO_2 and wastewater as feedstocks. Such integration can transform waste-management costs into productive inputs. The combination of algae with anaerobic digestion may create nutrient and energy loops, while residual biomass can be converted into biogas, biochar, fertilizers, or other materials. Future research should also focus on durable carbon storage. Rather than directing all biomass toward short-lived fuels, a fraction could be incorporated into long-lived bioproducts or stabilized carbon materials where environmental safety and permanence can be demonstrated.

Table 3. Strategies for improving the sustainability of algal carbon-capture systems

Challenge	Potential strategy	Expected benefit
Low CO_2 transfer	Improved gas-transfer systems and reactor design	Greater carbon utilization
High energy use	Renewable electricity and low-energy mixing	Reduced carbon footprint
Nutrient costs	Wastewater and nutrient recovery	Lower input demand
Harvesting costs	Flocculation, filtration, membrane and hybrid methods	Reduced energy consumption
Contamination	Robust strains and controlled cultivation	Greater culture stability
Low fuel profitability	Multi-product biorefinery	Improved economic viability
Carbon re-emission	Durable materials and stable carbon products	Greater carbon retention
Process variability	AI and sensor-based control	Improved productivity
High freshwater demand	Saline water and treated wastewater	Reduced freshwater consumption
Biomass waste	Anaerobic digestion, biochar and fertilizer recovery	Near-zero-waste processing

17. Role in the Circular Bioeconomy

Algae can function as a biological bridge between waste streams and valuable products. In a circular system, carbon, nutrients, water, and biomass are continuously recycled rather than discarded. For example, wastewater provides nitrogen and phosphorus, industrial facilities provide CO_2, sunlight supplies renewable energy, and algae convert these inputs into biomass. High-value compounds can be extracted from the biomass, while residual material can be converted into energy, fertilizer, or carbon-rich products. This approach changes the conceptual role of algae from a simple biofuel crop to a multifunctional biological production platform. The emerging literature increasingly emphasizes this multi-product and resource-recovery perspective as an important pathway toward sustainable algal commercialization [7,16].

18. Conclusion

Algae provide a versatile biological platform for connecting carbon capture with renewable biomass production and circular-resource utilization. Through photosynthesis, microalgae and cyanobacteria can convert CO_2 into biomass while simultaneously producing oxygen. Their ability to grow rapidly, utilize diverse carbon sources, and accumulate proteins, lipids, carbohydrates, pigments, and other valuable metabolites creates opportunities extending far beyond conventional biofuel production. The greatest potential of algae is likely to emerge from integrated systems rather than isolated carbon-capture facilities. Coupling algal cultivation with industrial CO_2 emissions, wastewater treatment, nutrient recovery, renewable energy, and multi-product biorefineries can improve resource efficiency and potentially strengthen both environmental and economic performance. Recent research supports this integrated direction, while also emphasizing the importance of techno-economic analysis, life-cycle assessment, and process optimization [6,12,15]. Nevertheless, high harvesting and processing costs, energy requirements, contamination, nutrient demand, water management, and uncertain carbon permanence remain substantial barriers. Consequently, the amount of CO_2 fixed during algal growth should not be interpreted as equivalent to permanent carbon removal. The overall climate value depends on the complete life cycle and final fate of the biomass.

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