

Innovative Use of Algae for Carbon Sequestration and Renewable Energy Generation

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ABSTRACT

The global urgency to address climate change and reduce greenhouse gas emissions has driven the exploration of innovative technologies for carbon sequestration and renewable energy generation. Algae, with its rapid growth rate, high photosynthetic efficiency, and ability to thrive in diverse environments, has emerged as a promising solution. Algae can capture large amounts of atmospheric CO₂, making it an efficient carbon sink, while simultaneously producing biomass that can be converted into biofuels and other renewable energy sources. This article examines the potential of algae in carbon capture and highlights its role in generating biofuels, biogas, and hydrogen. It explores key innovations such as algae bioreactors, open-pond systems, and the integration of algae with wastewater treatment for enhanced carbon capture. The multifaceted benefits of algae, including its fast growth, non-competition with food crops, and versatile applications, position it as a critical tool in the global transition to cleaner energy. However, challenges such as production costs, water requirements, and scalability must be addressed for large-scale adoption. The future of algae-based carbon sequestration and renewable energy generation lies in continued research and technological advancement, offering a sustainable pathway toward mitigating climate change while meeting energy demands.

Keywords: Algae, carbon sequestration, renewable energy, *Chlamydomonas reinhardtii*, carbon concentration mechanism

Introduction

As global carbon dioxide (CO₂) emissions continue to escalate, driven by the combustion of fossil fuels and unsustainable industrial practices, the consequences of climate change are becoming more apparent and increasingly difficult to ignore. Rising temperatures, more frequent and intense weather events, and disruptions to ecosystems and agriculture highlight the urgent need for innovative solutions to mitigate these impacts [1]. Central to these efforts is the need to develop technologies capable of reducing atmospheric carbon while simultaneously providing sustainable alternatives to conventional energy sources, algae—a diverse group of photosynthetic microorganisms—has emerged as a promising solution. Algae, which includes microalgae and macroalgae (seaweed), has long been recognized for its remarkable photosynthetic efficiency and its ability to grow in diverse environments. Unlike terrestrial plants, algae does not require fertile land or large quantities of freshwater for cultivation, making it an appealing option for carbon sequestration and bioenergy production [2]. Algae can capture and utilize atmospheric CO₂ far more efficiently than most land-based plants, turning it into valuable biomass. This ability makes algae an effective tool for reducing greenhouse gas concentrations, thus offering significant potential to combat climate change. Moreover, algae can grow at exceptionally fast rates, with certain species doubling their biomass in just a few days, allowing for rapid carbon absorption, algae is increasingly being explored for its capacity to generate renewable energy. Algal biomass can be processed into a wide variety of biofuels, including biodiesel, bioethanol, and biogas, providing a sustainable alternative to fossil fuels [3].

Given the global demand for cleaner energy sources, algae-based biofuels are particularly attractive due to their potential to significantly reduce carbon emissions when compared to conventional fossil fuels, algae's versatility extends beyond biofuels. It can also be used to produce other valuable products such as animal feed, bioplastics, pharmaceuticals, and even hydrogen fuel under specific conditions. Recent advances in algal biotechnology have enabled the development of innovative systems for large-scale cultivation, including algae bioreactors and open-pond systems. These technologies are designed to maximize carbon capture and energy production efficiency, making algae a feasible option for industrial-scale applications, integrating algae with other processes—such as wastewater treatment and industrial emissions capture—enhances its overall environmental and economic viability, the innovative uses of algae for carbon sequestration and renewable energy generation [4]. By highlighting the advancements and challenges in these fields, we aim to underscore the importance of algae as a pivotal technology in addressing both climate change and energy security. With continued research and development, algae has the potential to play a crucial role in the transition toward a more sustainable, low-carbon future [11].

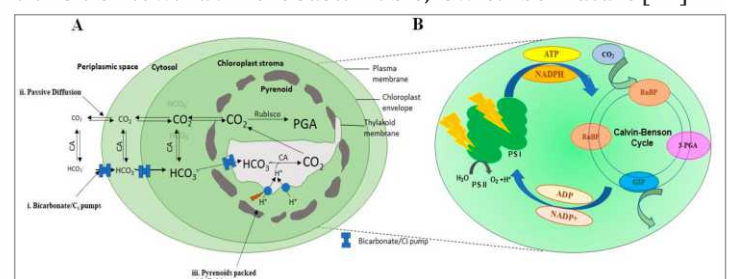


Fig 1: Adopted copyright permission from MDPI and Ref from [11]. The carbon concentration mechanism (CCM) in *Chlamydomonas reinhardtii* is a highly efficient process that enhances CO₂ fixation under low ambient CO₂ conditions. This mechanism involves multiple coordinated processes, including bicarbonate (HCO₃⁻) and inorganic carbon (Ci) pumps that actively transport Ci into the cell. These pumps ensure that even in CO₂-limiting environments, the algae can maintain high levels of Ci within its cells, which is then converted to CO₂ by carbonic anhydrases near the chloroplast. Along with this active transport, CO₂ can also enter the cell via passive diffusion through membrane pores, although this method is less effective in maintaining elevated internal CO₂ levels. Once inside, the CO₂ is concentrated in the pyrenoid, a specialized structure in the chloroplast packed with ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco), the enzyme responsible for fixing CO₂ during the Calvin–Benson cycle. The pyrenoid's microenvironment ensures high CO₂ concentrations near Rubisco, reducing the enzyme's interaction with O₂ and thereby minimizing photorespiration, which otherwise lowers photosynthetic efficiency. Inside the chloroplast, CO₂ undergoes fixation through the Calvin–Benson cycle, resulting in the production of organic compounds that fuel the algae's growth. This CCM, particularly the role of the pyrenoid and the active Ci transport systems, is critical for *Chlamydomonas reinhardtii* to thrive in low- CO₂ environments, allowing it to capture carbon effectively while optimizing photosynthesis.

1. Algae and Carbon Sequestration

Algae possess a remarkable ability to capture and utilize carbon dioxide (CO₂) due to their high photosynthetic efficiency, making them a highly promising candidate for carbon sequestration. During photosynthesis, algae absorb CO₂ from the atmosphere or from other sources such as industrial emissions, transforming it into oxygen and biomass. This biomass can then be processed into valuable products like biofuels, animal feed, and bioplastics, offering both an environmental and economic incentive for their cultivation [5]. Algae's versatility allows it to grow in a wide range of environments, including non-arable land, saline water, brackish water, and even wastewater. This flexibility reduces the competition for arable land and freshwater resources, which are often needed for traditional agricultural crops, while also mitigating the impact on food production. Given that CO₂ is a major contributor to global warming, finding innovative ways to capture and sequester it is a crucial step toward achieving climate goals. Algae-based carbon sequestration not only removes CO₂ from the atmosphere but also offers multiple downstream benefits, such as generating renewable energy, producing bio-based products, and improving water quality [6]. Several innovative methods of utilizing algae for carbon sequestration have gained prominence in recent years, including algae bioreactors, open-pond systems, and the integration of algae in wastewater treatment.

1.1 Algae Bioreactors

Algae bioreactors are highly efficient, closed-loop systems designed to cultivate algae while capturing CO₂ from industrial emissions, making them one of the most innovative solutions for carbon sequestration. In a typical setup, CO₂-rich flue gas from power plants, cement factories, or other heavy industries is directed into the bioreactor, where it is absorbed by the algae for photosynthesis.

This process transforms the CO₂ into biomass, which can then be harvested for various applications, including the production of biofuels, bioplastics, animal feed, and other valuable byproducts [7]. An important advantage of algae bioreactors is their scalability and adaptability. They can be customized to fit various industrial settings, from small-scale operations to large commercial installations. This makes them ideal for use in carbon-heavy industries, as they can be positioned near the source of emissions, minimizing transportation costs and logistical challenges associated with CO₂ capture [8]. Additionally, bioreactors operate in a controlled environment, which ensures optimized water and nutrient usage. This reduces waste and enhances the efficiency of algae growth, making bioreactors a highly resource-efficient solution for carbon sequestration, one challenge with algae bioreactors lies in their initial cost of construction and operation. Despite the high upfront costs, the long-term economic and environmental benefits, coupled with advancements in technology, are expected to make bioreactors more affordable and accessible in the future. Research continues to focus on improving the design and efficiency of bioreactors, such as enhancing light penetration, reducing energy inputs, and optimizing CO₂ absorption rates [9].

1.2 Open-Pond Systems

Open-pond systems represent another method for using algae in carbon sequestration. In these systems, large-scale open ponds are constructed in non-arable or degraded land areas to cultivate algae. Algae in these ponds absorb CO₂ directly from the atmosphere, functioning as a natural carbon sink. The high growth rate of algae in open-pond systems ensures a continuous cycle of carbon capture, making it a viable strategy for reducing overall greenhouse gas emissions [10].

One of the major advantages of open-pond systems is their simplicity and low cost of operation. These systems rely on natural sunlight and atmospheric CO₂, which minimizes the need for expensive infrastructure and energy inputs. In addition, open-pond systems can be scaled up relatively easily, covering vast areas of land to maximize carbon sequestration potential, open-pond systems face several challenges. Evaporation can lead to significant water loss, particularly in hot and arid climates, which may require frequent replenishment of water supplies. Additionally, these systems require large land areas, which could be a limiting factor in densely populated or land-constrained regions. Open-pond systems are also more vulnerable to contamination from other microorganisms and environmental factors, such as changes in temperature and light conditions, which can affect algae growth and carbon capture efficiency [12-13]. Researchers are working on mitigating these challenges by exploring innovative designs for open-pond systems, such as using semi-closed ponds or covering the ponds with transparent membranes to reduce evaporation and contamination. Despite these challenges, open-pond systems remain an attractive, low-cost option for large-scale carbon sequestration in regions where water and land resources are abundant.

1.3 Algae and Wastewater Treatment

Algae can also play a critical role in wastewater treatment, offering a dual benefit of carbon sequestration and nutrient recycling. Wastewater, particularly from agricultural runoff and industrial processes, often contains excess nutrients such as nitrogen and phosphorus, which can lead to environmental issues like eutrophication.

Algae can absorb these nutrients, promoting rapid growth while simultaneously capturing CO₂ from the atmosphere or from the wastewater itself [14]. Integrating algae cultivation with wastewater treatment has several advantages. First, it reduces the need for chemical fertilizers, as the nutrients present in the wastewater serve as a natural source of nutrition for the algae. Second, this process results in the production of algae biomass, which can be harvested and converted into biofuels or other bio-based products. Third, it enhances the overall sustainability of wastewater treatment by reducing the environmental footprint of the process. In addition to carbon sequestration, using algae in wastewater treatment helps improve water quality by removing contaminants and excess nutrients. This makes it an eco-friendly approach that addresses both water pollution and carbon emissions in a single solution. Furthermore, algae-based wastewater treatment systems are relatively low-cost and can be implemented in both urban and rural settings, making them a scalable option for various regions, algae-based carbon sequestration offers a range of innovative and sustainable solutions for addressing the urgent challenge of reducing CO₂ emissions [15]. From bioreactors to open-pond systems and wastewater integration, algae presents a versatile approach to capturing carbon while providing economic and environmental benefits. As research continues to improve the efficiency and scalability of these methods, algae has the potential to play a pivotal role in global efforts to mitigate climate change and promote a more sustainable future.

Table 1: Environmental Factors Affecting Algal Growth

Factor	Optimal Conditions	Impact on Growth	Impact on Carbon Sequestration
Light Intensity	High light intensity (e.g., > 400 $\mu\text{mol m}^2/\text{s}$)	Increases biomass production	Enhances carbon fixation rates
Nutrient Availability	High nitrogen and phosphorus levels	Stimulates algal growth	Improves efficiency of carbon uptake
Temperature	20°C - 30°C	Optimal growth rates for many algal species	Affects metabolic activity and photosynthesis efficiency
pH	Neutral to slightly alkaline (pH 7-8)	Promotes healthy algal growth	Influences bicarbonate availability for carbon capture

Table 2: Benefits of Algae in Carbon Sequestration and Renewable Energy

Benefit	Description	Impact on Sustainability
Fast Growth Rates	Algae can double their biomass in hours, enhancing carbon capture	Rapid response to CO ₂ emissions
Non-Competition with Food Crops	Algae can be cultivated on non-arable land and using wastewater	Minimizes land use conflict with food production
Versatile Applications	Can produce biofuels, bioplastics, and animal feed	Diversifies economic opportunities
Waste Reduction	Integrating algae in wastewater treatment minimizes pollution	Reduces environmental footprint of wastewater management

Table 3: Integrated Systems for Algal Carbon Sequestration

System	Description	Benefits	Challenges
Algae Bioreactors	Closed-loop systems for cultivating algae with industrial CO ₂ emissions	High efficiency in carbon capture and biomass production	Initial setup costs and operational management
Open-Pond Systems	Large-scale ponds in non-arable land for algal growth	Cost-effective and simple to implement	Water loss due to evaporation; space requirements
Wastewater Treatment Integration	Algae used in wastewater treatment to absorb nutrients and CO ₂	Dual function of treating water and capturing carbon	Variability in nutrient load and water quality

2. Algae for Renewable Energy Generation

Algae's ability to generate significant amounts of biomass makes it a prime candidate for renewable energy production. Several innovative methods have been developed to harness the energy potential of algae, offering sustainable alternatives to traditional fossil fuels [16].

2.1 Algae-Based Biofuels

Algae is particularly promising for biofuel production due to its high lipid content, especially in certain species. These lipids can be extracted and processed into biodiesel, a renewable and cleaner alternative to conventional diesel fuel. Algae-based biodiesel has the potential to significantly reduce carbon emissions compared to fossil fuels, as the carbon released during combustion is offset by the carbon absorbed by the algae during growth [17], algae can also be used to produce bioethanol, which is fermented from the carbohydrates in the algae biomass. The versatility of algae for various biofuels makes it an attractive option for diversifying the renewable energy landscape.

2.2 Algal Biogas

Anaerobic digestion of algae biomass produces methane-rich biogas, which can be used for electricity generation or heating. The anaerobic digestion process breaks down organic matter in

the absence of oxygen, releasing methane as a byproduct [12]. This methane can be captured and used as a clean energy source, reducing the reliance on natural gas and other non-renewable energy sources, the residual biomass from anaerobic digestion can be repurposed as fertilizer, contributing to a circular economy model and reducing the need for chemical fertilizers in agriculture.

2.3 Hydrogen Production

Hydrogen is another clean energy source that can be produced from algae. Under specific conditions, such as sulfur deprivation, certain species of algae produce hydrogen gas through photosynthesis. This process holds immense potential for the future of renewable energy, as hydrogen is a clean fuel with no greenhouse gas emissions [14]. Research is ongoing to optimize algae strains and cultivation conditions for commercial-scale hydrogen production, positioning algae as a key player in the hydrogen economy.

3. Benefits of Algae for Carbon Sequestration and Energy Generation

The use of algae for carbon sequestration and renewable energy generation presents a number of unique benefits that make it an attractive solution for addressing both environmental and energy challenges. Below are some of the key advantages

Fast Growth Rates: Algae have one of the highest growth rates among all photosynthetic organisms, with some species doubling their biomass in just a few hours or days. This rapid growth enables algae to capture large amounts of atmospheric carbon dioxide (CO₂) in a relatively short period, making it a highly efficient carbon sink. Compared to terrestrial plants, which require longer growing seasons and larger land areas, algae offer a much faster and scalable method for CO₂ capture [15].

No Competition with Food Crops: One of the main drawbacks of using traditional biofuel crops such as corn, soybeans, or sugarcane is that they compete for arable land, freshwater, and other resources needed for food production. Algae, on the other hand, do not require fertile land or freshwater for cultivation. They can grow in a variety of environments, including brackish water, saltwater, and even wastewater. This flexibility eliminates the need for land that could otherwise be used for growing food, reducing the pressure on global food security while still offering a viable biofuel option [6].

Versatile Applications: Algae's potential extends far beyond carbon sequestration and biofuel production. Algal biomass can be processed into a wide variety of products, ranging from biofuels (biodiesel, bioethanol, and biogas) to bioplastics, pharmaceuticals, animal feed, and even cosmetics. This versatility makes algae a highly valuable resource across multiple industries, providing economic benefits and creating opportunities for the development of new markets. Algae-based biofuels, for example, have been tested in aviation and other transport sectors as a sustainable alternative to fossil fuels, significantly reducing carbon emissions [7].

Waste Reduction: Algae's role in carbon capture can be further enhanced by integrating it with wastewater treatment systems. Algae thrive on the nutrients present in wastewater, such as nitrogen and phosphorus, which are essential for their growth. By using algae in wastewater treatment, harmful pollutants are removed from the water, reducing the risk of environmental degradation in aquatic ecosystems. This integration not only enhances the overall sustainability of water treatment processes but also results in the production of valuable biomass, which can be converted into bioenergy or used in agriculture as a biofertilizer [13].

Environmental Restoration: In addition to reducing CO₂ levels and providing a renewable energy source, algae cultivation can contribute to environmental restoration. Algal farms can be set up on degraded land or in contaminated water bodies, helping to restore these environments by absorbing excess nutrients, reducing the impacts of pollution, and providing habitat for aquatic organisms. The process of phytoremediation—using algae to remove toxic substances from the environment—offers a sustainable and natural method for rehabilitating ecosystems [2-4].

Energy Efficiency: Algae can convert sunlight into energy more efficiently than most terrestrial plants, thanks to their simple cellular structure and high photosynthetic efficiency. This translates into a higher energy yield per unit area when compared to traditional crops. Algae's ability to grow in closed-loop systems, such as bioreactors, allows for the controlled optimization of light, nutrients, and CO₂ levels, further improving energy production efficiency [8].

The energy-rich biomass produced from algae can then be converted into various forms of renewable energy, such as biofuels, biogas, and even hydrogen, which is emerging as a clean fuel option for the future.

Reducing Dependence on Fossil Fuels: Algae-based biofuels have the potential to replace a significant portion of the world's reliance on fossil fuels. By harnessing algae for energy production, we can reduce greenhouse gas emissions, decrease air pollution, and move closer to achieving energy independence. The ability of algae to sequester CO₂ while simultaneously producing energy-dense biomass is a major advantage in the global transition toward cleaner and more sustainable energy systems, algae offers a promising solution to the dual challenges of carbon sequestration and renewable energy generation. Its fast growth rate, versatility, lack of competition with food crops, and ability to reduce waste and pollution make it a key player in the global effort to mitigate climate change. As technological advancements continue to improve the scalability and efficiency of algae-based systems, the potential for algae to contribute to a more sustainable, low-carbon future becomes increasingly clear [9].

4. Challenges and Future Outlook

Despite the promise of algae for carbon sequestration and renewable energy generation, several challenges must be addressed to fully realize its potential. The cost of cultivating and processing algae at a commercial scale remains a significant barrier. Further innovations in bioreactor design, harvesting technologies, and strain optimization are necessary to reduce costs. Although algae can grow in various environments, large-scale cultivation requires significant water and nutrient inputs, which may limit the feasibility of algae-based carbon capture in water-scarce regions. Successful integration of algae systems with existing industrial and energy infrastructure will be key to widespread adoption. Advances in bioreactor technology, CO₂ capture efficiency, and algal strain improvement are critical to overcoming these challenges.

Conclusion

The innovative use of algae for carbon sequestration and renewable energy generation offers a promising solution to two of the most pressing global challenges: climate change and energy security. Algae's ability to capture CO₂ and generate biofuels, biogas, and hydrogen provides a multifaceted approach to creating a more sustainable energy future. While challenges remain, ongoing research and technological advancements are likely to unlock the full potential of algae, paving the way for its large-scale implementation. As the world transitions towards a low-carbon economy, algae is poised to play a central role in mitigating environmental impact and ensuring a sustainable energy supply.

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