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## Photosynthetic algae: A key player in carbon sequestration

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### ABSTRACT

The growing challenge of rising greenhouse gas emissions and climate change demands effective carbon mitigation strategies. Photosynthetic algae, including microalgae and macroalgae, offer a sustainable solution by capturing atmospheric CO<sub>2</sub> through photosynthesis while producing oxygen and valuable biomass. Algae contribute to nearly half of the oxygen on Earth and play a crucial role in the carbon cycle. Microalgae, such as *Chlorella* and *Diatoms* grow rapidly in freshwater and marine environments, efficiently accumulating biomass and lipids. Macroalgae, such as kelps and seaweeds, provide large-scale carbon sequestration through long-term oceanic deposition. Advances in biotechnology, such as improved photobioreactors, genetic engineering, and AI-driven optimization, have enhanced the feasibility of large-scale algae cultivation, when integrated with carbon sequestration or wastewater treatment. Despite challenges such as enzyme inefficiency and high costs, algae remain a versatile tool for reducing greenhouse gases, supporting biofuels, and promoting a low-carbon future through targeted research and policy incentives. This review focuses on exploring the ability of photosynthetic algal organisms as suitable instruments to mitigate carbon accumulation and enhance oxygen availability in the environment.

**Keywords:** Photosynthetic algae, Carbon sequestration, Oxygen production, Environmental sustainability, Carbon fixation, CO<sub>2</sub> emission.

### INTRODUCTION

As global carbon dioxide (CO<sub>2</sub>) emissions from fossil fuels and industrial activities continue to rise, climate change effects such as extreme weather, rising temperatures and ecological disruptions have become increasingly evident. Innovative solutions are urgently needed and photosynthetic algae offer significant promise in carbon mitigation. These organisms convert CO<sub>2</sub> and water into organic matter and oxygen through photosynthesis, contributing to nearly half of global oxygen production and playing a vital role in the carbon cycle. Algae can capture and fix atmospheric CO<sub>2</sub> far more efficiently than most land-based plants. Their rapid growth, with some species doubling biomass in just a few days, enables high carbon absorption in short timeframes. This fixed carbon is stored as biomass or transferred to deep sea sediments contributing to long term sequestration. Algal biomass is also a valuable resource for producing renewable biofuels including biodiesel, bioethanol, and biogas [1]. Advancements in algal biotechnology have enabled large scale cultivation using systems like open ponds and photobioreactors. These systems can be integrated with industrial emission sources and wastewater treatment, enhancing both carbon capture and sustainability. With their adaptability, fast growth and efficient photosynthesis, eco-friendly solution for reducing greenhouse gases and supporting renewable energy development [2].

### CLASSIFICATION OF PHOTOSYNTHETIC ALGAE

Photosynthetic algae are a diverse group of organisms unified by their ability to perform oxygenic photosynthesis. They are broadly categorized into microalgae and macroalgae are distinguished by their size, structure, and ecological roles.

**Microalgae:** Microalgae are unicellular or simple multicellular organisms that typically inhabit freshwater and marine environments. They may be free-floating or attached to substrates and are usually microscopic. Microalgae are efficient at converting solar energy into biomass and contribute significantly to global oxygen production. Due to their rapid growth and high lipid content, they are increasingly being studied for biofuel and biotechnology applications. These organisms include several major groups.

1. Green microalgae (Chlorophyta): These algae contain chlorophyll a and b and store starch as a carbohydrate reserve. Common genera include *Chlorella*, *Scenedesmus*, and *Dunaliella*. *Chlorella* can grow at 40 % CO<sub>2</sub> concentration and its powerful biological carbon sequestration efficiency is 10-50 times higher than terrestrial plants [3].

2. Diatoms (Bacillariophyta): Characterized by their silica-based cell walls (frustules), diatoms are key components of phytoplankton and play a significant role in primary marine productivity. Example: *Paralia sulcata*.

3. Dinoflagellates (Dinophyta): These algae are often motile, with two flagella, and are known for their role in red tides and bioluminescence. Example: *Noctiluca scintillans*

**Macroalgae:** Macroalgae are ecologically significant as they provide habitat and food for marine organisms, contribute to nutrient cycling, and participate in carbon fixation and storage in coastal ecosystems. Macroalgae, commonly referred to as seaweeds, are large multicellular algae found primarily in marine environments, although some species occur in freshwater [4]. They are categorized into three major phyla:

1. Brown algae (Phaeophyceae): These include the largest seaweeds, such as kelps which form underwater forests. They contain the pigment fucoxanthin, which imparts a brown color. Example: *Laminaria*

2. Red algae (Rhodophyta): These are typically found in deeper waters and are rich in the pigment phycoerythrin. Notable genera include *Gelidium* and *Gracilaria*, which are often used in agar and carrageenan production. Example: *Chondrus crispus*

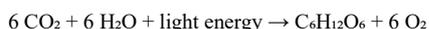
3. Green algae (Chlorophyta): Structurally similar to green microalgae, green macroalgae such as *Ulva* (sea lettuce) are commonly found in coastal areas. Example: *Chlamydomonas reinhardtii*.

### OXYGEN GENERATION BY PHOTOSYNTHETIC ALGAE

Photosynthetic algae play a fundamental role in maintaining atmospheric oxygen levels, supporting life on Earth by continually replenishing the oxygen consumed by respiration and combustion. Their contribution is both vast and efficient, owing to their biological structures and ecological distribution. Most microalgal strains are photoautotrophic and use light as an energy source. The physicochemical process of microalgal photosynthesis converts inorganic carbon into organic molecules (carbohydrates) and releases molecular O<sub>2</sub> [5]. Algae, particularly phytoplankton in the oceans, are responsible for producing a significant portion of the Earth's oxygen, estimated to be between 30% and 50% [6]. Through photosynthesis, they not only release oxygen but also regulate carbon dioxide levels, influencing climate and air quality [4].

### Mechanism of Oxygen Generation

The photosynthetic process in algae involves the conversion of light energy into chemical energy using water as an electron donor [7]. The general photosynthetic reaction is as follows:



During the light reaction, water molecules are split (photolysis) in thylakoid membranes of the chloroplasts. This reaction releases electrons, protons, and oxygen (O<sub>2</sub>). Electrons are used to synthesize ATP and NADPH, which are later used in the Calvin cycle (light-independent reactions) to fix carbon dioxide into organic molecules. Algal pigments, including chlorophylls, carotenoids, and phycobilins, absorb light energy at different wavelengths, enabling algae to thrive at various depths and lighting conditions in aquatic environments.

**Photosynthetic Efficiency:** Algae are highly efficient phototrophs due to their unique biological traits. Microalgae have a high surface area to volume ratio, enhancing light and nutrient absorption for rapid growth and oxygen production. Their fast reproduction rates enable frequent biomass doubling, supporting continuous oxygen generation.

Algae possess diverse pigments that capture light across various wavelengths, making them more effective under different lighting conditions than terrestrial plants. In controlled systems like photobioreactors, microalgae exhibit photosynthetic efficiencies surpassing conventional crops, making them ideal for oxygen generation in closed environments and sustainable technologies.

### CARBON SEQUESTRATION BY PHOTOSYNTHETIC ALGAE

Carbon sequestration refers to the process of capturing and storing carbon compounds from the environment, thereby reducing the greenhouse effect and mitigating climate change [8]. Algae are powerful carbon sequestration agents that capture atmospheric carbon dioxide (CO<sub>2</sub>) and convert it into organic compounds through photosynthesis. This not only supports their growth but also contributes significantly to the mitigation of global carbon levels. Their biological pathways and structural adaptations make them efficient in carbon uptake and storage, both short-term in biomass and long-term through sedimentation. Microalgae are able to convert solar energy into chemical energy at a rate much higher than that of even the most efficient plants (C4 plants) [9].

The efficiency of carbon sequestration by algae is governed by a combination of environmental and physiological factors that influence both photosynthetic activity and the long-term storage of carbon in biomass or sediments. Key variables include carbon dioxide concentration, light intensity, nutrient availability, temperature, and oxygen levels [10]. Algal species without efficient carbon concentrating mechanisms (CCMs) benefit more from elevated CO<sub>2</sub> levels, while those with CCMs show a limited response. Light intensity directly affects the rate of photosynthesis with optimal levels enhancing carbon fixation, whereas too much light can cause photoinhibition and too little can limit growth. Nutrient rich environments support rapid algal proliferation and biomass accumulation, while nutrient limitations reduce photosynthetic efficiency, even under favorable CO<sub>2</sub> and light conditions. Temperature influences enzymatic activity and metabolic processes. Oxygen concentration also plays a crucial role as high oxygen levels can increase photorespiration, especially in species with less selective RuBisCO enzymes, while low oxygen may trigger alternative less efficient metabolic pathways. These interacting factors create a dynamic environment where algal carbon sequestration varies widely depending on specific conditions and species traits.

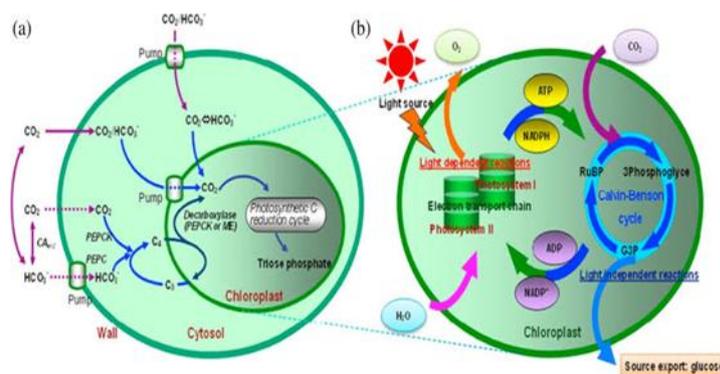


Figure 1: Carbon fixation pathway

Source: Shupin Zhang et al., 2021 [11]

**Carbon Fixation Pathways:** Photosynthetic algae predominantly utilize the Calvin-Benson cycle for carbon fixation. In this cycle, CO<sub>2</sub> is assimilated into 3-phosphoglycerate (3-PGA) through the action of the enzyme RuBisCO (ribulose-1, 5-bisphosphate carboxylase/oxygenase). Some algal groups, especially under low CO<sub>2</sub> conditions, also engage auxiliary mechanisms, such as C<sub>4</sub>-like pathways or β-carboxylation, enhancing their carbon fixation efficiency (Figure 1). Additionally, some microalgae possess carbon

concentrating mechanisms (CCMs) that actively transport inorganic carbon (as CO<sub>2</sub> or bicarbonate) into the cell, thereby maintaining high local concentrations near RuBisCO and minimizing photorespiration.

#### APPLICATIONS ASPECTS OF CARBON SEQUESTRATION

Algae have gained prominence in recent years for their potential in carbon capture, utilization and storage (CCUS) offering a sustainable strategy to mitigate climate change. Their rapid growth, high CO<sub>2</sub> fixation efficiency and adaptability make them ideal candidates for bio-based climate solutions. In algae based CCU systems, CO<sub>2</sub> rich gases from sources like power plants and industrial facilities are directed into cultivation systems such as open ponds or photobioreactors. Algae absorb CO<sub>2</sub> through photosynthesis converting it into biomass. Technological advancements including artificial intelligence and system optimization have further improved the efficiency and scalability of these systems. The biomass produced

can be utilized in various applications. Lipid rich algae are processed into biofuels such as biodiesel, bioethanol, and biogas<sup>[12]</sup>. Protein rich algal biomass serves as a nutritious feed source for livestock and aquaculture. Algae can also be refined into bioplastics and biochemical contributing to a circular bioeconomy. Post extraction residues are rich in nutrients and used as fertilizers or soil conditioners. Additionally, algal biomass can be converted into biochar for long term carbon storage in soils or intentionally sunk into the deep ocean to enhance permanent sequestration. These diverse applications highlight algae's critical role in carbon management and sustainable resource development.

#### CHALLENGES AND LIMITATIONS OF ALGAL CARBON SEQUESTRATION

Despite the potential of photosynthetic algae in carbon capture, several challenges hinder their large-scale implementation. A major biological limitation is the low efficiency of RuBisCO, the key enzyme in CO<sub>2</sub> fixation which also reacts with O<sub>2</sub> leading to photorespiration and reduced carbon capture. While some algae possess carbon concentrating mechanisms (CCMs) to improve efficiency, these require additional energy and may not perform consistently in all environments. Scaling up algal cultivation also presents technical difficulties. Open pond systems are economical but vulnerable to contamination and low productivity whereas closed systems are costly and complex. Large scale operations demand high inputs of water, nutrients, CO<sub>2</sub> and harvesting biomass efficiently remains a major hurdle. Environmental factors such as fluctuating light, temperature, nutrient levels and water quality further impact algal growth and sequestration efficiency. Strain selection adapted to local conditions is essential for stable and productive cultivation. Addressing these challenges is critical for realizing the full potential of algae in climate mitigation<sup>[13]</sup>.

#### FUTURE DIRECTIONS FOR ALGAL CARBON SEQUESTRATION

Microalgae are promising agents for carbon sequestration due to their rapid growth, high carbon fixation efficiency, and ability to thrive in diverse environments, including non-fertile land and wastewater<sup>[14]</sup>. To unlock their full potential, future efforts must focus on synthetic biology, hybrid systems, and supportive policy frameworks. Synthetic biology can enhance algal performance by engineering more efficient RuBisCO enzymes, strengthening carbon concentrating mechanisms (CCMs), and optimizing carbon storage pathways. Hybrid systems combining algae with CO<sub>2</sub> scrubbers, wastewater treatment, and bioenergy setups improve scalability and efficiency. Innovations like microbubble-assisted photobioreactors further boost CO<sub>2</sub> capture by increasing gas liquid contact. Policy support is vital for large scale deployment, including integrating algal carbon capture into carbon credit markets, funding research and development, regulating genetically modified strains and fostering public-private partnerships.

Together, these approaches can position algae as a key player in global carbon management and climate mitigation<sup>[15]</sup>.

#### CONCLUSION

Photosynthetic algae play a fundamental role in maintaining the Earth's atmospheric balance by serving as primary oxygen producers and efficient agents of carbon sequestration. Through oxygenic photosynthesis, they contribute significantly to global oxygen output, supporting aquatic and terrestrial life. From microalgae such as *Chlorella*, *Scenedesmus*, *Spirulina*, and cyanobacteria to macroalgae such as seaweeds, these diverse organisms exhibit specialized adaptations, such as carbon-concentrating mechanisms and pyrenoids that optimize carbon fixation even in fluctuating environments. While they offer immense potential in biotechnology, including biofuel production and CO<sub>2</sub> mitigation, challenges remain in enzyme efficiency, large-scale cultivation, and environmental variability. Integrating algae into broader carbon capture and utilization strategies will not only reduce greenhouse gas emissions but also drive innovation in the emerging green economy.

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