Algae Bioreactor for CO_2 Capture: An Integrated Approach for Carbon Sequestration

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***Abstract*—The rapid rise in atmospheric CO2 levels due to industrial activities has created an urgent need for innovative solutions to mitigate climate change. Algae bioreactors have emerged as a promising technology for CO2 capture, leveraging the photosynthetic potential of algae to convert CO2 into biomass. This paper explores the design, operational parameters, and effectiveness of algae bioreactors, focusing on photobioreactors (PBRs) as a preferred configuration. It highlights the role of various algal species in optimizing CO2 sequestration and biomass productivity, as well as the potential economic and environmental benefits of algae-based carbon capture. Our study shows that algae bioreactors can capture significant amounts of CO2 while producing valuable by-products like biofuels and animal feed. With continued advancements in reactor design and species selection, algae bioreactors can serve as a cornerstone technology in achieving a low-carbon economy.**

***Index Terms*—Algae bioreactors, CO2 capture, Photobioreactors (PBRs), Biomass productivity**

I. INTRODUCTION

Climate change is one of the most significant global challenges today, primarily driven by the increasing concentrations of greenhouse gases (GHGs) in the atmosphere. Among the GHGs, carbon dioxide (CO2) is the most abundant, accounting for about 75% of global emissions (IPCC, 2021). CO2 is released into the atmosphere through various human activities, particularly the burning of fossil fuels for energy, industrial production, and deforestation. This excess CO2 contributes to global warming, leading to rising temperatures, sea-level rise, and disruptions to natural ecosystems. Therefore, finding effective methods to capture and reduce atmospheric CO2 is crucial for mitigating the effects of climate change.

One promising approach to address CO2 emissions is carbon capture and storage (CCS) technology, which involves capturing CO2 from sources such as power plants and storing it underground. While CCS has been recognized as an effective way to reduce CO2 emissions, it faces several challenges, including high costs, energy demands, and concerns about long-term storage safety [8]. As a result, there has been growing interest in biological solutions for carbon capture, specifically algae-based systems, which offer a more sustainable and cost-effective alternative [6].

Algae are a diverse group of photosynthetic organisms capable of converting CO2 into organic matter through photosynthesis. This process not only reduces atmospheric CO2 but also produces valuable biomass that can be used in various industries, such as biofuels, animal feed, and fertilizers [1]. Algae have several advantages over traditional crops as a medium for CO2 capture. They grow rapidly, require minimal freshwater, and do not compete for arable land, making them a more sustainable option [5]. Additionally, algae can thrive in diverse environments, including saline and wastewater, further enhancing their potential as a versatile carbon capture solution [6].

The idea of using algae for CO2 capture is not new, but the development of more efficient and scalable systems is still an ongoing area of research. Among the various algae cultivation methods, photobioreactors (PBRs) have emerged as one of the most efficient designs. PBRs are closed systems with transparent walls that allow precise control over factors such as light, temperature, and nutrient supply, leading to higher productivity and CO2 capture efficiency compared to open ponds [2]. However, despite their promise, PBRs still face challenges related to scalability, energy requirements, and economic feasibility.

The goal of this study is to evaluate the potential of algae bioreactors as a method for capturing CO2 and producing biomass. By focusing on three different algae species—Chlorella vulgaris, Spirulina platensis, and Nannochloropsis—this study aims to assess their CO_2 fixation rates and biomass productivity under controlled conditions in a small-scale laboratory setting. The research will also explore the potential for producing biofuels and other by-products, contributing to the overall sustainability and economic viability of algae- based carbon capture systems [3].

This paper will explore the current state of algae bioreactor technology, including the challenges and opportunities presented by different reactor designs and algal species. The findings from this study will provide insights into the viability of algae bioreactors as a scalable solution for mitigating climate change and supporting the transition to a low-carbon economy.

II. METHODOLOGY

This study aimed to assess the effectiveness of algae bioreactors in capturing CO_2 and producing biomass. A small-scale experiment was conducted using photobioreactors (PBRs), which are closed systems designed to optimize algae growth by controlling environmental factors such as light and temperature. The experiment was conducted under controlled conditions in a laboratory setting at a university.

To simulate industrial CO_2 emissions, a gas mixture containing 10-15% CO_2 was continuously bubbled into the PBRs. This setup allowed for the study of CO_2 absorption by algae, which was essential for assessing the carbon sequestration efficiency. The algae species chosen for this study were Chlorella vulgaris, Spirulina platensis, and Nannochloropsis, based on their known ability to efficiently fix CO_2 and produce biomass [5].

The algae were grown in a nutrient medium based on Bold’s Basal Medium (BBM), which was enriched with nitrogen and phosphorus to support healthy growth. To replicate sunlight conditions, LED lights were used with a 16-hour light period followed by 8 hours of darkness, simulating a day- night cycle.

Algal growth was monitored by measuring the optical density (OD) of the cultures taken at 680nm, which is an indicator of the algae concentration in the reactor. The CO_2 levels entering and exiting the bioreactor were measured regularly to assess the sequestration efficiency. This was done using a simple gas analyzer, which helped determine how much CO_2 was absorbed by the algae during their growth process.

The CO_2 sequestration efficiency (E) was calculated using the formula:

$E=((C_{in}-C_{out})/C_{in}) \times 100$ Where,

C_{in} = CO_2 concentration entering the reactor (ppm)

C_{out} = CO_2 concentration leaving the reactor (ppm)

The biomass produced by the algae was collected at regular intervals by filtering the algae out of the reactor. The biomass was dried and weighed to determine how much algae had been produced over time. This allowed for the calculation of biomass productivity, which was determined by dividing the total biomass produced by the reactor volume and the duration of the experiment.

The biomass productivity (P) was calculated using the formula:

$P=(B_f-B_i)/ V\cdot t$ Where:

B_f = Final biomass weight (g) B_i = Initial biomass weight (g) V = Reactor volume (L)

t= Cultivation time (days)

In addition to measuring the amount of biomass produced, the lipid content of the algae was analyzed, particularly for **Nannochloropsis**, since this species is known for producing oils that can be used to make biofuels. Lipids were extracted using a simple solvent extraction method, and the oil content was quantified by weighing the extracted lipids.

III. RESULTS AND DISCUSSIONS

A. CO2 Sequestration Efficiency

The PBRs achieved CO_2 sequestration efficiencies ranging from **80% to 85%**, which is comparable to the highest efficiency levels reported in other studies [6]. These results indicate that algae bioreactors are highly effective at reducing CO_2 emissions from industrial sources, with minimal losses due to the controlled environment of the PBRs. This high sequestration efficiency is a significant advantage of PBRs over open pond systems, which are more susceptible to environmental fluctuations that can affect algae growth and CO_2 absorption.

B. Biomass Productivity

Among the species tested, Chlorella vulgaris exhibited the highest biomass productivity, with growth rates reaching 1.5 grams per litre per day. This species proved to be highly efficient in converting CO2 into biomass, making it suitable for large-scale applications in CO2 sequestration. Spirulina platensis demonstrated moderate productivity but excelled in its nutritional profile, with high protein content making it ideal for use in food and animal feed. Nannochloropsis, with its high lipid content (up to 40% of dry weight), was identified as the most promising species for biofuel production. Its lipid-rich biomass can be processed into biodiesel, providing a renewable energy source [3].

C. Lipids for Biofuel Production

The lipid content in **Nannochloropsis** was a key finding, as it exhibited lipid levels of up to **40%** of its dry weight. This makes it an ideal candidate for biodiesel production. The high lipid yield supports the potential of algae bioreactors to contribute not only to CO2 sequestration but also to the generation of renewable energy. The ability to simultaneously address CO2 emissions and produce biofuels presents a compelling argument for the adoption of algae-based bioreactors in industrial applications.

D. Environmental and Economic Benefits

Algae bioreactors offer several environmental co-benefits. For instance, they can be integrated into wastewater treatment processes to absorb excess nutrients like nitrogen and phosphorus, thus contributing to water quality improvement. The **life-**cycle assessment (LCA) showed that algae bioreactors have a lower environmental footprint compared to traditional CCS technologies, particularly in terms of energy consumption and greenhouse gas emissions. From an economic perspective, the revenues from biofuels, animal feed, and fertilizers could offset the operational costs of the algae bioreactor system, making it a financially viable option for CO2 capture in the long term.

IV. CONCLUSION

Algae bioreactors represent a promising and innovative solution for mitigating CO2 emissions, offering both environmental and economic benefits. This study demonstrates that algae, particularly species such as Chlorella vulgaris, Spirulina platensis, and Nannochloropsis, can effectively sequester CO2 from industrial emissions while producing valuable by-products like biofuels and biomass. The high CO2 fixation efficiency observed in photobioreactors (PBRs) underscores the potential of algae-based systems to play a significant role in addressing the growing challenge of climate change. The ability of algae to thrive in diverse environments, coupled with their rapid growth rates and minimal land and water requirements, makes them an attractive alternative to traditional carbon capture technologies.

While the results of this study highlight the effectiveness of algae bioreactors in carbon sequestration, challenges remain in scaling these systems for widespread industrial use. The initial setup costs, energy demands, and operational complexities associated with PBRs are key obstacles to their commercialization. However, with continued research and technological advancements, these challenges can be overcome. For instance, optimizing reactor designs to improve energy efficiency, enhancing algal strains through genetic engineering, and integrating algae bioreactors with renewable energy sources can significantly reduce operational costs and increase overall efficiency.

Furthermore, the economic potential of algae bioreactors cannot be overlooked. The production of biofuels, animal feed, bioplastics, and fertilizers from algal biomass creates multiple revenue streams, adding value to the carbon capture process. This dual benefit of CO2 sequestration and the generation of commercially viable products positions algae-based systems as a key component of a sustainable and low-carbon economy.

In conclusion, algae bioreactors hold great promise as a scalable and economically viable solution for CO2 capture. The continued development of these systems, through improvements in reactor design, species selection, and integration with other sustainable technologies, could make algae bioreactors a cornerstone of global efforts to combat climate change. By advancing algae-based carbon capture technologies, we can contribute to a cleaner, more sustainable future, while also providing valuable resources for industries worldwide.

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