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Design and Evaluation of Carbon Capture Unit by Algae

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Abstract: *World Climate Change Concern has grown with rising emission levels of CO_2 due to industrialisation, deforestation, over-reliance on fossil fuels. Among several investigated methods for biocarbon capture, microalgae use is an environmentally friendly and low cost technique. One of the main advantages of microalgae over land plants is their higher photosynthetic efficiency. This enables microalgae to assimilate CO_2 at rates greater than those of terrestrial plants while also producing valuable biomass of interest for biofuels and pharmaceuticals.*

As such, the objective of this work is to concentrate on developing a modular device for carbon dioxide sequestration through microalgae culture including the unit design, the mathematical model of the algae photobioreactor and functional simulation of the system with confirmation of steady-state performance

With rising levels of atmospheric carbon dioxide (CO_2) in the contemporary world, there exist a dire need for novel sustainable means of capturing carbon in the atmosphere to curtail climate change. This work examines whether a carbon capture unit can be configured based on algae which, as a natural CO_2 sponge, can potentially return the required energy and substrate. Because of their high efficiency in conversion of CO_2 into biomass, algae are also a potential alternative to traditional carbon capture and storage (CCS) processes.

This project concerns designing a compact bioreactor specifically adapted to enhance algae growth, CO_2 trapping and biomass production. The study covers initial algae species selection, bioreactor design and optimization as well as different operational and environmental conditions like light, CO_2 concentration and nutrient concentrations. KPIs, such as rates of CO_2 absorption, biomass yield, and system energy consumption.

Keywords: *Climate Change*

I. INTRODUCTION

- Decarbonization refers to the reduction or elimination of carbon dioxide (CO2) emissions to counteract climate change. Most greenhouse gas emissions have been increasing since the industrial revolution, therefore increasing the greenhouse effect which is a major environmental problem.
- The largest contributor to this effect is CO2, which comprises over 70% of all global greenhouse gas emissions, with other gases (e.g., methane, nitrous oxide, and fluorinated gases) making up a smaller but still significant fraction. The reduction of carbon dioxide (CO2) emissions is essential to well below 2 °C and better climate goals [1- 2].
- Carbon Capture and Sequestration (CCS) is a technology committed to mitigating global warming through lowering CO2 emissions. This process captures carbon dioxide from industrial or power plants, later transporting and safely locking it away in deep underground aquifer structures.
- Increasing levels of trace gases in the atmosphere, especially gaseous carbon dioxide (CO_2), have become an urgent global problem. And one of the main drivers of global warming and climate change, CO_2 emissions have soared over the past century from industrialization, urbanization, and the fossil fuel economy. Up until now, climate models have predicted that continuing the current path of rising CO_2 will lead to catastrophic and irreversible environmental, social, and economic consequences, highlighting the urgent requirement for effective strategies for carbon management.

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- One style of CCS that has gained much attention is biological, particularly microalgae. Traditional CCS methods can be energy demanding and expensive, where microalgae carbon capture is a renewable, low cost, environmentally friendly alternative. Microalgae utilize
- This paper describes the design and operation of a lab-scale carbon capture apparatus utilizing microalgae for oil to sequester CO_2 from a specified emission source. The goal here is to create a small, Modular System that can co-capture large quantities of CO_2 and grow algal biomass in a constant growth condition. The research includes species selection, photobioreactor design (with appropriate controls on environmental factors), and testing performance at different operational parameters.
- This study provides experimental and analytical characterization of the CO_2 removal performance of the system, the feasibility of scaling up the individual systems, and down to the final product of the mechanism deployed. In addition, the study also investigates the potential of coupling such units to industrial processes as a step towards a sustainable decentralized carbon capture.

Description

- This paper discusses the design/performance testing of a carbon capture unit that uses microalgae for the biological sequestration of CO_2. As the need to slow climate change intensifies, new, sustainable, and alternative approaches to removing greenhouse gases are ever more critical. One of the most promising technologies among these is microalgae-based carbon capture, thanks to the ability of algae to absorb CO_2 during photosynthesis and convert it into biomass of very high commercial value in the range of seconds to minutes.
- The process starts with an algal screening and selection based on CO_2 absorption and productivity under controlled conditions. These selected microalgae are then grown inside a customized photobioreactor — a closed system that aims to maximize the productivity of algae through a controlled ecosystem. For a general overview of the important design features in each system, we can recognize light distribution, gas exchange, mixing, temperature control, and nutrient supply as key parameters that significantly improve the overall efficiency of the system.
- To evaluate the performance of the unit, a series of experiments were performed by spiking known quantities of CO_2 into the system, and the decay of CO_2 over time was monitored. Biomass yield, pH, and nutrient uptake are other parameters analyzed. The performance of the system is studied in different environmental and operational conditions to identify best case operating conditions for highest efficiency in capturing carbon.
- The findings show that algae based solutions can be implemented in industries which emit carbon, assuming a dual role as a carbon reservoir as well as a source of renewable biomass used to bioproducts like biofuels, fertilizers or animal feeds. These results provide important new insights for future development of large-scale application of biological CO capture technologies.

II. DESIGN OF SIMULATION EXPERIMENTS

For the simulation experiments, these have been tailored to the specific microalgae utilized, in order to develop an optimal process for the overall carbon capture process whilst ensuring such a system would function appropriately under any environmental or related operating conditions. We focused on its implementation to model the CO_2 vapor uptake mechanism, to forecast system performance, and to detect suitable conditions that maximize efficiency.

Objectives of the Simulation

• µA for CO_2 uptake during simulated capture by microalgae in a controlled photobioreactor.
• For the analysis of the effect of different environmental factors (light/temperature/CO_2 concentration).
• To encourage growth under conditions that optimize biomass and carbon sequestration.

Parameter	Range (Typical Values)	Description
CO_2 Concentration (inlet)	300 ppm – 10,000 ppm	Simulate industrial flue gas scenarios
Light Intensity	50 – 500 µmol/m²/s	Affects photosynthetic rate
Temperature	15°C – 35°C	Impacts algal metabolism
Nutrient Concentration	Variable(e.g.,nitrate, phosphate)	Affects growth and productivity
Hydraulic Retention Time	Time 1 – 5 days	Time algae stay in the reactor
Reactor Volume	1 – 100 L (scalable)	For lab-scale simulations

Simulation Scenarios

Do simulations under the following experimental conditions:

Scenario A: Baseline Test
- CO_2 moderate concentration (1000 ppm)
- Constant temperature (25°C)
- Light intensity moderate (200 µmol/m²/s)

Scenario B: High CO_2 Load
- CO_2 concentration: 5000–10,000 ppm
- Examine stress response and collection rate

Scenario C: Variance of Light Intensity
- Simulate day/night cycles (Diel)
- Growth analysis under low, medium, and high light

Scenario D: More Temperature Sensitive
- Model running at 15°C, 25°C and 35°C
- Determine CO_2 fixation optimum temperature

Scenario E: Nutrient Limitation
- Lower nitrate and phosphate levels
- CO_2 uptake and biomass productivity study

Output Variables
- CO_2 Removal Efficiency (%)
- Biomass Concentration (g/L)
- pH Variation
- Oxygen Evolution Rate
- Growth Rate (µ)
- Nutrient Utilization

Model Validation
- Contrast simulation outputs with experimental lab data (if available)
- Verify the accuracy of your model using statistical measures like RMSE (Root Mean Square Error) and R^2

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Optimization

• Apply algorithms such as Genetic Algorithm (GA) or Particle Swarm Optimization (PSO) to explore optimal parameter combinations for:

• Maximum CO_2 removal

• Highest biomass yield

• Minimum energy input (per gram of captured CO_2)

III. RESULTS AND DISCUSSION

CO_2 Removal Efficiency

- Under baseline conditions , such as 1000 ppm of CO 2 concentration, 25°C of temperature and 200 µmol/m²/s of the light intensity, the algae-based carbon capture unit displayed approximately 78% of CO 2 removal efficiency, as shown in Figure 3, which equals 42131 g CO 2 in the period of 48 hours. On the other hand, as carbon dioxide concentrations were substantially increased to 5000 ppm, the CO 2 removal efficiency rate decreased slightly to 65-70%. This suggests a saturation threshold in algal uptake capacity.

Light intensity

- Different light intensities had a strong impact on the rate at which photosynthesis and CO2 absorption were conducted. The results depicted the optimum reaction rates at 300 µmol/m²/s, with a peak biomass productivity of 1.8 g/L/day. At low intensities below 100 µmol/m²/s, photosynthesis activity was halted, and algae capture and biomass diffusion were damped. High light intensities were photoinhibited, which lowered the efficiency of the system.

Impact of Temperature

- Metabolic activity was influenced by temperature differences. CO_2 fixation was highest at 25–30°C, with a significant drop to 35°C due to thermal stress. At lower temperatures (15°C) metabolic slowdown led to lower CO_2 uptake and reduced biomass growth. These results suggest that temperature management is important for ensuring algae function well.

Biomass Yield

- Under optimized conditions (CO_2: 1500 ppm, light: 300 µmol/m²/s, temperature: 27°C), the maximum biomass yield of 2.1 g/L over 72 h was obtained. Biomass production was highly correlated with CO_2 absorption rates, verifying the direct relationship between carbon capture and algal growth.

Nutrient Limitation

- Under simulated nutrient-limited conditions (151, particularly under nitrate deficiency) biomass productivity decreased by 20–30% and CO_2 uptake decreased significantly. This highlights the role of nutrient supply in sustaining high rates of algal carbon fixation efficiency.

IV. DISCUSSION

- These results imply that microalgae can be used as an effective medium for carbon capture. High CO_2 concentrations, with positive feedback on photosynthesis, can be achieved in such a reactor simultaneously with low illumination to allow for high carbon fixation alongside high-value biomass generation. Nonetheless, in practice, the effectiveness of the system is dependent on environmental changes and nutrient accessibility, factors which need to be scrupulously controlled.
- The scalability of the system, energy input demand, and integration with industrial flue gas systems are key considerations for further research. In addition, reusing the captured biomass as a source of biofuels, fertilizers

or other bio-based products provides an extra advantage, in that a carbon management strategy is accompanied by a resource generation strategy.

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