Design and Evaluation of Spirulina Algae Biofilter Using Exhaust Fan for Industrial Flue Gas Mitigation and Biomass Generation

Amyra Pasricha[1], Hitendra Vaishnav[2]
[1]*Vasant Valley School*

Abstract
This study demonstrates the design and testing of a biofilter system that uses Spirulina algae to dissipate flue gas emissions from industry while producing biomass. In following the urgent call for affordable carbon capture technology, this study approaches Spirulina, an algae that has an economic and environmental appeal because of its high rates of photosynthesis, rapid growth, and its tolerance to extreme conditions, including industrial carbon dioxide (CO_2) levels. The system uses an exhaust fan to cycle flue gas into the biofilter, a bubbling system to maximize gas-liquid interaction, and a series of real-time monitoring using a temperature gauge, pH meter, and CO_2 indicating bellow to maintain optimal algal growth and photosynthetic conditions. Experimental results confirmed the lethality of Spirulina algae demonstrated by the attenuation of CO_2 concentrations from inlet to outlet of the biofilter. The algal culture also showed a steady increase in biomass, demonstrating a transfer from inorganic carbon to organic substance. Spirulina demonstrated CO_2 absorption rates of 11-13%, which was under optimum conditions, and showed a high tolerance to CO_2 levels usually present in industrial emissions. This biomass is an additional economic benefit with different applications such as biofuels, food, fertilizers, and drugs. The study concludes that Spirulina is a promising organism for carbon capture and biomass production in a controlled setup. The compact, sensor-integrated biofilter system effectively simulates industrial conditions conducive to algal growth, suggesting that microalgae-based systems could play a critical role in climate change mitigation. While the current research was conducted in a laboratory environment, future efforts will focus on scaling the system for real-world industrial applications and evaluating its long-term efficiency and economic viability.

Keywords: *Spirulina, Biofilter, Biomass Production, Carbon Dioxide Absorption, Industrial Emissions Mitigation*

1. Introduction

The atmospheric carbon dioxide (CO_2) levels are rapidly rising, causing an imbalance in the global climate. The primary contributing factor is the industrial gases (flue gas). Industrial CO_2 significantly affects the greenhouse effect, resulting in global warming and climate change [1][7]. This effect causes an increase in the frequency of intense weather events, rise in sea level, and disruptions in the ecosystem. Moreover, CO_2 exposure poses risks to health. Depending on the concentration and duration of exposure, the symptoms can range from headaches and drowsiness to rapid breathing, confusion, elevated heart rate, elevated blood pressure, dizziness and in severe cases, unconsciousness or even death [8]. Since CO_2 is odorless and does not cause irritation, unhealthy levels may go unnoticed until symptoms start appearing.

Considering these issues, the development of a cost-effective carbon-capturing method has become essential. Traditional Carbon Capture and Storage (CCS) technologies can capture up to 90% of CO_2 emissions from power plants, proving to be highly efficient [6] but they have high operational costs, require a lot of energy [1], and there are concerns about their long term storage safety and leakage needing a suitable geographical location for the storage sites. On the other hand, the Direct Air Capture (DAC) mechanism removes CO_2 directly from the atmosphere, which makes it flexible in terms of installation, allowing it to be installed independently of emission sources. However, DAC consumes high levels of energy and can prove to be expensive. Additionally, it also requires significant renewable energy and infrastructure along with developments in many areas [19][33]. One other promising method is mineralization, which converts CO_2 into stable minerals. This offers permanent storage and its byproducts can be used. However, this process is quite lengthy as it has slow natural reaction rates and faces geographical constraints. Bioenergy with Carbon Capture and Storage (BECCS) has the potential to achieve negative emissions by generating renewable energy while simultaneously capturing CO_2 but it may compete with food production for land and water. Its efficiency depends on feedstock and land management practices [33].

Among these methods, algae-based Carbon Capture seems to be the most promising technique. Algae efficiently use photosynthesis to convert CO_2 into organic biomass at rates that surpass many other terrestrial plants. Through photosynthesis, algae uses sunlight, water, and CO_2 to produce biomass and oxygen. This biomass can be processed into biofuels, animal feed, fertilizers, and other valuable products [2]. The dual-function nature of this method not only reduces atmospheric CO_2 but it also helps create useful resources. This makes the algae-based biofilters, i.e. photobioreactors, attractive as they offer various advantages, such as quick growth rates, minimal freshwater requirements, and their ability to thrive in diverse environments, including saline and wastewater. These systems can be directly integrated with the emission sources - capturing CO_2 at the point where flue gas is released, converting it into useful byproducts. Photobioreactors have shown up to 85% of CO_2 sequestration efficiency under optimal conditions, resulting in almost double the biomass within hours. Since this method thrives in both non arable land and non potable water, it reduces the competition with food crops, and the sale of the byproducts can help with the operational costs [2].

While these advantages indicate this method to be quite promising, it does pose a few challenges like scalability, economic feasibility, and operational optimization. Recent developments in reactor design, strain selection, and process integration have improved performance significantly, however further study needs to be conducted for large scale deployment. While traditional methods such as CCS and DAC have their merits, their drawbacks highlight the need for new and innovative solutions. Algae-based biofiltration systems offer a compelling alternative and hold significant potential for future climate change mitigation [2].

2. Literature Review

Cantú, et al. [3] aimed to achieve high biomass productivity while effectively removing nutrients, particularly reducing chemical oxygen demand (COD) and enhancing resource recovery. The research conducted was batch experiments, using varying whey dilutions and a modified Schlösser medium with CO_2 to promote algal growth. It was reported a maximum biomass of 3.31 $g \cdot L^{-1}$ on day 13 and with high COD removal rates of 98.88% and a lipid accumulation of 7.07 g of lipid per 100 g of biomass occurred in cultures where the algal growth was driven by CO_2-only, implying lipid accumulation due to nutrient restrictions. Notwithstanding the findings in these experiments, there were important limitations noted, that highlighted the lack of potential for high dry biomass as a result of rapid depletion of COD, there was a lack of long-term stability saws for whey as a growth medium for consideration and the need to assess the nutrient profile of whey in greater detail for the eventual design of the spatial medium for planning large scale cultivation.

Oruganti, et al. [10], the aim was to examine the possible economic and environmental benefits of using CO_2 originating from biogas to grow Spirulina and enhance bioproductivity with potential benefits related to the operations of waste-water treatment and biogas upgrading. The study set up two reactors, including one with biogas as the carbon source and another with air, for yielding significantly different bioproductivity under natural sunlight conditions with controlled sparging at 0.8 L/min bio-gas and 1.5 L/min air sparging flow rates, respectively. They assessed lipid amount, productivity of biomass and specific growth rates over time. They concluded that the biogas-sparged reactor outperformed the air-sparged reactor with four times better biomass productivity of 0.123 g/L/day and higher specific growth rate of 0.48/day. Additionally, the biogas-sparged reactor outperformed the other reactor in a faster time to reach saturation and produced biomass with higher lipid content which suggests it could yield a better feedstock for production as a biofuel. Notwithstanding these results, gaps remain in the study involving optimal design and biogas sparging rates, quantifiable CO_2 uptake, and the sustainability of biogas CO_2 as the sole gas source in large scale cultivating systems.

Lopes, et al. [5] aimed to identify bioproducts derived from Spirulina in biorefineries and sustainability contributions. They utilized the integrative literature review framework to answer the main question: "What bioproducts can be produced in a Spirulina biorefinery and how can it add value to sustainability?" This study collected relevant literature in different languages by screening the titles and abstracts & by employing the Web of science, Google Scholar, CAPES Periodicals. The results indicated that Spirulina has the potential to produce bioproducts such as biofuels, food, feed, valuable bioactive compounds, and wastewater remediation or soil enhancement. In addition, microalgal biorefineries through biomass utilization, pollution mitigation, and emission reductions can enhance sustainability. However, this study also identified significant research gaps related to operational costs, biomass consistency, and the need for technologies that have broad applicability for broad practice.

Chunzhuk and collaborators [9] investigated the efficiency of capturing CO_2 in microalga Arthrospira platensis at high CO_2 concentrations; 1, 5, and 9 vol. %, considering growth rate, quality biomass, and biochemical compositions. The experiment was conducted over 15 days at 1, 5, and 9 CO_2 vol.% concentrations in a 90 L photobioreactor containing Zarrouk's medium, where the parameters of optical density, decreasing CO_2 concentration, and pH were routinely measured. The results demonstrated that CO_2 was reduced to the greatest desired amount at 5 vol.%, biomass was growing optimally at 1 and 5 vol. % CO_2 concentrations but at 9 vol.% CO_2 there was less growth and less pH alongside diminished lipid and protein content that was consistent with stressful metabolic conditions for the algae. One limitation found in the experiment at 9 vol.% CO_2 concentrations was unregulated microbial contaminations that might have confounded results, there by justifying conclusive future control studies to evaluate the productivity and controllability of microalgal productivity and comparably quality biomass, through separately isolated co-factors, during prolonged durations in large photobioreactors.

Glazunova et al. [12] evaluated three microalgae species - Chlorella vulgaris, Scenedesmus obliquus, and Spirulina platensis - capturing CO_2 from industrial emissions to show their potential for applications in biofuels and animal feed. All species were investigated in a photobioreactor, using transparent flasks and continuous illumination at 25°C during a 7-day study. Data collection included biomass yield, CO_2 biofixation, and biochemical composition, the results statistically validated by Fisher test. Of the three microalgae species, C. vulgaris had the highest biomass yield (2.68 g/L) and protein content (64.0%), followed by Sp. platensis with highest lipid content (23.0%). Sc. obliquus had the lowest biomass and protein content across the board. Overall, while the study has potential results, it only represented 3 species in a lab setting, indicating that more studies using more species and under standard environmental conditions for a longer duration will be necessary for determining sustainability and economic viability.

Parthiban, et al. [14] authored a review article titled "Reducing the Carbon Footprint through Cultivating and Consuming Spirulina" to review the potential of Arthrospira platensis (Spirulina) as an environmentally beneficial option for carbon emission reduction. By analyzing existing literature, the authors explored Spirulina photosynthesis, its ability to capture CO_2 from a planctonic state, from various sources and from the atmosphere as gases. The review noted the biomass productivity of Spirulina, rapid growth cycle of Spirulina, and the potential of Spirulina cultivation next to industrial emissions to mitigate their carbon emissions. The review also pointed out the status of Spirulina, as GRAS (Generally Recognized As Safe) food item, providing a way to promote global consumption and economic value. However, the review identified several knowledge gaps including economic viability, technological requirements and ecological consequences of mass cultivation. The authors acknowledged that the use of Spirulina for carbon emissions reduction needs additional study to understand long-term viability and potential use in industrial and agricultural systems.

Iglina and colleagues [18] sought to evaluate the ability of microalgae to capture carbon dioxide (CO_2) emissions from industrial sources, specifically as either a third-generation biofuel. This investigation consisted of a literature review of previous research on cultivation and experimental studies on Scenedesmus sp. and Chlorella sp. microalgae cultured in an environment with flue gases from coal-fired power plants and refineries. The algae were grown in nutrient media (F/2 and F/2A) and exposed to a high concentration of CO_2 to determine the absorption of pollutants. The resultant rate of CO_2 fixation, as well as other gaseous compounds was reported. Moreover, the authors reported that Chlorella vulgaris MTF-7 had the best exponential growth and CO_2 fixation efficiency (60%). The algae were also able to capture NO (70%) and SO_2 (50%). In conclusion, the authors believed that the ability to cultivate algae using a mix of flue gas, but also stressed a number of major gaps in research, such as an understanding of what parameter(s) could produce maximum biomass productivity, or how many studies have focused on the thermochemical processing of algae versus other biofuels.

Laamanen et al. [20] aimed to assess the potential of microalgae as a sustainable method for capturing industrial CO_2 emissions while producing biofuels. The aspects of economic feasibility and technological advancements were considered. The study analyzed almost all the various microalgae cultivation systems, particularly phototrophic methods, setting forth both the superior CO_2 capture capacity and CO_2-rich off-gas utilization of microalgae in comparison to terrestrial plants. The study, while successfully substantiating the aspects of CO_2 sequestration and biomass production, indicated that current economic conditions act as a handicap to the competitiveness of microalgal biofuels as an energy source. Nevertheless, the author proposed that sustained rises in fossil fuel prices and advances in culture technologies would work in favor of microalgal systems being closer to achieving economic viability. Research gaps were identified in, for instance, improving production technologies and further researching sustainable and large-scale biomass production systems in using microalgae for industrial emissions reduction.

Duarte, et al. [21] investigated the CO_2 biofixation performance of Spirulina sp and looked at how initial biomass concentration and design of the photobioreactor influenced the final performance by comparing tubular and raceway systems at two biomass concentrations 0.2 g/L and 0.4 g/L. The carbon source was 10% CO_2 and flow rate was set at 0.05 vvm. Growth parameters were measured and included biomass productivity and maximum specific growth rate. The growth parameters were determined by applying linear regression to the logarithmically transformed growth data. Both tubular photobioreactors and raceway systems were analyzed and the results indicate that tubular photobioreactors exhibited a specific growth rate of 0.450 d-1 which was 43% greater than the specific growth rate for raceway systems (0.314 d-1) which also had a CO_2 biofixation efficiency rate of 0.1 g CO_2/g biomass per day, and a higher biomass yield than raceway systems (210% greater than raceway). The lower initial biomass concentration of 0.2 g/L results indicated a 42% increase in specific growth rate than the higher initial biomass concentration. As mentioned, the study did not provide any information on the economic feasibility of scaling up the systems or a long-term sustainability position although they clearly noted the potential for enhanced CO_2 biofixation efficiency by obtaining more detailed information on Spirulina growth and fixation efficiency at varied CO_2 levels and other environmental parameters that influence Spirulina.

Zhu, Baohua, et al. [22] set out to assess the viability of Spirulina for large scale biotechnological CO_2 mitigation via low-cost cultivation in open raceway ponds utilizing purified CO_2 from coal chemical flue gas. The study first screened nine Spirulina strains (in columnar photobioreactors with 10% CO_2) to determine the most promising strains and followed by determining optimal pH, dissolved inorganic carbon (DIC) and phosphate concentrations for two selected strains (208 and 220) in 4 m^2 indoor raceway ponds. The two best strains were then semi-continuously cultivated in 605 m^2 raceway ponds using food-grade CO_2. The results indicated that good growth was achieved at pH 9.5, DIC 0.1 mol/L and phosphate 400 mg/L. Strain 208 (average daily biomass of 18.7 g/m²/day) had a higher average daily biomass than strain 220 (average daily biomass of 13.2g/m²/day) making 208 optimal. These conditions achieved effective CO_2 fixation and biomass production with Spirulina. Overall, while the results of this study showed promise for establishing Spirulina as a bioprocess capable of sequestering CO_2 at large scales, there were limitations on process optimization and applications for Spirulina cultivation and CO_2 sequestration, warranting future investigations.

Anguselvi, et al. [23] sought to require an environmentally friendly and sustainable CO_2 capturing process with algae, so it could be classified as an alternative to conventional chemical processes. They isolated freshwater algal species (Hydrodictyon, Spirogyra, Oscillatoria, Oedogonium and Chlorella) based on fast growth, high rates of photosynthesis, gas tolerance and the potential to create valuable by-products. CO_2 capture trials were performed in 400 ml and 25 L flat-panel photobioreactors using industrial sources containing 90–99% from natural gas processing and 13–15% CO_2 from power plant flue gases. The experiments showed that algae capture CO_2 while developing commercially valuable products such as amino acid feed, algal oil and pellets. The study found research knowledge gaps related to the costs of algae cultivation systems; and the systems must be efficient and cost-effective. There were also commercialization barriers that must overcome and require further grown technologies and scale-up research to address.

Yildirim, & Rana. [25] assessed the viability of Spirulina microalgae as a nature-based solution for removing carbon dioxide (CO_2) from the atmosphere and its development for secondary uses in environmental management. The team undertook a thorough literature review to assess best operating systems and growth conditions necessary for the cultivation of Spirulina including temperature, pH, nutrient supply and illumination. The significant applications considered included CO_2 sequestration, pigment production, produced water remediation and soil amendment. The research concluded that Spirulina has the potential to remove up to 50 tons of CO_2 per hectare per year if the growth conditions are optimal. Furthermore, Spirulina produces natural pigments and is a good source of bio-fertilizer and biomass for produced water remediation. While the research provided relevant concepts and conclusions, it also identified a lack of knowledge about large-scale economics, process optimization and scale-up of similar systems in reality. In conclusion, there is considerable potential for Spirulina as an ecosystem service solution for climate change mitigation and sustainable development; however, further research is needed to develop the operational and economic cases.

Moreira et al. [26] conducted a study to assess the role of CO_2 as the carbon source of Spirulina sp. LEB 18 and Chlorella fusca LEB 111 in semi-continuous cultivation based on biomass composition and production efficiency. The study compared independent nutrient renewal schedules (20% and 40%), used 10% CO_2 (v/v), and measured key growth factors in a controlled laboratory environment using vertical tubular photobioreactors. Growth parameters such as biomass productivity, specific growth rate, and biopolymer yield of both species were measured. Results indicated that Spirulina sp. LEB 18 outperformed Chlorella fusca than both species in kinetic responses and biopolymer production around 39.7% biomass increase using CO_2, and largest protein yield (60.1% at 20% renewal). The study found that the use of CO_2 determined optimum growth rate between both species also enhanced lipid accumulation in other specific nutrients, yet to achieve a successful outcome the study stressed improvements in nutrient limitations (nitrogen and phosphates) must be reached to explore economic feasibility for large-scale applications. Additionally, the semi-continuous method demonstrated cost-savings against future developments and greenhouse gas emissions by using CO_2 and also light energy while businesses were undertaken with feedstocks provided by the cultivation methods.

The research conducted by Wilson, et al. [27] indicated the ability to capture and recycle industrial CO_2 emissions by using microalgae with a pilot-scale photobioreactor (PBR) system. The PBR system was trialled at a coal-fired power plant, and a new often referred to digitally as a cyclic flow PBR was designed using a native Scenedesmus acutus strain with intermittent fluid packing and mechanical cleaning to minimize energy use and biofilm formation. The project developed the PBR system to operate for a 5 month continuous period from May to September 2015, and achieved an 44% average CO_2 capture efficiency during daylight hours, with a maximum CO_2 capture of 81% under optimal solar hours. Phase 1 of the PBR system project also removed 100% of SOx, and captured 41.5% of the amount of NOx in the flue gas produced in the combustion process of the coal plant. A solar shading analysis of tube spacing in the PBR was performed using the Autodesk Ecotect software, and showed increasing biomass productivity of the flue gas emissions were improved generally by locating the tubes closer together in the facility (further increasing self-shading at that spacing). Phase 1 of the PBR system study generally showed the opportunity for algae based CO_2 mitigation to become a secondary pollution control technique and as a biomass that can be sent to market. The research notes existing limitations related to the PBR reactor layout, associated costs, and the challenges to expand both in the scale of a species to be commercially viable and increasingly reduce the costs of construction and operation.

Jorge, et al. [28] had the objective to evaluate the use of Spirulina sp. LEB 18 and Scenedesmus obliquus LEB 22 for the biofixation of carbon dioxide (CO_2) from flue gas taken from a coal fired power station. The authors were primarily interested in the productivity of the biomass generated by kinetic growth and biochemical composition. The experiment was undertaken in raceway type photobioreactors. The CO_2-rich flue gas was used as the source of carbon replacing bicarbonate in the culture media. The results showed an interesting comparison between the two strains of algae (S. obliquus displayed lower biomass productivity and growth possibly due to toxic compounds in the flue gas). Under conditions with flue gas Spirulina demonstrated a 24% CO_2 reduction with a maximum rate of efficiency of 5.66% and displayed a 35% increase in biomass, whereas the S. obliquus LEB 22 demonstrated less productivity and growth possibly due to S. obliquus LEB 22 being sensitive to the toxic components of the flue gas. Both samples generated biomass with a high protein and lipid content indicating both species could serve as a bioproduct and/or biofuel. The authors discussed the need for future research to optimize the cultivation conditions for S. obliquus and suggested a more in-depth study to determine long term feasibility for industrial applications.

3. Methodology

Utilizing algae for industrial CO_2 capture is a very exciting possibility because of the high photosynthesis efficiencies, rapid growth rates, and adaptability to variable growth conditions that algae possess. Both microalgae and cyanobacteria can utilize concentrated CO_2 streams from flue gases, while also producing biomass that has commercial uses. For instance, the species of algae, Chlorella vulgaris, Scenedesmus obliquus, Nannochloropsis gaditana, as well and Arthrospira platensis (Spirulina) have demonstrated CO_2 assimilation rates that are considerably higher than those of terrestrial plants at rates of 10–50 times on the basis of area, making them suitable for carbon capture at an industrial scale [4]. Algae have the added benefit of being used to produce high-value bioproducts: lipids used for biodiesel (Scenedesmus, Nannochloropsis), high-protein biomass for nutraceuticals or aquaculture (Spirulina) , carbohydrates for bioethanol (e.g., Ulva, a macroalga); this is not the case when looking at terrestrial plants for carbon capture because of the overall lower biomass productivity achieved with those plants. There are two important traits that set algae apart from terrestrial plants for carbon dioxide (CO_2) capture: the rate of CO_2 fixation and the abiotic and biotic stress tolerance to CO_2. Many species have CO_2-concentrating mechanisms (CCMs), which can actively take up inorganic carbon (i.e., HCO_3–) and saturate the enzyme RuBisCO to improve their overall photosynthetic efficiency under elevated CO_2. Some microalgae can tolerate CO_2 concentrations higher than 10–15% found in industrial flue gases [16]. This tolerance can occur through physiological adaptations, such as maintaining an internal pH, achieving cellular homeostasis, and altering the photosynthetic apparatus. Natural sinking behaviours would also exist in strains like Cyanobacterium aponinum making long-term CO_2 sequestration possible without energy-intensive removal of biomass, although an ecological and life cycle analysis is needed.

Spirulina, one of the most effective strains reported, has shown carbon fixation rates up to 230 mg/L/day with sodium bicarbonate added as a carbon source, and had 26.7% carbon utilization efficiency [11]. Either under mixotrophic cultivation, which adds organic carbon sources (e.g., acetate) will increase metabolism and biomass production, rates of carbon fixation can be increased. Chlorella vulgaris and Scenedesmus obliquus, on the other hand showed fixation rate of 124 mg/L/day, and 88 mg/L/day under similar conditions, respectively [29]. Spirulina can survive under conditions that are alkaline, saline, and nitrogen limited, conditions that are observed in many waste streams. Additionally, spirulina has a high protein content, is multi-faceted as a commercial biomass, suggesting it is one of the most attractive candidates for CO_2 capture and utilization.

Algae Species/ Types	CO_2 Fixation Rate (mg/L/day)	CO_2 Tolerance (%)	Key Applications	Advantages	Limitations
Chlorella Vulgaris	~ 124	10 - 100	Flue gas remediation, Biofuels	High growth, works in PBRs and wastewater	Costs of reactor systems
Scenedesmus Obliquus	~ 88	~ 20	Biofuels, Wastewater treatment	High lipid content (~60%), flue gas-tolerant	Requires nutrients and CO_2 enrichment
Nannochloropsis Gaditana	~ 107	2 - 10	Biodiesel production	High lipid productivity, compact size	Sensitive to nutrient shifts
Spirulina Platensis	~ 197	~ 10	Nutraceutical, Animal feed	Commercially proven, high protein	Lower CO_2 uptake vs. other species

Table 1. Characteristics of Algae Species/ Types.

The choice of algae for biofilter systems is an evaluation of several factors, with the primary consideration being the species' ability to effectively remove target pollutants, such as CO_2 and nutrients. Microalgae and cyanobacteria are often favored because of their superior photosynthetic efficiency, strong carbon-concentrating mechanisms (CCMs), and relatively rapid growth rates in industrial flue gas concentrations (especially CO_2). Adaptability is also crucial—species must be able to withstand changes in temperature, salinity, pH, and contaminant concentrations to sustain long-term stability. Furthermore, it would be advantageous to select an algae species that produces a potentially valuable by-product, such as proteins, pigments, or biofuels, to support the economic sustainability of algae biofilter systems. The operational feasibility of cost-effectively scaling up the algae biofilter system will also be affected by the ease of cultivation, harvesting, and immobilization of the algae.

Algae selection is only one part of having effective filtration for CO_2; within biofilter systems the engineering and design of the systems is also a factor. More advanced hybrid technologies, such as two-stage membrane biofilters, have demonstrated excellent removal efficiencies (>90%) of not only CO_2 and nutrients, but also a range of VOCs, ammonia, and hydrogen sulfide [17]. These systems have capitalized on waste gas characterization studies and system conditions that can be controlled (i.e., environment like humidity, temperature, available nutrients) so that biological activity can be maintained to stationarity. The design of the biofilter system can promote other design strategies (i.e., recirculation of air to provide better mass transfer, and gas solubility).

Spirulina represents one of the most advanced CO_2 concentrating mechanisms which constantly pumps bicarbonate into its cells allowing for carbon fixation capacity even with varying concentrations of inorganic carbon. Studies have revealed that under optimal conditions, Spirulina can achieve carbon fixation rates as high as 230 mg/L/day with sodium bicarbonate as the carbon source - and a carbon utilization efficiency of as high as 26.7%, demonstrating the dysfunctionality of the standard atmospheric process [11]. The efficiency of CO_2 fixation by Spirulina is further augmented through mixotrophic cultivation while organic carbon sources (e.g., acetate) are supplemented, which substantially increases biomass yield and CO_2 sequestration rates due to upregulated metabolic pathways [13].

From an operational perspective, Spirulina has a favorable growth morphology and dynamics that support harvesting and system maintenance strategies, which highlight the viability of Spirulina for biofiltration at a larger scale, and continuous biofiltration or carbon filtering. The bubbling design aspect is the most advantageous, gas-liquid interaction which assists in the rapid dissolution of CO_2 and accessibility for photosynthesis, which allows Spirulina to have greater potential for equilibrating CO_2 from gas phase to biomass phase. Also, the biomass has a relatively high amount of protein and other useful compounds to provide increased economic benefit, while providing sustainability. Spirulina's high CO_2 fixation potential, adaptable industrial gas capabilities, ease of cultivation, and biomass production is an excellent choice for the design [22].

The biofilter design used in this experiment uses an exhaust fan to pull flue gas, as seen in figure 1 and bubble CO_2 rich air through a Spirulina culture with the CO_2 measured downstream, permits excellent transfer of CO_2 to Spirulina and the large gas-liquor interface provides for more mass transfer. It notes the exceptional bio-fixation of CO_2 by Spirulina, as the culture grows remarkably fast and provides increased CO_2 tolerances, and can withstand fluctuations in the environment. Many studies show rapid bio-fixation rates of up to 197.4 mg/L/day of CO_2 with Spirulina at optimized conditions, and significant bio-fixation rates when subject to industrial flue gas levels of CO_2 [24].

The sequential bubbling also ensures that the CO_2 is well dissolved in the culture, and that it spreads uniformly and supports consistent photosynthesis and continuous biomass generation. This helps in generation of spirulina biomass, which can be used in food, feed, and biofuel [3]. The exhaust fan helps with active gas delivery enabling precise control over flow rates which is important for both CO_2 absorption and algae growth. Moreover, real time measurement of CO_2 at the outlet gives feedback on the system's performance, allowing adjustments to operational parameters, ensuring removal efficiency. Figure 3 shows the CAD model of the design of the filter used for this.

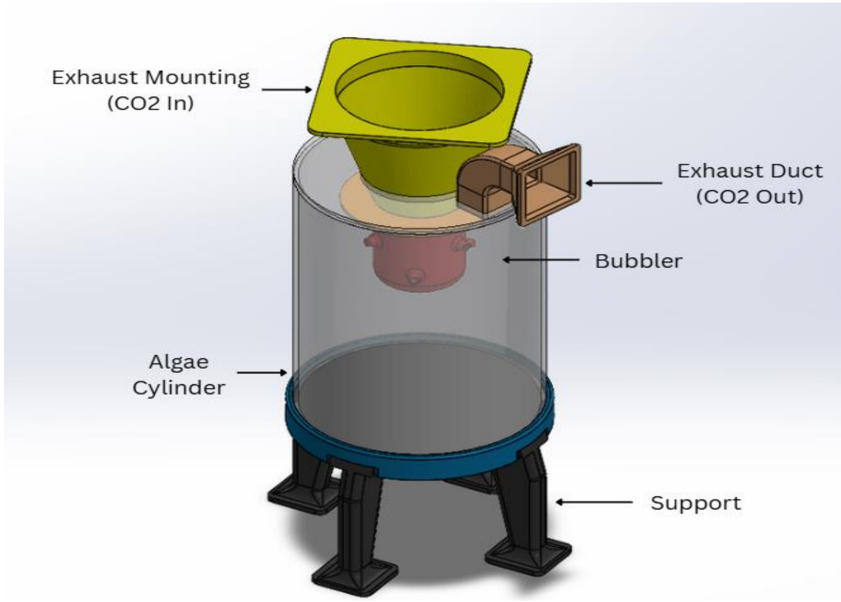

Figure 1. 3D CAD model of the algae-based carbon capture system, showcasing major components including the exhaust mounting for CO_2 inlet, exhaust duct for CO_2 outlet, algae cylinder, bubbler for gas diffusion, and support structure.

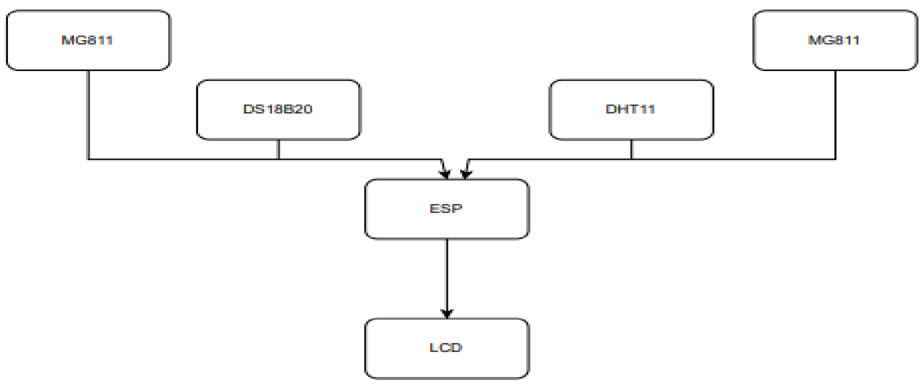

Figure 2. System block diagram illustrating the sensor network used for monitoring

Two MG-811 (CO_2 sensors) are implemented at the inlet and outlet of the system, which allows to measure the concentration of carbon dioxide, measuring CO_2 removal efficiency. This will enable tracking the variability of the CO_2 concentration as air passes through the system and help assess the absorption or release characteristics. An air pump will activate for 10 seconds after a 30-minute wait, and in that duration it will generate a bubbling motion in the system. Bubbling will promote gas exchange, circulation and mimic natural conditions, essential to keep the algae alive. 24 NeoPixel LEDs (2400 lm) are used to simulate sunlight-like light spectrum for three full days to analyze CO_2 uptake performance. The programmable LEDs will generate a sun-like light spectrum and this is critical to plant growth and photosynthesis. A DHT-11 temperature sensor will be added to measure the temperature and humidity of the system. An ESP will facilitate data collection and will display monitored data on the LCD. Data was collected at three time points each day (08:00, 12:00, 16:00), measuring ambient temperature, relative humidity, inlet CO_2 concentration, outlet CO_2 concentration, and then calculating the absolute reduction and the percentage reduction of CO_2 in the process.

By optimizing the design around Spirulina, the system leverages the sintering power of being able to fix CO_2, while taking advantage of the benefits from engineering gas transfer through bubbles as a practical, effective, efficient, scalable and sustainable solution, for industrial applications of flue gas - both in terms of biomass and CO_2 mitigation

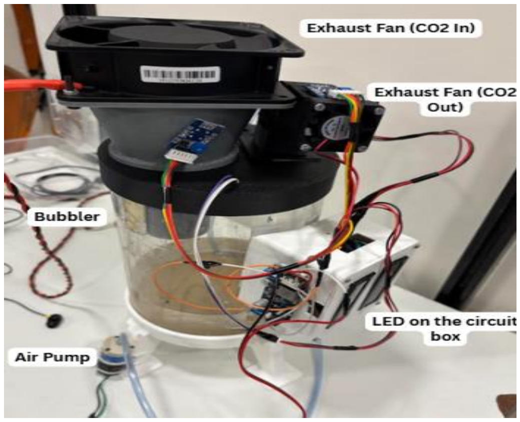

Fig 3. Assembled prototype of the carbon capture system with labeled components. CO_2 is introduced via the inlet fan, and excess is expelled through the outlet fan. The bubbler and air pump facilitate CO_2 diffusion into the algae culture. A control circuit with status LEDs monitors and regulates system performance.

The system evaluates the quantity of carbon dioxide (CO_2) absorbed by a culture of spirulina algae. Fresh air is pulled into the container by an inlet exhaust fan (CO_2 In). A CO_2 sensor on this inlet sensing the level of carbon dioxide in the air at the inlet provides reference conditions for calculations afterward. After the fresh air is introduced, it passes through a honeycomb-shaped bubbler, which breaks the air-flow into many small channels. This design produces turbulence and breaks the air into small, fine bubbles in the liquid culture and provides a high contact surface area between the gas and spirulina. An air pump was used to bubble the algae. Meanwhile, once inside the container, spirulina captures CO_2 during photosynthesis and converts it into biomass. The processed air is drawn out of the container by an exhaust fan (CO_2 Out), and a second CO_2 sensor captures the residual carbon dioxide level in the air leaving the container. With both inlet and outlet CO_2 measurements in hand, the difference between those measurements can be used to derive the net CO_2 uptake rate of the culture. This data can be used to examine the performance of the algae's carbon capture efficiency under various environmental conditions, aeration rates, or light intensities.

Results

An observable difference between inlet and outlet CO_2 concentrations demonstrated successful uptake of CO_2 by the Spirulina. Over time, the difference in concentrations grew larger, suggesting the culture has a higher rate of photosynthetic activity and CO_2 uptake as the culture matured.

Ambient temperature ranged from 27.8 °C to 33.2 °C, and humidity was in the range of 55% to 68%. Inlet CO_2 concentration, for every day, was within the range of 910–945 ppm. Outlet CO_2 concentration ranged from 790–820 ppm, indicating that every day the absolute reduction of CO_2 was on the scale of 100–125 ppm. The percentage of CO_2 reduction was a minimum of 10.99% (Day 1, 08:00) to a maximum of 13.44% (Day 3, 12:00). The data shown above indicates an improvement to CO_2 uptake over the three days, where the mean removal efficiency increased from approximately 11.95% (Day 1) to 13.28% (Day 3). This indicated increasing photosynthetic activity as the Spirulina culture matured and became able to assimilate CO_2 at a higher rate.

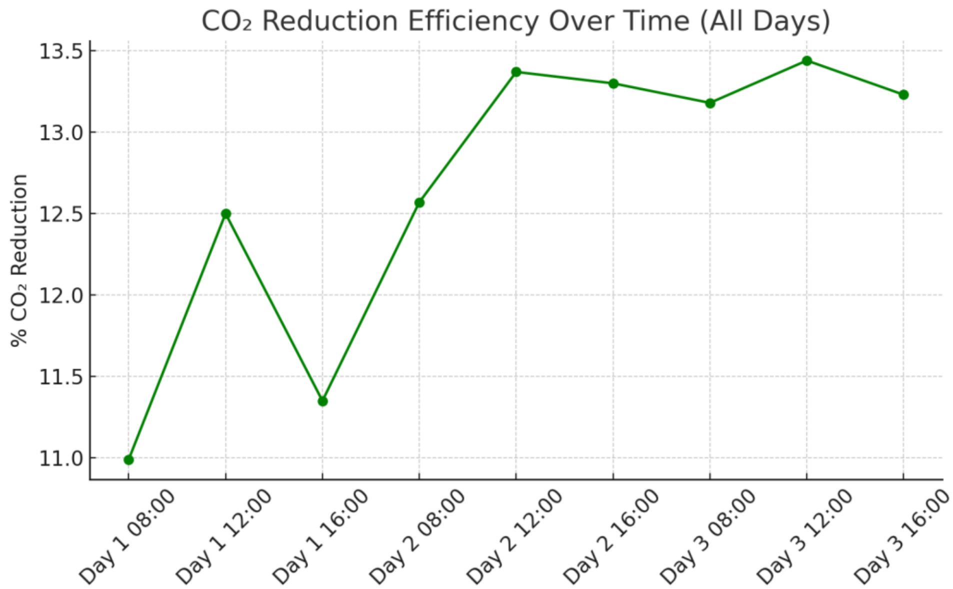

Fig 4. CO_2 reduction efficiency over time across three experimental days. The results show an increase in efficiency from Day 1 (11.0%) to Day 3 (13.4%), with minor fluctuations at different time points.

Biomass development of the culture showed gradual progress visibly by deepening colour and by weight/volume differences accumulated over time should show that it was effective to turn absorbed CO_2 into biomass. After maturing it had strong growth and high biofixation efficiency when grown in the mass concentrations of CO_2 one might find in industrial flue gases. Greatest efficiency appeared to occur in concentrations between 11-13% CO_2.

The data shows that moderate increases in temperature (approximately 30–32 °C) show increased CO_2 reduction percentages, in line with the literature which correlates optimal photosynthetic activity for Spirulina at those temperatures. When lower humidity levels (55–58%) were present, there tended to be slightly lower represents of removal efficiency (e.g., Day 1 at 16:00), whereas a higher humidity range (65–68%) tended to correlate with higher CO_2 reductions, which can possibly be attributed to less evaporative stress on the cultures and more stabilized conditions in the medium.

The carbonic anhydrase activity is reportedly very high in Spirulina, and Spirulina has a relatively high degree of bicarbonate usage which ensures that it sequesters more carbon than many of the conventional green algae, especially when carbon may be rare or in varying stressful conditions. Spirulina can also utilize saline conditions in combination with nutrient stress to fix CO_2 and produce biomass, which is generally considered to be higher value biomass, in sub-optimal nutrient conditions - a very common condition in many industries which do not maintain constant nutrient inputs.

Conclusion

Given the results and implications of this analysis, we can conclude that Spirulina is a viable and efficient organism for carbon dioxide absorption and biomass production in a controlled environment, thus supporting its possible application in industrial-related CO_2 minimization methods. The implementation of a small, housed chamber system coupled with real-time environmental monitoring, allowed the project to realistically simulate the conditions for algal photosynthesis and growth.

The measurement data provided showed a steady and verifiable decrease in CO_2 levels between the inlet and outlet, which indicates active absorption of CO_2 from the air by Spirulina. This confirms the species' bio-sequestration ability as well as a methodology to measure real-time CO_2 uptake. With the timed air pump delivering bubbling, the CO_2 absorption process was improved, and further assisted gas exchange and nutrient distribution for the Spirulina culture to allow for more uniform growth.

In order to maintain biological stability, we automated the environmental monitoring, using DS1820 and PHT11 environmental sensors to monitor temperature and pH, respectively. Biomedical environmental stability allowed for optimal conditions. Regarding sustainable light energy from artificial sources, the 24 NeoPixel LEDs that simulated sunlight allowed the algae to efficiently perform photosynthesis throughout the experiment.

Aside from CO_2 uptake, this project also noted an incremental increase in algal biomass, indicating positive conversion of fixed inorganic carbon to organic material. The biomass could potentially be utilized in a number of industries such as biofuels, food, fertilizer, and pharmaceuticals, multiplying value for the system beyond basic carbon capture.

In total, the system could be used as a prototype to scale-up and green industrial emissions biologically. Although the current study was completed under laboratory conditions, follow up studies could explore scaling to assimilate real world industrial exhaust outputs, to investigate long-term performance, maintenance and cost factors. Further study could also look to optimize inputs such as nutrients, and light intensity, and CO_2 enrichment to maximize biomass yield and carbon capture efficiency.

This project highlighted not only the environmental application potential of microalgae systems but also the economic opportunity a microalgal system can offer. The work discussed here contributes to the global discourse on managing climate change through sustainable technologies.

References:

1. Carrascal-Hernández, Domingo Cesar, et al. "CO2 capture: A comprehensive review and bibliometric analysis of scalable materials and sustainable solutions." Molecules 30.3 (2025): 563.
2. Shareefdeen, Zarook et al. "Recent Developments on the Performance of Algal Bioreactors for CO2 Removal: Focusing on the Light Intensity and Photoperiods." Biotech (Basel (Switzerland)) vol. 12,1 10. 11 Jan. 2023, doi:10.3390/biotech12010010.
3. Cantú, Denis, et al. "Harnessing of whey and CO 2 for the production of Arthrospira (Spirulina) platensis microalgae biomass: a circular economy approach." Acta Scientiarum: Biological Sciences 46 (2024).
4. Wei, Xuan, et al. "Biomass producing and CO2 capturing simultaneously by Chlorella vulgaris: Effect of CO2 concentration and aeration rate." Energy 306 (2024): 132321.
5. Lopes, Larissa Chivanski, Eleia Righi, and Jorge Alberto Vieira Costa. "Spirulina and its potential in bioproduct production: a review." Environmental Management and Sustainable Development 12.2 (2023): 30-53.
6. Jones, Christopher W. "Recent developments in CO2 capture and conversion." JACS Au 3.6 (2023): 1536-1538.
7. Yu, Xiang, et al. "Trends in research and development for CO2 capture and sequestration." ACS omega 8.13 (2023): 11643-11664.
8. da Silveira Cachola, Celso, et al. "Deploying of the carbon capture technologies for CO2 emission mitigation in the industrial sectors." Carbon Capture Science & Technology 7 (2023): 100102.
9. Chunzhuk, Elizaveta A., et al. "Direct study of CO2 capture efficiency during microalgae Arthrospira platensis cultivation at high CO2 concentrations." Energies 16.2 (2023): 822.

10. Oruganti, Raj Kumar, et al. "Spirulina Cultivation Using Biogas CO2 as the Carbon Source: Preliminary Study on Biomass Growth and Productivity." E3S Web of Conferences. Vol. 428. EDP Sciences, 2023.
11. Zhang, Pengyu, et al. "Effects of different bicarbonate on spirulina in CO2 absorption and microalgae conversion hybrid system." Frontiers in Bioengineering and Biotechnology 10 (2023): 1119111.
12. Glazunova, Darina, et al. "Carbon sequestration from industrial emissions using microalgae: results of laboratory modeling." International multidisciplinary scientific geo conference: SGEM. Vol. 22. No. 4.1. 2022.
13. Li, Pengcheng, et al. "Improving the growth of Spirulina in CO2 absorption and microalgae conversion (CAMC) system through mixotrophic cultivation: Reveal of metabolomics." Science of the Total Environment 858 (2023): 159920.
14. Parthiban, Meena S. "Reducing the Carbon Footprint by Cultivating and Consuming Spirulina: A Mini-review." International Journal of Environment and Climate Change 12.11 (2022): 3069-3076.
15. Ghobadian, Sasan, et al. "Design and Production of an Algal Biofilter for Industrial Wastewater Treatment." Plant, Algae, and Environment 6.2 (2022): 923-942.
16. Ighalo, Joshua O., et al. "Progress in microalgae application for CO2 sequestration." Cleaner Chemical Engineering 3 (2022): 100044.
17. Sheoran, Karamveer, et al. "Air pollutants removal using biofiltration technique: a challenge at the frontiers of sustainable environment." ACS Engineering Au 2.5 (2022): 378-396.
18. Iglina, Tatyana, Pavel Iglin, and Dmitry Pashchenko. "Industrial CO2 capture by algae: a review and recent advances." Sustainability 14.7 (2022): 3801.
19. Khosroabadi, Faezeh, et al. "Analysis of Carbon Dioxide Capturing Technologies and their technology developments." Cleaner Engineering and Technology 5 (2021): 100279.
20. Laamanen, Corey A., and John A. Scott. "Microalgae biofuel bioreactors for mitigation of industrial CO2 emissions." Bioreactors. Elsevier, 2020. 1-16.
21. Duarte, Jessica Hartwig, Letícia Schneider Fanka, and Jorge Alberto Vieira Costa. "CO2 biofixation via Spirulina sp. cultures: evaluation of initial biomass concentration in tubular and raceway photobioreactors." Bioenergy Research 13.3 (2020): 939-943.
22. Zhu, Baohua, et al. "Large-scale cultivation of Spirulina for biological CO2 mitigation in open raceway ponds using purified CO2 from a coal chemical flue gas." Frontiers in Bioengineering and Biotechnology 7 (2020): 441.
23. Anguselvi, Vetrivel, et al. "CO2 capture for industries by algae." Algae (2019): 1-11.
24. Moraes, Luiza, et al. "Carbon dioxide biofixation and production of Spirulina sp. LEB 18 biomass with different concentrations of NaNO3 and NaCl." Brazilian Archives of Biology and Technology 61 (2018): e18150711.
25. YILDIRIM, ZEYNEP RANA. "Nature based solution for CO2 emissions offset: spirulina microalgae cultivation." (2017).
26. Moreira, J. B., et al. "Utilization of CO2 in semi-continuous cultivation of Spirulina sp. and Chlorella fusca and evaluation of biomass composition." Brazilian Journal of Chemical Engineering 33.3 (2016): 691-698.
27. Wilson, Michael H., et al. "Capture and recycle of industrial CO2 emissions using microalgae." Applied Petrochemical Research 6.3 (2016): 279-293.
28. Costa, Jorge Alberto Vieira, et al. "Biofixation of carbon dioxide from coal station flue gas using Spirulina sp. LEB 18 and Scenedesmus obliquus LEB 22." African Journal of Microbiology Research 9.44 (2015): 2202-2208.
29. Basu, Samarpita, et al. "CO2 biofixation and carbonic anhydrase activity in Scenedesmus obliquus SA1 cultivated in large scale open system." Bioresource technology 164 (2014): 323-330.
30. Kang, Yun Hee, Sang Rul Park, and Ik Kyo Chung. "Biofiltration efficiency and biochemical composition of three seaweed species cultivated in a fish-seaweed integrated culture." Algae 26.1 (2011): 97-108.

31. Habib, M. Ahsan B., et al. A review on culture, production and use of Spirulina as food for humans and feeds for domestic animals. 2008.
32. Phillips, Ian. "Biofiltration systems for the treatment of waste gas from industrial plants." (2007).
33. Metz, Bert, et al. IPCC special report on carbon dioxide capture and storage. Cambridge: Cambridge University Press, 2005.