# Design and Evaluation of a Flat-Panel Airlift Photobioreactor for $CO_2$ Capture Using *Nannochloropsis* sp.

**Author: Zachary S. Winig**

Abstract:

The design and configuration of a photobioreactor (PBR) significantly influence its hydrodynamic performance, gas transfer efficiency, and overall biomass productivity. In this study, a pilot-scale closed flat-panel photobioreactor is designed and fabricated to assess the potential of *Nannochloropsis* sp. for $CO_2$ capture and biomass production in an industrial setting. The system is constructed with a height-to-length (H/L) ratio of 1.22 and a total working volume of 20 L. Unlike traditional tubular or airlift configurations, the flat-panel design aims to maximize the surface-area-to-volume ratio for improved light distribution and gas exchange. Our hypothesis is that the optimized panel dimensions and controlled aeration system enhance $CO_2$ absorption, minimize sedimentation, and improve overall mixing efficiency. The photobioreactor is characterized under varying aeration rates (0.3 vvm) to determine hydrodynamic performance, including mixing time and gas holdup. We measure biomass growth through optical density and dry weight measurements, while $CO_2$ fixation is quantified based on inlet and outlet gas concentrations. This study seeks to enhance global climate change mitigation by disseminating our findings to other industries for project replication.

## 1. Introduction

In 2023, about 153 million metric tons of carbon dioxide were released into the atmosphere, a record 1.1% increase from 2022 (Ritchie & Roser, 2020). Much of this rise stems from fossil fuel combustion and industrial activity. Alongside greenhouse gases, air pollution remains a pressing concern: in 2024, the Philippines recorded a PM2.5 value of 14.82 $\mu g/m^3$, more than double the U.S. average of 7.1 $\mu g/m^3$ and nearly three times the World Health Organization's annual guideline of 5 $\mu g/m^3$ (AirVisual, n.d.). Fine particulate matter is of tremendous concern because it can penetrate the bloodstream and cause serious health problems, highlighting the interconnected risks of fossil fuel dependence. Beyond particulates, reducing $CO_2$ emissions offers broader benefits. Cutting emissions by 45% by 2030 would help limit global warming to 1.5°C (IPCC, 2023) while simultaneously lowering co-pollutants such as $NO_x$ and $SO_2$. Because fossil fuel combustion produces both $CO_2$ and harmful pollutants, reducing its use could prevent up to 7 million premature deaths worldwide due to cleaner air (WHO, 2024).

These global figures underscore the dual threats of greenhouse gas accumulation and air pollution, but they are especially alarming for nations that face greater vulnerability to climate and health risks. The Philippines is one of them. The country experiences frequent natural disasters such as typhoons and floods, which strain infrastructure and displace communities while also exposing populations to waterborne and vector-borne diseases (Frontiers in Climate, 2025). Healthcare access is uneven, with rural and low-income areas often lacking sufficient medical facilities, personnel, and resources (Philippine Institute for Development Studies, 2024). These challenges make the population more susceptible to the effects of air pollution and rising temperatures. When fossil fuel combustion worsens air quality, communities with limited healthcare capacity face higher risks of respiratory and cardiovascular diseases. The Philippines' geographic vulnerability and health disparities intensify the human cost of its dependence on fossil fuels, making emission reduction not only an environmental priority but also a critical public health necessity.

One country of concern for experiencing unprecedented issues with global warming and $CO_2$ emissions is the Philippines. The Philippines' energy production is dominated by fossil fuels, with coal creating 83 million tons of $CO_2$ in 2023 and oil coming in second with 55 million tons of $CO_2$ (Ritchie & Roser, 2020a). The Philippines have made contributions to reduce their carbon dioxide output, but most aren't making a huge impact. They have implemented renewable energy promotion through the Renewable Energy Act of 2008, where the government pushed for a switch from coal and fossil fuels to solar, wind, hydro, and geothermal energy sources. However, due to high costs, grid instability, and outdated infrastructure, integration of the policy is difficult (Department of Energy Philippines, 2023).

Additionally, the Philippine Energy Plan (PEP) 2020–2040 was proposed by the Department of Energy (DOE) in the Philippines. PEP aims for a clean, sustainable, and resilient energy future. The policy includes aggressive Renewable Energy (RE) and Energy Efficiency and Conservation (EEC) programs; a moratorium on new coal power projects, allowing foreign ownership in large-scale geothermal projects under FTAA; and resumption of indigenous oil and gas exploration. Nonetheless, it is ineffective due to the Philippines' reliance on fossil fuels, with coal accounting for more than 50% of total energy use (Department of Energy Philippines, 2023).

Cornersteel Systems Corporation, located in Laguna, Philippines, is a manufacturing firm aiming to diminish its carbon emissions. Presently consuming between 36,000–54,000 liters of diesel and producing approximately 96,000 to 144,000 kilograms of carbon dioxide annually, they are tackling the pressing requirement for sustainable and scalable carbon mitigation strategies in industrial environments to achieve minimal to zero carbon emissions. Cornersteel Systems Corporation aims to demonstrate how microalgae-based photobioreactor systems can capture atmospheric carbon dioxide directly from the environment while operating efficiently within a manufacturing facility. By integrating a closed photobioreactor system at the Cornersteel facility, this research explores the potential of bio-based technologies to reduce the carbon footprint of industrial processes, support environmental compliance, and contribute to the company's long-term sustainability goals.

Cornersteel Systems' solution to reduce $CO_2$ levels in the Philippines is to design and develop a closed flat-panel, photobioreactor system for atmospheric carbon sequestration. A photobioreactor (PBR) is a vessel that uses light and different nutrients to develop photosynthetic organisms. In a photobioreactor, algae and cyanobacteria may be commercially cultivated to create oils that can be transformed into biodiesel fuel (Elmadhoun, n.d.). The use of microalgae to reduce $CO_2$ emissions is very promising due to its environmentally sustainable and economically viable nature in the long term (Zhang et al., 2023). Algae absorb emissions from power plants, including $CO_2$ flue gas. Using light energy in photobioreactors, algae performs photosynthesis, converting $CO_2$ into biomass (*Algae CO2 Capture Part 1: How It Works* | Research, 2025). Microalgae have a high $CO_2$ uptake efficiency, absorbing 10 to 50 times more carbon dioxide than terrestrial plants, making them extremely effective in carbon capture (Zhang et al., 2023).

A photobioreactor is required to simplify and manage the industrial usage of microalgae. In a photobioreactor, a closed system of clear tubes and panels are used instead of open ponds. A central tank is filled with nutrients, minerals, and $CO_2$, which are then circulated throughout the system. Algae in sunlight-exposed tubes absorb $CO_2$, decreasing greenhouse gases by absorbing $CO_2$ from industrial plant emissions (flue gas) and is then sequestered to algal biomass.

There are different types of closed photobioreactors. Tubular: glass or polymer tubes, arranged vertically or horizontally, circulate algae culture via a pump, optimizing production and space while ensuring easy cleaning and recycling. Flat panel: plates of glass or polymer house algae cultures, provide good light but face heating issues and troublesome biofilm formation. Plastic bags: Polyvinyl chloride (PVC) or polyethylene (PE) bags on holders collect culture supernatants; low costs, but high labor and waste due to biofilm and frequent replacements (*SCHOTT Photobioreactors*, 2022).

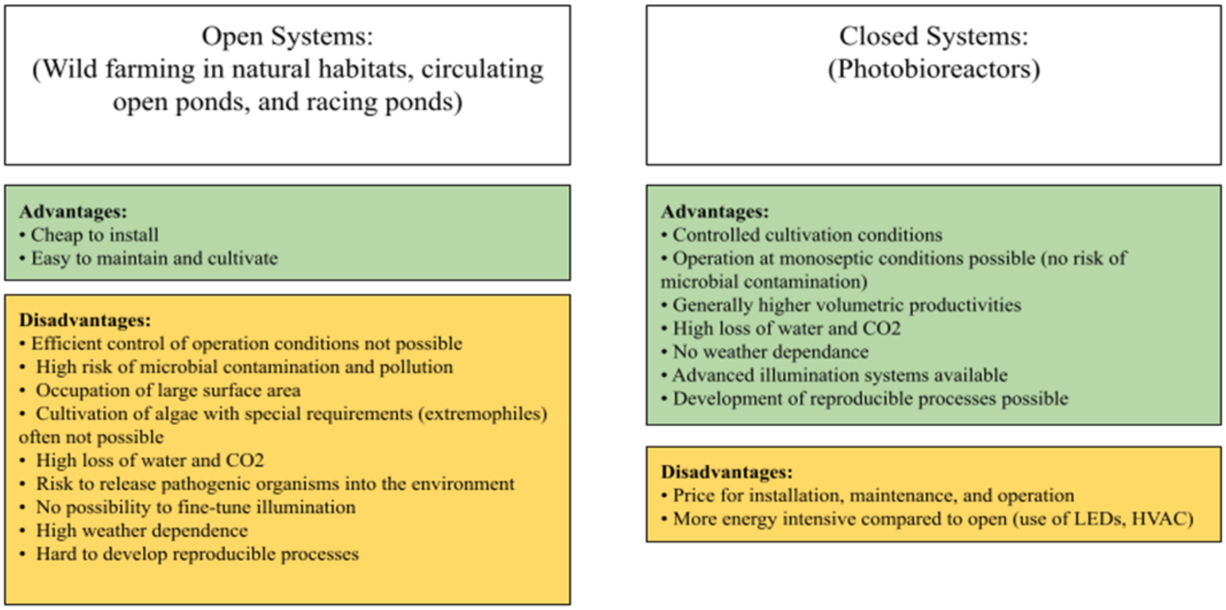


**Fig 1.** Comparison of advantages vs. disadvantages for open vs. closed photobioreactor systems (Koller, 2015).

The algae used in the study is *Nannochloropsis* sp. This species of algae is a unicellular microalgae widely regarded as one of the most promising candidates for biodiesel production. This is due to its ability to produce high lipid yields, its rapid growth rate, and its strong adaptability to varying environmental conditions. Algae may be used to create goods with additional value: anaerobic digestion produces methane, which may be used as fuel; lipid extraction produces resins that are renewable; and fish and animals eat dried algae. Cornersteel Systems Corporation plans to use resin from the lipids as a binding agent for separate projects due to their status as a materials manufacturer.

*Nannochloropsis* sp. also has a natural resistance to contamination and a favorable fatty acid profile. Furthermore, it offers advantages such as ease of genetic modification and scalability, making it suitable for large-scale biofuel applications (Hu & Gao, 2003). One of the main factors for choosing this species is its availability. Suppliers in the Philippines have readily available *Nannochloropsis* sp., and there are few suppliers of algal strands in the country also.

The primary objective of this study is to evaluate the efficiency of a closed flat-panel photobioreactor system using *Nannochloropsis* sp. in capturing industrial $CO_2$ emissions. Specifically, this research aims to design a pilot-scale flat plate photobioreactor for cultivating *Nannochloropsis* sp., analyzing its growth parameters, and measuring its $CO_2$ capture.

## 2. Literature Review

Industrial activities are one of the major contributors to the increasing greenhouse gas (GHG) emissions. Cornersteel Systems Corporation also generates substantial $CO_2$ emissions, mostly from burning fuel. In their factory, $CO_2$ is produced from the diesel engine in the plant, which is used to power the ovens for powder coating. To reduce carbon emissions, Cornersteel Systems Corporation is implementing a closed flat-panel photobioreactor (FPPBR). The review's goal is to identify gaps in PBR designs, industrial-scale $CO_2$ capture, and *Nannochloropsis* sp. data, and then address those gaps with Cornersteel's project research.

### *2.1 Existing Photobioreactor Designs: Focus on Flat-Plate Systems*

Flat-plate photobioreactors (PBRs) typically offer a high illuminated surface-area-to-volume ratio with a short light path, which helps minimize shading and improve photosynthetic efficiency. For example, one comparative pilot-scale study found that flat-panel PBRs achieved ground-areal productivity values of at least ~24 g $m^{-2}$ $day^{-1}$ and photosynthetic efficiencies ≥ 2.7%, outperforming other geometries under the same conditions (de Vree et al., 2015).

Modeling work for large-scale vertical flat-panel systems indicates that thin panels (≤ 0.05 m) and north-south orientation can yield around 10 kg $m^{-2}$ $yr^{-1}$ in many U.S. climates, provided optical path and spacing are optimized (Endres et al., 2018).

In another investigation, flow behavior and mixing inside a lab-scale flat-panel PBR were shown to be critical: modified sparger and mixing designs resulted in significantly enhanced microalgal growth and $CO_2$ uptake in a flat-panel configuration (Lim et al., 2023).

However, despite these advantages, flat-plate systems face challenges: heat buildup (especially outdoors) due to infrared load, biofilm formation on large transparent surfaces, and maintenance of uniform mixing and gas-liquid exchange. For example, a design using insulated glazing in a flat-plate format found inhibited growth at elevated temperatures (~42 °C) even though light transmission was improved for a strain of *Nannochloropsis* sp. (Vadiveloo et al., 2015).

In summary, flat-plate PBRs have clear design advantages (light path, surface area), but the literature indicates that scaling them effectively still requires careful control of hydrodynamics, thermal loads, and mass transfer.

### *2.2 Successes and Failures in Industrial-Scale $CO_2$ Capture Using Microalgae*

Microalgae cultivation for industrial $CO_2$ capture has been shown to be technically feasible but remains constrained by economic, operational, and scaling issues. A review of industrial applications reports that $CO_2$ fixation rates of ~0.44 kg $CO_2$ $m^{-3}$ $day^{-1}$ under 15 % $CO_2$ were achieved in closed systems, with biomass production around 0.36 kg $m^{-3}$ $day^{-1}$, but these values still fall short of commercial targets when considering costs, gas cleaning, and downstream processing (Iglina et al., 2022).

The same review highlights that enhancements in mass transfer and light transmission in PBRs are critical levers for scaling; without those improvements, many pilot systems do not deliver the expected capture efficiency or net carbon benefit (Chen et al., 2023).

On the success side, some pilot operations using modified flat-plate or air-lift reactors with improved gas–liquid contact and bubble generation report measurable improvements in $CO_2$ uptake and biomass yields compared to simpler configurations (Lim et al., 2023).

Yet failures or limitations are also common: high capital and operational costs (lighting, mixing, temperature control), instability in culture conditions (pH drift, contamination), and sometimes the net carbon benefit is reduced when energy inputs are accounted for. In short, industrial-scale $CO_2$ capture via algae shows promise but is still more of a demonstration than a mature commercial technology.

### *2.3 Studies on Nannochloropsis: Growth Rates, Lipid Yields, $CO_2$ Uptake Efficiency*

The microalgal genus *Nannochloropsis* has been frequently studied for both biomass and lipid production, making it a good candidate for $CO_2$ capture plus valorization. For instance, one study of *Nannochloropsis* sp. grown under $CO_2$-enriched (2800 μL $L^{-1}$) photoautotrophic conditions achieved ~634 mg $L^{-1}$ dry weight, a lipid content of ~9% of dry weight, and ~16 mg $g^{-1}$ dry weight of EPA (eicosapentaenoic acid) (Hu & Gao, 2003).

Another study found that for *Nannochloropsis oculata*, when aerated with 2% $CO_2$, biomass productivity of ~0.480 g $L^{-1}$ $day^{-1}$ and lipid productivity of ~0.142 g $L^{-1}$ $day^{-1}$ were achieved; at higher $CO_2$ (15%), productivity dropped to ~0.372 g $L^{-1}$ $day^{-1}$ biomass and ~0.084 g $L^{-1}$ $day^{-1}$ lipids (Peng et al., 2020).

Further work on *Nannochloropsis* sp. MASCC 11 showed that varying pH, temperature, and $CO_2$ concentration significantly affected both growth and lipid accumulation, highlighting the sensitivity of the strain to environmental conditions (Peng et al., 2020).

These studies suggest that *Nannochloropsis* offers good growth and lipid accumulation potential, but its performance is strongly condition-dependent ($CO_2$ concentration, pH, temperature, and light) and not yet widely demonstrated under full industrial $CO_2$ stream conditions.

### *2.4 Summary of Gaps and Implications for This Study*

Although flat-plate PBRs show strong design advantages, few studies link panel geometry, hydrodynamics (mixing time, gas holdup, kLa), and real industrial $CO_2$ feed streams in a single module at pilot scale. While *Nannochloropsis* has been examined under lab conditions for growth and lipid yields, there is less published work on growing it in a closed flat-panel reactor absorbing industrial exhaust or $CO_2$ streams, with comprehensive hydrodynamic characterization and $CO_2$ capture quantification. This study addresses this by combining reactor design (flat-panel geometry, aeration rates), hydrodynamic performance (mixing, gas holdup), and biological performance (biomass, $CO_2$ uptake) in one system.

**3. Methodology**

3.1 *Design of a pilot-scale flat plate photobioreactor for cultivating Nannochloropsis sp.*

A pilot-scale flat-plate photobioreactor (PBR) is designed to cultivate *Nannochloropsis* sp. for carbon capture under industrially relevant conditions. Each module consists of a 20 L capacity chamber, and the modular structure is selected for its scalability and mobility, enabling multiple units to be deployed or relocated as needed. Transparent flat panels provide a high surface-area-to-volume ratio and minimize light path length, thereby improving light penetration and reducing shading that can inhibit microalgal growth. The reactors are constructed using excess acrylic flat panels and other excess materials obtained from the Cornersteel plant, lowering costs and environmental impact. The height of the photobioreactor is 582 mm, with a length of 480 mm and a path length of 100 mm. There are two risers, which are hollow square prisms in geometry, with an equivalent diameter of 88 mm and a height of 357 mm. The risers are placed 64 mm above the base of the photobioreactor. For the aeration of the microalgae culture, porous spargers with a diameter of 60 mm are used and directly placed at the base of the photobioreactor. The ratio of the area of the riser to the downcomer is 0.63, with a surface area-to-volume ratio of 27.56 $m^2m^{-3}$.

The system operates as a closed loop with integrated automation and sensor arrays. Sensors continuously monitor $CO_2$ concentration, pH, temperature, photosynthetically active radiation (PAR), and biomass density. Feedback control ensures that if parameters deviated from set thresholds, the system automatically adjusted aeration or $CO_2$ injection to restore stability.

Safety protocols are implemented such that cultures outside safe operating ranges are disposed of according to biosafety procedures.

Gas exchange is maintained through an aeration at 0.3 to 1 vvm of filtered air, which provided mixing and contamination control. Aeration also plays a critical role in maintaining pH balance: as the microalgae consumes $CO_2$ during photosynthesis, the medium becomes more basic. Introducing air and $CO_2$ through aeration counteracts this by producing carbonic acid, thereby stabilizing the pH within the desired range. Industrial exhaust gases are supplied via a sparger to provide additional $CO_2$, with flow rates calibrated to achieve target capture rates expressed in kg $CO_2$ $d^{-1}$ per module.

T5 18-watt LED lights serve as the primary light source. No sunlight is used since the entire PBR is indoors. Temperature is controlled within 25–29°C, and pH is maintained between 7 and 8 using automated dosing. Cultivation follows a standardized operating procedure (SOP). Conway medium is prepared prior to inoculation with *Nannochloropsis* sp., and cultures are gradually scaled to full working volume. Each module is operated for ≥60 days under steady-state conditions with routine harvesting, nutrient replenishment, and periodic cleaning/sterilization. Independent variable tests include $CO_2$ loading rate, aeration intensity, and light path length, while control parameters are maintained within narrow ranges (pH ±0.2, temperature ±2°C, PAR μmol $m^{-2}$ $s^{-1}$).

System performance is evaluated by monitoring $CO_2$ uptake rate (g $CO_2$ $module^{-1}$ $d^{-1}$), biomass productivity (g $L^{-1}$ $d^{-1}$), and culture health indicators. Data from all sensors are logged continuously to enable detailed analysis of operational stability and efficiency.

$CO_2$ removal efficiency is determined by placing a $CO_2$ meter in the inflow and in the headspace of the photobioreactor and can be calculated by using the equation below:

$$CO_2 removal efficiency = \frac{Influent CO_2 - effluent CO_2}{Influent CO_2} \times 100$$

*3.2 Hydrodynamic characterization of a pilot-scale flat plate photobioreactor for cultivating Nannochloropsis sp.*

*3.2.1 Culture Medium Composition*

Modified Conway medium is used as the nutrients for cultivation of *Nannochloropsis* sp. Salinity of the culture medium is around 30-35 ppt, and pH is maintained at 7.0-8.0. The composition of stock solutions and the chemical reagents used are shown in the table:

**Table 1.** Composition of Modified Conway Medium

| STOCK SOLUTION COMPONENTS | Stock solution (g/ L distilled water) | Amount of stock solution to make lL medium (mL) |
|---|---|---|
| $NaNO_3$ | 100.00 | 1 |
| NaEDTA | 45.00 | |
| $H_3BO_3$ | 33.6 | |
| $Na_2HPO_4 \cdot H_2O$ | 20.0 | |
| $FeCl_3 \cdot 6H_2O$ | 1.3 | |
| $MnCl_3 \cdot 4H_2O$ | 3.6 | |

| | | |
|---|---|---|
| Vitamin Primary Stocks | 100.0 mL | ----- |
| Trace Metals Primary Stocks | 1.0 mL | ------ |
| Distilled water | 1 L | ------ |
| **VITAMIN PRIMARY STOCKS** | **Stock solution (mg/200mL distilled water)** | **Amount of stock solution to make lL medium (mL)** |
| $B_1$ | 200.0 | 1 |
| $B_{12}$ | 100.0 | |
| **TRACE METALS PRIMARY STOCKS** | **Stock solution (mg/200mL distilled water)** | **Amount of stock solution to make lL medium (mL)** |
| $ZnCl_2$ | 2.1 | 1 |
| $CoCl_2 \cdot 6H_2O$ | 2.0 | |
| $(NH_4) Mo_7O_{24} \cdot 4H_2O$ | 0.9 | |
| $CuSO_4 \cdot 5H_2O$ | 2.0 | |

*3.2.2 Mixing and Flow Regime*

The flat-panel airlift photobioreactor (ALR) in this study consists of two main vertical zones: the riser and the downcomer. Agitation in the reactor is achieved entirely through air bubbling. Air–$CO_2$ gas is injected into the riser, creating upward movement and generating circulation as the liquid descends through the downcomer after gas disengagement. The composition of the gas mixture is 95%-98% air, and the remaining carbon dioxide is being supplied. This continuous cycling between the illuminated and darker zones promotes efficient mixing, nutrient transfer, and light distribution while preventing oxygen buildup and sedimentation (Razzak et al., 2023).

*3.2.3 Mixing, Sedimentation Prevention, and Light Distribution*

The ALR promotes a circular mixing pattern that continuously moves the culture through alternating light and dark zones. This creates a "flashing light" effect, where algal cells experience rapid changes in illumination that enhance photosynthetic efficiency (Basar Uyar et al., 2024). Continuous circulation also keeps the cells suspended, preventing sedimentation at the bottom of the reactor.

*3.2.4 Determination of Mixing Time*

Mixing time was determined following the tracer response method described by Bataller and Capareda (2024). A 5-mL aliquot of saturated NaCl tracer solution was injected at the base of the riser through a 1-mm stainless steel capillary. Conductivity was measured every 1–2 seconds near the top of the riser while varying the superficial gas velocity. Each experiment is conducted in triplicate. The mixing time was defined as the time required for the conductivity to reach 95% of its final steady-state value, while circulation time is calculated from the average interval between consecutive conductivity peaks.

*3.2.5 Gas–Liquid Mass Transfer*

The volumetric mass transfer coefficient ($k_La$) is determined using a modified version of the American Society of Civil Engineers (ASCE) Standard 2-91 protocol (Babcock, Malda, & Radway). The photobioreactor contents are first deoxygenated by sparging with nitrogen gas. Once the dissolved oxygen concentration reaches near zero, nitrogen flow is stopped and air sparging begins at the target superficial gas velocity. Dissolved oxygen concentration is recorded every 10 seconds using a Dissolved Oxygen Meter until a constant value is observed. The $k_La$ is calculated from the linearized form of the oxygen transfer rate equation:

$$\frac{dC}{dt} = k_La\,(C_{sat} - C)$$

Where:

$\frac{dC}{dt}$ = Gas dissolution rate

$k_L$ = Mass-transfer coefficient

a = Gas-liquid interface area

$C_{sat}$ = Gas saturation in liquid

C = Gas concentration in liquid

*3.3 Growth parameters of a pilot-scale flat plate photobioreactor for cultivating Nannochloropsis sp.*

The growth characteristics of a pilot-scale flat plate photobioreactor are evaluated for cultivating *Nannochloropsis* sp. A starter culture is obtained and subcultured into replicates to assess growth performance under varying conditions. Once a subculture reaches a target cell density, additional subcultures are prepared. Maintaining sufficient cell density is critical, as dilute cultures absorb less light and accumulate biomass more slowly. We set a target optical density (OD) at 750 nm of approximately 1.2, based on reports that similar absorbance values correspond to significant biomass accumulation in *Nannochloropsis*. For example, in a study of *Nannochloropsis oculata*, a dry-weight calibration given by AFDW (g/L) = 0.185 × $OD_{750}$ ($R^2 > 0.98$) supports the use of $OD_{750}$ in this range to approximate biomass concentration. Moreover, other work on *Nannochloropsis oculata* under high $CO_2$ and light reported $OD_{750}$ values around 1.23 at peak biomass (Van Wagenen et al., 2012). Upon reaching this density, the culture could either be used to inoculate additional photobioreactors via dilution with fresh medium or harvested to obtain dry biomass for downstream processing.

The algae are cultivated in a nutrient medium that provides the necessary carbon, nitrogen, and other nutrients for growth. Initial cultures are expanded from 200 mL to 2 L using two inoculation concentrations, 10% and 20%, to compare growth efficiency. Cell densities are measured spectrophotometrically at 750 nm to monitor growth. Aeration is not applied at this stage due to the limitations of the small 200 mL vessels; therefore, lower growth rates are expected. Once the cultures are scaled up from 2 L to 20 L, aeration is introduced, increasing gas exchange and promoting faster biomass accumulation. However, obtaining accurate absorbance measurements at this scale presents challenges, as separating and drying the biomass for weighing could result in material loss.

Absorbance readings are recorded daily for each sample, and the mean values are compared to those of the starter culture. Biomass concentration ($gL^{-1}$) is quantified as a function of optical density at 750 nm to create a biomass calibration curve. This curve is generated by correlating absorbance values with measured biomass from known volumes and tare weights, allowing biomass concentration to be estimated without removing algae from the growth medium. Growth curves are developed for both the 10% and 20% inocula samples. Statistical analyses, including regression, ANOVA, and growth curve fitting, are planned to evaluate differences in growth rates and overall productivity between conditions. To determine biomass concentration and productivity, the following equation is used:

$$BiomassConcentration(gL^{-1}) = \frac{drybiomassweight(g)}{samplevolume(L)}$$

## 4. Results

### *4.1 Biomass Growth and Optical Density Trends*

The growth of *Nannochloropsis* sp. is monitored spectrophotometrically at 750 nm to assess biomass accumulation across different inoculation ratios and culture volumes. Figure 2 presents the growth curves for cultures inoculated at 20% v/v in 200 mL and 2 L working volumes over a 6-day period. Mean absorbance values increase steadily across all treatments, indicating successful culture growth and photosynthetic activity (Chiu et al., 2009; de Vree et al., 2015).

At Day 0, the mean optical density ($OD_{750}$) of the 2 L culture at 20% v/v is 0.296, which increased to 0.507 by Day 5. The 200 mL culture at 20% v/v exhibits slightly higher readings, increasing from 0.307 to 0.545 during the same period (Table 1, Figure 2).

**Table 2.** Absorbance and Specific Growth Rate of *Nannochloropsis sp.* at 750 nm at different inocula.

| **Date** | ABSORBANCE (750 nm) | | SPECIFIC GROWTH RATE, $d^{-1}$ | |
|---|---|---|---|---|
| | 2L (20% v/v) | 200mL (20% v/v) | 2L (20% v/v) | 200mL (20% v/v) |
| Day 0 | 0.296 | 0.307 | - | - |
| Day 1 | 0.256 | 0.305 | -0.0758 | -0.0044 |
| Day 2 | 0.292 | 0.365 | 0.0693 | 0.0947 |
| Day 3 | 0.351 | - | 0.1040 | 0.2025 |
| Day 4 | 0.414 | 0.514 | 0.1017 | 0.0378 |
| Day 5 | 0.507 | 0.545 | 0.1318 | 0.0470 |

*(Note: Missing values indicate sampling was not conducted on Sundays and holidays.)*

A high pH of approximately 8.8 is observed in the 200 mL cultures. High pH values (~8.8) in non-aerated cultures are common due to $CO_2$ limitation and bicarbonate depletion, which inhibit photosynthetic carbon fixation (Peng et al., 2020). Upon scaling to 2 L and applying aeration, the pH stabilizes between 7.7 and 7.9, aligning with the optimal range for *Nannochloropsis* growth (Razzak et al., 2023). This trend supports the role of controlled aeration in improving $CO_2$ dissolution and maintaining enzyme activity.

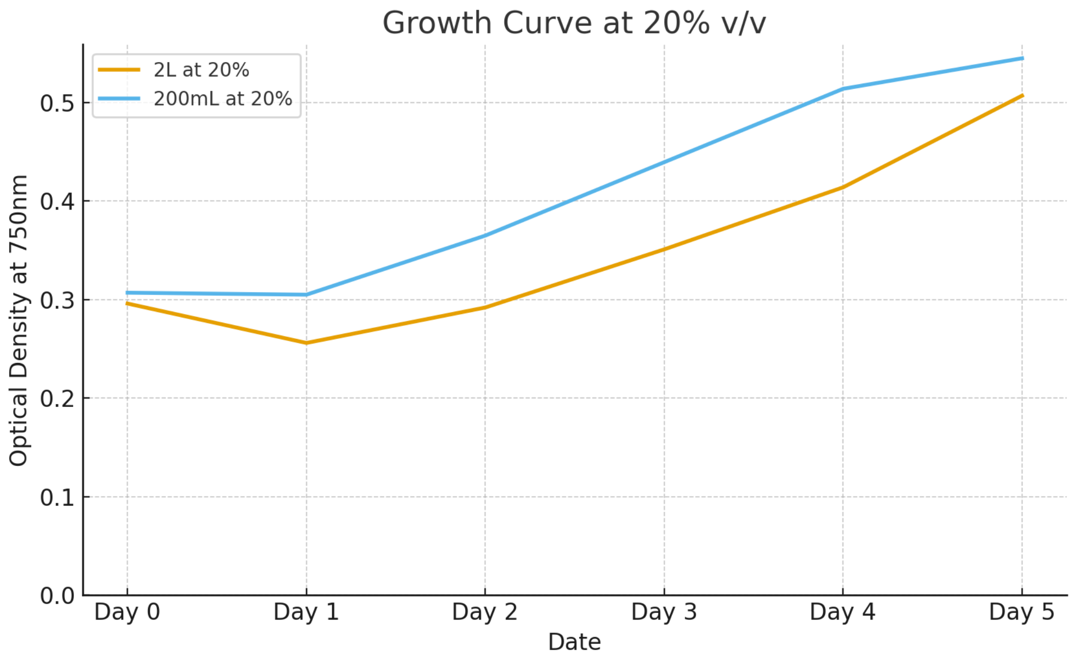


**Fig 2.** Growth curves of *Nannochloropsis* sp. at different inoculation volumes (2 L and 200 mL). Optical density was measured at 750 nm over 6 days.

*4.2 Scale-Up Performance*

The culture required roughly four weeks to scale up from 200 mL to 2 L. This duration matches other studies where scale-up of *Nannochloropsis* cultures led to delayed growth under static conditions, later accelerating once gas exchange and light exposure improved (Lim et al., 2023). Flat-panel systems are particularly sensitive to $CO_2$ availability; introducing aeration increases mass transfer and photosynthetic efficiency (Basar Uyar et al., 2024).

The improved productivity observed upon aeration agrees with previous flat-panel PBR studies showing that superficial gas velocity strongly influences mixing time and nutrient distribution (Bataller & Capareda, 2024). These hydrodynamic conditions directly impact biomass yield and carbon fixation efficiency (Iglina et al., 2022).

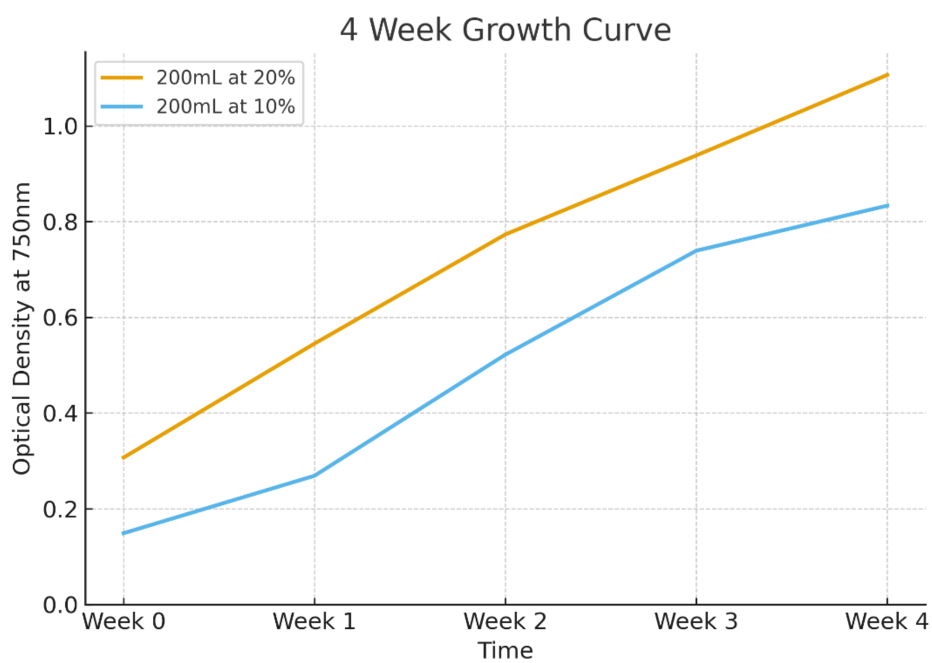


**Fig 3.** Optical density progression during 4-week scale-up from 200 mL to 2 L culture volumes of *Nannochloropsis* sp.

*4.3 Comparative Growth at 10% v/v and 20% v/v Inoculation Ratios*

Cultures with higher initial cell densities exhibited shorter lag phases and higher final optical densities (1.106 vs. 0.833). This pattern is consistent with earlier work reporting that higher *Nannochloropsis* concentrations promote faster biomass accumulation by improving light utilization and nutrient uptake efficiency (Endres et al., 2018). These results confirm that optimizing inoculation ratios is essential to achieving rapid growth and stable productivity in scaled-up photobioreactor systems.

*4.4 Establishment of the Optical Density–Biomass Correlation Curve*

Optical density readings were correlated with dry cell weight (DCW) to enable nondestructive biomass estimation. Five 15 mL samples were centrifuged at 4000 rpm for 10 minutes, washed, dried, and weighed. The resulting linear regression yielded a strong correlation ($R^2 > 0.98$) between $OD_{750}$ and DCW (Figure 4), consistent with the calibration results of *Nannochloropsis salina* reported by Van Wagenen et al. (2012). This validates $OD_{750}$ as a reliable indicator of biomass concentration, simplifying continuous monitoring in closed reactor systems. The relationship between optical density and biomass was expressed as a standard curve derived from the linear regression of measured dry cell weights versus $OD_{750}$ values:

$$\text{DCW (g L}^{-1}\text{)} = 0.185\ (\text{OD}_{750})$$

This equation enables non-destructive estimation of biomass concentration from absorbance measurements, consistent with calibration data for *Nannochloropsis* sp. reported by Van Wagenen et al. (2012).

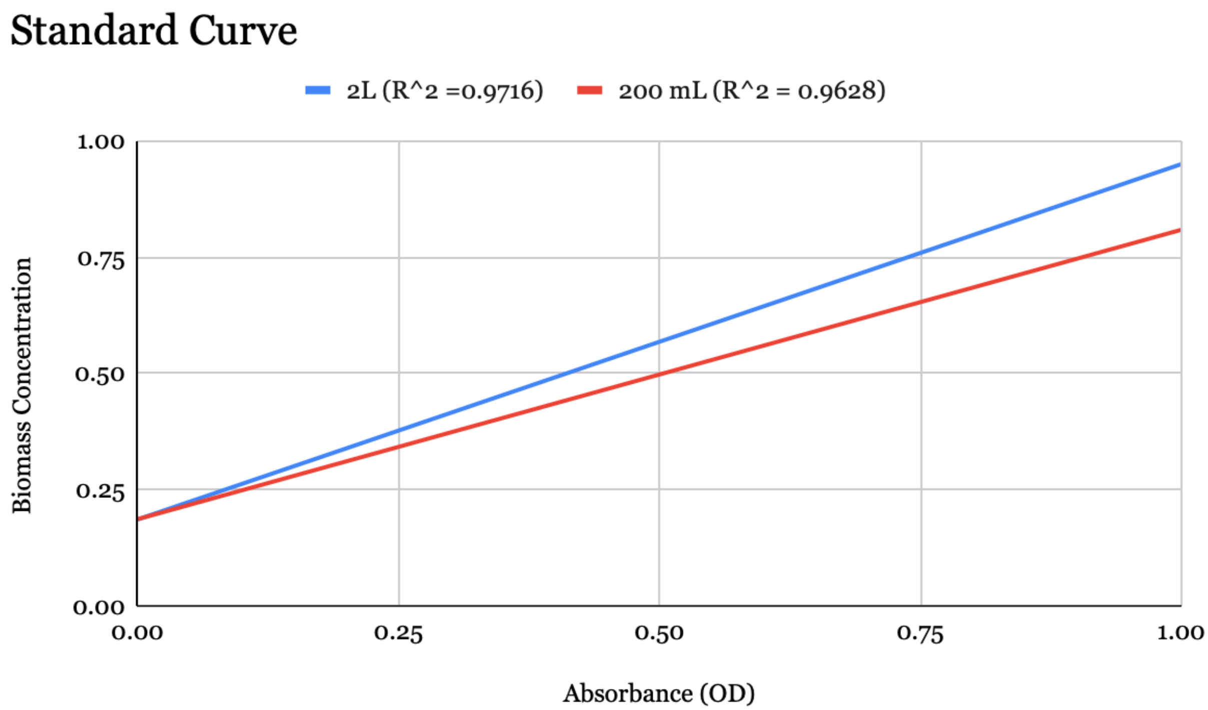


**Fig 4.** Comparison of standard curves between *Nannochloropsis* samples at 2 L and 200 ml.

## 5. Discussion/Conclusion

This study demonstrates that the designed flat-panel airlift photobioreactor successfully supports the cultivation of *Nannochloropsis* sp. for $CO_2$ capture in an industrial setting. The system's controlled aeration and compact geometry improved mixing, pH stability, and light distribution, resulting in consistent biomass growth and measurable $CO_2$ uptake efficiency.

Compared to traditional open or tubular systems, the flat-panel configuration offered superior light exposure and scalability potential, aligning with previous findings on efficient gas–liquid mass transfer and productivity in similar designs (de Vree et al., 2015; Lim et al., 2023). Results indicate that higher inoculation ratios and active aeration significantly enhance growth kinetics and overall productivity, consistent with established microalgal cultivation principles (Hu & Gao, 2003; Endres et al., 2018).

While current trials were conducted indoors and at pilot scale, the findings support the feasibility of integrating closed photobioreactors into industrial operations in the Philippines. Future research should focus on continuous $CO_2$ fixation measurements, life-cycle energy analysis, and outdoor operation tests to evaluate long-term sustainability. Overall, this system represents a practical and scalable step toward carbon-neutral industrial manufacturing through bio-based $CO_2$ capture.

## 6. Acknowledgements:

Thank you to Cornersteel Corporation for their assistance and letting me borrow their data. Thank you to Solomon admissions for helping write and edit this paper.

## References:

Abdur Razzak, S., Bahar, K., Islam, K. M. O., Haniffa, A. K., Faruque, M. O., Hossain, S. M. Z., & Hossain, M. M. (2023). Microalgae cultivation in photobioreactors: Sustainable solutions for a greener future. Green Chemical Engineering, 5(4). https://doi.org/10.1016/j.gce.2023.10.004

Algae CO2 Capture Part 1: How it Works | Research. (2025). Research | University of Kentucky. https://research.uky.edu/news/algae-co2-capture-part-1-how-it-works

Basar Uyar, Moussa Djibrine Ali, & Ozer, E. (2024). Design parameters comparison of bubble column, airlift and stirred tank photobioreactors for microalgae production. Bioprocess and Biosystems Engineering, 47. https://doi.org/10.1007/s00449-023-02952-8

Bataller, B. G., & Capareda, S. C. (2024). Hydrodynamic and mass transfer characterization of an internally illuminated airlift photobioreactor for growing Spirulina platensis. IOP Conference Series: Materials Science and Engineering, 1318(1), 012001. https://doi.org/10.1088/1757-899x/1318/1/012001

Chen, H., Jiang, Y., Zhu, K., Yang, J., Fu, Y., & Wang, S. (2023). A Review on Industrial CO2 Capture through Microalgae Regulated by Phytohormones and Cultivation Processes. Energies, 16(2), 897–897. https://doi.org/10.3390/en16020897

Chiu, S.-Y., Kao, C.-Y., Tsai, M.-T., Ong, S.-C., Chen, C.-H., & Lin, C.-S. (2009). Lipid accumulation and CO2 utilization of Nannochloropsis oculata in response to CO2 aeration. Bioresource Technology, 100(2), 833–838. https://doi.org/10.1016/j.biortech.2008.06.061

de Vree, J. H., Bosma, R., Janssen, M., Barbosa, M. J., & Wijffels, R. H. (2015). Comparison of four outdoor pilot-scale photobioreactors. Biotechnology for Biofuels, 8(1). https://doi.org/10.1186/s13068-015-0400-2

Department of Energy Philippines. (2023). Doe.gov.ph. https://legacy.doe.gov.ph/pepElmadhoun, A. (n.d.). Algae Photobioreactor. Chemical Engineering | University of Utah. https://www.che.utah.edu/teaching_module/algae-photobioreactor/

Endres, C. H., Roth, A., & Brück, T. B. (2018). Modeling Microalgae Productivity in Industrial-Scale Vertical Flat Panel Photobioreactors. Environmental Science & Technology, 52(9), 5490–5498. https://doi.org/10.1021/acs.est.7b05545

Hu, H., & Gao, K. (2003). Optimization of growth and fatty acid composition of a unicellular marine picoplankton, Nannochloropsis sp., with enriched carbon sources. Biotechnology Letters, 25(5), 421–425. https://doi.org/10.1023/a:1022489108980

Iglina, T., Iglin, P., & Pashchenko, D. (2022). Industrial CO2 Capture by Algae: A Review and Recent Advances. Sustainability, 14(7), 3801. https://doi.org/10.3390/su14073801

IPCC. (2023). AR6 Synthesis Report: Summary for Policymakers Headline Statements. Www.ipcc.ch. https://www.ipcc.ch/report/ar6/syr/resources/spm-headline-statements

IQAir. (2025). World Live Air Quality Map | AirVisual. Www.iqair.com. https://www.iqair.com/world-air-quality

Koller, M. (2015). Design of Closed Photobioreactors for Algal Cultivation. Algal Biorefineries, 133–186. https://doi.org/10.1007/978-3-319-20200-6_4

Lim, Y. A., Ilankoon, I. M. S. K., Chong, M. N., & Foo, S. C. (2023). Improving microalgae growth and carbon capture through micro-size bubbles generation in flat-panel photobioreactors: Impacts of different gas sparger designs on mixing performance. Renewable and Sustainable Energy Reviews, 171, 113001. https://doi.org/10.1016/j.rser.2022.113001

Peng, X., Meng, F., Wang, Y., Yi, X., & Cui, H. (2020). Effect of pH, Temperature, and CO2 Concentration on Growth and Lipid Accumulation of Nannochloropsis sp. MASCC 11.

Journal of Ocean University of China, 19(5), 1183–1192. https://doi.org/10.1007/s11802-020-4302-y

Philippines Air Quality Index (AQI) and Air Pollution information | AirVisual. (n.d.). Www.iqair.com. https://www.iqair.com/us/philippinesRitchie, H., & Roser, M. (2020). CO2 and Greenhouse Gas Emissions. Our World in Data. https://ourworldindata.org/co2/country/philippines

SCHOTT Photobioreactors. (2022). Schott.com. https://www.schott.com/en-us/expertise/applications/photobioreactors?tab=7aacc9acc68d452d8d65547bc3c4d972&selected=ec414b01b27b4616bbb4381e4979649b

Vadiveloo, A., Moheimani, Navid. R., Alghamedi, R., Cosgrove, J. J., Alameh, K., & Parlevliet, D. (2015). Sustainable cultivation of microalgae by an insulated glazed glass plate photobioreactor. Biotechnology Journal, 11(3), 363–374. https://doi.org/10.1002/biot.201500358

Van Wagenen, J., Miller, T. W., Hobbs, S., Hook, P., Crowe, B., & Huesemann, M. (2012). Effects of Light and Temperature on Fatty Acid Production in Nannochloropsis Salina. Energies, 5(3), 731–740. https://doi.org/10.3390/en5030731

WHO. (2024, October 24). Ambient (outdoor) Air Quality and Health. World Health Organization. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

Zhang, X., An, L., Tian, J., Ji, B., Lu, J., & Liu, Y. (2023). Microalgal capture of carbon dioxide: A carbon sink or source? Bioresource Technology, 390, 129824–129824. https://doi.org/10.1016/j.biortech.2023.129824