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Design, Fabrication, and Performance Evaluation of a Laboratory-Scale Bubble Column Photobioreactor for the Cultivation of *Chlorella vulgaris*

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The increasing global demand for energy presents significant challenges to the availability of sustainable resources for future generations. Microalgae have emerged as a promising renewable energy source; however, further optimization of large-scale cultivation is necessary to enhance economic viability and sustainability. This study focuses on the design, fabrication, and performance evaluation of a laboratory-scale bubble column photobioreactor (PBR) for the cultivation of *Chlorella vulgaris*. The fabricated bubble column PBR consists of a stainless-steel frame and an acrylic column with a working volume of 32 L and a height of 75 cm. It is equipped with an 80 W air pump, LED lamps, and a three-arm spider sparger to ensure efficient gas distribution. A temperature-pH sensor and a light automation controller were integrated to maintain optimal cultivation conditions, with temperature and pH levels monitored at 25 °C-30 °C and 7-10, respectively. Nutrient concentration optimization was conducted using 14:14:14 NPK fertilizer, with the optimal concentration determined to be 40 mg/L, yielding a specific growth rate of 0.1979 cells/ml-d and a generation time of 3.50 d. Growth kinetics analysis revealed the characteristic phases of microalgal growth (lag, exponential, stationary, and death phases), with the highest biomass yield of 5.95 × 10^6 cells/ml observed on the fifth day of cultivation, indicating the optimal harvesting time. These findings highlight the potential of the bubble column PBR for efficient Chlorella vulgaris cultivation, demonstrating its applicability for biofuel production and other biotechnological applications.

1. Introduction

There is an increasing global demand for sustainable energy sources and environmentally friendly bioproducts (Mamuad et al., 2022). This has propelled significant interest in microalgae as a potential feedstock, particularly *Chlorella vulgaris*. *Chlorella vulgaris* is a unicellular green microalga that has emerged as a model organism due to its rapid growth rate, high lipid content, and ability to fix atmospheric carbon dioxide (Mendes et al., 2024). It is widely used ranging from biofuel production to nutraceuticals, animal feed, and wastewater treatment. Cultivating microalgae like Chlorella vulgaris offers significant environmental benefits, including carbon sequestration, reduction of nutrient pollution, and the potential for integrating into circular bioeconomy systems. These advantages make microalgae-based systems a promising strategy for mitigating climate change and supporting sustainable development goals.To fully harness its potential, optimized cultivation systems are essential especially those that can be effectively scaled from laboratory to industrial levels. Photobioreactors (PBRs) are engineered systems that provide controlled environments for the cultivation of photoautotrophic microorganisms such as microalgae. Among the various PBR types, bubble column photobioreactors (BCPBRs) have gained attention due to their simple design, low operational cost, efficient gas exchange, and relatively high mass transfer rates (Penloglou et al., 2024). These reactors rely on the upward motion of gas bubbles to mix and aerate the culture medium, enhancing light penetration, nutrient distribution, and carbon dioxide

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utilization. Most existing studies on BCPBRs focus either on large-scale models or generalized designs not specifically optimized for *Chlorella vulgaris despite their disadvantages*. Moreover, there is a lack of detailed investigations into cost-effective**,** small-scale PBRs that integrate real-time environmental monitoring for pH, temperature, and light intensity and their effect on biomass productivity under controlled conditions. This gap in literature highlights the need for a modular, lab-scale bubble column PBR specifically tailored for *Chlorella vulgaris* cultivation, which allows for replicable performance testing and systematic growth analysis under varied environmental conditions. This study aims to address the existing gap by designing and fabricating a low-cost, efficient, and sensor-integrated laboratory-scale bubble column photobioreactor tailored for Chlorella vulgaris cultivation. Evaluating the capability of photobioreactor to support sustained microalgal growth under controlled conditions has been conducted. This study also investigates the effect of varying fertilizer concentrations on biomass productivity, with the goal of identifying optimal nutrient levels for enhanced cultivation performance. Systematic testing and analysis, including triplicate experiments and statistical evaluation has been carried out. The outcomes of this study are expected to provide foundational insights for future scale-up and contribute to the development of sustainable bioprocesses for biofuel production and other high-value bioproducts derived from microalgae

2. Materials and Methods

A laboratory-scale bubble column photobioreactor was designed, fabricated, and tested in this study. Developmental method procedures were employed for the design and fabrication of the solar dryer equipment, while an experimental approach was used to assess the performance of the fabricated photobioreactor. All experiments were conducted in triplicate to ensure the accuracy, reliability, and reproducibility of the results. The system was tested for its ability to support the growth of Chlorella vulgaris, a model microalga, under controlled conditions. The strain was cultured in a synthetic growth medium for a period of 10 days. Daily measurements of cell density were performed using a hemocytometer, while biomass concentration was estimated spectrophotometrically. To assess the effect of nutrient availability, a parallel experiment was conducted to optimize fertilizer concentration. The resulting data were subjected to statistical analysis, and standard deviation was used to interpret the variability and consistency of the measurements. The design, fabrication, and experimental testing were carried out at the Unit Operations Laboratory of the Chemical Engineering Department at Mariano Marcos State University, City of Batac, Ilocos Norte, and at PhytoLab of the College of Aquatic Sciences and Applied Technology in the Municipality of Currimao, Ilocos Norte.

The selected design was guided by key criteria for an effective photobioreactor, including the specific needs of the target microalgae species, processing requirements, and energy efficiency. Taking these factors into account, a bubble column photobioreactor was chosen due to its straightforward construction and high surface-area-to-volume ratio. This reactor type incorporates minimal mechanical components, which is advantageous as it minimizes mechanical stress on the algal cells and lowers both operational costs and energy consumption. The determination of dimensions of the photobioreactor is given by the standard height/diameter ratio of the vessel which ranges from 1.5 to 20 (Perry and Green, 2008). The system components, including the air pump, LED lighting, and control sensors, were powered using a standard 220V AC supply. The volume of the vessel, surface area and surface area/volume ratio were determined using Eqs (1), (2) and (3), respectively. In addition, the distance of the light source from the reactor vessel was determined using Eq(4).

$$V = \frac{1}{3}\pi r^2 h \tag{1}$$

where V is the volume of the reactor, r is the radius of the working volume, and h is the height of the reactor.

$$S = 2\pi r h \tag{2}$$

where S is the illuminated surface area.

$$\frac{S}{V} = \frac{6}{r} \tag{3}$$

where S/V is the surface to volume ratio.

$$I = \frac{P}{4\pi d^2} \tag{4}$$

where I is the intensity of light, P is the power of the light source, and d is the distance from the light source.

3. Results and Discussion

The designed and fabricated laboratory bubble column PBR is made of materials found in the locality. The equipment was tested by cultivation of microalgae in the bubble column PBR fertilizer medium.

3.1 Design of the Fabricated bubble column PBR

The main parts of the fabricated bubble column PBR are the sparger, hopper and bubble column. The specifications utilized in the design and fabrication of the bubble column PBR is shown in Table 1.

Table 1: Specification of the bubble column PBR

Description	Specification
Height of the Frame	127 cm
Diameter of the column	20.32 cm
Height of the column	75 cm
Valves	1.27 cm and 1 in 2.54 cm
Pump	80 W
Light Bulbs	9 W LED Bulbs
Sparger	3-arm spider sparger
Gas Holdup	0.035
Volume	32.43 L
Surface Area	9,576 cm^2
Surface to Volume ratio	0.29

The Laboratory Scale Bubble Column PBR, shown in Figure 1, is constructed with a 50-inch tall fabricated stainless-steel frame, a column with a diameter of 8 inches and a height of 29.5 inches, Temperature-pH Sensor and Light Automation Controller, 80W pump, LED Bulbs and valves. The frame of the photobioreactor was constructed using stainless steel pipes, chosen for their excellent strength, toughness, and corrosion resistance. The column itself was made from acrylic, chemically known as polymethyl methacrylate (PMMA), due to its favorable properties. Acrylic is an ideal material for photobioreactors because of its high light transmittance, glass-like clarity, and exceptional durability. A stainless-steel cap was installed at the top of the column, while a stainless-steel hopper equipped with a 2.54 cm PVC ball valve was used for dispensing the culture media. The cap includes perforations with a 2.54 cm diameter and 2.54 cm pitch spacing to prevent the buildup of oxygen within the system. Airflow during cultivation was regulated using 1.27-cm diameter valves, and a 2.54 cm garden hose was used to connect the pump to the air inlet. LED bulbs served as the light source, selected for their high energy efficiency and ability to emit intense light while consuming minimal power. Additional advantages such as compact size, lightweight structure, long operational life, and durability further justified the use of LED lighting in the reactor design.

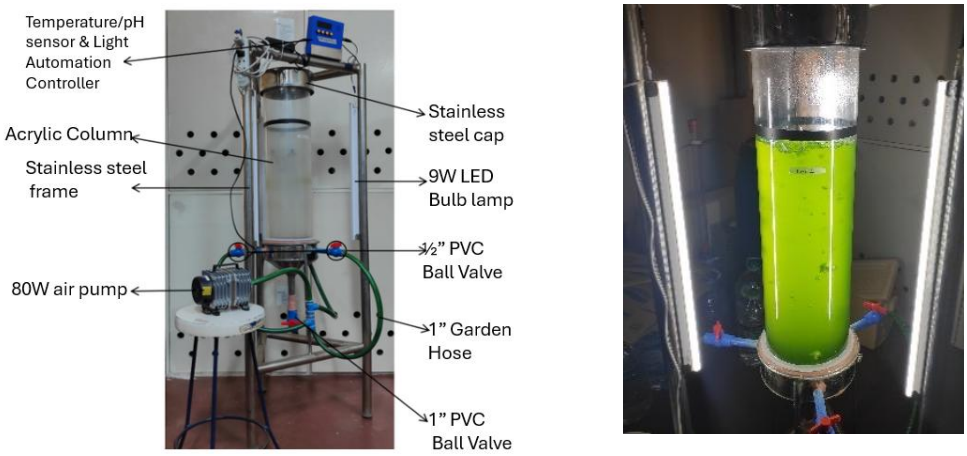

Figure 1: Fabricated laboratory-scale bubble column photobioreactor (PBR). (a) Annotated image of the complete system showing key components (b) Operational image of the PBR during microalgae cultivation, showing the illuminated culture medium under controlled aeration and lighting conditions.

3.2 Determination of the Optimum Fertilizer Concentration

Microalgae such as Chlorella vulgaris are widely recognized for their ability to thrive in nutrient-rich environments, making the application of fertilizer-enriched media essential for maximizing biomass yield and enhancing growth performance. The addition of macronutrients not only stimulates algal bloom but also supports critical metabolic pathways. Nitrogen plays a central role in influencing cell composition, division rate, and the stability of the culture system (Suthar and Verma, 2017). Phosphorus is indispensable for cellular development and is directly involved in ATP synthesis, nucleic acid production, photosynthesis, and energy transfer processes (Alazaiza et al., 2023). Potassium contributes to protein synthesis and enzymatic activation, with deficiencies often resulting in increased respiration rates and reduced algal productivity (Khan et al., 2018). These macronutrients are critical in supporting the cellular functions necessary for biomass accumulation, particularly in high-density cultures aimed at biofuel or nutraceutical production.

To determine the optimal fertilizer concentration, small-scale cultivation trials were conducted under controlled conditions with varying nutrient levels, including a control group. Cultures were monitored over 11 d. As reported by Lathifah et al. (2021), and supported by more recent studies such as Ogbonna et al. (2017), the specific growth rate (μ) and generation time (G) are key parameters in assessing the effectiveness of nutrient concentrations in promoting algal growth.

The specific growth rate represents the increase in biomass relative to the existing biomass concentration over time, serving as a measure of how rapidly cells are proliferating under the given conditions. A higher μ reflects faster cellular activity and favorable growth conditions. Conversely, generation time is the time required for the population to double, with shorter generation times indicating more efficient cell division and overall culture performance (Wayne et al., 2018).

The calculated specific growth rates and generation times for each nutrient concentration level are summarized in Table 2. Treatments 1 to 4 (T1–T4) correspond to increasing fertilizer concentrations of 20, 40, 60, and 80 mg/L, respectively. Among the treatments, the highest specific growth rate (0.1979 cell/ml·d) and the shortest generation time of 3.5022 d were recorded at a nutrient concentration of 40 mg/l. This concentration was selected as the optimum for subsequent mass cultivation of Chlorella vulgaris in the fabricated bubble column photobioreactor. Furthermore, as shown in Figure 2, the treatment corresponding to this generation time (T2) exhibited the highest cell density is T2.

Table 2: Growth rates and generation time of different treatments.

	Specific Growth Rate (cell/ml-d)	Generation time (d)
Treatment 1 (T1)	0.1958 ± 0.00493	3.5404± 0.0999
Treatment 2 (T2)	0.1979 ± 0.00141	3.5022± 0.0995
Treatment 3 (T3)	0.1933 ± 0.00138	3.5859± 0.0964
Treatment 4 (T4)	0.1740 ± 0.00122	3.9376± 0.0188
Control	0.0844 ± 0.00060	8.2156± 0.5650

Nutrient concentration plays a critical role in regulating both the specific growth rate and generation time of microalgae. However, exceeding the optimal concentration threshold can negatively impact growth performance. Elevated nutrient levels were observed to result in a decline in growth rate and an increase in generation time. Lathifah et al., (2021) noted that excessively high concentrations of fertilizers may inhibit pigment synthesis essential for photosynthesis, potentially due to metabolic imbalances or cellular stress responses. Consequently, higher NPK concentrations require a longer period to reach the stationary phase of growth and may, in some cases, exert toxic effects on the microalgae. Additionally, nutrient oversupply can lead to intracellular accumulation in the form of granules, which may disrupt normal cellular functions.

3.3 Determination of Growth Kinetics of the Biomass Culture and Optimum Time of Cultivation

Mass cultivation of Chlorella vulgaris was carried out over an 11-d period using a laboratory-scale bubble column photobioreactor, with a total culture volume of 19,000 mL composed of 17,100 mL of seawater and 1,900 mL of algal inoculum. The cultivation was conducted using an optimized fertilizer concentration of 40 mg/L, as determined from preliminary trials. Throughout the experiment, daily monitoring of absorbance and pH was performed to assess algal growth and physiological status. Absorbance readings served as a non-invasive proxy for estimating biomass concentration, a method commonly employed in algal cultivation studies (Jesus et al., 2019).

The growth curve of *C. vulgaris* followed the typical four-phase pattern observed in microalgal cultures is shown in Figure 2. The lag phase, characterized by minimal cellular activity, was observed on the first day the microalgae acclimated to the new environmental conditions. By the second day, the culture had transitioned into

the exponential phase, marked by a rapid increase in cell density, which continued until the fifth day. This phase reflects optimal physiological activity and nutrient availability, consistent with findings reported by Chanquia and Kara, (2022), where *C. vulgaris* demonstrated accelerated biomass accumulation under well-aerated and nutrient-optimized conditions.

From the sixth to the ninth day, growth plateaued, indicating entry into the stationary phase, during which nutrient depletion and waste accumulation limited further biomass increase. The final stage, the decline phase, occurred between ninth and eleventh day, characterized by a significant reduction in cell density. This decline can be attributed to the exhaustion of nutrients, potential oxygen limitation, and increased susceptibility to microbial contamination, common limiting factors in batch culture systems. A peak cell density of 5.95 × 10^6 cells/mL was achieved on the fifth d, corresponding to the transition from the exponential to stationary phase. Based on this, a 5-day cultivation period was identified as optimal for biomass harvesting. This agrees with previous studies, such as (Ras, et al. (2011), and Lathifah et al. (2021), which reported that *C. vulgaris* achieves maximum productivity within 4–6 d under batch cultivation when provided with optimal nutrient and light conditions. Furthermore, a visible color shift from light green to dark green was observed at peak biomass, a phenomenon previously noted as indicative of chlorophyll accumulation and high algal density. Following the death phase, the culture progressively turned brown, signalling cellular degradation and chlorophyll breakdown, commonly associated with senescence and nutrient exhaustion (Converti et al., 2009).

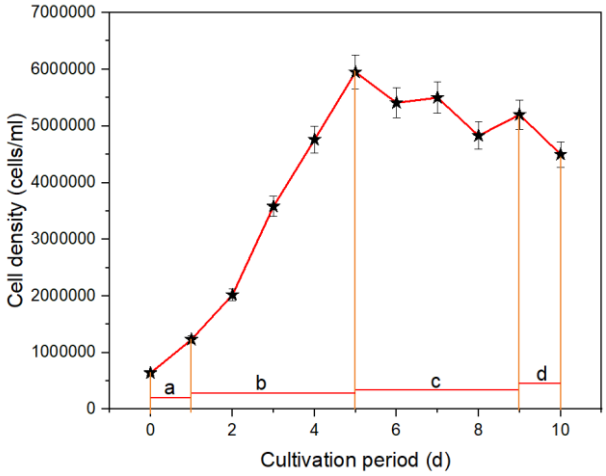

Figure 2: Growth kinetics of microalgae cultured in the bubble column photobioreactor, represented by cell density (cells/ml) over a 10-day cultivation period. The distinct growth phases are indicated: (a) Lag phase (b) Exponential (log) phase, (c) Stationary phase, and (d) Death phase.

3.4 Determination of % yield of the microalgae inside the Bubble Column PBR

The percent yield of Chlorella vulgaris biomass was determined using the initial and peak cell densities of 6.4 × 10^5 cells/mL and 5.95 × 10^6 cells/mL, respectively, resulting in a calculated biomass yield of approximately 930 %. This substantial increase in biomass is consistent with findings from previous studies. Ras et al. (2011), reported that under optimized photobioreactor conditions, C. vulgaris could achieve exponential growth rates with biomass yields exceeding 800 % within 5–7 d. The study of Sa et al. (2014) observed biomass yields above 900 % during batch cultivation in closed photobioreactor systems, particularly when nutrient concentrations and light intensity were optimized. The high yield obtained in the present study can be attributed to the bubble column photobioreactor, which promotes efficient gas exchange and light distribution, factors known to enhance algal productivity. The use of a tailored fertilizer concentration (40 mg/L), identified through small-scale optimization trials, aligns with the conclusions of Lathifah et al. (2021), who emphasized that optimizing nutrient levels significantly improves microalgal growth performance and biomass output. These results validate the effectiveness of the reactor design and cultivation strategy in achieving high microalgal productivity, reinforcing the suitability of Chlorella vulgaris for large-scale biomass applications under controlled photobioreactor systems.

4. Conclusions

The study successfully designed, fabricated, and tested a bubble column PBR for the mass cultivation of Chlorella vulgaris. The optimal concentration was 40 mg/L, resulting in a specific growth rate of 0.1979 cells/(ml·d) and a generation time of 3.50 d. Maximum biomass yield of 5.95×10^6 cells/mL was achieved on the 5th day, marking the optimum cultivation time. The growth followed the typical phases: lag, from day 0–1, exponential from day 1–5, stationary from day 6–9, and death from day 9–11. The microalgae culture achieved a yield increase of 930 %, demonstrating the efficiency of the bubble column PBR for algal biomass production.

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