

Design and System Level Optimization of Photobioreactor.pdf

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Design and System Level Optimization of a Modular Algal Photobioreactor for Enhanced CO₂ Sequestration In ASEAN

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ABSTRACT

The continued rise in carbon emissions across ASEAN economies, driven by industrial growth and increasing energy demand, necessitates scalable and climate-adaptive carbon sequestration strategies within the agritech sector. Microalgae-based photobioreactors offer a viable pathway due to their substantially higher carbon fixation rates compared to terrestrial plants; however, existing systems are often constrained by suboptimal reactor design, limited process control, and inadequate adaptation to tropical operating conditions. This paper presents a systematic design and optimization framework for a modular closed photobioreactor developed for ASEAN deployment. A flat-panel reactor configuration is selected based on its favourable surface-area-to-volume ratio and light distribution characteristics. A source-flexible carbon dioxide delivery mechanism is integrated to enable compatibility with both ambient and industrial emissions. A multi-parameter control methodology is established to regulate temperature, light exposure, pH, nutrient availability, and carbon dioxide injection, ensuring stable and efficient biomass growth. The system incorporates an embedded control architecture with cloud-enabled monitoring and a data-driven optimization layer for predictive growth assessment and adaptive parameter tuning. Under controlled conditions, the proposed system achieves a carbon fixation rate of approximately 0.412 g/L/day. The presented framework offers a practical approach for integrating microalgae-based carbon capture into scalable agritech applications across the ASEAN region.

Keywords- Carbon Sequestration, Photobioreactor, Microalgae, CO₂ Capture, Sustainable Engineering, IoT Systems, Biofuel, Smart Agriculture

1. INTRODUCTION

The rapid expansion of industrial activity and energy demand across the ASEAN region has resulted in a sustained increase in carbon dioxide emissions over recent decades. Projections from regional energy outlooks indicate that emissions may rise by up to 140% by 2040 under business-as-usual scenarios, significantly challenging national commitments under the Paris Agreement (ASEAN Centre for Energy, 2020; Anadon et al., 2020). Despite the establishment of Nationally Determined Contributions (NDCs), several ASEAN countries continue to face gaps between projected emissions and reduction targets, particularly in rapidly industrializing economies such as Indonesia, Malaysia, and Singapore (IPCC, 2021).

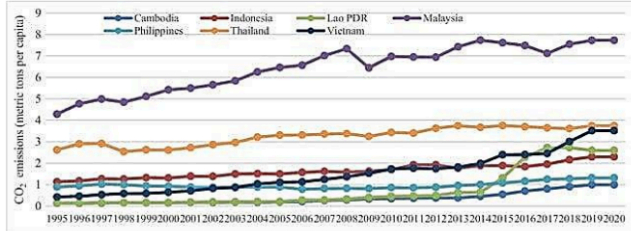


Fig. 1. Per capita carbon dioxide emissions trend across selected ASEAN member states, 1995–2020, illustrating divergent national emission trajectories relative to Paris Agreement commitments.

Source: Our World in Data (2022).

To contextualize this challenge, Table 1 summarizes the Nationally Determined Contributions (NDCs) of selected ASEAN countries under the Paris Agreement, including both conditional and unconditional emission reduction targets, reference baselines, and target years. The variation in targets and implementation timelines highlights the uneven progression of decarbonization efforts across the region. While these commitments represent significant policy direction, achieving them remains challenging under current development trajectories, indicating the need for scalable and deployable carbon mitigation strategies beyond conventional approaches such as energy transition and efficiency improvements.

ASEAN NDCs under the Paris agreement.

	Conditional emissions reduction targets	Unconditional emissions reduction targets	Ref. point	Target year
Indonesia	41%	29%	BAU	2030
Myanmar	—	20% electricity saving, 30% RE in rural electrification, 9.4 GW hydroelectric, 260,000 units of energy efficient cookstoves, 30% reserved and protected forest	BAU	2030
Thailand	25%	20%	BAU	2030
Malaysia	45% (per unit of GDP)	35% (per unit of GDP)	2005	2030
Singapore	—	36% (per unit of GDP)	2005	2030
Brunei	—	63% energy consumption reduction, 10% renewables in primary energy mix	—	2035
Philippines	70%	—	BAU	2030
Vietnam	25%	8%	BAU	2030
Laos	—	30% RE in energy consumption, 191 ktCO ₂ e/year from transportation, 16,284 ktCO ₂ avoidance from hydroelectricity, 70% forest cover	2000–2015	2015–2030
Cambodia	—	27%	BAU	2030

Table 1. Summary of ASEAN Nationally Determined Contributions (NDCs), including conditional and unconditional emission reduction targets, reference baselines, and target years (UNFCCC, 2020).

Biological carbon capture using microalgae has emerged as a promising alternative due to its high photosynthetic efficiency and rapid growth rates. Species such as *Chlorella vulgaris* demonstrate carbon fixation rates significantly higher than terrestrial plants (Politaeva et al., 2021), while simultaneously producing biomass that can be utilized for downstream applications including biofuels, fertilizers, and bioproducts. (Lam & Lee, 2012; Brennan & Owende, 2010) This dual capability positions microalgae systems as a viable component of circular bioeconomy frameworks increasingly emphasized in ASEAN agritech development.

Photobioreactors provide a controlled environment for microalgae cultivation, offering advantages over open pond systems in terms of contamination control, productivity, and process stability (Ugwu et al., 2008; Posten, 2009). However, existing photobioreactor implementations remain constrained by several engineering limitations. These include suboptimal reactor geometries that reduce light utilization efficiency, inadequate control of critical growth parameters, and limited adaptability to the high-temperature, high-humidity conditions characteristic of tropical climates (Carvalho et al., 2006). In many cases, the absence of coordinated control across parameters such as temperature, pH, light intensity, nutrient availability, and carbon dioxide supply leads to unstable operation and reduced biomass yield. Recent advances in embedded systems and data-driven control present opportunities to address these limitations. The integration of sensor networks, real-time monitoring, and automated feedback control enables more precise regulation of biological processes within photobioreactors. Furthermore, the incorporation of predictive models based on historical sensor data allows for adaptive optimization of operating conditions (Kiet et al., 2021). Despite these developments, there remains a lack of integrated photobioreactor designs that combine optimized geometry, multi-parameter control, and scalable automation within a unified framework suitable for ASEAN deployment.

In this context, the objective of this study is to develop a systematic engineering approach for the design and optimization of a modular closed photobioreactor for carbon sequestration in agritech applications. This study makes three contributions: a performance-driven reactor design methodology emphasising geometry selection and scalability; a multi-parameter closed-loop control framework for stable microalgae cultivation; and an integrated automation architecture with a data-driven optimization layer for real-time adaptive operation. By combining reactor design, control strategy, and system integration, this work aims to provide a practical and scalable solution for microalgae-based carbon capture. The proposed system is intended to support sustainable agritech deployment while addressing the growing need for effective carbon management solutions across the ASEAN region.

2. BACKGROUND

Microalgae-based carbon capture has gained significant attention due to its high photosynthetic efficiency and rapid biomass production. Unlike terrestrial plants, which typically convert only a small fraction of incident carbon dioxide through photosynthesis, certain microalgae species have demonstrated carbon fixation rates that are 10 to 50 times higher under controlled conditions (Politaeva et al., 2021). Among these, *Chlorella vulgaris* is widely recognized as one of the most suitable candidates for carbon sequestration applications due to its robust growth characteristics, adaptability to varying environmental conditions, and relatively high biomass productivity.

The selection of *Chlorella vulgaris* in this study is based on its compatibility with tropical operating environments and its well-documented growth performance. The species exhibits optimal growth within a temperature range of approximately 25°C to 35°C, with peak metabolic activity typically observed near 30°C (Ashour et al., 2023; Converti et al., 2009). Its preferred pH range lies between 7 and 8, aligning closely with neutral aqueous conditions and reducing the need for extensive chemical buffering (Ashour et al., 2023). In terms of light requirements, *Chlorella vulgaris* responds effectively to moderate to high photon flux densities, with optimal growth observed under controlled photoperiods such as 16:8 (light: dark), which supports sustained biomass accumulation (Khalili et al., 2013).

From a carbon capture perspective, the species demonstrates significant fixation capability, with reported rates reaching up to 0.412 g CO₂/L/day under controlled conditions (Politaeva et al., 2021). Additionally, the biomass-to-carbon dioxide conversion ratio is approximately 1:1.8 (dry biomass to CO₂), indicating efficient utilization of supplied carbon. These characteristics, combined with its resilience to fluctuating environmental conditions, make *Chlorella vulgaris* a practical choice for scalable deployment in ASEAN climates.

The effectiveness of microalgae cultivation systems is strongly influenced by the reactor configuration. Two primary approaches are commonly employed: open pond systems and closed photobioreactors. Open pond systems are widely used due to their low capital cost and simplicity; however, they are associated with several limitations, including contamination risk, poor control over environmental parameters, and relatively low biomass productivity. In contrast, closed photobioreactors provide a controlled cultivation environment, allowing for higher productivity and more efficient carbon utilization (Klein-Marcuschamer et al., 2013).

Parameter	Open systems	Closed systems
Space requirement	10,000 m ²	100 m ²
Weather dependency	High	Low
Water loss	Very high	Low
CO ₂ loss	Higher	Lower
Biomass concentration	0.5–1 kg m ⁻³	5 kg m ⁻³
Volumetric algal productivity	0.12–0.48 g L ⁻¹ d ⁻¹	0.2–3.8 g L ⁻¹ d ⁻¹
Photoconversion efficiency	±1.5%	±5%
Light efficiency	Poor	Good
Process controllability	Difficult	Easy
Biomass quality	Variable	Reproducible
Contamination risk	High	Negligible
Harvesting efficiency	Lower	Higher
Harvesting cost	Higher	Lower
Energy requirement	±57 MJ m ⁻² y ⁻¹	±207 MJ m ⁻² y ⁻¹
Primary cost driver	Mixing	Temperature control

Table 2. Comparison between open pond systems and closed photobioreactors in terms of productivity, control, contamination risk, and scalability. Compiled from Klein-Marcuschamer et al. (2013); Kumar et al. (2015); Paul et al. (2021); Ketheesan and Nirmalakhandan (2012); Razzak et al. (2021)

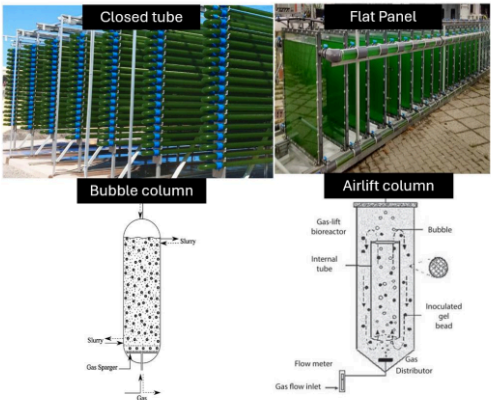


Fig. 2. Representative configurations of common photobioreactor geometries, including tubular, flat-panel, and bubble column design. Adapted from Ugwu et al. (2008).

Closed photobioreactors can be further categorized based on their geometry, including tubular, flat-panel, and bubble column configurations as depicted in Fig2. Each configuration presents distinct advantages and limitations in terms of light distribution, gas exchange efficiency, ease of maintenance, and scalability.

Despite these advancements, several challenges remain in the practical deployment of photobioreactors, particularly in ASEAN environments. Elevated ambient temperatures can lead to thermal stress and reduced enzymatic efficiency, while fluctuating solar irradiance affects photosynthetic consistency. Furthermore, many existing systems lack integrated control strategies capable of maintaining the specific growth conditions required by species such as *Chlorella vulgaris*. The absence of coordinated regulation across temperature, light intensity, pH, nutrient availability, and carbon dioxide supply often results in suboptimal growth and reduced carbon fixation performance.

Given these considerations, there is a clear need for photobioreactor systems that combine optimized geometry with species-specific environmental control and scalability. Closed systems, particularly flat-panel configurations, provide a suitable foundation due to their favourable light distribution characteristics and compatibility with controlled operation. However, their effectiveness depends on the integration of precise control mechanisms tailored to the biological requirements of the selected microalgae species. These design and control considerations form the basis for the methodology presented in the subsequent sections.

3. Geometry and Material Design

The performance of a photobioreactor is fundamentally governed by its geometric configuration and material properties, which directly influence light distribution, mass transfer efficiency, thermal behaviour, and scalability. The reactor design is approached as a constrained engineering problem, where multiple performance criteria are evaluated to determine an optimal configuration for tropical deployment in ASEAN conditions.

3.1 Geometry Selection

A comparative evaluation of tubular, flat-panel, bubble column, airlift, and open raceway photobioreactor geometries was conducted against key performance criteria: light utilisation efficiency, mixing characteristics, scalability, maintenance complexity, and thermal stability. These factors are particularly critical in ASEAN environments, where high ambient temperatures and intense solar irradiance impose additional operational constraints.

Tubular photobioreactors provide a high surface-area-to-volume ratio and are widely used for large-scale cultivation; however, long flow paths can lead to oxygen accumulation and non-uniform light exposure, necessitating complex circulation systems (Posten, 2009; Zittelli et al., 2013). Bubble column reactors offer simpler, energy-efficient operation but suffer from limited light penetration at higher cell densities, constraining productivity (Pulz, 2001).

In contrast, flat-panel photobioreactors demonstrate superior overall performance. Their short light path enables uniform photon distribution and improved photosynthetic efficiency, while the planar geometry supports compact, modular deployment suitable for space-constrained settings (Carvalho et al., 2006; Endres, 2017; Abdel-Baset et al., 2024). Although susceptible to thermal buildup under high irradiance, this limitation is mitigated through the active temperature regulation strategy described in Section 5. Accordingly, a vertical flat-panel configuration was selected as the primary reactor design.

While detailed computational fluid dynamics (CFD) and radiative transfer modelling are beyond the scope of this study, the selection is supported by reported quantitative performance data. Flat-panel systems with a light path of 20–50 mm achieve photosynthetic efficiencies of approximately 5%, compared to ~1.5% for open raceway systems, and volumetric productivities of 0.2–3.8 g L⁻¹ d⁻¹ versus 0.12–0.48 g L⁻¹ d⁻¹, respectively (Klein-Marcuschamer et al., 2013; Paul et al., 2021). Biomass concentrations of up to 5 kg m⁻³ have also been reported for closed flat-panel systems, significantly exceeding the 0.5–1 kg m⁻³ typical of open configurations (Paul et al., 2021).

Geometry	Key advantages	Key limitations	Suitability
Tubular PBR	- High SA:V ratio - Good light exposure - Suited to outdoor use	- O₂ accumulation risk - Complex pumping - Difficult to clean	High-density production; high maintenance
Flat-panel PBR †	- Superior light utilisation - Compact and modular - Easy harvest and monitoring	- Overheating risk - Biofilm formation - Requires active cooling	Optimal for CO ₂ capture; compact industrial setups
Bubble column PBR	- Simple design - Low energy input - Adequate mixing	- Limited light penetration - Poor scalability - Low culture density	Lab-scale only; not suited for high-yield systems
Airlift PBR	- Improved mixing over bubble column - Lower shear stress	- More complex design - Reduced light exposure - Moderate scalability	Moderate yield; light efficiency inferior to flat-panel
Open raceway pond	- Very low capital cost - Simple to construct	- High contamination risk - High evaporation loss - No process control - Low productivity	Unsuitable for controlled CO ₂ sequestration

Table 3. Performance comparison of photobioreactor geometries based on light distribution, mixing efficiency, scalability, maintenance, and thermal characteristics. SA: V = surface area-to-volume ratio. † Flat-panel PBR selected as the primary geometry for this study.

3.2 Structural Design and Modular Configuration

The proposed reactor adopts a vertical flat-panel architecture with integrated ports for fluid and gas exchange. The design incorporates multiple inlet and outlet channels to support continuous operation, including carbon dioxide injection, nutrient delivery, pH adjustment, and biomass harvesting. The internal volume is optimized to maintain a high surface-area-to-volume ratio while ensuring sufficient culture depth for stable flow dynamics.

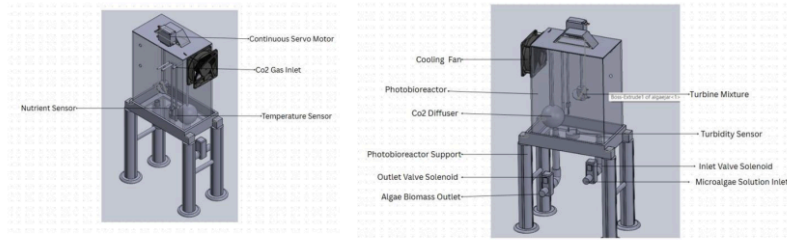


Fig. 3. SolidWorks model of the proposed flat-panel photobioreactor showing structural layout, sensor integration points, and pipeline connections.

A key design feature is the modular configuration, which allows individual reactor units to operate independently or as part of a larger interconnected system. Each unit is equipped with standardized connection interfaces, enabling rapid expansion through a plug-and-play approach. This modularity facilitates scalability from laboratory-scale setups to industrial deployments without requiring significant redesign of the system architecture.

The vertical orientation further supports efficient land utilization and enables stacking or array-based configurations, which are advantageous in both urban and industrial environments.

3.3 Material Selection: The reactor body is constructed from acrylic, selected for its high optical transparency in the photosynthetically active radiation range, with 90–95% light transmission (Abdel-Baset et al., 2024; Zanetti et al., 2021). This maximises photon availability to the microalgae culture

while offering cost-effectiveness, ease of fabrication, and corrosion resistance in aqueous environments. Borosilicate glass, though thermally superior, is heavier and costlier, limiting scalable deployment. Polycarbonate, while mechanically robust, exhibits reduced optical clarity over prolonged exposure (Carvalho et al., 2006). Acrylic therefore represents the optimal balance between optical performance and economic feasibility for ASEAN deployment conditions.

3.4 Biofilm Management and Long-term Maintenance: Biofilm formation on the inner surfaces of flat-panel photobioreactors represents a known operational challenge, as accumulated cell layers reduce light transmittance and increase hydraulic resistance over time (Carvalho et al., 2006). In the proposed design, several measures are incorporated to mitigate this effect. The internal agitation provided by the CO₂ diffuser airstone creates a continuous turbulent flow regime along panel surfaces, reducing the probability of cell adhesion and initial biofilm nucleation. The acrylic panel material, while highly transparent, also presents a relatively low surface energy compared to borosilicate glass, which moderately reduces biofilm attachment affinity. Scheduled cleaning cycles are incorporated into the system's operational protocol, triggered based on turbidity trend divergence specifically, when measured turbidity falls below the expected growth curve despite confirmed nutrient and CO₂ availability, indicating potential light obstruction by fouling. In such cases, the system flags a maintenance alert through the dashboard's anomaly detection module and schedules a drain-and-rinse cycle via the harvesting solenoid. Future iterations will incorporate automated backflushing mechanisms to further reduce manual cleaning requirements and extend continuous operation periods.

4. CO₂ Sourcing

The efficiency of microalgae-based carbon capture systems is strongly influenced by the availability, concentration, and delivery method of carbon dioxide. In photobioreactor systems, the choice of carbon source affects not only biomass productivity but also system energy requirements, operational cost, and scalability. *Chlorella vulgaris* requires a continuous inorganic carbon supply to sustain photosynthesis; atmospheric air at approximately 0.04% CO₂ is insufficient for high-density cultivation due to poor mass transfer rates and low solubility, necessitating enriched carbon sources (Ashour et al., 2023).

	Air	HCO ₃ ⁻	Commercial grade CO ₂	Purified grade of pure CO ₂	Raw flue gas	CO ₂ -containing solvents
CO ₂ concentration	0.042%	0.1–5 g L ⁻¹ (NaHCO ₃)	> 95%	> 95%	4% – 33%	0.5 mol CO ₂ /mol solvent (20%)
CO ₂ volume required	Very high	None	Low	Low	Moderate	None
Availability	Unlimited	Moderate	Low	High	High	Moderate
CO ₂ utilization	Very low	Very high	High	High	Moderate	Very high
CO ₂ cost (\$ per ton)	0	380	3–55	29–111	0	10–35
Energy for compression and transportation	None	Low	Moderate	Moderate	High	Low
OP injection energy	Very high	Low	Moderate	Moderate	High	Low
PBR injection energy	None	Low	Very high	Very high	Very high	High

Table 4. Comparison of CO₂ sourcing methods based on concentration, utilization efficiency, cost, and suitability for different deployment scales. Adapted from M. Ashour et al. 2023

Several sourcing methods are available, each with distinct trade-offs. Direct air capture is abundant but energy-intensive and poorly efficient at low concentrations. Commercial-grade CO₂ offers high purity and controlled delivery suitable for laboratory and pilot-scale systems, but external supply dependency limits scalability. Bicarbonate-based sources provide high utilisation efficiency within aqueous media, though replenishment cost restricts large-scale application. CO₂-containing solvents enable controlled release with moderate efficiency but introduce additional complexity in regeneration and handling.

Industrial flue gas represents the most viable source for large-scale deployment. Flue gas streams contain 4–33% CO₂ as a combustion byproduct from power generation and manufacturing industries (Razzak et al., 2013), offering high availability at negligible cost. Studies have reported that *Chlorella vulgaris* can tolerate SO₂ concentrations below 400 ppm and NO_x below 150 ppm, beyond which growth inhibition becomes significant (Ashour et al., 2023; Razzak et al., 2013). Pre-treatment via desulfurisation, cooling, and particulate filtration is therefore required prior to reactor injection. Additionally, CO₂ concentration itself influences growth rate non-linearly: concentrations between 5% and 15% have been reported to yield optimal biomass productivity for *Chlorella vulgaris*, while concentrations exceeding 20% may suppress growth through acidification effects (Politaeva et al., 2021).

A key feature of the proposed system is its source-agnostic CO₂ delivery architecture. A centralised inlet manifold with controlled injection supports seamless integration with any of the above sources without structural modification. Carbon dioxide is introduced through submerged diffusers, enabling fine bubble distribution and enhanced gas–liquid mass transfer (Kumar et al., 2010). For laboratory and pilot-scale use, compressed CO₂ or bicarbonate solutions ensure stability and reproducibility; for industrial deployment, the system integrates directly with treated flue gas streams. This flexibility is particularly relevant across ASEAN's diverse industrial landscape, where emission sources, concentrations, and regulatory contexts vary considerably between member states.

5. Growth Parameter Design

The performance of a microalgae-based photobioreactor is critically dependent on the precise regulation of environmental parameters that govern photosynthesis and biomass growth. For *Chlorella vulgaris*, key variables include temperature, light intensity, pH, nutrient availability, and carbon dioxide concentration. These parameters are interdependent, and deviations from optimal ranges can significantly reduce carbon fixation efficiency.

In this study, a multi-parameter closed-loop control framework is developed to maintain these variables within biologically optimal ranges. The control strategy is designed based on species-specific growth requirements and implemented through real-time sensor feedback and actuator response.

5.1 Growth Dynamics and Harvest Strategy: The growth of *Chlorella vulgaris* follows a characteristic pattern consisting of lag, exponential, linear, stationary, and decline phases. Maximum biomass productivity is achieved near the transition between exponential and stationary phases, where cell density and metabolic activity are high (Ma'mun et al., 2022).

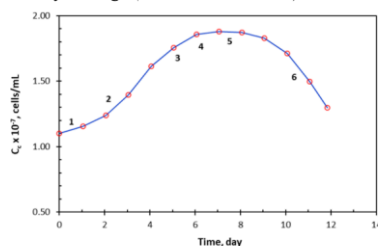


Fig. 4. Typical growth curve of *Chlorella vulgaris* showing lag, exponential, stationary, and decline phases.

To capture this behaviour, turbidity is used as a proxy for biomass concentration. The system continuously monitors turbidity levels and identifies the saturation threshold corresponding to the stationary phase. Upon reaching this threshold, an automated harvesting mechanism is triggered through a solenoid-controlled outlet, enabling timely biomass extraction without manual intervention. This approach ensures consistent productivity across growth cycles and prevents overgrowth-related efficiency losses.

5.2 Temperature Regulation: Temperature plays a critical role in enzymatic activity and overall metabolic performance. For *Chlorella vulgaris*, optimal growth occurs within a range of 25°C to 35°C, with peak efficiency near 30°C. Temperatures exceeding this range reduce CO₂ solubility and increase photorespiration, thereby decreasing carbon fixation efficiency (Ashour et al., 2023).

To maintain thermal stability, a temperature sensor continuously monitors the culture environment. When the temperature exceeds a predefined threshold (typically 30°C), a cooling fan is activated via a relay-controlled actuator. The control logic incorporates a tolerance band to prevent rapid switching and unnecessary energy consumption.

In addition, external environmental conditions are considered to improve efficiency. Gradual temperature changes associated with weather patterns, such as rainfall, are used to suppress premature actuation, reducing energy usage while maintaining stable conditions.

5.3 Light Intensity and Photoperiod Control: Light intensity directly influences the rate of photosynthesis and, consequently, biomass production. *Chlorella vulgaris* requires sufficient light to initiate and sustain carbon fixation, with optimal growth observed under moderate to high irradiance conditions. However, excessive light leads to photoinhibition, reducing photosynthetic efficiency. To balance these effects, a controlled photoperiod of 16 hours of light followed by 8 hours of darkness is implemented, based on experimentally observed growth patterns (Khalili et al., 2013).

Light sensors are used to measure ambient irradiance, and an LED array supplements natural light when required. The control system dynamically adjusts LED intensity to maintain a consistent photon flux, avoiding both insufficient irradiance and oversaturation. This adaptive approach ensures stable photosynthetic activity under varying environmental conditions (Jui et al., 2024).

5.4 pH Regulation: The pH of the culture medium is a critical factor influencing enzyme activity, nutrient availability, and carbon uptake. For *Chlorella vulgaris*, the optimal pH range lies between 7 and 8. However, continuous CO₂ injection leads to the formation of carbonic acid, which reduces pH and can inhibit growth if not corrected (Ashour et al., 2023; Wang et al., 2008).

The system employs a real-time pH monitoring sensor coupled with a feedback control mechanism. When the pH falls below the defined threshold, a peristaltic pump is activated to introduce an alkaline buffering solution. The duration of pump activation is proportional to the deviation from the desired pH range, allowing gradual correction without overshooting.

This closed-loop approach maintains pH stability while accommodating fluctuations caused by carbon dioxide injection and metabolic activity.

5.5 Nutrient Supply Control: Microalgae growth requires adequate availability of essential macronutrients, particularly nitrogen, phosphorus, and potassium. Nutrient depletion can limit biomass production, while excessive concentrations may lead to inhibitory effects or system imbalance.

To address this, a time-based nutrient dosing strategy is implemented. A nutrient reservoir containing a balanced medium is connected to the reactor through a controlled delivery system. At predefined intervals, a peristaltic pump dispenses a measured quantity of nutrients into the culture.

This approach simplifies system design by avoiding the need for complex real-time nutrient sensing, while still ensuring sufficient availability for sustained growth. The dosing schedule can be adjusted based on observed growth trends and system performance.

5.6 Carbon Dioxide Injection Control: Carbon dioxide serves as the primary carbon source for photosynthesis and must be supplied at sufficient concentrations to sustain high growth rates. In the proposed system, CO₂ is introduced into the culture medium through a pneumatic delivery system connected to a diffuser, enabling fine bubble formation and enhanced gas-liquid mass transfer.

The injection process is controlled periodically to maintain adequate carbon availability without causing excessive acidification. The control logic considers both growth phase and pH conditions, ensuring that CO₂ supply is synchronized with the metabolic demand of the culture.

Under optimized conditions, *Chlorella vulgaris* demonstrates a carbon fixation rate of up to 0.412 g CO₂/L/day (Politaeva et al., 2021; Ashour et al., 2023). For a reactor volume of approximately 40 L,

this corresponds to an estimated carbon capture capacity of around 360 g per growth cycle, assuming operation within the optimal growth phase.

5.7 Integrated Control Framework: The individual control strategies described above are integrated into a unified closed-loop system, where sensor inputs are continuously processed to regulate actuator responses. The interaction between parameters is carefully managed to avoid conflicting control actions, such as simultaneous CO₂ injection and pH correction. This integrated approach ensures that all growth parameters are maintained within optimal ranges, maximizing biomass productivity and carbon fixation efficiency. By combining biological understanding with real-time control mechanisms, the system achieves stable and repeatable operation under varying environmental conditions.

6. Automation Architecture

The effective operation of the proposed photobioreactor relies on the integration of sensing, control, data management, and user interaction within a unified automation framework. To achieve this, a three-layer architecture is developed, consisting of an embedded control layer, a cloud-based data layer, and a user interface layer. This structure enables real-time monitoring, closed-loop control, and remote system management while maintaining operational reliability under varying deployment conditions.

6.1 System Architecture Overview: The overall automation framework is designed to support continuous data acquisition, processing, and actuation. Sensor nodes embedded within each photobioreactor collect real-time data on key growth parameters, including temperature, pH, turbidity, and light intensity. These inputs are processed locally by a microcontroller, which executes control logic and actuates system components accordingly.

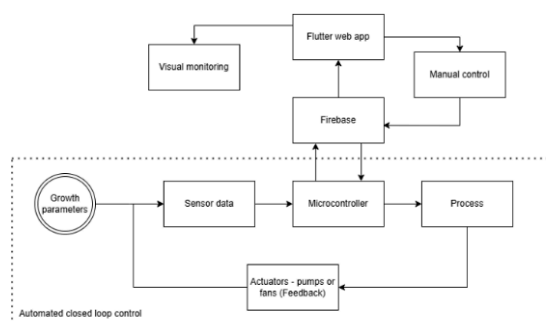


Fig. 6. Three-layer automation architecture illustrating embedded control, cloud data management, and user interface integration.

The architecture is structured into three functional layers:

- **Embedded control layer:** Responsible for real-time sensing, decision-making, and actuation
- **Cloud data layer:** Provides data storage, synchronization, and system-wide analytics
- **Interface layer:** Enables user interaction, visualization, and manual control

This layered approach ensures modularity, scalability, and clear separation of system responsibilities.

6.2 Embedded Control Layer: The embedded control layer forms the core of the system's real-time operation. An ESP32 microcontroller is used due to its integrated wireless capability, sufficient processing power, and compatibility with multiple sensor interfaces. The controller continuously acquires data from connected sensors and executes control algorithms to maintain optimal growth conditions.

Control actions include:

- Activation of cooling mechanisms based on temperature thresholds
- Regulation of pH through controlled dosing
- Adjustment of lighting intensity
- Scheduled nutrient delivery
- Controlled CO₂ injection

The control loop operates at a defined sampling interval, ensuring timely response to environmental changes. Threshold-based logic with tolerance bands is implemented to prevent rapid switching of actuators, thereby improving system stability and reducing energy consumption.

Importantly, the embedded system is designed to operate independently of external connectivity. All critical control functions are executed locally, ensuring uninterrupted operation even in the absence of network access. This design choice enhances system reliability, particularly in remote or industrial deployment scenarios.

6.3 Cloud Data Layer: The cloud layer is implemented using a real-time database platform, enabling continuous synchronization of system data across multiple reactor units. Sensor readings, actuator states, and system logs are transmitted to the cloud at regular intervals, providing a centralized repository for monitoring and analysis.

The cloud infrastructure supports:

- Historical data storage for trend analysis
- Real-time updates for remote monitoring
- Event logging for diagnostics and maintenance
- Aggregation of data across multiple reactors

A hierarchical data structure is employed to organize information efficiently, allowing individual reactor units to be monitored independently or as part of a larger system. The use of a subscription-based data model ensures that only relevant data updates are transmitted to the user interface, reducing latency and bandwidth usage.

6.4 User Interface Layer: The interface layer provides a visual and interactive platform for system monitoring and control. Developed using a cross-platform framework, the interface enables users to access real-time data, historical trends, and system status from remote locations.

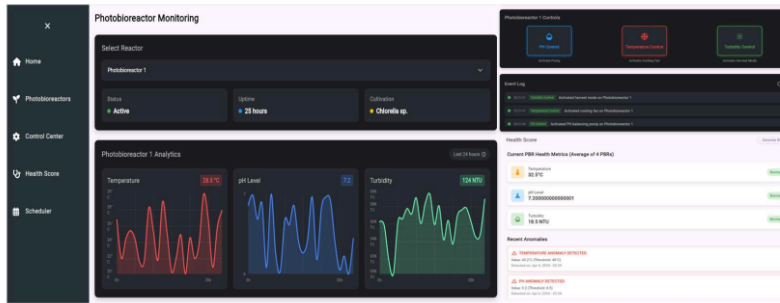


Fig. 7. Dashboard interface displaying real-time monitoring of temperature, pH, turbidity, and system status.

Key functionalities include:

- Visualization of sensor data through time-series graphs
- Monitoring of reactor performance and operational status including sensor anomalies and health scores of the photobioreactors
- Manual override of automated control functions
- Configuration of control parameters and scheduling harvesting or new batches

The interface is designed to be responsive and intuitive, allowing operators to quickly identify anomalies and adjust system behaviour when necessary. This capability is particularly important in large-scale deployments, where multiple reactor units must be managed simultaneously.

6.5 System Reliability and Operational Considerations: A critical aspect of the proposed architecture is its emphasis on reliability and fault tolerance. By decoupling real-time control from cloud dependency, the system ensures continuous operation even under network disruptions. Local control logic maintains stable environmental conditions, while cloud connectivity enhances monitoring and data-driven optimization. Additionally, event logging and alert mechanisms are incorporated to notify users of abnormal conditions, such as parameter deviations or component failures. This supports proactive maintenance and reduces system downtime.

The modular structure of the architecture also allows for straightforward expansion. Additional photobioreactor units can be integrated into the system with minimal configuration, leveraging the same control and data infrastructure.

Overall, the proposed automation architecture provides a robust and scalable foundation for photobioreactor operation. By integrating embedded control, cloud-based data management, and user interaction within a cohesive framework, the system enables precise regulation of biological processes while supporting real-world deployment across diverse agritech and industrial environments.

7. AI Optimization

While conventional photobioreactor systems rely on fixed-threshold or rule-based control strategies, such approaches are often insufficient to handle the dynamic and interdependent nature of biological growth processes. Variations in environmental conditions, coupled with nonlinear interactions between parameters such as temperature, light intensity, and carbon dioxide availability, require more adaptive and predictive control mechanisms. To address these limitations, an AI-enhanced optimization layer is integrated into the proposed system. This layer operates on top of the baseline closed-loop control framework described in Section 5, utilizing historical and real-time sensor data to improve decision-making, enhance efficiency, and reduce manual intervention.

7.1 Growth Prediction Model: The growth behavior of *Chlorella vulgaris* is inherently dynamic and influenced by multiple interacting variables. In the proposed system, a data-driven prediction model is employed to estimate the current growth phase and anticipate transitions between phases based on sensor inputs such as turbidity, temperature, and light exposure. By analyzing historical trends in turbidity and environmental conditions, the model identifies patterns corresponding to lag, exponential, and stationary phases. This enables the system to determine optimal harvesting windows more accurately than fixed-time scheduling. Additionally, the prediction of growth trends allows for proactive adjustment of carbon dioxide supply and nutrient dosing, aligning resource input with biological demand.

7.2 Self-Tuning Parameter Control: Traditional control systems treat each parameter independently, often leading to conflicting actions. For instance, increased carbon dioxide injection improves carbon availability but simultaneously reduces pH due to acid formation. The proposed system incorporates a self-tuning control mechanism that learns the relationships between parameters over time. By observing how changes in one parameter affect others, the system adjusts control actions to avoid counterproductive behaviour. For example, carbon dioxide injection can be temporarily reduced during active pH correction, preventing unnecessary oscillations in system conditions. This adaptive coordination improves overall system stability and reduces energy and resource consumption by minimizing redundant actuation.

7.3 Weather-Aware Thermal Regulation: Environmental conditions play a significant role in reactor performance, particularly in outdoor or semi-outdoor deployments. Rather than relying solely on instantaneous temperature readings, the system incorporates weather-based contextual information to enhance control decisions. Forecast data, including expected temperature trends and precipitation, is used to anticipate natural cooling effects. For example, if a gradual temperature drop is predicted due to incoming rainfall, the system delays activation of cooling mechanisms, reducing energy usage without compromising thermal stability. This approach introduces a predictive element to temperature regulation, improving efficiency while maintaining optimal growth conditions.

7.4 Health Scoring and Anomaly Detection: To enable continuous system assessment, a health scoring mechanism is implemented for each photobioreactor unit. The health score is computed using weighted inputs from key parameters, including temperature, pH, turbidity, and light intensity. Each parameter is evaluated against its optimal range, and deviations contribute to a reduction in the overall score. This provides a simple yet effective representation of system performance, allowing operators to quickly identify underperforming units. In addition, anomaly detection is incorporated by monitoring deviations from expected trends. Sudden changes in turbidity or persistent parameter instability may indicate issues such as sensor malfunction, contamination, or system faults. These events are flagged for further inspection, supporting targeted maintenance and reducing downtime.

7.5 Integrated AI Functionality: The AI-enhanced features are summarized in Table 5, which outlines the relationship between input data, processing function, and system output for each module.

Module	Input data	Function	Output
Growth prediction	Turbidity, temperature, light	Phase estimation and trend prediction	Optimal harvest timing and proactive CO ₂ /nutrient adjustment
Self-tuning control	pH, CO ₂ , temperature	Parameter interaction learning; conflict avoidance	Coordinated control actions; reduced pH oscillation
Weather-aware regulation	Temperature, forecast data	Predictive cooling adjustment	Reduced energy consumption; maintained thermal stability
Health scoring & anomaly detection	All sensor inputs	Weighted performance evaluation; deviation flagging	System health index, maintenance alerts, fault isolation

Table 5. AI module functions, associated sensor inputs, and operational outcomes.

7.6 System-Level Impact: The integration of AI-based functionalities transforms the photobioreactor from a reactive control system into an adaptive and predictive platform. By leveraging data-driven insights, the system is able to anticipate changes in biological behavior, coordinate parameter control, and optimize resource utilization. Importantly, these enhancements are implemented as extensions to the existing control framework rather than replacements, ensuring that baseline operation remains stable and reliable. This layered approach maintains system robustness while enabling incremental performance improvements. Overall, the AI-enhanced optimization framework contributes to improved carbon fixation efficiency, reduced operational overhead, and enhanced scalability, making the system more suitable for real-world agritech and industrial deployment.

8. Scalability and Comparative Analysis

The practical deployment of photobioreactor systems for carbon capture depends not only on biological efficiency but also on scalability, adaptability, and ease of integration with existing infrastructure. Many current systems achieve high productivity under controlled conditions but are limited by rigid configurations, high capital costs, or lack of automation, restricting their applicability beyond laboratory or pilot-scale environments.

8.1 Modular Scalability: The proposed system adopts a modular design approach, where individual photobioreactor units function as independent yet interoperable modules. Each unit is equipped with standardized interfaces for carbon dioxide input, nutrient delivery, pH regulation, and harvesting, allowing seamless integration into a shared pipeline network.

This architecture enables incremental scaling by adding reactor units without requiring structural redesign or interruption of existing operations. Unlike conventional fixed-capacity systems, the modular configuration allows deployment to be tailored based on available space, emission levels, and operational requirements. The vertical flat-panel arrangement further supports efficient land utilization, making it suitable for both industrial and urban installations. In addition, the distributed nature of the system allows individual units to be isolated for maintenance without affecting overall system functionality, thereby reducing downtime and improving operational resilience.

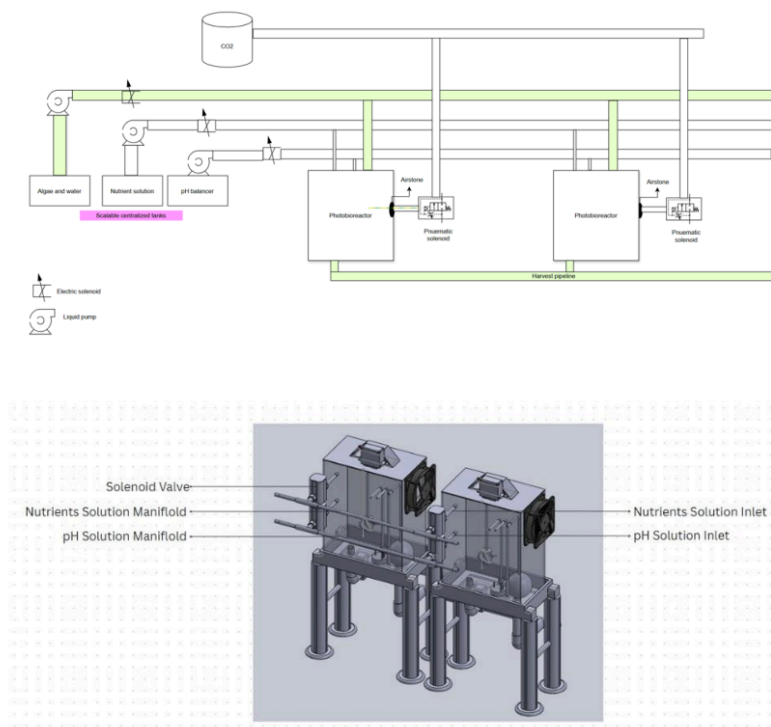


Fig. 8. Scaled configuration of multiple photobioreactor units connected through a shared pipeline and control architecture.

8.2 Comparative Analysis with Existing Systems: A structured comparison was conducted against four representative commercial photobioreactor systems: the Industrial Plankton PBR, Varicon Aqua PBR, Ollital Tubular PBR, and Ollital SS Bioreactor, across eight performance dimensions including modularity, automation, AI integration, control interface, monitoring, CO₂ utilisation, deployment flexibility, and maintenance.

As shown in Table 6, no existing system simultaneously satisfies all evaluated criteria. The Industrial Plankton PBR, while fully automated, is constrained by fixed tank volumes and local-only control with partial data logging. Varicon Aqua supports limited modularity but lacks AI integration and cloud connectivity. Both Ollital configurations are designed for fixed industrial scales, with manual or PID-only control and no remote monitoring capability. Across all benchmarked systems, AI-based optimization, web-based interfaces, and dynamic CO₂ adjustment are either absent or rudimentary.

Feature	Industrial Plankton	Varicon Aqua	Ollital Tubular	Ollital SS	Proposed system
Modularity & scalability	Fixed tank sizes	Partly modular	Fixed tubular	Rigid capacity	Fully modular; plug-and-play
Automation level	Fully automated	Basic	Manual / semi	Programmable	Closed loop; fully automated
AI & smart optimization	None	None	None	PID only	Predictive AI; adaptive control
Control interface	Local GUI	Local GUI	Local only	Manual setup	Web dashboard; remote access
Data monitoring & logging	Partial	Limited	Rare	External device	Full cloud-based; real-time sync
CO ₂ utilisation	Controlled	Variable	Basic aeration	Manual	Dynamic; phase-aware
Deployment flexibility	Large-scale only	Lab / pilot-scale	Industrial	Industrial	Lab to industrial; any scale
Maintenance & integration	Medium	Moderate	Complex piping	Difficult to clean	Quick-connect; low overhead

Table 6. Comparison of the proposed system with existing photobioreactor solutions based on scalability, automation, control, and deployment flexibility.

The proposed system addresses these gaps within a unified framework. Its modular plug-and-play architecture enables incremental scaling without structural redesign a capability absent in all four comparators. The multi-parameter closed-loop control framework coordinates temperature, pH, light, nutrient, and CO₂ regulation simultaneously, preventing the conflicting actuator behaviour that arises in systems managing parameters independently. The AI optimization layer further extends this through growth phase prediction, self-tuning parameter coordination, and weather-aware thermal regulation, none of which are present in the evaluated commercial systems. At the operational level, the cloud-connected dashboard enables real-time remote monitoring and manual override across multiple reactor units, contrasting with the local interfaces of all benchmarked systems. CO₂ delivery is dynamically adjusted based on growth phase and pH state rather than fixed scheduling, and the source-agnostic inlet manifold supports integration with ambient, compressed, or industrial flue gas sources without hardware modification.

While individual features such as automation or modularity exist in isolation across current systems, their simultaneous integration within a scalable, remotely operable framework remains unaddressed in the commercial landscape. The proposed design consolidates these capabilities into a cohesive platform suited for diverse agritech and industrial deployment contexts across the ASEAN region.

8.3 Integrated System Advantage: While individual features such as automation, modularity, or monitoring may exist in isolation within current photobioreactor systems, their combined implementation remains limited. The proposed system simultaneously integrates modular scalability,

multi-parameter closed-loop control, data-driven optimization, and flexible carbon sourcing within a unified framework. This integration enables the system to adapt to varying operational conditions while maintaining stable performance, addressing key challenges associated with real-world deployment. The ability to coordinate multiple reactor units through a shared control and data infrastructure further enhances scalability and system-level optimization.

Overall, the proposed design moves beyond conventional reactor configurations by combining engineering, control, and system integration into a cohesive platform. This positions it as a practical solution for large-scale carbon capture and biomass production in agritech and industrial applications across the ASEAN region.

9. Sustainability and Impact

The proposed photobioreactor system is designed to address both environmental and economic challenges associated with carbon emissions in the ASEAN region. By integrating carbon capture with biomass generation, the system supports a circular resource model in which waste carbon dioxide is converted into valuable products. From an environmental perspective, the use of *Chlorella vulgaris* enables continuous biological carbon fixation with high efficiency under controlled conditions. The closed photobioreactor configuration minimizes contamination and resource loss, while the integration of multi-parameter control ensures optimal utilization of light, nutrients, and carbon dioxide. This results in improved biomass productivity and reduced operational inefficiencies compared to conventional systems. The system also offers potential for resource recovery through downstream applications of algal biomass. Harvested biomass can be processed into biofuels, organic fertilizers, and feedstock for agricultural use, contributing to reduced dependence on fossil-based inputs. This aligns with broader agritech objectives focused on sustainable production and resource optimization (Lam & Lee, 2012; Chisti, 2007; Markou & Nerantzis, 2013).

From an economic standpoint, the system enables participation in emerging carbon markets. Carbon credits generated through verified carbon dioxide sequestration can provide an additional revenue stream, particularly within voluntary carbon markets. Given typical carbon credit valuations ranging from approximately USD 5 to USD 20 per ton (Selvaraju, 2019), the integration of carbon capture with biomass utilization improves the overall feasibility of deployment. The modular design further enhances economic viability by allowing gradual scaling based on demand and available resources. This reduces upfront investment requirements and enables flexible deployment across different sectors, including agriculture, industry, and research environments.

Overall, the proposed system supports sustainable carbon management while contributing to resource efficiency and economic value creation, making it relevant for agritech applications in the ASEAN region.

10. Conclusion

This paper presented a systematic engineering approach for the design and optimization of a modular photobioreactor for microalgae-based carbon sequestration. The study combined reactor geometry selection, material considerations, and a multi-parameter control framework to achieve stable and efficient growth conditions for *Chlorella vulgaris*. The integration of embedded control, cloud-based monitoring, and data-driven optimization enabled real-time regulation and improved system performance. The proposed design is particularly suited for deployment in ASEAN environments, where high temperatures, variable sunlight, and diverse carbon emission sources present unique challenges. By incorporating flexible carbon dioxide sourcing, modular scalability, and adaptive control strategies, the system provides a practical pathway for integrating biological carbon capture into agritech and industrial applications.

Future work will focus on further enhancing system intelligence and deployment capabilities. This includes the integration of low-power communication protocols for distributed operation, incorporation of renewable energy sources for off-grid deployment, and development of advanced predictive models for improved process optimization. In addition, validation under large-scale operating conditions and the implementation of standardized monitoring frameworks for carbon accounting will be essential for real-world adoption. The presented framework demonstrates that the combination of optimized reactor design, intelligent control, and a scalable architecture can enable effective and practical carbon capture solutions. Such systems have the potential to contribute meaningfully to sustainable development and carbon management efforts across the ASEAN region.

REFERENCES

- Ashour, M., Mansour, A.T., Alkhamis, Y.A. and Elshobary, M. (2023). Usage of *Chlorella* and diverse microalgae for CO₂ capture towards a bioenergy transition. *Front. Mar. Sci.* 10:1193556.
- Politaeva, N., Ilin, I., Velmozhina, K. and Shinkevich, P. (2021). Carbon dioxide utilization using *Chlorella* microalgae. *Sustainability*. 13(22):12653.
- Lam, M.K. and Lee, K.T. (2012). Microalgae biofuels: A critical review of issues, problems and future perspectives. *Biotechnol. Adv.* 30(3):673–690.
- Singh, J. and Gu, S. (2010). Commercialization potential of microalgae for biofuels production. *Renew. Sustain. Energy Rev.* 14(9):2596–2610.
- Ugwu, C.U., Aoyagi, H. and Uchiyama, H. (2008). Photobioreactors for mass cultivation of algae. *Bioresour. Technol.* 99(10):4021–4028.
- Posten, C. (2009). Design principles of photobioreactors for cultivation of microalgae. *Eng. Life Sci.* 9(3):165–177.
- Carvalho, A.P., Meireles, L.A. and Malcata, F.X. (2006). Microalgal reactors: A review of enclosed system designs and performances. *Biotechnol. Prog.* 22(6):1490–1506.
- Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnol. Adv.* 25(3):294–306.
- Brennan, L. and Owende, P. (2010). Biofuels from microalgae: A review of technologies for production, processing and extraction. *Renew. Sustain. Energy Rev.* 14(2):557–577.
- Pulz, O. (2001). Photobioreactors: Production systems for phototrophic microorganisms. *Appl. Microbiol. Biotechnol.* 57(3):287–293.
- Richmond, A. (2004). *Handbook of Microalgal Culture: Biotechnology and Applied Phycology*. Blackwell Science Ltd.
- Tredici, M.R. (2010). Photobiology of microalgae mass cultures: Understanding the tools for the next green revolution. *Biofuels*. 1(1):143–162.

- Converti, A., Casazza, A.A., Ortiz, E.Y., Perego, P. and Del Borghi, M. (2009). Effect of temperature on microalgae growth and lipid content. *Chem. Eng. Process.* 48(6):1146–1151.
- Razzak, S.A., Hossain, M.M., Lucky, R.A., Bassi, A.S. and De Lasa, H. (2013). Integrated CO₂ capture and biofuel production by microalgae. *Renew. Sustain. Energy Rev.* 27:622–653.
- Kumar, A., Ergas, S., Yuan, X., Sahu, A., Zhang, Q., Dewulf, J. and Van Langenhove, H. (2010). Enhanced CO₂ fixation via microalgae: Recent developments. *Trends Biotechnol.* 28(7):371–380.
- Borowitzka, M.A. (1999). Commercial production of microalgae: Ponds, tanks, tubes and fermenters. *J. Biotechnol.* 70(1–3):313–321.
- Wijffels, R.H. and Barbosa, M.J. (2010). An outlook on microalgal biofuels. *Science.* 329(5993):796–799.
- Chen, C.Y., Yeh, K.L., Aisyah, R., Lee, D.J. and Chang, J.S. (2011). Cultivation and photobioreactor design for microalgae. *Bioresour. Technol.* 102(1):71–81.
- Ho, S.H., Chen, C.Y. and Chang, J.S. (2010). Effect of light intensity on CO₂ fixation in microalgae. *Bioresour. Technol.* 102(5):4329–4335.
- IPCC. (2021). *Climate Change 2021: The Physical Science Basis*. Intergovernmental Panel on Climate Change.
- IRENA. (2022). *World Energy Transitions Outlook 2022*. International Renewable Energy Agency.
- ASEAN Centre for Energy. (2020). *ASEAN Energy Outlook 6*. ACE Publications.
- Markou, G. and Nerantzis, E. (2013). Microalgae for high-value compounds and biofuels production. *Ind. Crops Prod.* 45:42–48.
- Zittelli, G.C., Rodolfi, L., Biondi, N. and Tredici, M.R. (2013). Productivity of microalgae in tubular photobioreactors. *Aquaculture.* 412–413:1–8.
- Anadon, L., Chan, K., Gallagher, J., Hasanbeigi, S. and Lo, A. (2020). The ASEAN climate and energy paradox. *Energy Policy.*
- Paul, S., Bera, S., Dasgupta, R., Mondal, S. and Roy, S. (2021). Advances in open and closed systems for algal carbon capture. *J. Clean. Prod.* 327:129409.
- Khalili, M.R., Khosravi, M.A. and Malekzadeh, A.R. (2013). Effects of light intensity on *Chlorella vulgaris*. *Iran. J. Fish. Sci.* 12(1):123–134.
- Kiet, T.A., Mahendra, S.S., Vasant, S.S. and Subash, L.K. (2021). AI-based predictive control in photobioreactors. *J. Ind. Microbiol. Biotechnol.* 47(2):127–137.
- Zanetti, M., Carone, M., Malaguti, M. and Riggio, V. (2021). Design of flat panel photobioreactors for CO₂ fixation. *Renew. Energy.* 177:129–138.
- Selvaraju, S.B.R. (2019). Carbon credit pricing trends and market developments. *Environ. Econ. Policy Stud.* 21(2):169–182.
- Jui, T.J. et al. (2024). Optimal growth conditions for *Chlorella vulgaris* biomass production. *Heliyon.* 10(11):e31900.
- Abdel-Baset, A., Matter, I.A. and Ali, M.A. (2024). Enhanced *Scenedesmus obliquus* cultivation in plastic-type flat panel photobioreactor for biodiesel production. *Sustainability.* 16(8):3148
- Anadon, L., Chan, K., Gallagher, J., Hasanbeigi, S. and Lo, A. (2020). The ASEAN climate and energy paradox. *Energy Policy.*
- Klein-Marcuschamer, D., Chisti, Y., Benemann, J.R. and Lewis, D. (2013). A matter of detail: assessing the true potential of microalgal biofuels. *Energy Environ. Sci.* 6(10):2821–2836.
- Ma'mun, S., Wahyudi, A. and Raghdanesa, A.S. (2022). Growth rate measurements of *Chlorella vulgaris* in a photobioreactor. *IOP Conf. Ser. Earth Environ. Sci.* 963(1):012015.

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