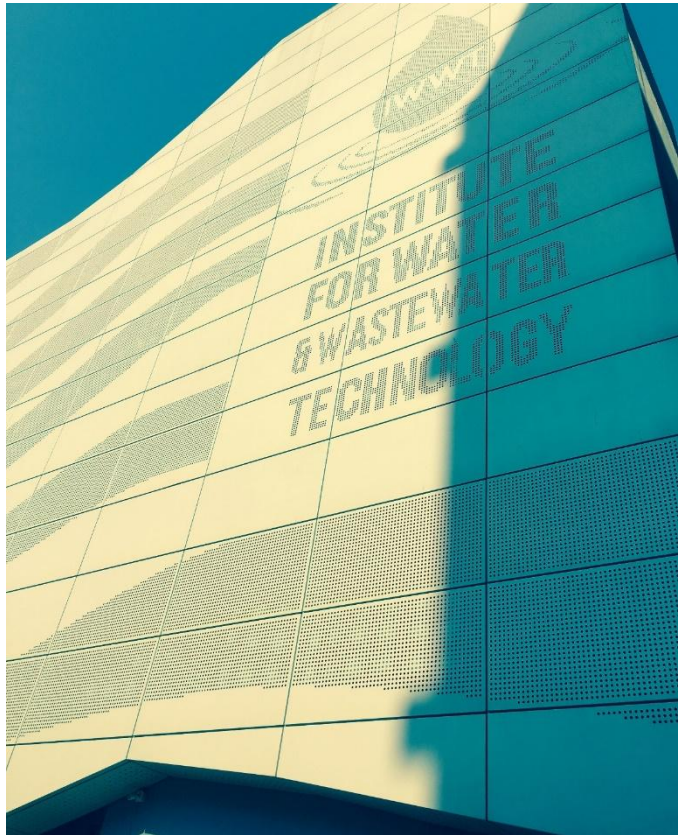
Light Optimization in a Novel Airlift Photobioreactor System for Enhanced Microalgal Cultivation



GLOBAL ALGAE INDUSTRY PRESENTATIONS AND NETWORKING WEBINAR
FRIDAY, OCTOBER 9TH , 2026
9:00 am-11:00 am (Central Time)/4:00 pm SAST

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Presentation Outline



- Introduction about the vertical systems-At a glance
- Existing problems with the BC-PBR
- Proposed Novel BC-AL PBR
- CFD Modelling Assumptions and Numerical Simulation Setup
- Bubbles Diffusion into BCAL PBR & Velocity Contours for the Inne/Outer Cylinder
- Light Attenuation
- Biomass density vs Penetration depth
- Simulation for Light Attenuation
- Discussion
- Conclusions
- Publications

Bubble Column PBR (BC PBR) vs Airlift PBR (BC-AL PBR)

A bubble column reactor relies on bubble buoyancy and bubble-induced turbulence to generate liquid mixing. Without internal flow-directing structures, circulation is relatively unstructured, back-mixing is generally high, and hydrodynamics depend strongly on superficial gas velocity.

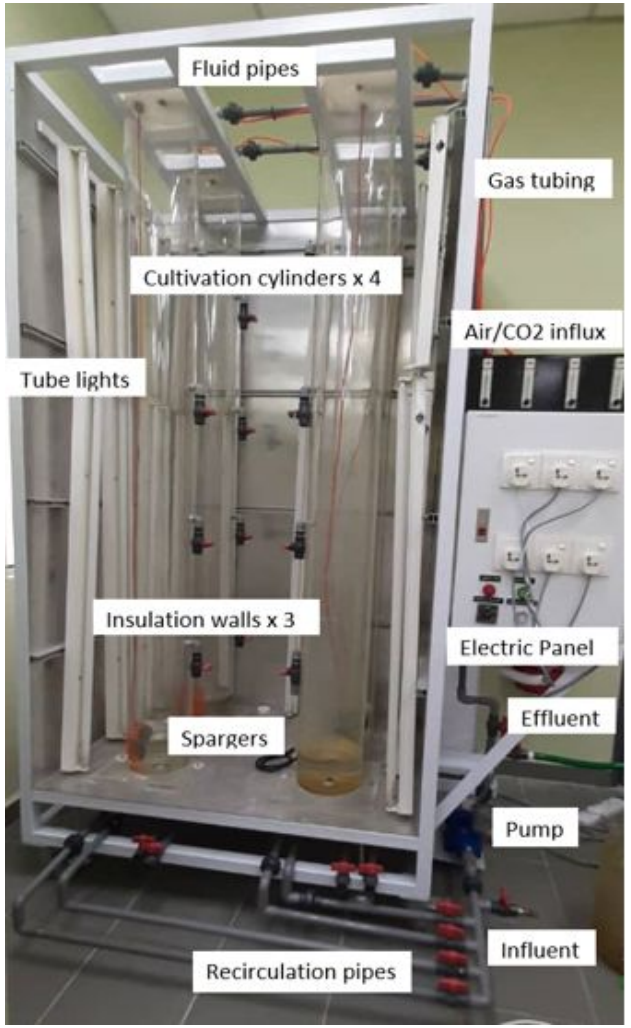
An airlift reactor incorporates distinct riser and downcomer regions. Gas holdup differences create a hydrostatic pressure imbalance that drives controlled liquid circulation. This promotes a more organized flow, potentially a more uniform shear distribution, and improved control of mixing and residence time.

Key distinction: Bubble columns rely primarily on bubble-induced mixing, whereas airlift reactors use gas-induced density differences and reactor geometry to establish a defined circulation loop.

Parameter	Bubble Column PBR	Airlift PBR
Reactor Configuration & Internal Structure	Simple vertical cylindrical column & No internal partitions	Cylindrical vessel divided into riser and downcomer (Split cylinder)
Mixing Mechanism	Gas bubbles provide mixing	Gas injection creates density-driven circulation loop
Flow Pattern	Random bubble-induced mixing	Defined circulation (upflow in riser, downflow in downcomer)
Circulation Control	Limited control	**Well-controlled hydrodynamics**
Gas Injection Location	Bottom sparger	Sparger located in riser zone
Shear Stress	Moderate–high near sparger	Lower and more uniform
Mass Transfer (kLa)	Moderate	Higher than bubble column
Gas Hold-Up	Moderate	**Better controlled and more uniform**
Mixing Efficiency	Moderate	High
Light/Dark Cycling	Less predictable	More regular due to defined flow path
Dead Zones	Possible	Minimal
Energy Efficiency	Moderate	Higher circulation efficiency per unit gas input
CAPEX	Lower	**Slightly higher**
OPEX	Moderate	Moderate
Maintenance	Simple (no internals)	Slightly complex (draft tube cleaning)
Scale-Up Potential	Good	**Very good**
Suitable For	General microalgae cultivation	Shear-sensitive strains & high-performance systems
Hydrodynamic Stability	Moderate	High

Existing problems with the BC-PBR

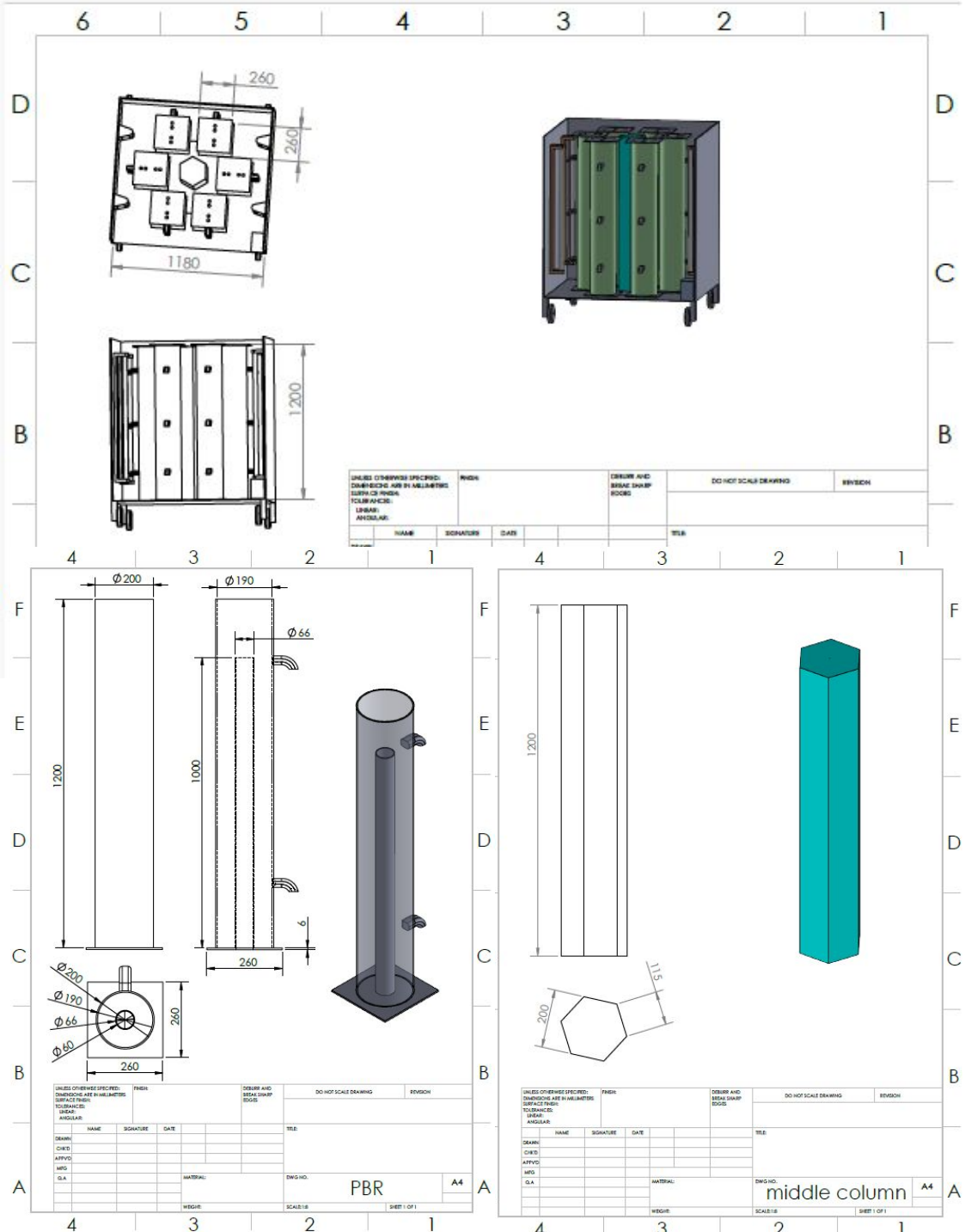
PROBLEMS CHALLENGES	DEGREE
MIXING	MODERATE
ILLUMINATION	EXTREME ATTENUATION LED TO DARK ZONES
BUBBLE DIFFUSION	SPARGING LED TO NON UNIFORM DIFFUSION
Aspect Ratio (H/D) & S/V Ratio	NOT AN ISSUE
Wall MATERIAL	NOT FULLY INSULATING
Light Path (max)	8-10 cm (SIDE FACING LIGHT)
PUMPING	SINGLE WAY/DEPENDING ON GRAVITY



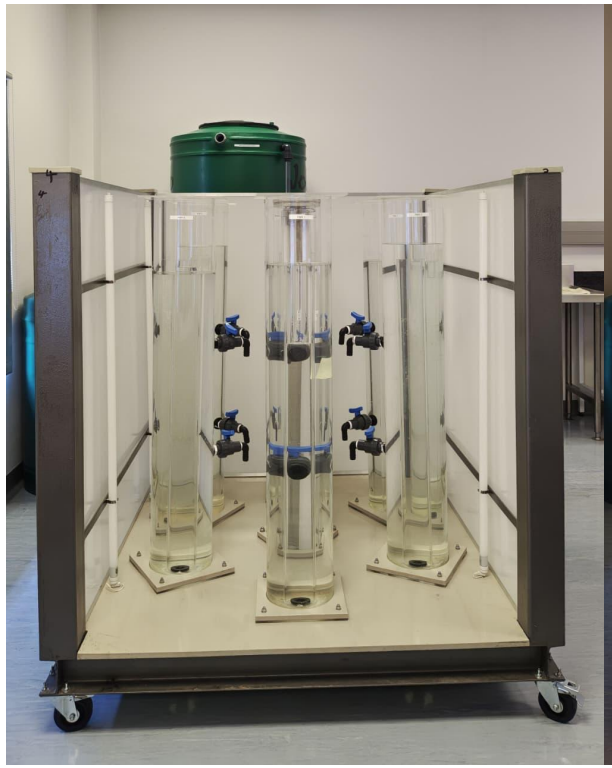


Proposed Novel BCAL PBR

Parameter	Value	Design Rationale
Total Volume	37 L	Fixed
Working Volume	~34-35 L	Leaves headspace for gas disengagement
Height (H)	120 cm (1.2 m)	Supports vertical light gradient, airlift loop
Inner Diameter (D)	20 cm	Optimized for light penetration without significant dark zone
Aspect Ratio (H/D) & S/V Ratio	**6 & 20**	Ideal for mixing and gas-liquid mass transfer
Wall Thickness	5 mm	Durable yet allows sufficient light passage
Light Path (max)	10 cm (one side of cylinder)	Ensures efficient photosynthesis in dense cultures
Riser Tube Dia (Central)-Detachable	8-10 cm	Promotes efficient upward airlift flow
Downcomer Annulus Width	~5-6 cm	Provides enough volume for return flow



BC-AL PBR IN THE REACTOR ROOM



BC-AL PBR WITHOUT LIGHT



BC-AL PBR WITH WALL LIGHT



BC-AL PBR WITH CENTRAL LIGHT



BC-AL PBR WITH ALL LIGHTS

CFD Modelling Assumptions and Numerical Simulation Setup

Numerical simulations were conducted using ANSYS Fluent 19.2 based on the finite volume method. Light attenuation was modelled using the Beer–Lambert law and implemented via a compiled C-based user-defined function (UDF). The Volume of Fluid (VOF) model, coupled with the level-set approach, was used to track multiphase interfaces. Pressure–velocity coupling was achieved using the PISO algorithm, with second-order upwind discretisation for flow parameters and the Geo-Reconstruct scheme for interface reconstruction.

Parameter	Inner cylinder	Outer cylinder
Physics preference	CFD	CFD
Solver preference	Fluent	Fluent
Element order	Linear	Linear
Element size	--	0.060828 m
Adaptive sizing	No	--
Growth rate	1.2	--
Mesh defeaturing	Yes	--
Defeature size	2.1303×10^{-4} m	--
Capture curvature	Yes	--
Curvature minimum size	4.2606×10^{-4} m	--
Curvature normal angle	18°	--
Capture proximity	No	--
Bounding box diagonal	0.85212 m	--
Average surface area	5.1×10^{-2} m²	--
Minimum edge length	0.060 m	--
Number of nodes	2,057,007	191,251
Number of elements	2,038,380	189,000

Bubbles Diffusion into BCAL PBR

- **Bubble Plume Dynamics & Regime Transition**
  - **Jet Initiation (0–5 s)**
- •Gas injected at **0.3 m/s**
- •Local acceleration up to **3.79 m/s**
- •Strong vertical jet due to contraction
  - **Plume Development (5–15 s)**
- •Formation of cylindrical rising bubble plume
- •Sharp gas–liquid interface (VOF captured accurately)
- •Recirculation zones enhance mixing
  - **Breakthrough Event (~20 s)**
- •Increased pressure & velocity oscillations
- **•Gas breakthrough marks regime shift**
- •Effective plume rise velocity ≈ **0.0425 m/s**
- •Transition to intermittent gas-dominated outlet flow
  - **Post-Breakthrough (20–40 s)**
- •Cyclic plume pulsation & vortex shedding
- •Gas volume fraction at outlet → periodically ≈ 1
- •Sustained recirculation → beneficial for algae reactor mixing

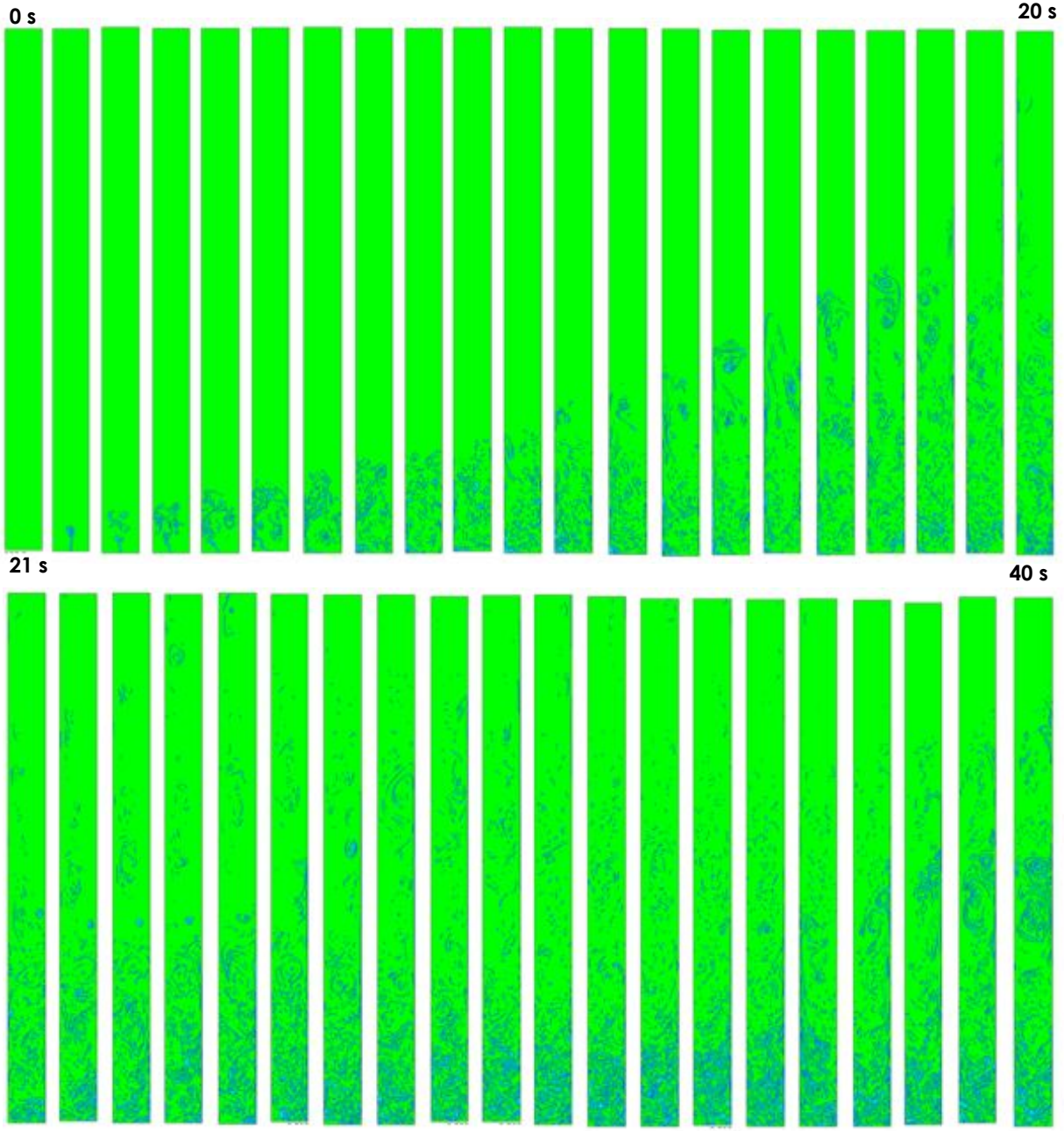


Figure 11: Bubbles diffusion in the BC AL PBR system from (A) 0-20 s & (B) 21-40 s

Velocity Contours for the Inner Cylinder

- **Velocity Field Evolution & Momentum Attenuation**
  - **Inner Cylinder**
    - Peak velocity: **3.79 m/s**
    - Quasi-steady plume before breakthrough
    - Cyclic velocity fluctuations after 20 s
  - **Outer Cylinder**
    - Initial jet velocity ≈ **0.10 m/s**
    - Rapid decay due to sudden expansion
    - Final peak velocity ≈ **0.015 m/s**
    - Transition to diffusion-dominated plume
  - **Momentum Analysis**
    - Velocity reduction factor ≈ **36.5**
    - Momentum loss ≈ **97.3%**
    - Caused by sudden expansion + entrainment
  - **Key Physical Insight**
    - Buoyancy governs plume rise
    - Unsteady multiphase dynamics naturally captured
    - Coupled simulation preserves transient realism

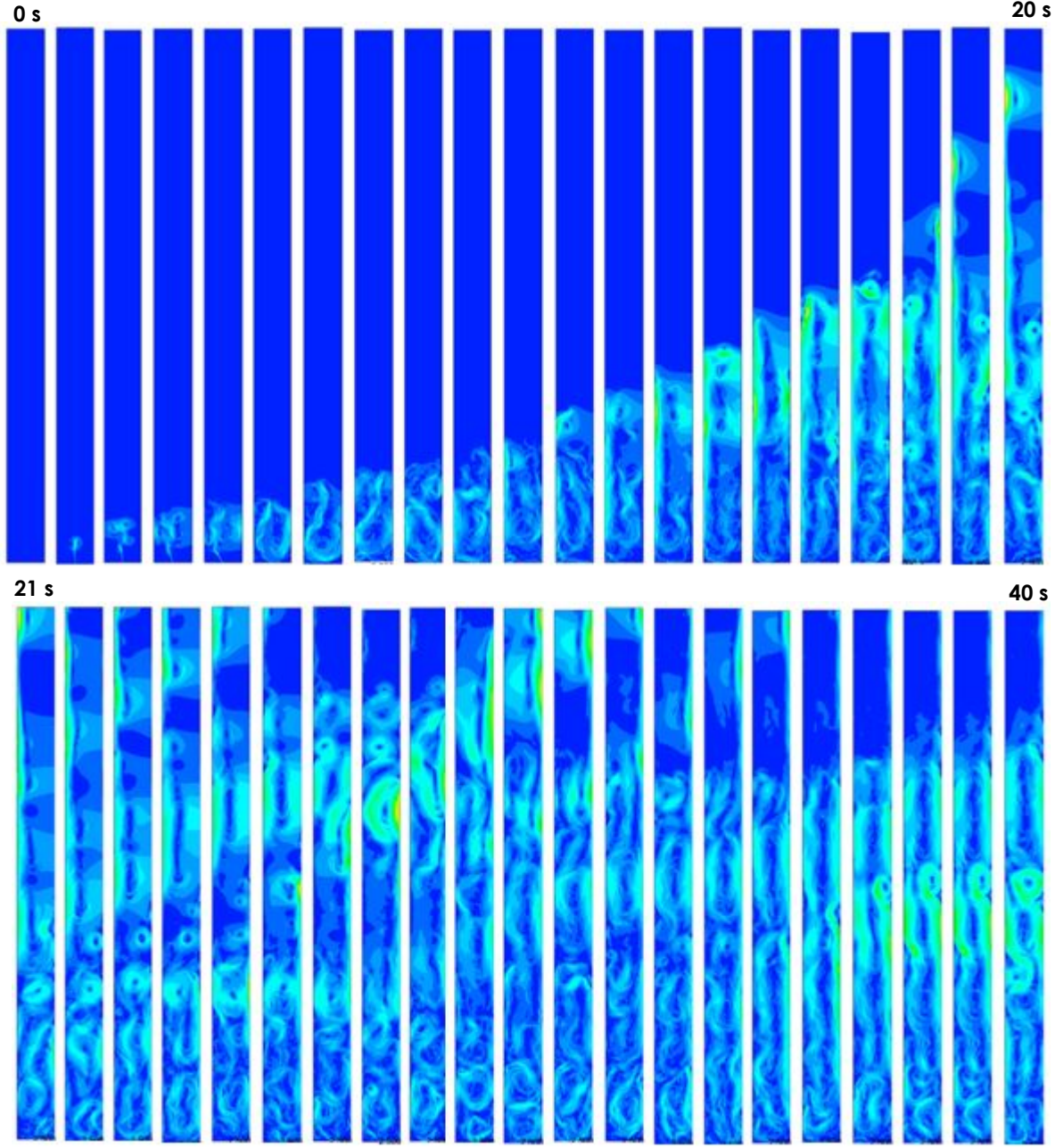


Figure 12: Velocity Contours for the inner cylinder(draft tubing) from 0-20 s & 21-40 s

Velocity Contours for the Outer Cylinder

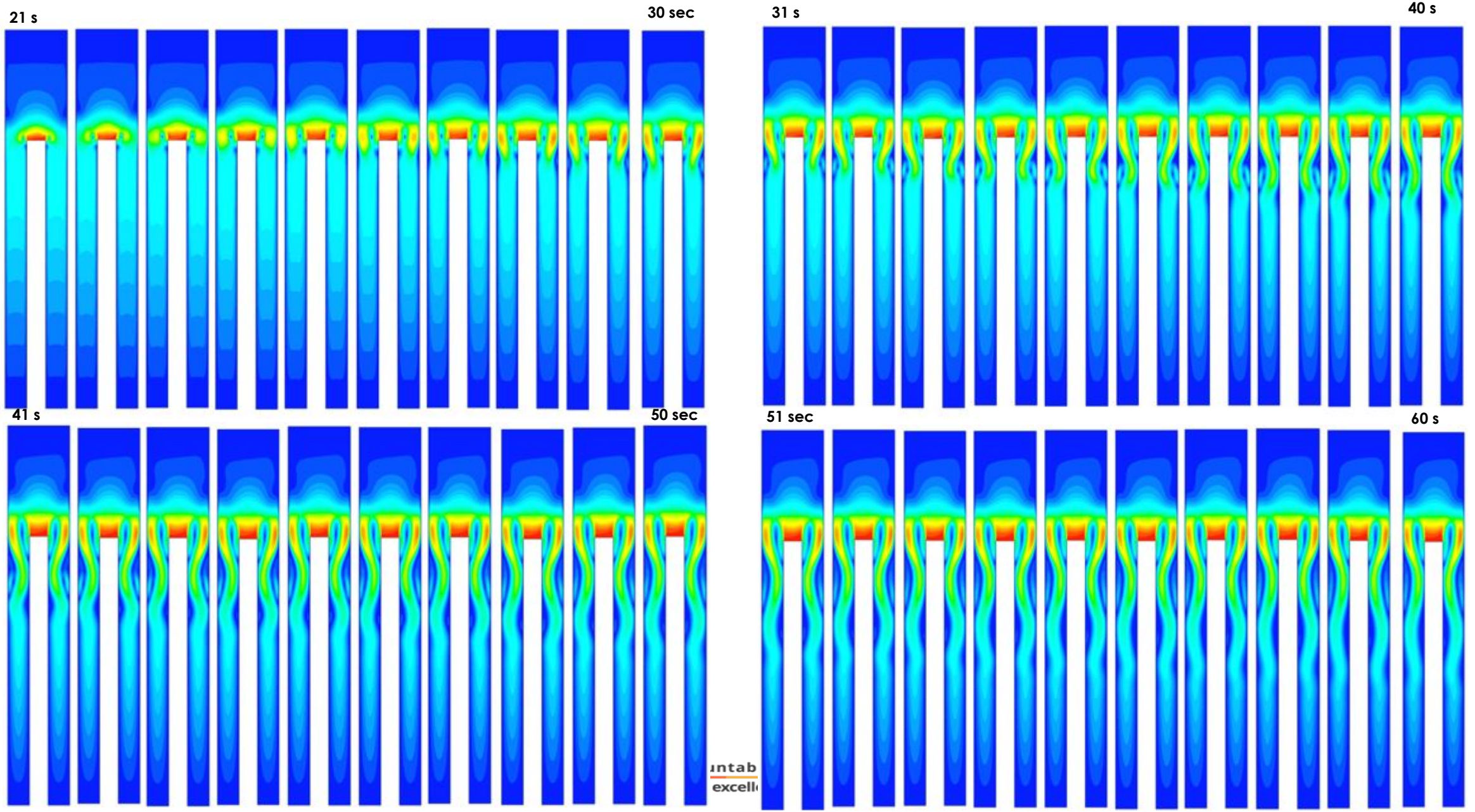
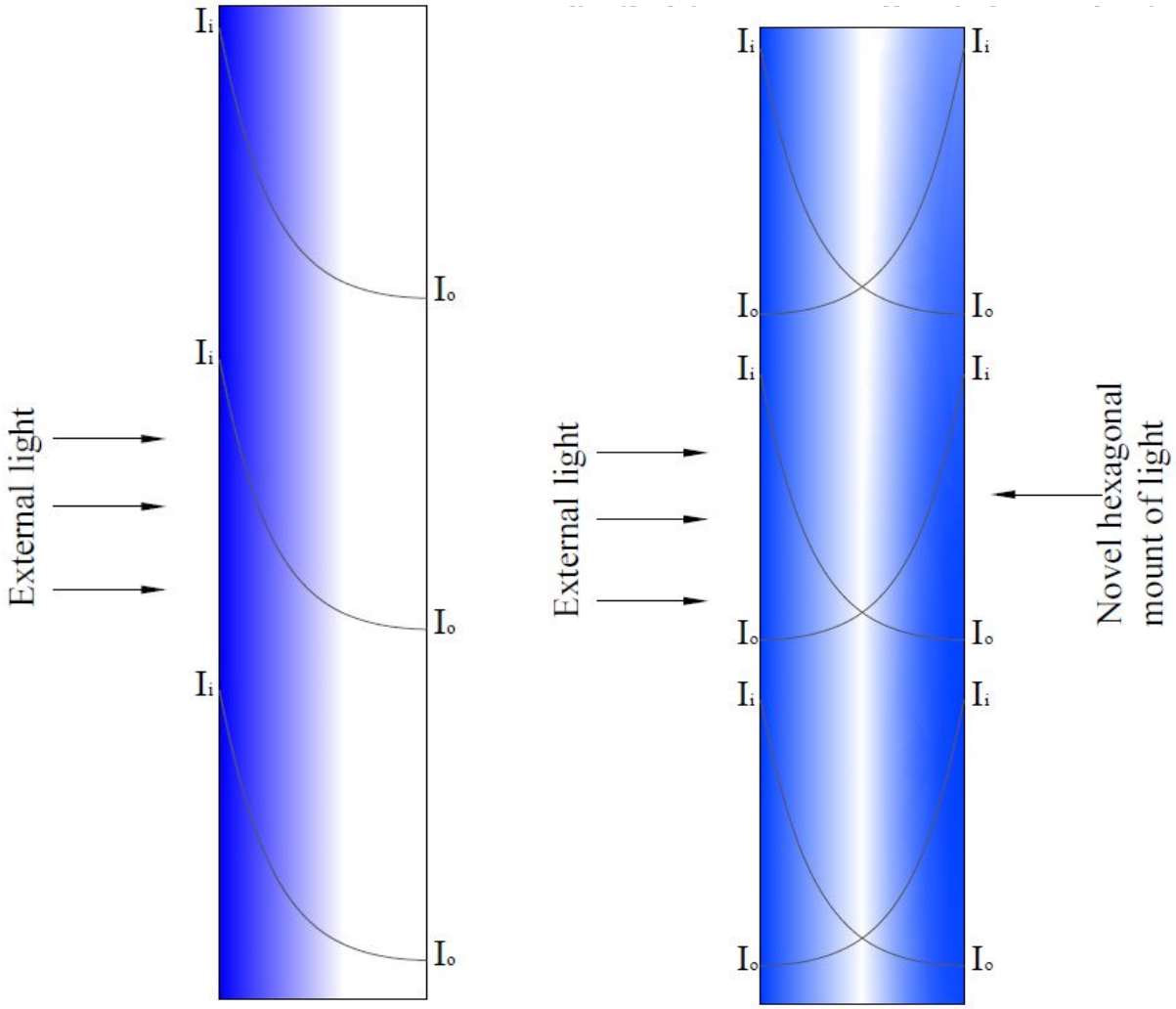


Figure 13: Transient velocity contour evolution in the outer cylinder (20–60 s) showing transition from momentum-driven jet to buoyancy-controlled plume regime.

Light Attenuation



light transmission and causing mutual shading. As a result, incident ecreases over time as the culture density increases and the colour e system, as illustrated in the Figure. That is the problem with s by Barbosa et al. (2005), Beer-Lambert's law was used to determine on chamber, and these values can be evaluated using equation (1).

ines the specific growth rate of microalgae in a PBR system. To find ceptors, integration along the path length inside the photobioreactor

an absorption spectral coefficient based on dry mass.
r with a central light mount has been designed and developed. In nt, while the mixing issue was addressed by producing bubbles with a er and generates the necessary turbulence, ultimately improving

Biomass density vs Penetration depth

Biomass, X (g/m^3)	Penetration Depth for Single Light (m)	Penetration Depth for Double Light (m)	Key Observation
I=150 $\mu mol/m^2 \cdot s$			
300	0.30 –0.35	~0.35	Both similar (full penetration)
600	0.22 –0.28	0.28 –0.32	**Double improves center illumination**
900	0.15 –0.20	0.22 –0.25	**Single has dark core, double reduces it**
1200	0.08 –0.12	0.15 –0.18	**Large dark zone in single, reduced in double**
I=200 $\mu mol/m^2 \cdot s$			
300	~0.35	~0.35	Both uniform
600	0.28 –0.32	0.30 –0.34	**Slight improvement with double light**
900	0.22 –0.27	0.26 –0.30	**Better center illumination in double**
1200	0.15 –0.20	0.20 –0.24	Double maintains usable light
I=250 $\mu mol/m^2 \cdot s$			
300	~0.35	~0.35	No difference
600	0.32 –0.35	~0.35	Nearly identical
900	0.27 –0.32	0.30 –0.34	**Slight improvement**
1200	0.20 –0.25	0.24 –0.28	**Moderate improvement**

Simulation for Light Attenuation

(a) single-sided illumination

(b) double-sided illumination

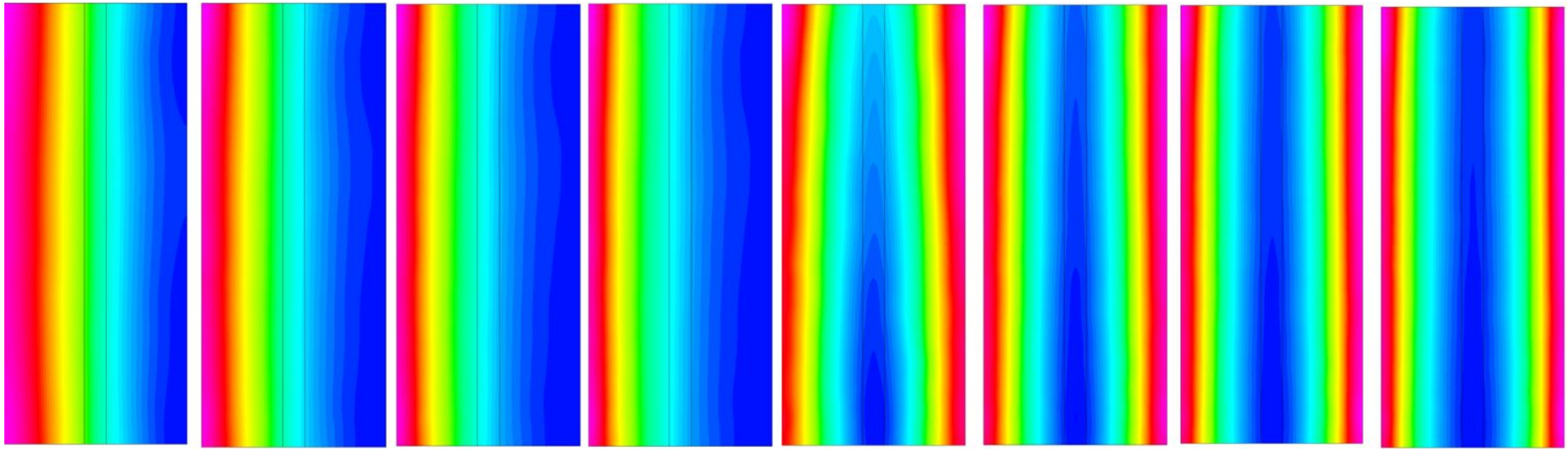


Figure : The distribution of light intensity within the photobioreactor was analyzed for varying biomass concentrations **(X = 300, 600, 900, and 1200 g/m³)** and incident **light intensity (I=150 µmol/m² ·s).** Two illumination configurations were considered. The penetration depth was defined as the distance from the irradiated wall up to which usable light (~10–20% of incident intensity) is maintained.

Figure 13: Transient velocity contour evolution in the outer cylinder (20–60 s) showing transition from momentum-driven jet to buoyancy-controlled plume regime.

Simulation for Light Attenuation

(a) single-sided illumination

(b) double-sided illumination

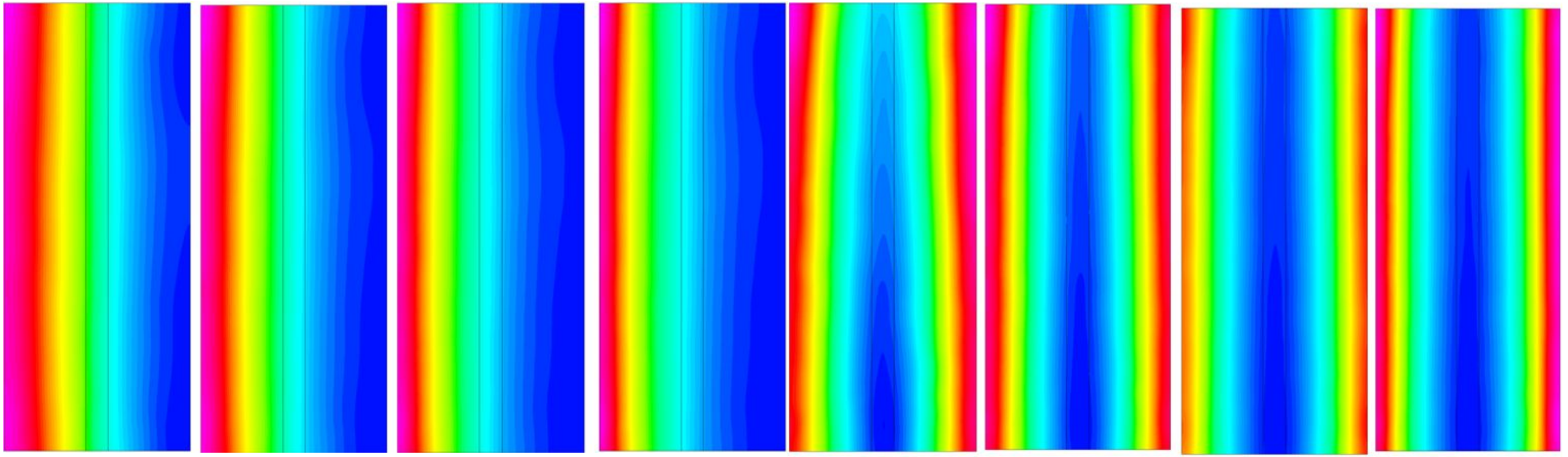


Figure : The distribution of light intensity within the photobioreactor was analyzed for varying biomass concentrations **(X = 300, 600, 900, and 1200 g/m³)** and incident **light intensity (I=200 µmol/m² ·s).** Two illumination configurations were considered. The results clearly demonstrate that light attenuation follows an exponential decay pattern consistent with the Beer–Lambert law, with biomass concentration acting as the primary attenuation parameter and incident intensity influencing the extent of light penetration.

Figure 13: Transient velocity contour evolution in the outer cylinder (20–60 s) showing transition from momentum-driven jet to buoyancy-controlled plume regime.

Simulation for Light Attenuation

(a) single-sided illumination

(b) double-sided illumination

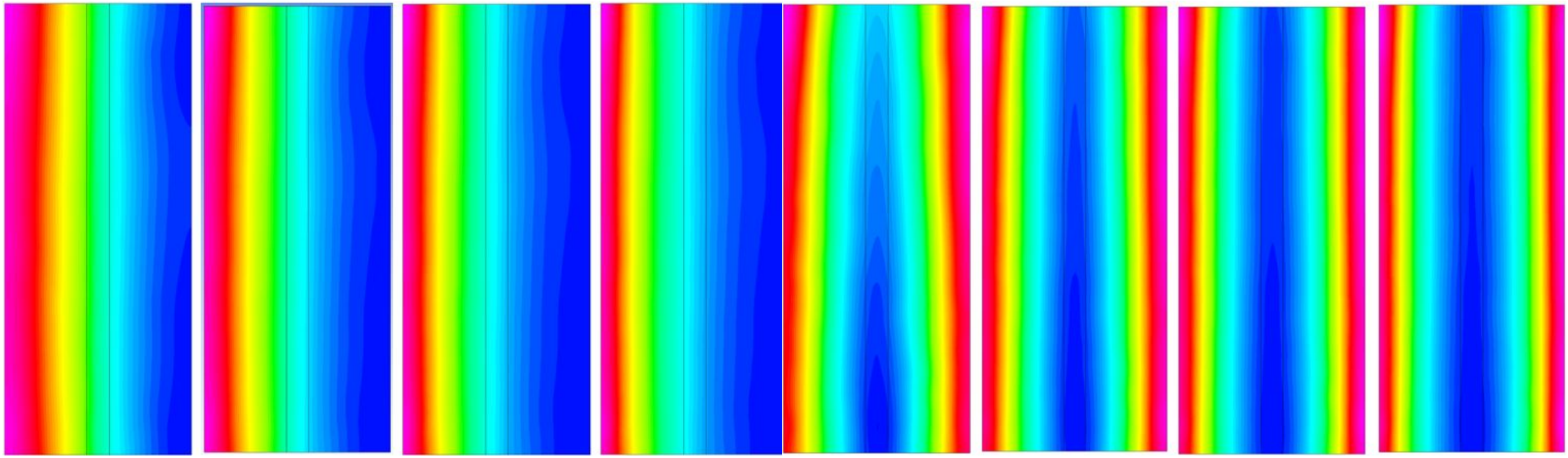


Figure : The distribution of light intensity within the photobioreactor was analysed at varying biomass concentrations **(X = 300, 600, 900, and 1200 g/m³)** and an incident **light intensity of I = 250 µmol/m² s**. At high intensity (I = 250 µmol/m²·s), light penetrates effectively throughout the reactor. Even at high biomass concentrations, the central region remains illuminated. The difference between single- and double-sided illumination becomes less pronounced under these conditions, as the increased incident intensity compensates for attenuation. However, excessive light near the irradiated surfaces may lead to inefficient utilization or photoinhibition.

Discussion

- Biomass concentration was the dominant factor influencing light attenuation, with increasing biomass (300–1200 g/m³) intensifying absorption and self-shading.
- Incident light intensity improved penetration: Increasing illumination from 150 to 250 µmol/m²·s enhanced light availability within the reactor, although excessive surface illumination may reduce utilisation efficiency or cause photoinhibition.
- Double-sided illumination improved light distribution by supplying light from both the sides (walls & central mount), reducing central dark zones and increasing penetration depth, particularly at high biomass concentrations.
- Single-sided illumination produced stronger light gradients, leaving the reactor core increasingly light-limited as biomass concentration increased.
- The advantage of double-sided illumination was most pronounced at high biomass concentrations under low to moderate light intensities. At low biomass or high incident intensity, the difference between configurations became less significant.
- Light attenuation followed an exponential decay pattern, consistent with the Beer–Lambert law, while illumination configuration influenced the spatial distribution of usable light.

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Conclusion

- Biomass concentration is the primary **determinant of light** attenuation and the development of **light-limited** zones.
- Increasing incident light intensity improves light penetration, but the benefit may diminish at higher intensities.
- Double-sided illumination is more effective for high-density microalgal cultivation, improving central light availability and reducing dark zones.
- Optimising biomass concentration, incident light intensity and illumination configuration together is essential for improving light utilisation in the BCAL-PBR system.
- The findings support double-sided illumination as a promising design strategy for enhancing light distribution in high-density photobioreactors.

Publications

National Algae Association



Environmental Technology & Innovation 38 (2025) 104138

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

Efficient pollutant and nutrient removal from restaurant wastewater using *Chlorella vulgaris* in a bubble column photobioreactor

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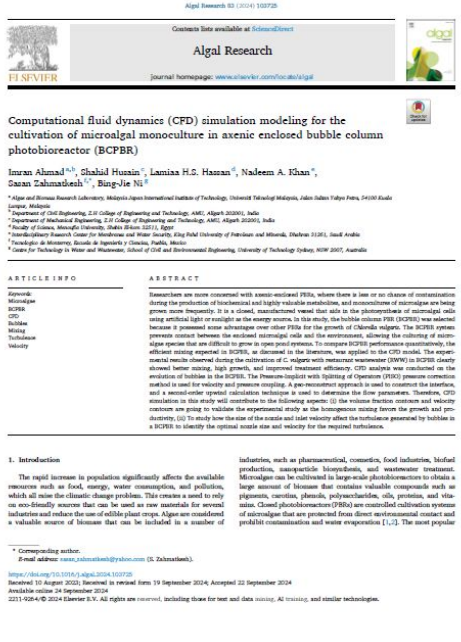
Keywords:
Wastewater treatment
Chlorella vulgaris
Bubble column photobioreactor
BOD
COD

ABSTRACT

The rapid growth of restaurants due to people's changing lifestyles has been implicated in negative impacts on environmental sustainability made by restaurant wastewater (RWW). To overcome this challenge, this work cultivated *Chlorella vulgaris* with RWW in the Bubble Column Photobioreactor (BCPBR) to investigate the efficiency of removing pollutants and nutrients in this type of wastewater. Biomass productivity, chlorophyll, and lipid content were also determined. Fatty acid methyl esters (FAME) were extracted and analyzed by GC/MS. Maximum growth rate (0.16 day^{-1}) and productivity (88.7 mg/L/d) were achieved in autotrophic mode at 150 µmol/m^2/sec (12:12 light-dark cycle). The highest pollutant removal efficiency from RWW was recorded at 120 µmol/m^2/sec (16:8 light-dark cycle) with COD: 96.4% | BOD: 98.2% | FOG: 97.1% | TN: 99.7% | AN: 99.9% | TP: 99.9% | K: 98.3%. *Chlorella vulgaris* exhibited high lipid content (51.5%) and lipid productivity (2 mg/L/d) at 150 µmol/m^2/sec (12:12 light-dark cycle), supporting its biofuel applications. Maximum chlorophyll content (42 µg/mL) was achieved during autotrophic growth at 100 µmol/m^2/sec (24:0 light-dark cycle), highlighting its potential for high-value bioactive compounds. The FAME analysis results showed that long-chain saturated fatty acid (SFA) concentration increased when cultivated in RWW, enhancing biofuel quality. The fatty acid profile was composed of SFA (45–49%), MUFA (37–41%), and PUFA (9–12%), making it a suitable feedstock for sustainable biodiesel production. The treatment contributes to the circular

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https://doi.org/10.1016/j.eti.2025.104138
Received 19 January 2025; Received in revised form 19 February 2025; Accepted 6 March 2025
Available online 18 March 2025
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Algal Research 83 (2024) 103725

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

Computational fluid dynamics (CFD) simulation modeling for the cultivation of microalgal monoculture in axenic enclosed bubble column photobioreactor (BCPBR)

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ARTICLE INFO

Keywords:
Microalgae
BCPBR
CFD
Bubbles
Mixing
Turbulence
Velocity

ABSTRACT

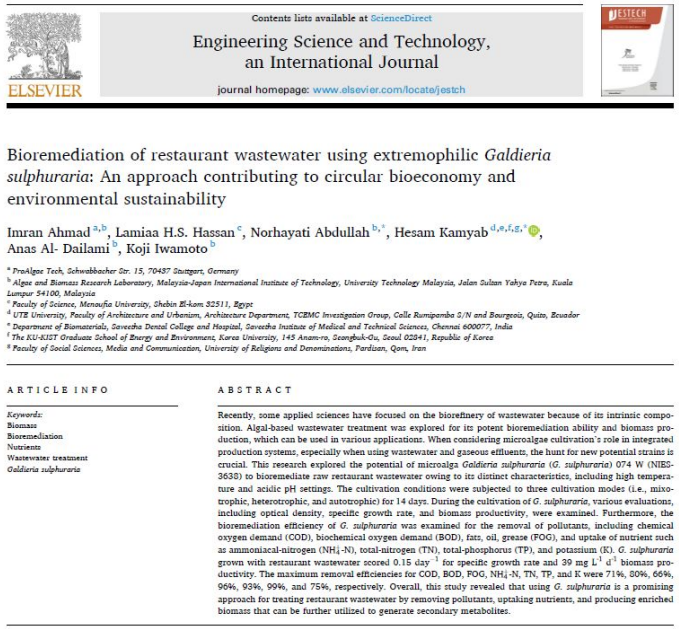
Researchers are more concerned with axenic-enclosed PBRs, where there is less or no chance of contamination during the production of biochemical and highly valuable metabolites, and monocultures of microalgae are being grown more frequently. It is a closed, manufactured vessel that aids in the photosynthesis of microalgal cells using artificial light or sunlight as the energy source. In this study, the bubble column PBR (BCPBR) was selected because it possessed some advantages over other PBRs for the growth of *Chlorella vulgaris*. The BCPBR system prevents contact between the enclosed microalgal cells and the environment, allowing the culturing of microalgae species that are difficult to grow in open pond systems. To compare BCPBR performance quantitatively, the efficient mixing expected in BCPBR, as discussed in the literature, was applied to the CFD model. The experimental results observed during the cultivation of *C. vulgaris* with restaurant wastewater (RWW) in BCPBR clearly showed better mixing, high growth, and improved treatment efficiency. CFD analysis was conducted on the evolution of bubbles in the BCPBR. The Pressure-Implicit with Splitting of Operators (PISO) pressure correction method is used for velocity and pressure coupling. A geo-reconstruct approach is used to construct the interface, and a second-order upwind calculation technique is used to determine the flow parameters. Therefore, CFD simulation in this study will contribute to the following aspects: (i) the volume fraction contours and velocity contours are going to validate the experimental study as the homogenous mixing favors the growth and productivity, (ii) To study how the size of the nozzle and inlet velocity affect the turbulence generated by bubbles in a BCPBR to identify the optimal nozzle size and velocity for the required turbulence.

1. Introduction

The rapid increase in population significantly affects the available resources such as food, energy, water consumption, and pollution, which all raise the climatic change problem. This creates a need to rely on eco-friendly sources that can be used as raw materials for several industries and reduce the use of edible plant crops. Algae are considered a valuable source of biomass that can be included in a number of industries, such as pharmaceutical, cosmetics, food industries, biofuel production, nanoparticle biosynthesis, and wastewater treatment. Microalgae can be cultivated in large-scale photobioreactors to obtain a large amount of biomass that contains valuable compounds such as pigments, carotin, phenols, polysaccharides, oils, proteins, and vitamins. Closed photobioreactors (PBRs) are controlled cultivation systems of microalgae that are protected from direct environmental contact and prohibit contamination and water evaporation [1,2]. The most popular

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https://doi.org/10.1016/j.algal.2024.103725
Received 10 August 2023; Received in revised form 19 September 2024; Accepted 22 September 2024
Available online 24 September 2024
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Engineering Science and Technology, an International Journal

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Bioremediation of restaurant wastewater using extremophilic *Galdieria sulphuraria*: An approach contributing to circular bioeconomy and environmental sustainability

Imran Ahmad [a,b], Lamiaa H.S. Hassan [c], Norhayati Abdullah [b,*], Hesam Kamyab [d,e,f,g,*], Anas Al- Dailami [b], Koji Iwamoto [b]

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ARTICLE INFO

Keywords:
Biomass
Bioremediation
Nutrients
Wastewater treatment
Galdieria sulphuraria

ABSTRACT

Recently, some applied sciences have focused on the biorefinery of wastewater because of its intrinsic composition. Algal-based wastewater treatment was explored for its potent bioremediation ability and biomass production, which can be used in various applications. When considering microalgae cultivation's role in integrated production systems, especially when using wastewater and gaseous effluents, the hunt for new potential strains is crucial. This research explored the potential of microalga *Galdieria sulphuraria* (*G. sulphuraria*) 074 W (NIES-3638) to bioremediate raw restaurant wastewater owing to its distinct characteristics, including high temperature and acidic pH settings. The cultivation conditions were subjected to three cultivation modes (i.e., mixotrophic, heterotrophic, and autotrophic) for 14 days. During the cultivation of *G. sulphuraria*, various evaluations, including optical density, specific growth rate, and biomass productivity, were examined. Furthermore, the bioremediation efficiency of *G. sulphuraria* was examined for the removal of pollutants, including chemical oxygen demand (COD), biochemical oxygen demand (BOD), fats, oil, grease (FOG), and uptake of nutrient such as ammoniacal-nitrogen (NH_4-N), total-nitrogen (TN), total-phosphorus (TP), and potassium (K). *G. sulphuraria* grown with restaurant wastewater scored 0.15 day^{-1} for specific growth rate and 39 mg L^{-1} d^{-1} biomass productivity. The maximum removal efficiencies for COD, BOD, FOG, NH_4-N, TN, TP, and K were 71%, 80%, 66%, 96%, 93%, 99%, and 75%, respectively. Overall, this study revealed that using *G. sulphuraria* is a promising approach for treating restaurant wastewater by removing pollutants, uptaking nutrients, and producing enriched biomass that can be further utilized to generate secondary metabolites.



doi: 10.2166/9781789064100_0121

Chapter 7

Open and closed photobioreactors for microalgal cultivation and wastewater treatment

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ABSTRACT

The utilization of microalgae in wastewater treatment (WWT) witnesses a global interest. From this sector, there are two main cultivation systems that can be used for microalgae cultivation, either open or closed systems; the choice of which of these cultivation systems to be used depends on the purpose of the produced biomass. Use of closed photobioreactors (PBRs) is better than open systems because they can provide uncontaminated monoalgal culture. Design of PBR allows controlling light intensity, light penetration ratio, with good gas exchange sectors, air/carbon dioxide supply, and mixing strategy. Different configurations of PBRs, including aerobic, horizontal tube, moving tank, and tubular aerobic PBRs, are studied in terms of their design, operation, and performance, with emphasis on their efficiency in generating microalgae biomass. Airlift pressure-feedback PBRs are energy-efficient and improve mass transfer in both internal and external loop configurations. Horizontal tube PBRs maximize light exposure but face biofouling and uneven distribution. Stirred tank PBRs have good mixing efficiency but limited light penetration and high energy requirements. PBRs are preferred for continuous cultivation systems due to their superior light penetration and high biomass productivity. The most common PBRs are flat panel reactors, tubular, and bubble column PBRs. Microalgae cultivation technology using PBRs depends on cultivation mode, factors that control the optimal growth, and harvesting techniques. PBRs are used in WWT, with suspended systems offering economical alternatives. Fixed systems, such as PBRs, improve separation but struggle with accurate biomass measurement. Hence, this chapter emphasizes the need for engineering improvements and optimization techniques to overcome operational and economic limitations of open and closed PBRs. This provides an overview of commercial WWT using microalgae, highlighting growth factors, different types and designs, and their applications.

Keywords: Microalgae, bioremediation, wastewater treatment, raceway, open ponds, photobioreactors, airlift photobioreactors, photosynthetic efficiency, tubular PBRs, bioresource recovery, biomass, biofuel

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