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Flow Rate Optimization in a Flat-Panel Photobioreactor for the Cultivation of Microalgae for Mitigating Waste Gas

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Abstract: Biofuel production is a renewable energy resource that is not only the most stabilized source of energy but also one of the sustainable alternatives to non-renewable-sourced fuels. Microalgal biomass is emerging as a third-generation biofuel owing to its high lipid content. The specific biomass concentration and lipid content are responsible for direct biodiesel production. Computational Fluid Dynamics (C.F.D.) studies are gaining importance due to the luxury of exploration without requiring a considerable capital cost. The microalgal strains of *Chlorella sorokiniana* have shown the maximum specific growth rate of 0.11 h^{−1} among several algal species and contain 19% w w^{−1} lipid. Characterization reveals that the lipid content is suitable for biodiesel production. CO₂ sequestration, biodiesel production, and secondary metabolites by green algae, *C. sorokiniana*, are reported in this work. A C.F.D. study is also being conducted for the flat-panel photobioreactor.

Keywords: *Chlorella sorokiniana*; biodiesel; flat-panel photobioreactor; CFD

1. Introduction

As countries tend to improve their G.D.P. per capita, the statistics indicate that their consumption of fossil fuels will enhance the subsequent inter-competition for the specified limited resources resulting in climate change mediated through greenhouse gases (GHGs) on a global platform [1]. The increasing demand for energy in the present global scenario has necessitated research towards developing sustainable renewable energy sources. The reliability of fossil fuels requires their substitution through the implementation of multiple strategies to provide long-term relevant solutions [2]. The adverse effect of climate change due to the considerable increase in atmospheric greenhouse gases has drawn the attention of many countries. Contextually, the prospect of biofuel originating from biomass serving as a substitute for fossil fuels is increasing. Among these, microalgal biomass

has demonstrated its efficacy as an up-and-coming source of biofuel production and is considered generation biofuel [3]. The microalgal cells' biomass concentration and lipid content may influence biodiesel generation [4]. *Chlorella sorokiniana* has the highest specific growth rate (0.11 h^{-1}) among several algal species and contains $w \text{ w}^{-1}$ lipid. According to the International Energy Agency, biofuels are expected to account for 6% of overall fuel consumption by 2030; when compared to other crops, they possess the benefits of highly rapid growth periods, improved susceptibility to substantial U.V. radiation dosages, and a greater efficiency of energy transformation to biomass owing to minimal demands on other metabolic processes [5].

Algal biofuels are a comparatively novel substitute to traditional fuels and are not so far in the competition. To improve its competitiveness, scientific advancements are required, for which there are two main goals, a growth medium for algae and a method for removing intracellular components of algae [6]. Recent advances in algal biotechnology, focusing on the production of biological products by managing various waste streams within the circular economy framework, address the cultivation, safety, feasibility, and availability of waste streams as a source of nutrients for algal biomass cultivation and bioproduction [7], as shown in Figures 1 and 2.

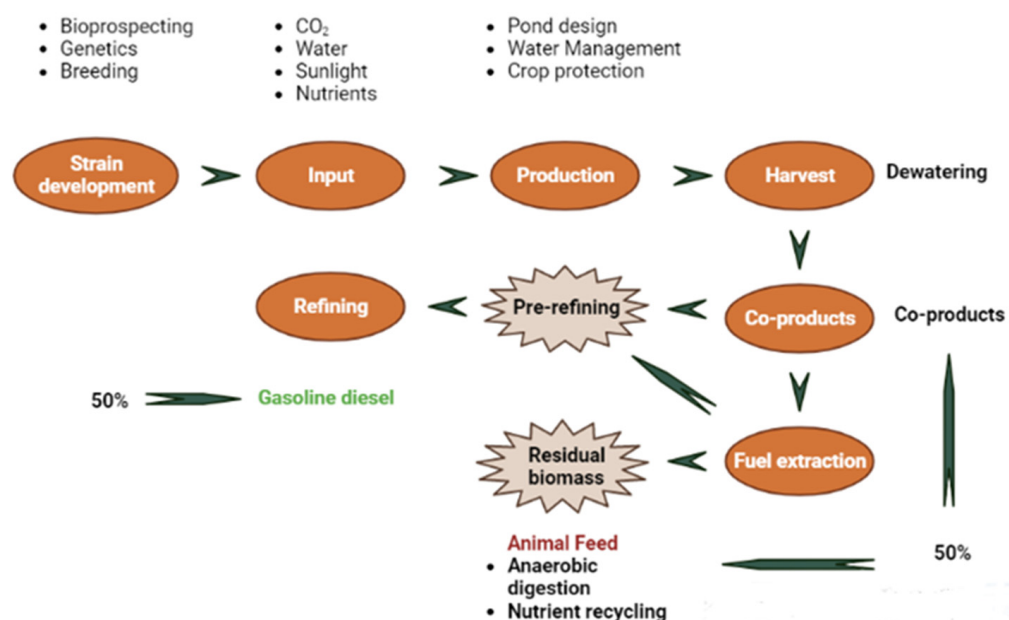


Figure 1. The production chain of algal biofuels.

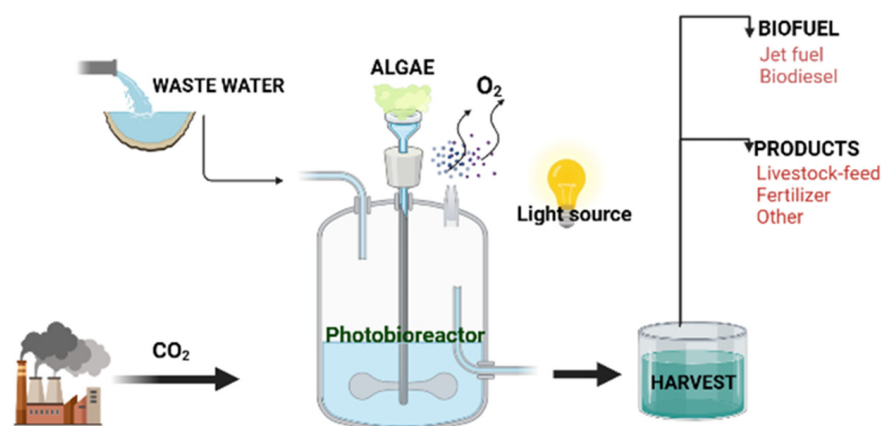


Figure 2. Production of biofuel from algae.

Other studies have shown that algae-based biofuels have a positive greenhouse gas balance. For example, we found that the cyanobacterial production of ethanol can reduce the carbon footprint by 67% to 87% compared to fossil fuel-based gasoline [8].

Biofuel production from algal sources is still in the pre-industrial stage of technological development. However, algal biofuels are seen as a propitious substitute for fossil energy sources because they can lower greenhouse gas release, have a greater yield per hectare, and have a more negligible contention for arable fields [9]. The prime impediment to the widespread utilization of algal biofuels is the elevated cost of production. Many research programs are working to improve production processes and reduce costs [10].

Chlorella, a largescale cultured alga, was the first type of algae to be commercially produced as a food additive in countries like Japan in the early 1960s. From there, it spread to other countries such as America, the Indian subcontinent, Israel, and the Australian states [11]. Since algal cells develop in water-based suspensions and have easy accessibility to CO₂, water, and different salts, algae are typically more effective solar energy converters. As a result, through various conversion processes like verification, anaerobic digestion, hydro treatment, fermentation, pyrolysis, and direct combustion, algae became the ideal renewable fuel and energy source [12]. However, some conversion techniques can be economically and commercially feasible if all the byproducts are used to their full potential [13].

As a result of the detrimental environmental impacts of fossil fuels, considerable effort is being invested into enhancing biofuels. However, the straight use of biofuels to replace existing fuels has faced several operational challenges because of their physiochemical properties for producing fuel with the desirable physiochemical characteristics; biofuel blends and emulsions have been improved because of these difficulties [14]. Improved fuel properties lead to fuel blends, in which various fuel types are combined in varying proportions to achieve a specific development objective [15].

Flat-panel P.B.R.s are typically characterized by an extensively lighted specific surface area, a relatively brief light pathway, a minimal required site area, and reduced energy utilization. Flow rate optimization plays a pivotal role in the proper growth of microalgae. The flow rate also regulates proper mixing and mass transfer inside the photobioreactor. The functioning of P.B.R.s in cultivating biomass can be enhanced by the optimization of internal mixing conditions as a result of manipulating flow behavior. Although several reports have been submitted on flat-panel photobioreactors, this specific type of flat-panel photobioreactor provides a rocking arrangement for maintaining the niche mimic condition for the growth of microalgae and cyanobacteria. This reactor can also be used for biohydrogen production in rocking conditions. A computational fluid dynamic (C.F.D.) study was employed to optimize the flow behavior for enhanced microalgae growth in the flat-panel P.B.R. used in this work. C.F.D. studies for flow rate optimization on this specific type of reactor have yet to be reported. *C. Sorokiniana* was chosen as the microalgae species for CO₂ sequestration and biodiesel production [16–20].

Closed P.B.R.s are preferable for algal cultivation due to their reduced contagion benefits, increased reproducibility of culture conditions, and better control over hydrodynamic and temperature parameters [21]. Homogeneity in the nutrient feed supply is essential for the desirable growth of microalgae. Although batch operation is typical, the continuous operation of P.B.R.s can be accomplished by incorporating nutrients, air, and CO₂ in the supply media. Biomass production can be maximized by equalizing the CO₂ diffusion rate in the culture media and the biomass production rate. Recent advancements in Computational Fluid Dynamics (C.F.D.) can effectively model P.B.R.s for microalgae cultivation, thus reducing the burden of sole experimentation. Hydrodynamic studies, which are integral to designing P.B.R.s, can adequately be analyzed using C.F.D. techniques [22–24]. The current data represent the specific growth rate of 0.11 h^{−1} of *Chlorella sorokiniana* containing 19% w w^{−1} lipid content, which is suitable for biodiesel production. Further, CO₂ sequestration, biodiesel, and secondary metabolites production with C.F.D. studies have also been conducted and described for the flat-panel photobioreactor.

2. Materials and Methods

2.1. Microalgae and Culture Medium

The microalga *Chlorella sorokiniana* was utilized for the experiment, and the strain was received from Dr Kari Skjanes (Bioforsk, Norway). A modified T.A.P. (+acetate) medium was employed to cultivate the microalgae [25]. The optimized initial pH for the medium was 7.3, and the temperature was 30 °C, maintained during the entire cultivation period for the proper microalgae growth. The light intensity was 100 $\mu\text{mol photons}^{-1} \text{m}^{-2} \text{s}^{-1}$ [26].

2.2. Photobioreactor (P.B.R.)

A flat-panel P.B.R. of a 1.4 L working volume was used to cultivate the microalgae. The reactor has a large surface-area-to-volume ratio and available gas distribution lines. An air pump operating at an ideal flow rate of 600 mL min^{-1} bubbled air from one side via a perforated tube to generate agitation (determined from a C.F.D. study). An external light illumination system with a light intensity of 100 $\mu\text{mol photons}^{-1} \text{m}^{-2} \text{s}^{-1}$ was used for the cultivation (Figure 3).

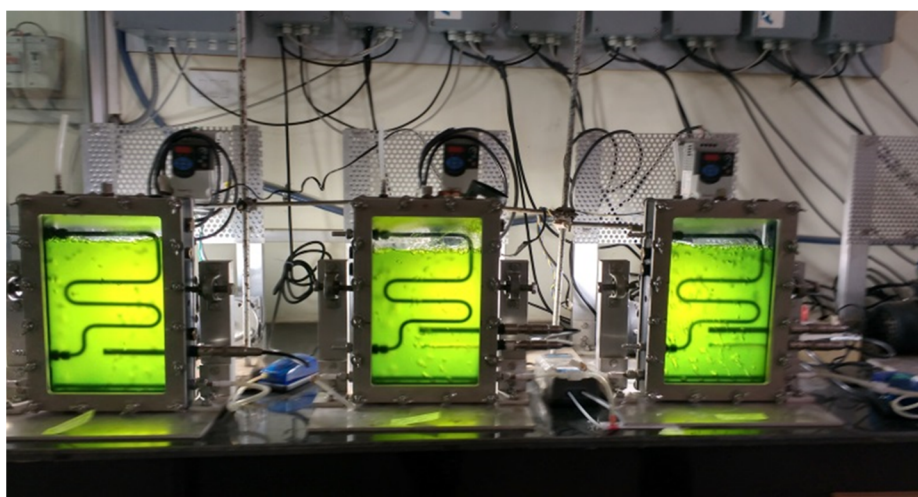


Figure 3. Flat-Panel Reactor (experimental setup).

2.3. Lipid Estimation

Lipid was extracted from the lyophilized microalgal biomass using Bligh and Dyer's method [27]. The extracted lipid was transesterified by methanolic-HCl at 70 °C for 2 h. The transesterified sample was analyzed using a gas chromatograph (Clarus 500, PerkinElmer) equipped with an Omegawax 250 capillary column (30 m length, 0.25 μm film thickness, 0.25 mm internal diameter, Sigma, St. Louis, MI, USA) and a flame ionization detector. The oven temperature was increased from 50 to 240 °C at 4 °C min^{-1} and maintained at 240 °C for fifteen minutes. Nitrogen was employed as the carrier gas, with a flow rate of 1 mL min^{-1} . The retention periods and fragmentation profiles of the chromatographic peaks were compared to standards of fatty acid methyl ester (FAME) mixes (37mix, Supelco Inc., Bellefonte, PA, USA) [28].

2.4. Biodiesel Characterization

The characterization of the fuel properties of *Chlorella sorokiniana* biodiesel, namely, the density (specific gravity bottle), kinematic viscosity (rheometer), and cetane number (ignition quality tester), was evaluated and paralleled with ASTM (American Society for Testing and Materials) D 6571 and normal commercial biodiesel standards.

2.5. Computational Model

A 3D C.F.D. model was created to simulate the airflow inside a flat plate photobioreactor containing the algal suspension. A hydrodynamic study was carried out to gain insight

into the distribution of the air entering the reactor. The geometry and meshing were carried out in the design and meshing modeller of the commercial C.F.D. code solver ANSYS 15.0. The computational domain was a cuboid with dimensions of 30.5 cm × 5 cm × 35.5 cm, consisting of six circular apertures of 0.05 cm diameters at the bottom wall for the gas inlet, as shown in Figure 4a. The top wall has a single circular opening that is 0.5 cm in diameter for the air to leave the reactor. A computational grid of 52,215 fine tetrahedral mesh elements was generated to obtain the numerical solutions, as shown in Figure 4b.

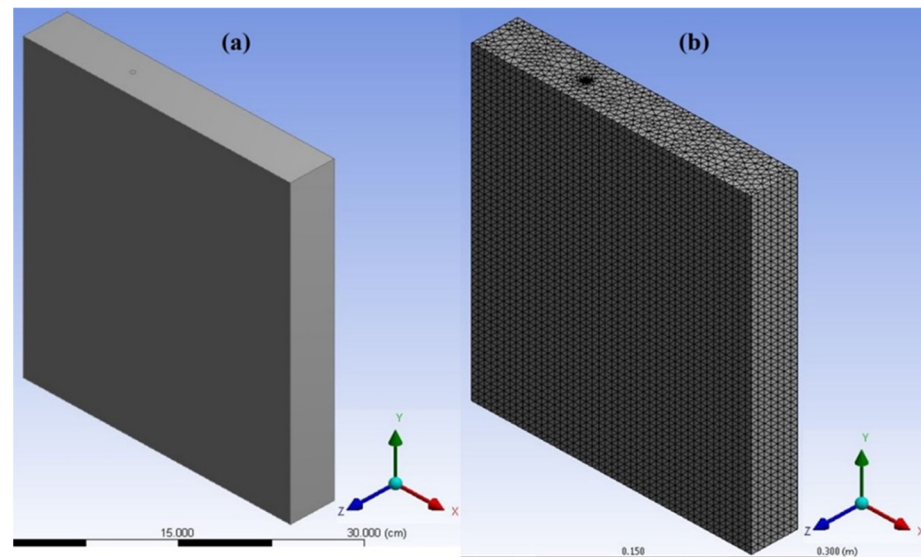


Figure 4. Computational domain: (a) geometry, (b) meshing.

The inlet openings for the air were defined as the velocity inlet boundary conditions, and the aperture at the top wall was exposed to atmospheric pressure conditions. The entire flow domain was patched with water (properties similar to those of the algal suspension). The V.O.F. method captured the gas–liquid interface and volume fraction measurements [29]. No-slip wall boundary conditions defined all the faces. In this case, the surface tension value of an air–water system was considered as the algal suspension and had similar properties to water. Under relaxation, the parameters for pressure and momentum were maintained at 0.25 and 0.4 throughout the simulations. The SIMPLE algorithm with a second-order discretization approach was used to solve the equations that govern mass and momentum. Transient simulations were executed with a time step measure of 1×10^{-6} to obtain a converged solution and restrict the global Courant number to less than unity.

Continuity equation (Equation (1)):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

Momentum equation (Equation (2)):

$$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla (\rho \vec{v} \vec{v}) = -(\nabla P - \rho \vec{g}) + \nabla \cdot \bar{\bar{\tau}} + \vec{F}_{SF} \quad (2)$$

where ' ρ ' is the density of the fluid, ' $\vec{v}$ ' is the velocity, ρ is the density, P indicates the pressure, and $\vec{g}$ is the acceleration due to gravity. $\bar{\bar{\tau}}$ is the volume averaged viscous stress

tensor, and $\vec{F}_{SF}$ is the continuum surface force per unit volume of the reactor. The volume fractions of each phase are solved via the following equation (Equation (3)):

$$\frac{\partial \varepsilon_k}{\partial t} + \vec{v} \cdot \nabla \varepsilon_k = 0 \quad (3)$$

where ε is the volume fraction, and k represents the gas or liquid phase. The V.O.F. method is characterized by conserving volume fractions for all phases throughout the computational domain denoted by $\sum \varepsilon_k = 1$. A particular computational cell is considered devoid of the phase k for $\varepsilon_k = 0$ and filled for $\varepsilon_k = 1$. Contextually, the volume fraction in the range $0 < \varepsilon_k < 1$ is evaluated to demarcate the interface between the two phases. The detailed mathematical model and governing equations of the continuum surface force can be found elsewhere.

3. Results

Analysis showed that *Chlorella sorokiniana* contains 19% w w⁻¹ lipid without any stress condition and in the normal autotrophic growth mode (Table 1).

Table 1. Biomass productivity of *Chlorella sorokiniana* grown in a flat-panel photobioreactor.

The Organism Has Grown on	Max Biomass (g L ⁻¹)	Biomass Productivity (g L ⁻¹ d ⁻¹)	Total Lipid Content (%w w ⁻¹)	Total Protein Content (%w w ⁻¹)	Total Carbohydrate Content (%w w ⁻¹)	Total Chlorophyll Content (µg mg ⁻¹)
<i>Chlorella sorokiniana</i>	1.892 ± 0.05	0.52 ± 0.03	19 ± 0.05	36 ± 0.03	27 ± 0.05	0.022 ± 0.01

The fatty acid composition was also analyzed, and the results showed that the majority of the fatty acids were composed of myristic acid (14:0), palmitic acid (16:0), stearic acid (18:0), and oleic acid (18:1), as reported in Table 2.

Table 2. FAME analysis of the lipid from *Chlorella sorokiniana*.

Fatty Acids	Algal Biomass is Grown in 5% CO ₂ (Relative Percent of Fatty Acid)
Capric acid (C10:0)	4.6 ± 0.18
Lauric (C12:0)	16.23 ± 0.48
Myristic (C14:0)	19.53 ± 0.39
10-Pentadecenoic (C15:1)	2.21 ± 0.11
Palmitic (C16:0)	16.42 ± 0.72
Palmitoleic acid (C16:1)	3.67 ± 0.18
Margaric (C17:0)	-
Stearic (C18:0)	16.41 ± 0.67
Oleic (C18:1)	2.12 ± 0.11
Linoleic acid (C18:2)	-
α Linolenic acid (C18:3)	1.82 ± 0.1
Arachidic (C20:0)	6.2 ± 0.2
Eicosenoic acid (C20:1)	1.72 ± 0.08
Eicosapentaenoic acid (C20:5)	-
Erucic acid (C22:1)	3.1 ± 0.15
Tricosanoic acid (C23:0)	1.0 ± 0.1
Other unknown fatty acids	5.0 ± 0.4
MUFA	12.81 ± 0.63
PUFA	1.82 ± 0.1
Saturated fatty acids (S.F.A.)	80.39 ± 2.26
Medium-chain fatty acids (C10-C15)	42.57 ± 1.16
Long-chain fatty acids (C16-C18)	40.44 ± 1.78
Very long-chain fatty acids (≥C20)	12.03 ± 0.53

The quality of biodiesel produced depends on the unsaturated fatty acid content and a significant number of saturated fatty acids, which have sound oxidative stability [30]. The fatty acids obtained in this study demonstrated a majority carbon chain length of C₁₄–C₂₂. This carbon chain length range has been identified as beneficial for producing biodiesel. The characterization of the physical characteristics of the biodiesel showed similar properties (kinematic viscosity, density, and cetane number) to ASTM standard commercial diesel (Table 3).

Table 3. Physical properties of biodiesel.

Properties	ASTM (Standard)	Diesel	Biodiesel from <i>Chlorella sorokiniana</i>
Kinematic viscosity at 40 °C (mm ² s ^{−1})	5.2	4.1	5
Density (kg m ^{−3})		825	900
Cetane number	47	59	63

Gas Distribution for Appropriate Mixing State Determination inside the P.B.R. (C.F.D. Simulation)

Channeling is one of the significant problems encountered inside the reactor leading to the maldistribution of the gas. Qualitative and quantitative analyses of gas distribution were performed based on volume fraction contours and plots, respectively. Air was purged through six consecutive inlets from the bottom of the reactor at three different flow rates of 462, 600, and 800 mL min^{−1}. Volume fraction contours of air were observed along the x–y plane at a particular time step inside the reactor, as shown in Figure 5 where e indicates value × 10³. The contours indicate that the flow rate of 600 mL min^{−1} produces a better gas distribution. Here e indicates 10³.

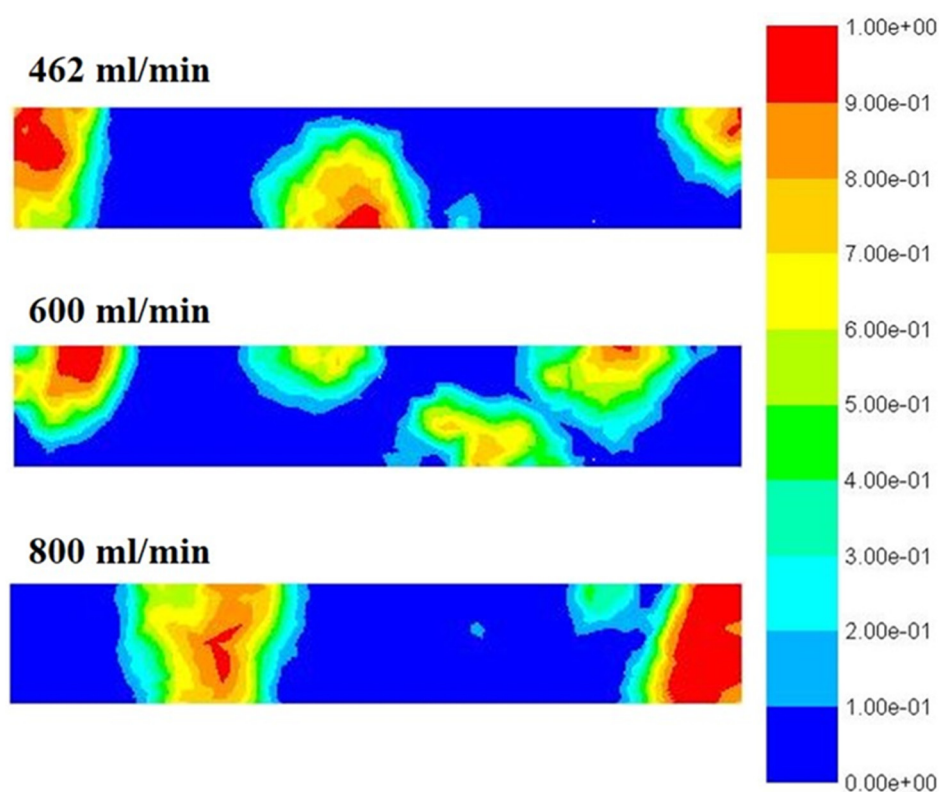


Figure 5. Volume fraction contours of air at different flow rates.

A quantitative analysis of the gas distribution was carried out by plotting the air volume fraction along the radial direction. Figure 6 shows that the 600 mL min^{−1} flow rate provides the best distribution, depicting a relatively flatter profile. Thus, a better homogeneity can be obtained with an airflow rate of 600 mL min^{−1}, which signifies better mixing and mass transfer, with a consequential reduction in algal sedimentation inside the P.B.R. This is desirable regarding the conversion of the algal suspension, leading to better productivity. The numerical predictions were also in line with the previous experimental results.

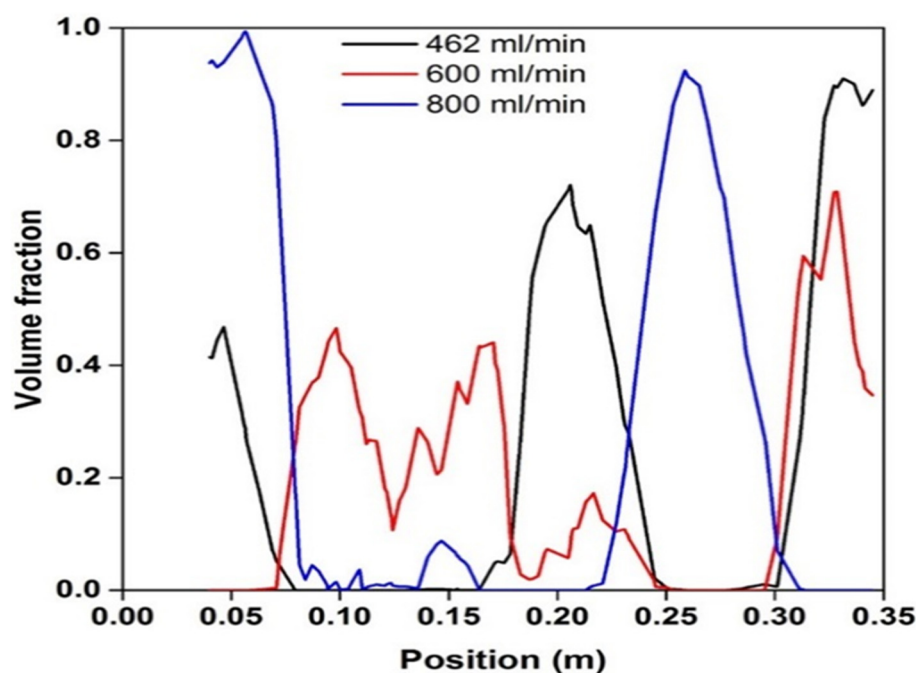


Figure 6. Volume fraction vs. position along the x–y plane.

A gas distribution coefficient (C_g) was proposed based on the deviation about the mean value of the volume fraction according to the following correlation (Equation (4)):

$$C_g = \sqrt{\frac{1}{N(N-1)} \sum_i^n \left(\frac{\epsilon_i - \epsilon'}{\epsilon'} \right)^2} \quad (4)$$

C_g is the gas distribution coefficient, ϵ_i is the volume fraction at position i , ϵ' is the mean volume fraction, and N is the number of data points. The range of C_g varies from 0 to 1, where 0 signifies an ideal gas mixing without maldistribution. The distribution analysis substantiated the earlier analysis presenting the lowest value at the flow rate of 600 mL min^{−1}, as given in Table 4.

Table 4. Gas distribution analysis.

Flow Rate (mL min ^{−1})	C_g
462	0.11
600	0.07
800	0.12

4. Discussion

Chlorella sorokiniana can be used as a promising feedstock for biodiesel production, as it has the highest specific growth rate among several algal species. The lipid content in the biomass of *Chlorella sorokiniana* is 19% w w^{−1}. The lipid quality favors the production

of biodiesel because of the C₁₄–C₂₂ carbon chain. The physical properties of biodiesel have significant similarities with the commercial diesel. The appropriate flow rate for the microalgae growth inside the flat-panel P.B.R. was also optimized by running the C.F.D. simulation studies. Maintaining this optimum flow rate (600 mL min^{−1}) allows for homogeneity and an appropriate mixing state inside the P.B.R. for a better biomass and product formation.

5. Conclusions and Future Studies

Previously, much work has been conducted on flat-panel P.B.R.s with C.F.D. simulation. However, few reports with the combined experimental work and C.F.D. simulation are known. The current article reports combined experimental work and a C.F.D. simulation to maximize output. Future studies invite opportunities for improvement in using the non-destructive sorting of combined algae treatment routes to pursue isolation and upgrades to value products.

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Data Availability Statement: Data available on request due to restrictions eg privacy or ethical.

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Conflicts of Interest: The authors declare no conflict of interest.

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