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Reconciling algal growth understanding in photobioreactors through a statistical and facile single parameter (ψ) approach

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As the global energy crisis intensifies, there is an urgent need for sustainable alternatives to fossil fuels. Algae, with their high growth rates and ability to sequester carbon, present a promising solution for renewable energy and carbon capture. This study investigates the potential of various algal species for carbon capture through a comprehensive analysis of bubble column photobioreactors (BC-PBRs). By reviewing 102 relevant studies over the past 15 years, a total of 24 articles were identified, providing 650 data points on biomass yield in relation to design parameters such as aeration rate, column height, diameter, volume, and carbon dioxide concentration. The analysis revealed a positive correlation between biomass yield and column height ($R = 0.48$; range: 20–200 cm), total volume ($R = 0.48$; range: 1–70 L), and cultivation time ($R = 0.47$; range: 2–22 days). In contrast, a negative correlation was observed with carbon dioxide concentration ($R = -0.12$; range: 0.03–20%) and column diameter ($R = -0.21$; range: 2–24 cm). Notably, *Chlorella spinulatus* emerged as the most promising species among those studied, with the highest biomass yield (mean of 3.03 ± 1.12 g L^{-1}). This research highlights critical design considerations for optimizing BC-PBRs to enhance algal growth and biomass production.

Environmental significance

The increasing atmospheric carbon dioxide levels and air pollution in urban areas pose a serious global issue. This research tackles these environmental issues by designing and simulating a bubble column photobioreactor (PBR) system optimized for microalgae cultivation. Microalgae provide a sustainable and efficient pathway for biological CO_2 sequestration while simultaneously enhancing air quality. The study provides insights into bubble behavior dynamics and mass transfer phenomena in the PBR, which can facilitate more efficient design and operation for massive deployment. It integrates statistical and data-based methods for performance evaluation of nature-inspired, environmentally friendly carbon capture and air cleaning technologies. The research is promising to develop scalable solutions towards climate change mitigation and the enhancement of cleaner cities.

1 Introduction

The escalating energy crisis is primarily driven by substantial industrial development and the exponential growth of the global population. The current rate of fossil fuel consumption, estimated at 136 762 TWh per annum, substantially exceeds natural replenishment rates, highlighting a looming energy crisis.[1]

Biofuels are considered superior to fossil fuels due to their lower environmental impact and potential to significantly reduce greenhouse gas (GHG) emissions. Unlike fossil fuels, biofuels originate from biomass, which recycles atmospheric CO_2 through photosynthesis, helping to maintain a balanced carbon cycle. Combustion of pure biofuels typically results in lower emissions of particulates, SOx and hazardous air pollutants compared to traditional fossil fuels. Blends of biofuels with petroleum-based fuels lead to reduced emissions relative to conventional fuels.[2]

Liquid fuels contribute significantly to the global CO_2 footprint, accounting for 36% of the total emissions. Projections indicate that overall CO_2 emissions could potentially double by 2035, reaching up to 45 000 Mt by 2040.[3] The United States, China, India, and the European Union have committed to achieving net-zero emissions, collectively addressing approximately 88% of global emissions. Over 9000 corporations, more than 1000 cities, over 1000 academic institutions, and upwards

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of 600 financial institutions have joined the Race to Zero initiative, aiming to reduce global emissions by 50% by 2030.[4]

Energy consumption in the United States is projected to increase by 50% by 2030. Biofuels must play a crucial role in diversifying the nation's energy sources to meet rising energy requirements.[5] The Intergovernmental Panel on Climate Change (IPCC) warned in October 2018 that CO_2 emissions must be reduced by 45% from 2010 levels by 2030 and achieve net-zero by 2050 to limit global temperature rise to 1.5 °C.[6]

The biofuel market is projected to reach USD 284.95 billion by 2030, with an anticipated compound annual growth rate (CAGR) of 7% from 2024 to 2030.

Biofuels are categorized into three generations based on the type of feedstock utilized: first-generation biofuels from food sources, second-generation biofuels from lignocellulosic biomass and agricultural wastes, and third-generation biofuels from algae.

Microalgae have gained significant interest as a promising source of biochemicals, including lipids, carbohydrates, proteins, biofuels, and various bioactive compounds. This surge in attention is attributed to their higher production rates and relatively simple cultivation processes when compared to terrestrial plants.[7] Algae-based biofuels are a viable alternative to traditional biofuel sources derived from corn and sugarcane. Algae exhibit higher photosynthetic efficiency, can be cultivated on non-arable land, and yield significantly higher biomass per unit area, making them a sustainable solution for renewable energy production.[8]

Commercial algal biofuel production utilizes both open pond and closed photobioreactor (PBR) cultivation systems. Open pond systems have lower costs but face contamination and environmental control challenges. Closed PBRs offer enhanced control and reduced contamination risk but are more expensive to construct and operate.[7] Both systems currently face economic challenges, with lipid production costs. Lipid production costs are estimated to range from \$9.80 to \$17.18 per gallon for open pond systems and from \$25.16 to \$43.83 per gallon for PBRs. These figures highlight the economic challenges faced by algal biofuel production using current technologies and underscore the necessity for significant advancements to improve cost-efficiency and economic viability.[9]

This article focuses on two main microalgae orders that are commonly studied: *Chlorellales* and *Sphaeropleales*, both of which represent the *Chlorophyta* division.[10] The *Chlorellales* mainly include freshwater and terrestrial coccoid forms, along with a few marine members, and their diversity and phylogenetic relationships within the Chlorellales have been well studied.[11] *Sphaeropleales* are diverse *Chlorophyceae*, including common freshwater phytoplankton, and they exist as non-motile unicells, colonies, or filaments, producing biflagellate zoospores or non-motile spores. Key genera of *Sphaeropleales* include *Scenedesmus*, *Desmodesmus*, *Pediastrum*, and *Microspora*. Numerous studies have explored their diversity and phylogenetic relationships.[11] Both of the above-mentioned orders are ecologically important and have potential biotechnological applications.

In this work, a comprehensive literature review and short-listing of potential studies regarding *Chlorellales* and *Sphaeropleales* were carried out, resulting in 24 relevant reports whose data were extracted for data-driven analysis. This data set has been subjected to a detailed statistical analysis to understand the relationships of various operating parameters on two major orders of algae and their respective species. To the best of our understanding, this is a first-of-its-kind study on developing a comprehensive understanding of optimal operating parameters of biomass yield in photobioreactor systems.

In this study, a significant knowledge gap in algal biotechnology was addressed by providing standardized, comparative evaluations of multiple microalgal species cultivated in bubble column photobioreactors (BC-PBRs). While previous research has explored the performance of individual species such as *Chlorella vulgaris* or *Scenedesmus obliquus* under varying operational conditions, few studies have undertaken a comprehensive, side-by-side analysis of multiple strains within consistent photobioreactor geometries and controlled operational parameters. This absence of uniform comparative analysis limits the ability to make informed decisions regarding species selection and reactor design for large-scale cultivation. By conducting a statistical meta-analysis of seven prominent microalgal species across two *Chlorophyta* orders, and synthesizing data from 24 carefully selected studies comprising 650 data points, a robust framework is provided for evaluating biomass productivity. Furthermore, by introducing a novel dimensionless metric (Ψ), this work enables multi-parametric performance benchmarking across species, thereby supporting more rational and scalable decision-making in photobioreactor-based algal cultivation.

2 Background: design of a photobioreactor

A PBR is characterized as a predominantly enclosed system designed for phototrophic cultivation, wherein the required energy is provided through artificial illumination.[12] A standard photobioreactor operates as a three-phase system, comprising a liquid phase that serves as the growth medium, a solid phase represented by the cells, and a gas phase. Closed PBRs are the preferred systems as they provide optimal conditions for growth, including light, temperature, and nutrients, which enhance biomass production. Additionally, closed PBRs substantially reduce the risk of contamination by bacteria, protozoa, and unwanted algal species, as well as minimize competition that is common in open pond systems. The PBR system offers several advantages over traditional pond systems. These include precise control over internal environmental conditions, enhanced productivity due to higher cell densities, improved light absorption efficiency, and more effective land utilization.[13]

Bubble column reactors are widely employed in commercial applications for microalgae cultivation and wastewater treatment. Their design is simple, characterized by a height that exceeds twice the diameter. Apart from the sparger, these reactors lack any internal structures.[12] A bubble column photobioreactor should exhibit a high surface area-to-volume ratio compared to other photobioreactor types, thereby enhancing efficiency in achieving greater volumetric and areal productivity alongside improved photosynthetic efficiency of microalgae. The aspect ratio, or H/D ratio, is a crucial design parameter influencing the performance of photobioreactors and the growth of cultivated microalgae. This ratio affects the mixing of the culture media and the mass transfer characteristics of the system. For industrial bubble column reactors, the aspect ratio should generally be at least 5.[8]

3 Materials and methods

3.1 Data mining

To conduct a comprehensive review of literature related to bubble column photobioreactors for microalgal cultivation, a systematic search was performed using relevant keywords across scientific databases. The initial search yielded 102 research papers. A preliminary screening was conducted through data mining techniques to assess the completeness and relevance of the information presented in each study. During this process, several papers were excluded due to missing critical parameters necessary for comparative evaluation. After applying inclusion and exclusion criteria, only those studies containing complete and relevant data specific to bubble column photobioreactor design and performance for microalgal cultivation were considered. This rigorous selection process ultimately resulted in the identification of 24 papers that provided all necessary technical and operational details required for further analysis: diameter (cm), volume (L), height (cm), CO_2 concentration (%), aeration rate (L m^{-1}), number of runs, microalgae species, cultivation time (days) and maximum biomass (g L^{-1}) were the input parameters. This yielded a total of 650 data points for analysis.[14–34]

To ensure reproducibility and transparency, this study employed a structured and comprehensive literature search strategy aimed at filling a critical gap in the comparative evaluation of microalgal species in BC-PBRs. The gap addressed lies in the absence of standardized, cross-species analyses under consistent geometric and operational conditions—an issue that limits rational reactor design and species selection. The search was executed using a full syntax that combined key terms such as (“bubble column photobioreactor” or “BC-PBR”) and (“microalgal cultivation in bubble column photobioreactor” or “microalgal biomass”). Searches were conducted across titles, abstracts, author keywords, and journal keywords using three major databases: Scopus, Web of Science, and Google Scholar. The scope was restricted to peer-reviewed articles published in English between January 2005 and March 2025. Studies were included only if they reported experimental data for at least one of the seven target microalgal species and used a BC-PBR or structurally equivalent system. Additionally, papers had to report biomass yield (g L^{-1}) and at least three of the following parameters: reactor height, diameter, volume, aeration rate, CO_2 concentration, and cultivation time. Only full-text, English-language articles with sufficient experimental or quantitative data were retained, resulting in a final set of 24 papers comprising 650 data points. This rigorous and transparent methodology ensures that the analysis is both statistically sound and reproducible by other researchers in the field.

3.2 Combination parameter (psi)

To analyze the combined effect of all parameters and capture their influence in a collective manner, the authors define a dimensionless parameter, psi (ψ), which takes into consideration the aeration rate, CO_2 concentration, cultivation time and volume, as follows:

$$\Psi = \frac{\text{aeration rate}\left(\text{L min}^{-1}\right) \times \text{CO}_2(\%) \times \text{cultivation time(days)}}{\text{volume(L)}} \tag{1}$$

3.3 Statistical analysis

To analyze the association between biomass maximum yield and the other input parameters, several statistical tests were conducted. Due to the non-normal distribution of both the biomass maximum yield and the input parameters, nonparametric statistical tests were employed to analyze the data. A statistical significance threshold of 0.05 was established to determine the significance of our findings.

Spearman correlations were used to assess the associations between maximum biomass yield and the input parameters.

Next, the characteristics of the different algae species were compared. Due to the low representation of several species, the analysis was focused on those with at least 15 data points (instances): *Chlorella sorokiniana* (34 instances); *Scenedesmus almeriensis* (85 instances); *Chlorella vulgaris* (223 instances); *Chlorella spinulatus* (19 instances); *Scenedesmus obliquus* (95 instances); *Scenedesmus obtusus* (28 instances); *Chlorella pyrenoidosa* (83 instances). For the following parameters – maximum biomass yield, cultivation time, total volume, working volume, CO_2 concentration, and aerial rate – a Kruskal–Wallis nonparametric test was conducted, followed by pairwise Wilcoxon non-paired tests.

4 Results and discussion

4.1 Results

This work focuses on understanding the impact of various operating and design parameters of bubble column photobioreactors on algal growth. In this regard, the parameters considered are: column height (cm, Fig. 1), column diameter (cm), total volume (L), working volume (L), CO_2 concentration (%), aeration rate (L min^{-1}), algal species, and cultivation time (days), and the target parameter was maximum biomass yield (g L^{-1}). Hence, the effect of each of the parameters was tested on the biomass yield (hereby referred to as BY).

Microalgal BY is known to be influenced by several factors: CO_2 concentration affects carbon fixation rates, while pH levels directly impact nutrient uptake and cellular functions.[35] Aeration rate is important for CO_2 and nutrient distribution in the media, as well as for cell suspension. Contamination by competing microorganisms can reduce biomass yield.

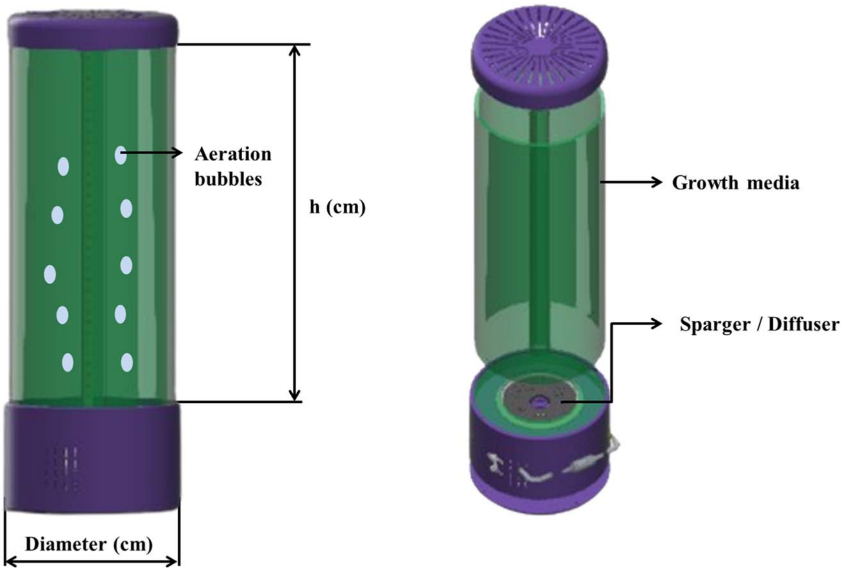

Fig. 1 Design of a photobioreactor.

4.1.1 pH. Microalgal metabolism is closely linked to pH levels, as pH controls multiple critical processes including ion uptake, enzyme function, phosphorus bioavailability, inorganic carbon accessibility, and ammonia toxicity.[35]

Psi does not currently include pH, but temperature could be treated as a normalization factor or control variable in future psi-like indices for better scalability across climate zones.

4.1.2 Temperature. Temperature serves as a principal environmental determinant influencing enzymatic activity, carbon fixation efficiency, and biomass productivity in both indoor and outdoor microalgal cultures. Most freshwater microalgae thrive within an optimal temperature range of 25–35 °C, while strain-specific tolerance varies considerably. Non-optimal temperatures can, for example, impair enzyme-mediated dark reactions and exacerbate oxidative stress.[36] Thermal management in closed photobioreactors is particularly critical due to rapid temperature rises, often requiring active cooling to maintain optimal physiological conditions.

Psi does not currently include temperature, but temperature could be treated as a normalization factor or control variable in future psi-like indices for better scalability across climate zones.

4.1.3 Light intensity and duration. Light intensity regulates photosynthetic activity and biomass accumulation in both indoor and outdoor microalgal cultures. Species-dependent optimal growth is generally achieved at irradiance levels between 200 and 400 μmol photons per m^2 per s, beyond which excess light can lead to photoinhibition due to the over-excitation of photosystem II and impaired photochemical efficiency.[35] In indoor systems, artificial lighting (*e.g.*, LEDs) allows precise control of spectral quality and intensity,[37,38] whereas outdoor systems require careful design to modulate natural sunlight exposure. Efficient utilization of high irradiance requires short light paths, adequate cell density, and high turbulence to promote rapid light–dark cycling of cells.[35]

In BC-PBRs, light attenuation with depth and biomass density must be accounted for. Internal or external LED panels can be used for uniform illumination. Artificial light increases operational cost (OPEX) and should be optimized based on Ψ.

4.1.4 Incorporating physical parameters into Ψ optimization. To integrate physical parameters:

(1) Extended psi (Ψ') could include pH deviation penalty, temperature deviation multiplier, or light efficiency factor:

$$\Psi' = \Psi \times f(\mathrm{pH}, T, I)$$

where $f(\mathrm{pH}, T, I)$ is a dimensionless correction factor (*e.g.*, a score from 0 to 1 based on closeness to optimal range).

(2) Example of f:

$$f = \min\left(1, \frac{\text{measured intensity}}{\text{optimal intensity}}\right)$$

- Or a product of Gaussian-shaped tolerance curves around optimal values for pH, T, and I.

This approach allows Ψ' to become a universal optimization index, adaptable across photobioreactor types and environmental conditions, supporting scale-up decisions.

Other factors are outside this review data and include biotic and abiotic contaminations, light regimes and temperatures. Understanding and optimizing these parameters is essential for maximizing biomass production in microalgae cultivation systems.

Spearman correlations between BY and the operating parameters were carried out, and the results are reported in Table 1. A look at Table 1 reveals that BY is positively correlated with height, total volume ($R = 0.36$ for both) and cultivation rate ($R = 0.6$), whereas % CO_2 has low correlation ($R = 0.05$), and diameter is negatively correlated with BY ($R = -0.14$). All

Table 1 Spearman correlation between biomass (g L^{-1}) and various operating parameters

Variables	Correlation coefficient (R)	P value
% CO_2	0.05	0.21
Aeration rate (L min^{-1})	−0.1	0.02
Diameter (cm)	−0.14	0.002
Height (cm)	0.4	<0.0001
Total volume (L)	0.36	<0.0001
Working volume (L)	0.18	<0.0001
Cultivation time (days)	0.6	<0.0001

correlations, except aeration rate and working volume, were statistically significant (P value < 0.05), except that of % CO_2.

4.1.5 Comparison with empirical and numerical studies. The results of the present study align with several empirical and numerical investigations on microalgal cultivation in BC-PBRs. For instance, the observed optimal biomass productivity trends under varying superficial gas velocities and light intensities are consistent with empirical findings by Dasan *et al.*, 2020,[17] who reported that moderate gas velocities improve mixing without imposing excessive shear stress on delicate microalgal cells. Numerical simulations by Pruvost *et al.*, 2011 (ref. 39) and Pottier *et al.*, 2005 (ref. 40) also showed that light attenuation and hydrodynamics significantly influence cell growth kinetics, which our findings corroborate. Moreover, our observation that dense biomass leads to suboptimal light penetration aligns with the simulation-based light distribution patterns highlighted by Cornet and Dussap *et al.*, 2009.[41] These comparative insights validate the robustness of our numerical framework and highlight its applicability across multiple microalgal species cultivated in BC-PBRs.

Fig. 2a illustrates a holistic perspective of two orders (*Chlorellales* and *Sphaeropleales*) considered in this study. It can be seen that the *Chlorellales* order has a statistically significantly higher BY in comparison to *Sphaeropleales* (*p < 0.01*). Fig. 2b illustrates the differences in BY at a species resolution and illustrates that *C. spinulatus* has the highest BY (mean of 3.03 ± 1.12 g L^{-1}) whereas *S. obtusus* has the lowest BY (mean of 0.33 ± 0.14 g L^{-1}). The Kruskal–Wallis (KW) test shows a significant statistical difference of BY between the different species (P value < 0.001). Of note, *C. vulgaris* has the highest BY range while *S. obtusus* has the lowest range of BY. Pairwise comparisons (Table 2) reveal that while some of the species (*C. sorkiniana* and *S. obliquus*) are similar in terms of BY, most of the rest show statistically significant differences in BY.

Fig. 3a depicts the comparative analysis of the two orders, and Fig. 3b presents the comparison between the species. Although the aeration rate for *Chlorellales* is higher than *Sphaeropleales*, there is no statistically significant difference between the two orders (Fig. 3a). Therefore, aeration rate data do not play a statistically significant role between the orders. However, at the species resolution, there are statistically significant differences between some of the species (Table 3). This result is of paramount importance, because one may choose any of the two orders, but having chosen one, it is important to operate with a specific species.

CO_2 intake concentrations is known to significantly affect algal growth, physiology, and metabolism. Different algal species exhibit varying responses to elevated CO_2 levels; the effect can be positive or negative depending on the strain.[42] When high CO_2 levels are applied it can alter cellular pH, affecting enzymatic activities and nutrient uptake, thereby impacting the biomass yield as lipid and carbohydrate compositions change. The CO_2 effects are also dependent on other factors such as PBR dimensions, aeration rate, number of algal cells and cultivation time (Table 4).

The length of cultivation affects the growth of certain microalgae strains. Fast-growing species are usually favored by shorter times, while slower-growing species might establish themselves over longer times. Longer times can cause

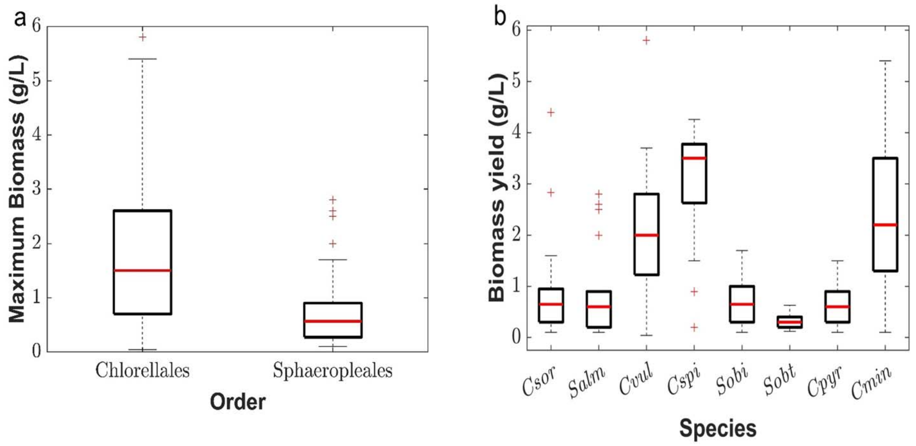

Fig. 2 (a) Biomass yield comparison of two orders; (b) biomass yield comparison of the species. Csor: *Chlorella sorokiniana*; Salm: *Scenedesmus almeriensis*; Cvul: *Chlorella vulgaris*; Cspi: *Chlorella spinulatus*; Sobl: *Scenedesmus obliquus*; Sobt: *Scenedesmus obtusus*; Cpyr: *Chlorella pyrenoidosa*; Cmin: *Chlorella minutissima 26a*.

Table 2 Pairwise comparison (unpaired Wilcoxon test p-value) of biomass of different species[a]

Species	*Csor*	*Salm*	*Cvul*	*Cspi*	*Sobl*	*Sobt*	*Cpyr*	*Cmin*
Csor		0.33	<0.0001	<0.0001	0.89	<0.0001	0.52	<0.0001
Salm			<0.0001	<0.0001	0.34	0.002	0.74	<0.0001
Cvul				<0.0001	<0.0001	<0.0001	<0.0001	0.15
Cspi					<0.0001	<0.0001	<0.0001	0.05
Sobl						<0.0001	0.44	<0.0001
Sobt							0.0002	<0.0001
Cpyr								<0.0001
Cmin								

[a] Csor: *Chlorella sorokiniana*; Salm: *Scenedesmus almeriensis*; Cvul: *Chlorella vulgaris*; Cspi: *Chlorella spinulatus*; Sobl: *Scenedesmus obliquus*; Sobt: *Scenedesmus obtusus*; Cpyr: *Chlorella pyrenoidosa*; Cmin: *Chlorella minutissima 26a*.

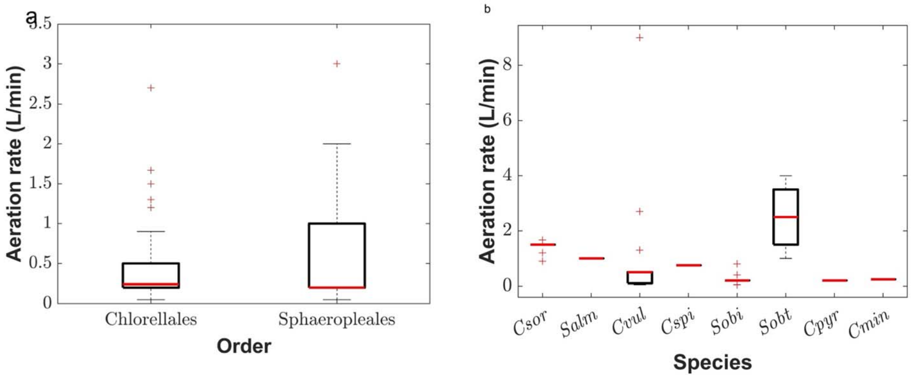

Fig. 3 Aeration rate comparison of (a) the two orders and (b) the various algal species. Csor: *Chlorella sorokiniana*; Salm: *Scenedesmus almeriensis*; Cvul: *Chlorella vulgaris*; Cspi: *Chlorella spinulatus*; Sobl: *Scenedesmus obliquus*; Sobt: *Scenedesmus obtusus*; Cpyr: *Chlorella pyrenoidosa*; Cmin: *Chlorella minutissima 26a*.

Table 3 Pairwise comparison (unpaired Wilcoxon test p-value) of aeration rate of different species[a]

Species	Csor	Salm	Cvul	Cspi	Sobl	Sobt	Cpyr	Cmin
Csor		0.006	<0.0001	<0.0001	<0.0001	0.006	<0.0001	<0.0001
Salm			<0.0001	<0.0001	<0.0001	0.001	<0.0001	<0.0001
Cvul				<0.0001	0.0001	<0.0001	0.0001	0.003
Cspi					<0.0001	<0.0001	<0.0001	<0.0001
Sobl						<0.0001	0.061	<0.0001
Sobt							<0.0001	<0.0001
Cpyr								<0.0001
Cmin								

[a] Csor: *Chlorella sorokiniana*; Salm: *Scenedesmus almeriensis*; Cvul: *Chlorella vulgaris*; Cspi: *Chlorella spinulatus*; Sobl: *Scenedesmus obliquus*; Sobt: *Scenedesmus obtusus*; Cpyr: *Chlorella pyrenoidosa*; Cmin: *Chlorella minutissima 26a*.

population crashes due to nutritional and light limitations, but they can also increase biomass.[43] The ideal duration for cultivation differs depending on the species and intended results, aiming to balance target compound accumulation, culture stability, and productivity.

Fig. 5 depicts the differences in cultivation time (CT) of various algal species. It illustrates that *S. almeriensis* (mean 10.5 ± 5.7) and *C. spinulatus* (mean 10.0 ± 5.5) have the highest CT, whereas *C. sorokiniana* (mean 4.5 ± 3.0) and *S. obtusus* (mean 4.0 ± 2.0) have the least CT. The Kruskal–Wallis (KW) test shows a significant statistical difference in CT between the different species (P value < 0.001). Pairwise comparisons (Table 5) reveal that some of the species (*C. sorokiniana* and *S. almeriensis*) are similar, whereas others are different.

Fig. 6 depicts the combined effect of the dimensionless parameters lumped into one parameter (psi), which captures the operating variables' effect on biomass yield. It is observed that the *Chlorella* species have higher Ψ in comparison with *Scenedesmus.* A lower value of psi would indicate the opposite. In this work, it is apparent from Fig. 6 that the order *Sphaeropleales* can yield marginally higher biomass (as per previous sections) in lower volumes while handling higher aeration rates

Table 4 Pairwise (unpaired Wilcoxon test p-value) comparison of intake CO_2 (%) of different species[a]

Species	Csor	Salm	Cvul	Cspi	Sobl	Sobt	Cpyr	Cmin
Csor		0.03	<0.0001	0.22	0.0002	<0.0001	<0.0001	<0.0001
Salm			<0.0001	0.013	<0.0001	<0.0001	<0.0001	<0.0001
Cvul				<0.0001	0.08	<0.0001	0.0001	<0.0001
Cspi					<0.0001	<0.0001	<0.0001	<0.0001
Sobl						<0.0001	0.25	<0.0001
Sobt							<0.0001	1
Cpyr								<0.0001
Cmin								

[a] Csor: *Chlorella sorokiniana*; Salm: *Scenedesmus almeriensis*; Cvul: *Chlorella vulgaris*; Cspi: *Chlorella spinulatus*; Sobl: *Scenedesmus obliquus*; Sobt: *Scenedesmus obtusus*; Cpyr: *Chlorella pyrenoidosa*; Cmin: *Chlorella minutissima 26a*.

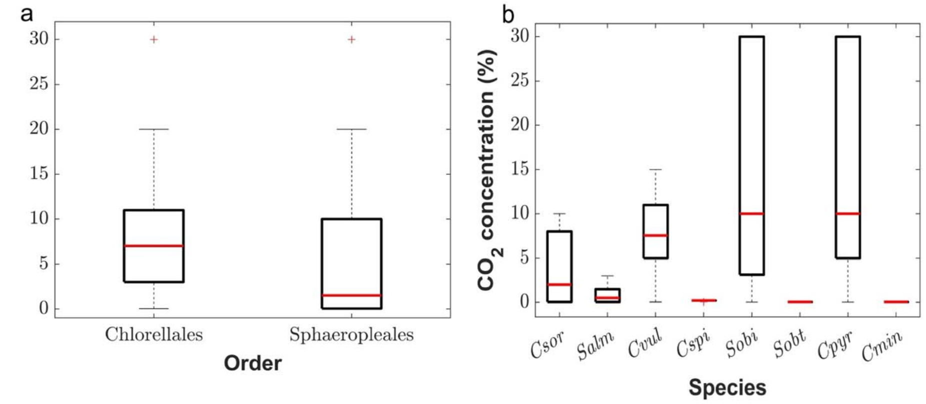

Fig. 4 Comparison of CO_2 intake concentration of (a) the two orders and (b) the various algal species. Csor: *Chlorella sorokiniana*; Salm: *Scenedesmus almeriensis*; Cvul: *Chlorella vulgaris*: Cspi: *Chlorella spinulatus*; Sobl: *Scenedesmus obliquus*; Sobt: *Scenedesmus obtusus*; Cpyr: *Chlorella pyrenoidosa*; Cmin: *Chlorella minutissima 26a*.

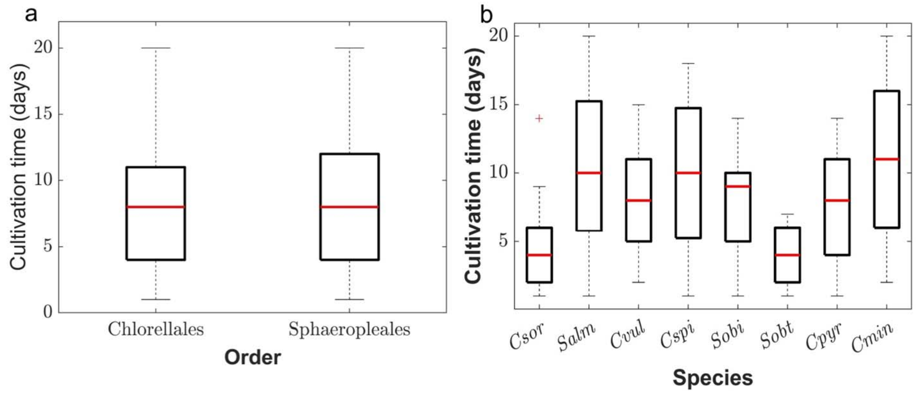

Fig. 5 Comparison of cultivation time of (a) the two orders and (b) the various algal species Csor: *Chlorella sorokiniana*; Salm: *Scenedesmus almeriensis*; Cvul: *Chlorella vulgaris*; Cspi: *Chlorella spinulatus*; Sobl: *Scenedesmus obliquus*; Sobt: *Scenedesmus obtusus*; Cpyr: *Chlorella pyrenoidosa*; Cmin: *Chlorella minutissima 26a*.

and CO_2 concentrations. Both orders have almost identical mean Ψ.

4.2 Discussion

The design and operation of BC-PBRs play a pivotal role in determining the efficiency of microalgal biomass production. While BC-PBRs are lauded for their simplicity and efficient mass transfer due to bubble-induced mixing, their overall performance is shaped by a complex interplay of operational and structural parameters. This study analyzes key design variables—height, diameter, volume, CO_2 concentration, and aeration rate—which were statistically evaluated using 650 literature data points.

Table 5 Pairwise comparison (unpaired Wilcoxon test p-value) of cultivation time of different species[a]

Species	Csor	Salm	Cvul	Cspi	Sobl	Sobt	Cpyr	Cmin
Csor		<0.0001	<0.0001	0.0005	<0.0001	0.825	0.0002	<0.0001
Salm			0.001	0.717	0.002	<0.0001	0.001	0.65
Cvul				0.138	0.547	<0.0001	0.383	<0.0001
Cspi					0.098	0.003	0.084	0.52
Sobl						<0.0001	0.821	0.003
Sobt							<0.0001	<0.0001
Cpyr								0.002
Cmin								

[a] Csor: *Chlorella sorokiniana*; Salm: *Scenedesmus almeriensis*; Cvul: *Chlorella vulgaris*; Cspi: *Chlorella spinulatus*; Sobl: *Scenedesmus obliquus*; Sobt: *Scenedesmus obtusus*; Cpyr: *Chlorella pyrenoidosa*; Cmin: *Chlorella minutissima 26a*.

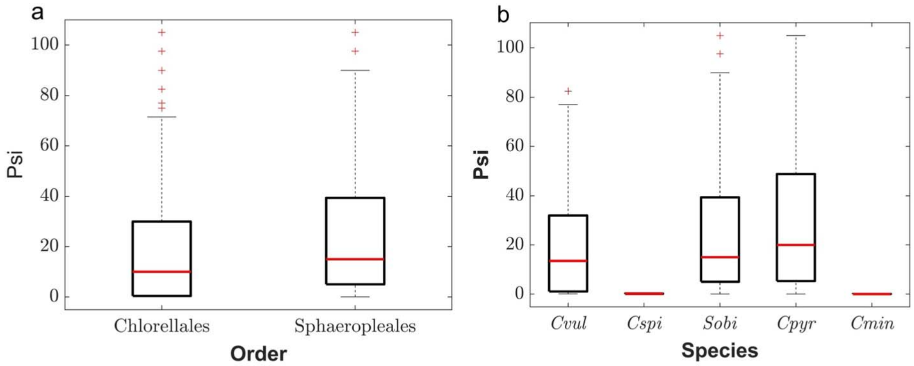

Fig. 6 Comparison of psi of (a) the orders, (b) the various algal species. Cvul: *Chlorella vulgaris*; Cspi: *Chlorella spinulatus*; Sobl: *Scenedesmus obliquus*; Cpyr: *Chlorella pyrenoidosa*; Cmin: *Chlorella minutissima 26a*.

4.2.1 Reactor height. Reactor height exhibited the strongest positive correlation with biomass yield ($R = 0.48$). Taller columns enhance CO_2 dissolution due to increased bubble residence time and improve hydrodynamic circulation, leading to better light exposure and mixing. However, these advantages are coupled with engineering constraints such as increased pressure drop, structural load, and energy consumption for gas sparging. Importantly, as height increases, bubble sizes may initially decrease due to shear but later coalesce, affecting gas transfer dynamics. Optimizing height must therefore balance biological benefit with mechanical feasibility and energy demand.[14]

4.2.2 Total volume. Total reactor volume also demonstrated a positive correlation ($R = 0.48$) with biomass yield. Larger volumes reduce the impact of transient fluctuations in CO_2 levels, temperature, and light, enabling more stable cultivation conditions. However, they also introduce challenges in ensuring uniform nutrient and light distribution. Inadequate mixing in larger systems may create gradients, which limit productivity. Thus, scale-up must be complemented with effective aeration and light delivery mechanisms to maintain internal homogeneity.[14]

4.2.3 Diameter and aspect ratio. Diameter showed a statistically significant negative correlation ($R = -0.21$) with biomass productivity. A wider diameter reduces the surface-area-to-volume ratio and can hinder vertical mixing, promoting sedimentation and uneven CO_2/nutrient availability. High aspect ratio designs (height-to-diameter, $H/D > 5$) are thus favored, as they promote better mixing and gas–liquid mass transfer while enhancing light exposure throughout the column. The relationship between diameter and productivity must also consider internal hydrodynamics, as wider systems may suffer from stagnant zones.[44]

4.2.4 Aeration rate. Aeration rate had a marginal, statistically non-significant negative correlation ($R = -0.06$, $p = 0.18$), suggesting a nuanced role in algal cultivation. While aeration facilitates CO_2 supply, cell suspension, and pH control, excessive rates may cause mechanical stress, shear-induced cell lysis, or oversaturation of gases. Moreover, the formation of large bubbles under high aeration reduces the gas–liquid interfacial area and limits mass transfer efficiency. Notably, species-level analysis revealed significant variations in tolerance, emphasizing the importance of species-specific aeration strategies. Microbubbles and nanobubbles, though energy-intensive to generate, have shown 100-fold improvements in mass transfer due to higher surface-area-to-volume ratios and slower rise velocities.[45]

4.2.5 CO_2 concentration. CO_2 concentration exhibited a weak but statistically significant negative correlation ($R = -0.12$, $p = 0.004$). While CO_2 is the primary carbon source, excess levels can lead to acidification of the culture medium, inhibiting enzymatic activity and nutrient uptake. The optimal

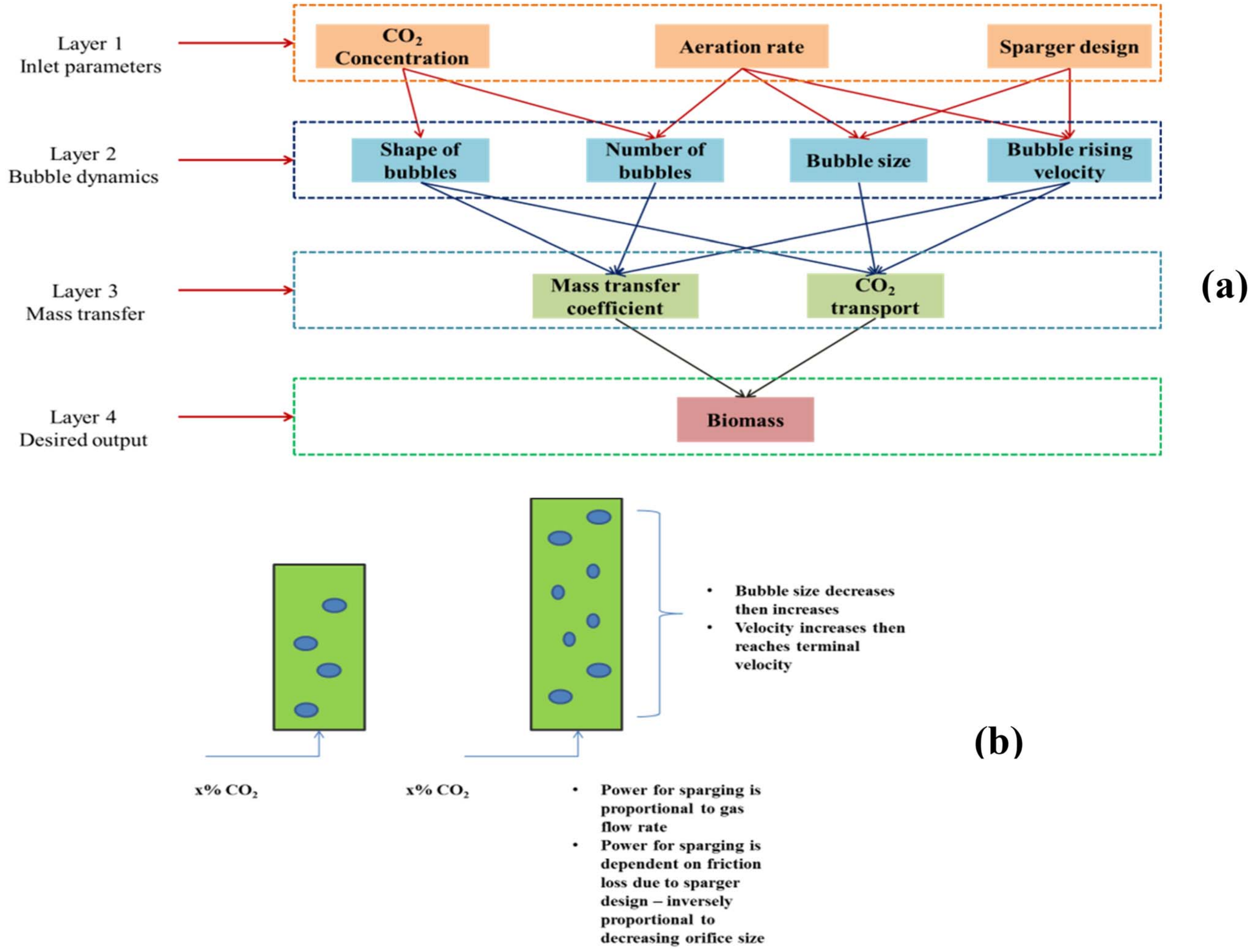

Fig. 7 (a) Photobioreactor design layer by layer approach; (b) size comparison of bubbles according to PBR height.

Table 6 Pairwise comparison (unpaired Wilcoxon test *p*-value) of psi of different species[a]

Species	Cvul	Cspi	Sobl	Cpyr	Cmin
Cvul		<0.001	0.25	0.04	<0.001
Cspi			<0.001	<0.001	<0.001
Sobl				0.46	<0.001
Cpyr					<0.001
Cmin					

[a] Cvul: *Chlorella vulgaris*; Cspi: *Chlorella spinulatus*; Sobl: *Scenedesmus obliquus*; Cpyr: *Chlorella pyrenoidosa*; Cmin: *Chlorella minutissima 26a*.

concentration varies across species, typically ranging between 2 and 5%. Beyond this threshold, CO_2 toxicity or rapid pH drops can suppress biomass accumulation. The interaction of CO_2 with sparger design, bubble dynamics, and algal physiology necessitates careful tuning.[46]

4.2.6 Layered understanding of BC-PBR performance. The mechanistic understanding of PBR performance can be stratified into four interlinked layers:

(1) Inlet parameters – CO_2 concentration, aeration rate, and sparger design govern bubble formation.

(2) Bubble characteristics – bubble size, rise velocity, and number affect gas–liquid mass transfer rates.

(3) Mass transfer & mixing – efficient mixing enhances CO_2 delivery and light exposure while controlling pH and temperature.

(4) Biomass growth – the ultimate result of all upstream parameters, modulated by species-specific responses and reactor geometry.

Each layer must be optimized to achieve maximal biomass productivity, as illustrated in the schematic framework (Fig. 7a and b). Importantly, overdesign at any level—be it excess CO_2, high aeration, or extreme geometry—can lead to diminished returns or increased operational costs.

4.2.7 Psi (Ψ): a dimensionless optimization metric. To synthesize these diverse variables, a dimensionless parameter, psi (Ψ), was introduced. It encapsulates aeration rate, CO_2 concentration, cultivation time, and reactor volume into a single, scalable metric. High Ψ values correspond to energy-intensive operations (high aeration or CO_2 inputs in small volumes), while low Ψ values imply capital-intensive systems (large volumes, longer durations). For *Chlorellales*, Ψ ranged from 0.8 to 2.4, while Sphaeropleales exhibited a narrower operational window—indicating stricter tolerance limits.

This metric not only facilitates cross-study comparison and scale-up analysis but also reflects the balance between operational cost (OPEX) and capital cost (CAPEX).

4.2.8 Comparative analysis of psi (Ψ) for *Chlorella* spp. *vs.* *Scenedesmus* spp. This parameter is used to evaluate how well a given algal species tolerates and utilizes CO_2 under different aeration and volumetric loading conditions. The comparative analysis of *Chlorella* species (under Chlorellales) and *Scenedesmus* species (under Sphaeropleales) based on the data (Fig. 6 and Table 6 in the manuscript) is summarized below:

Chlorella species, classified under Chlorellales, exhibit a broader Ψ range of 0.8 to 2.4. The species included in this group are *C. vulgaris*, *C. sorokiniana*, *C. spinulatus*, and *C. pyrenoidosa*. These higher Ψ values reflect greater operational tolerance, enabling *Chlorella* to perform well under elevated CO_2 concentrations, extended cultivation durations, and increased aeration rates, even when cultivated in smaller reactor volumes. This indicates a high degree of flexibility in both design and operational aspects, allowing these species to adapt to diverse photobioreactor configurations and withstand fluctuations in process parameters. As a result, *Chlorella* species are considered more scalable and robust, making them particularly suitable for deployment in BC-PBRs.

In contrast, *Scenedesmus* species, which belong to the order Sphaeropleales, display a narrower and generally lower Ψ range compared to *Chlorella*. This group includes species such as *S. obliquus*, *S. almeriensis*, and *S. obtusus*. The lower Ψ range suggests that these species require stricter control of operating conditions. They show limited tolerance to variations in CO_2 concentration, aeration intensity, and prolonged cultivation periods. *Scenedesmus* species tend to perform better in smaller volumes and often benefit from moderate to low gas input. However, their sensitivity to operational changes presents a challenge for scale-up, necessitating highly optimized and stable process conditions for effective performance in larger systems.

The design and operation of BC-PBRs significantly influence the efficiency of microalgal biomass production. This study statistically analyzes the impact of key operational and structural parameters—such as reactor height, diameter, volume, CO_2 concentration, aeration rate, and species characteristics—on biomass yield (BY), using a robust dataset compiled from 24 studies.

4.2.9 Reactor height. Our analysis found a moderate positive correlation between height and BY ($R = 0.48$), which aligns well with findings by Banerjee *et al.*, 2020 (ref. 14) and Seo *et al.*, 2012,[13] who reported that increased column height improves gas–liquid mass transfer by increasing bubble residence time and vertical mixing. However, our work uniquely highlights how this benefit is species-dependent; Chlorellales showed more biomass enhancement with increased height than Sphaeropleales, which has not been extensively delineated in earlier studies.

4.2.10 Total volume. Similarly, a positive correlation with total volume ($R = 0.48$) supports earlier findings by Pottier *et al.*, 2005,[40] which demonstrated volume buffering effects on environmental fluctuations. Our results extend these observations by quantitatively correlating total volume to biomass across species and by integrating it into a dimensionless metric (Ψ), enabling comparative scalability analysis—something previously unreported.

4.2.11 Diameter and aspect ratio. A negative correlation ($R = -0.21$) between diameter and BY in our study complements prior hydrodynamic modeling results,[44] which suggest that wider diameters promote sedimentation and reduce vertical circulation. Our findings confirm the superiority of higher aspect ratios ($H/D > 5$), echoing recommendations by Mubarak *et al.*, 2023,[8] but go further by quantifying their statistical impact across 650 data points—making it one of the most comprehensive validations.

4.2.12 Aeration rate. While our result shows a marginal, non-significant negative correlation ($R = -0.06$), the nuanced impact of aeration aligns with Fu *et al.*, 2024,[18] who demonstrated that high aeration improves CO_2 transfer but also introduces shear stress. Unlike previous studies focused on single strains, our species-wise analysis reveals significant differences—e.g., *Chlorella* spp. tolerating higher aeration better than *Scenedesmus* spp.—a novel contribution to the literature.

4.2.13 CO_2 concentration. A weak yet significant negative correlation was found ($R = -0.12$), confirming the inhibitory effects of CO_2 oversaturation reported by Gonçalves *et al.*, 2016 (ref. 42) and Yan *et al.*, 2024.[46] However, previous studies often evaluated CO_2 impact in isolation, whereas our Ψ-index integrates CO_2 concentration with volume and time, allowing a holistic performance assessment.

4.2.14 Species-specific insights. Our comparative analysis between Chlorellales and Sphaeropleales echoes earlier taxonomic insights[10] but introduces for the first time a species-level statistical comparison of multiple operating parameters (cultivation time, aeration rate, and CO_2 concentration). This adds a layer of specificity absent in prior generalized conclusions. In particular, the superior yield of *Chlorella* sp. (3.03 ± 1.12 g L^{-1}) reinforces the findings of Sarat Chandra *et al.*, 2017 (ref. 7) on strain-level performance variations, yet our work further quantifies its performance using Ψ as an integrative index.

Previous studies have independently examined the performance of various microalgal species in BC-PBRs, often focusing on individual strains such as *Chlorella vulgaris* or *Scenedesmus obliquus*. However, comparative insights across multiple species under standardized PBR design and operational conditions remain limited. In previous studies, Banerjee *et al.*, 2020,[14] Dasan *et al.*, 2020,[17] and Kumar & Das *et al.*, 2012 (ref. 21) investigated individual strains under varied aeration or CO_2 conditions, yet few have attempted side-by-side comparisons of multiple species within consistent geometric and operational constraints.

4.2.15 Psi (Ψ) parameter innovation. The introduction of the Ψ index marks a novel approach not found in prior empirical or modeling studies. While Pruvost *et al.*, 2011 (ref. 39) emphasized the importance of multidimensional optimization, our Ψ provides a dimensionless framework that allows cross-system comparability and scale-up guidance—a major methodological advancement.

4.2.16 Layered performance understanding. A four-layer mechanistic framework is proposed—from inlet parameters to biomass growth—which builds upon and synthesizes fragmented understandings from prior studies such as Posten *et al.*, 2009.[47] This framework contextualizes Ψ within physical and biological realities, offering a systemic roadmap for reactor design and optimization.

The design of any algal PBR is complex. Although seemingly simple (as discussed in Fig. 1), there are a multitude of factors that affect the algal growth in photobioreactors. The interplay of various operating and hardware-related parameters is depicted in Fig. 7a. Biomass growth in a PBR is affected at 4 layers, which are represented in Fig. 7a.[48] The inlet parameters, such as CO_2 concentration, aeration rate and sparger design, form the first layer. In the current work, except for sparger design, the CO_2 concentration and aeration rates have been considered. Of course, sparger design is difficult to capture, as the dimensions of openings and the number of openings are difficult to determine for authors and are not reported. The effect of an increase in CO_2 concentration is already discussed in the previous section, considering Fig. 4.

At layers 2 & 3 lie the shape of bubbles, number of bubbles, bubble size and bubble rise velocity (amongst other bubble characteristics) affecting the mass transfer coefficients. Larger bubbles help with mixing, whereas smaller bubbles help with improved gas transfer. Smaller bubbles offer a better surface area to volume ratio and a slower rise velocity as compared to larger bubbles. This improves the overall mass transfer coefficient and allows higher CO_2 delivery from within the bubble to the bulk. It has been reported that microbubbles improve mass transfer by 100-fold,[49] whereas nanobubbles almost experience no buoyancy and hence do not rise at all. However, generating smaller bubbles increases energy penalties.

At layer 4 lies the ultimate output of the interplay of all layers, which is biomass growth. It is evident that at each layer, there is an optimum condition required for maximizing algal growth. Too much CO_2 or too high aeration rates are detrimental; similarly too large bubbles or too small bubbles are also not desirable. There is another important relation between these parameters and operational costs and capital costs.

This can be explained in a simple manner. A taller PBR (Fig. 7b) has been reported to have decreasing bubble size and then a subsequent increase as bubbles rise through the columns (against a shorter one with the same CO_2 inlet concentration).[48] This also comes at an energy penalty, as pressure generation for smaller orifice sizes (hence smaller bubbles) increases proportionally. Hence, it can be summarized that taller PBRs have the potential to exchange CO_2 more effectively, however, at a higher energy penalty. Similarly, shorter PBRs can have relatively bigger bubble sizes, which can, of course, aid in mixing, thereby controlling pH and temperature more effectively. It is quite evident that designing an optimum energy-efficient PBR includes interplay for a variety of operating parameters. However, the sizing of a PBR directly impacts the capital costs, and operating the same involves operating costs.[48]

The current study is a unique effort in this regard, where the literature data have been utilized to arrive at important observations, but to bring the entirety of the literature on a common platform, a simple unit-less parameter (Ψ) has been proposed. It can be easily inferred that the parameter, being dimensionless, can also be used for simple scaling up projections. Importantly, this parameter indirectly captures the effect of OPEX and CAPEX. Higher values of Ψ would indicate higher aeration rates (higher OPEX), lower values of Ψ can indicate higher CAPEX (larger volumes, hence larger diameters and/or taller PBRs). It is important to understand the parameter at this juncture. Lower psi may arise from a lower numerator (aeration rate or inlet CO_2 concentration or cultivation time), a higher denominator (volume), or a combination of the two. This would indicate that a higher value of psi would mean the algae culture's ability to handle higher inlet CO_2 concentrations, higher aeration rates and longer cultivation times in lower volumes.

For a given algal species, Ψ has a minimum and a maximum value. In fact, in the studied literature, this parameter lies between 0.8 and 2.4 for *Chlorellales* but has a very narrow range for *Sphaeropleales*. This indicates that *Sphaeropleales* biomass growth has to be maintained under a set of stricter conditions.

5 Conclusion

The present study has explored the underlying patterns, challenges, and opportunities surrounding microalgal growth understanding in photobioreactors through statistical analysis using a combination of different analytical methods. The research methodology provided insights into overcoming potential barriers towards scaling up of algal systems for carbon capture and mitigation, demonstrating the potential of different classes of microalgae.

However, several methodological issues and limitations must be acknowledged. Firstly, the study's findings are based on a limited sample size, which may not be representative of the broader population or varying operational conditions across different geographies or systems. Secondly, the research methods employed, while robust for exploratory purposes, may not capture long-term dynamic responses or systemic feedback loops inherent in complex bioengineering systems for sustainable carbon management. Thirdly, certain assumptions made during data collection or analysis may have influenced the interpretation of the results.

Despite these limitations, the study offers a foundational framework that can inform future empirical work, particularly in refining the models, improving the sampling strategy, and incorporating real-time monitoring and feedback systems. Future research should focus on expanding the sample across diverse operational settings, integrating AI-driven decision-making tools, and conducting longitudinal studies to assess system performance over time. Moreover, interdisciplinary collaboration is essential to bridge technological, environmental, and socioeconomic dimensions in the context of intelligent resource management.

In conclusion, this study not only advances our understanding of microalgal growth in photobioreactors but also lays the groundwork for a more integrated, scalable, and adaptive approach to addressing the challenges in microalgal cultivation at a larger scale.

The current work establishes a rational approach towards understanding the effect of various operating parameters on biomass growth of various algal species in bubble column photobioreactors. The work is based on literature data to establish an in-depth understanding of such systems with the focus on overcoming potential barriers towards scaling up of algal systems for carbon capture and mitigation. It was revealed that microalgal strains belonging to the order *Chlorellales* exhibit significantly higher biomass yields compared to those from the order *Sphaeropleales*. Consistent with this, it was found that operating parameters such as a wide range of aeration rates and CO_2 concentrations have a lesser impact on the growth of *Chlorellales* species, whereas these species exhibit higher sensitivity to cultivation time. These findings suggest that *Chlorellales* may be well-suited for cultivation under variable operating conditions, although precise monitoring of cultivation duration is essential to ensure optimal biomass productivity. Furthermore, a novel dimensionless term, "psi", is introduced, which captures the combined effect of all operating parameters and presents a single metric to evaluate algal growth in PBR systems. This work is believed to consolidate the literature data into a single report, thereby contributing to the development of a framework that can support further advancements in this field.

Abbreviations

PBRs	Photobioreactors
BC-PBRs	Bubble column photobioreactors
TWh	Terawatt hour
GHG	Greenhouse gas
CO_2	Carbon dioxide
SO_x	Sulfur oxides
IPCC	Intergovernmental Panel on Climate Change
CAGR	Compound annual growth rate
BY	Biomass yield
OPEX	Operational cost
Csor	*Chlorella sorokiniana*
Salm	*Scenedesmus almeriensis*
Cvul	*Chlorella vulgaris*
Cspi	*Chlorella spinulatus*
Sobl	*Scenedesmus obliquus*
Sobt	*Scenedesmus obtusus*
Cpyr	*Chlorella pyrenoidosa*
Cmin	*Chlorella minutissima 26a*
CT	Cultivation time
CAPEX	Capital cost

Author contributions

Rupesh Kumar – data collection, manuscript preparation. Zohar Barnett-Itzhaki – data analysis, manuscript preparation. Asher Wishkerman – data analysis, editing and preparation of the manuscript. Snehanshu Saha – reviewing manuscript, manuscript preparation. Santonu Sarkar – reviewing manuscript, manuscript preparation. Anirban Roy – ideation, conceptualization, reviewing manuscript, manuscript preparation.

Conflicts of interest

There are no conflicts to declare.

Data availability

This study was carried out using publicly available data from different publicly available research papers, and the Excel sheet containing the data has been made available as SI.

Detailed data table is included in SI. See DOI: **https://doi.org/10.1039/d5va00083a**.

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