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Posted Date: 5 July 2024

doi: 10.20944/preprints2024070475.v1

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Article

Comparison of Light Intensity Effect on Microalgal Growth in Cactus-like and Cylindrical Photo Bioreactors

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Abstract: Improving photobioreactor performance for microalgae cultivation has attracted many researchers over the past years. One of the primary challenges associated with existing photobioreactors is the light penetration. An effective photobioreactor design should maximize light penetration, ensuring uniform illumination throughout the reactor. This study aims to assess the impact of light intensity on microalgal growth from the perspective of energy efficiency and productivity in two photobioreactors. A novel cactus-like and a cylindrical photobioreactor were designed and fabricated using 3D printing technology. These two photobioreactors were used to cultivate two strains of microalgae. The novel photobioreactor achieved a maximum biomass productivity of 0.99 g/L/d and a maximum energy efficiency of 0.3139 g/d/kWh. The cylindrical photobioreactor reached a maximum biomass productivity of 0.74 g/L/d and 0.2199 g/d/kWh of energy efficiency. **The increase in biomass productivity can be linked to enhancements in the photobioreactor's surface-to-volume ratio and better light utilization.**

Keywords: cactus-like photobioreactor; microalgae growth; biomass productivity; energy efficiency; light intensity; surface-to-volume Ratio

1. Introduction

With the increase in population and economic and technological development, energy consumption has rapidly increased, resulting in high greenhouse gas emissions and global warming. Therefore, the interest in alternative renewable energy sources has received international attention. Biofuels are renewable energy sources from biomass such as animal fats and vegetable oils. Most biofuel production heavily relies on conventional feedstock like sugar cane, corn, and soybeans. However, to achieve a significant increase in biofuel production while minimising negative impacts on land use, food and feed prices, and the environment, it is essential to expand the utilization of advanced feedstocks. These advanced feedstocks consist of biofuels derived from waste materials, residues, and dedicated crops that do not compete with food crops, such as crops grown on marginal land. Microalgae have emerged as up-and-coming contenders for fuel production. The oil collected from microalgae can be converted into biodiesel, which makes the microalgae a substantial alternative energy source [1]. Microalgae biomass holds great promise, as it can produce various organic compounds such as proteins, carotenoids, vitamins, and fatty acids. Microalgae are used to create animal feed, nutraceuticals, cosmetics, and pharmaceutical end products [2]. Two primary cultivation systems are available industrially: the open pond systems and the closed Photobioreactors (PBR). The selection of the microalgae cultivation system depends on the end product, microalgae species, the total cost, and many other factors. The open pond systems are the most commonly preferred because of their ease of operation, scalability, and lower energy and production costs, however, they suffer mainly from contamination and evaporation losses [3].

PBR systems overcome these limitations, prevent contamination, minimize water loss, and enhance biomass productivity. Many PBRs are present industrially, these systems include flat-plate

PBR, Tubular PBR (TPBR), helical PBR, airlift PBR, and bubble column, the cylindrical PBRs are the most utilized [4,5]. Cylindrical PBRs are recognized for their mixing efficiency, which provides homogenous nutrient dispersion inside the reactor, homogenizing single or multi phases in terms of concentration of components, physical properties, and temperature. Cylindrical PBRs ensure good absorption of carbon dioxide (CO₂) and prevent dioxygen (O₂) accumulation. However, cylindrical PBRs present a low surface area-to-volume ratio (SVR) and, therefore, insufficient light capture capacity [6,7].

Still, the light path and flow regime should be considered for scale-up and design considerations such as baffle structure selection and height-to-diameter ratio. The effect of PBR geometry on light penetration inside the reactor has attracted researchers. Therefore, many studies and experiments designed PBR with internal illumination [8–11]. However, this technology suffers from algae adhesion and difficulty in operation and maintenance. Posten [12] pointed out that SVR was the principal trait in the design of a PBR. It determines the light intensity received by the reactor's volume, thus playing an essential function in the photosynthetic growth of microalgae. Another important factor to consider in PBR design is the choice of the fabrication material. A wide variety of materials have been used for PBRs' construction, including glass, LDPE film, clear acrylic (polymethyl methyl acrylate, PMMA, also known by the trade names Plexiglas® and Perspex®), and Polylactic acid (PLA). When it comes to microalgae cultivation, PLA offers several advantages [13–15]: Firstly, its non-toxic and biocompatible nature ensures safety in cultivation environments, aligning with environmentally friendly practices owing to its biodegradability. PLA's transparency optimizes light utilization, enhancing the cultivation process, while its commendable thermal stability enables it to withstand moderate temperatures without deformation. Additionally, PLA offers cost-effectiveness, making it a favorable choice for PBR construction.

This study analyses the light irradiance corresponding to the surface-to-volume ratio in affecting the biomass growth productivities and energy efficiencies between the novel cactus-like PBR versus conventional cylindrical PBR. For the comparison study, the reactors were fabricated by 3D printing technology using PLA as the source material.

2. Materials and Methods

2.1. PBR Geometry Description

A unique PBR, resembling a cactus in shape, was created to optimize light utilization and improve the SVR compared to traditional cylindrical PBRs. Taking inspiration from the conical shape of a cactus plant and featuring a cross-section in the form of a wavy circle (see Figure 1), the dimensions of this reactor were thoughtfully selected. The column's diameter was restricted to 0.2m to ensure sufficient light penetration [16–18], and the height-to-diameter ratio was set at a minimum of two [16–18].

Consequently, the cactus PBR has a bottom inner diameter of 0.1 m and an outer diameter of 0.2 m. In contrast, the top inner diameter is 0.08 m, with an outer diameter of 0.14 m and a height of 0.3 m, as illustrated in Figure 1.

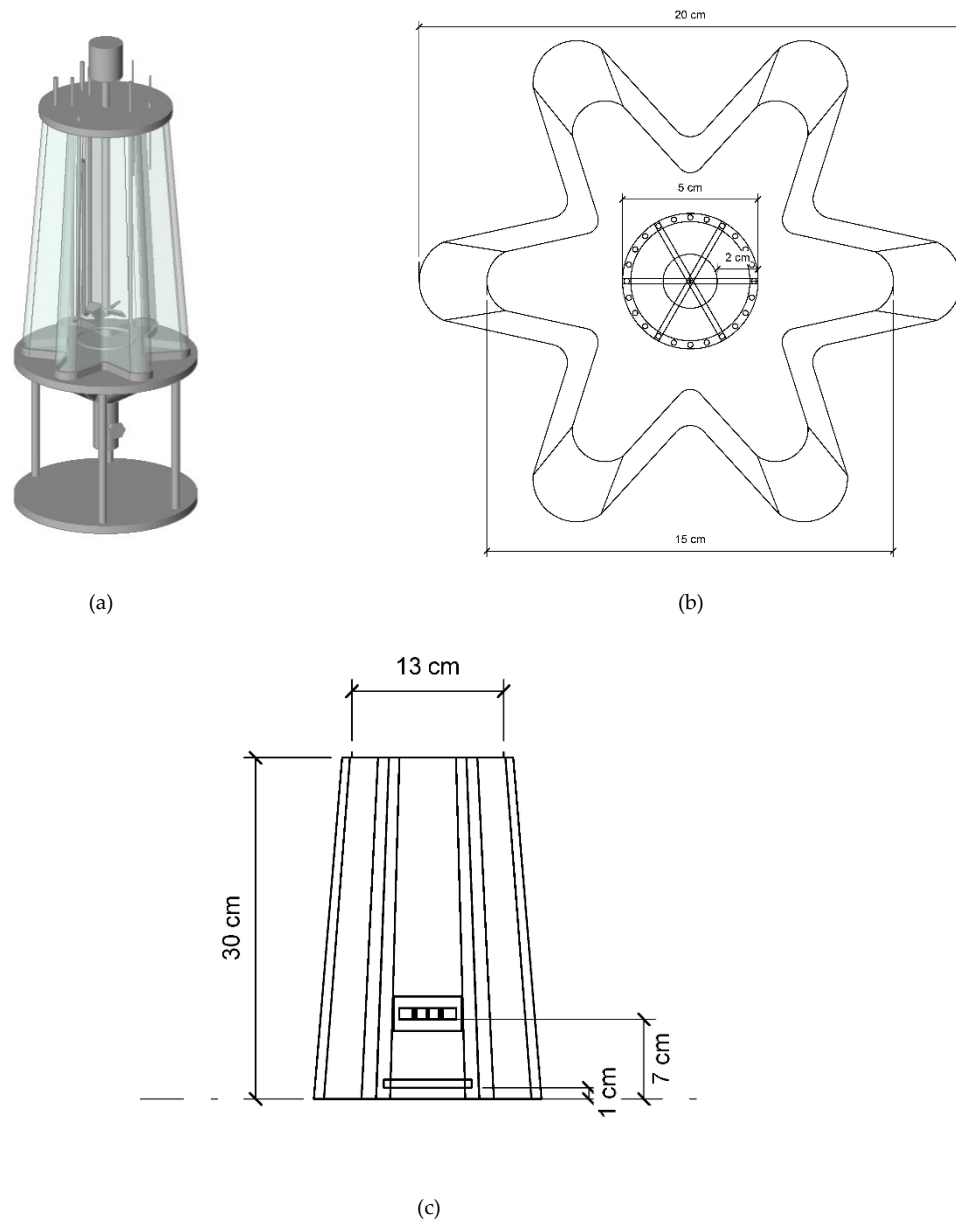


Figure 1. (a) Cactus-like PBR, (b) Schematic of the circular sparger, (c) Elevation view of the cactus-like PBR.

The novel PBR's design was executed using Autodesk Revit 2020, a software platform well-known for its proficiency in crafting detailed three-dimensional models. A notable tool employed in this process is the Solid Blend Tool. This tool allows for the creation of intricate geometric forms by blending two distinct profiles, resulting in a continuous, solid 3D shape that smoothly transitions from the characteristics of the first profile to the second profile. Therefore, the reactor's wall was constructed by employing the blend tool to create two distinct profiles for the upper and lower sections of the structure. The detailed characteristics of these profiles, encompassing their specific dimensions, are illustrated in Figure 1. The PBR incorporates a ring sparger with 24 holes positioned 0.01 m above the bottom to minimize the formation of dead zones. For comparative analysis, a cylindrical PBR with identical height and volume to the novel PBR but with a 0.14 m diameter was also designed, as depicted in Figure 2.

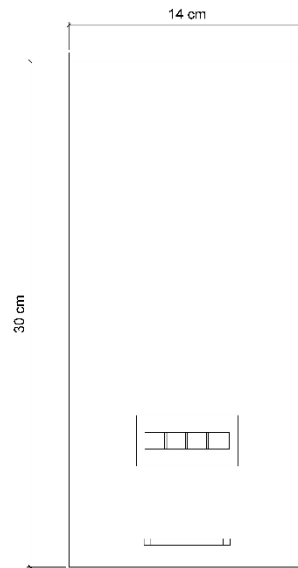


Figure 2. Elevation view of the cylindrical PBR.

The cactus PBR, measured at 4.38 L in volume and featuring an illuminated surface area of 0.2345 m², was determined using Autodesk Revit 2020. It exhibits an SVR of 53.53 m⁻¹, which is twice that of a standard column PBR of equivalent height and volume (26.6 m⁻¹).

For the comparison of algal growth inside the novel PBR and the cylindrical PBR, the reactors were fabricated by 3D printing technology using the fused deposition modelling technology (FDM) and Polylactic acid (PLA) as the source material, as shown in Figure 3.

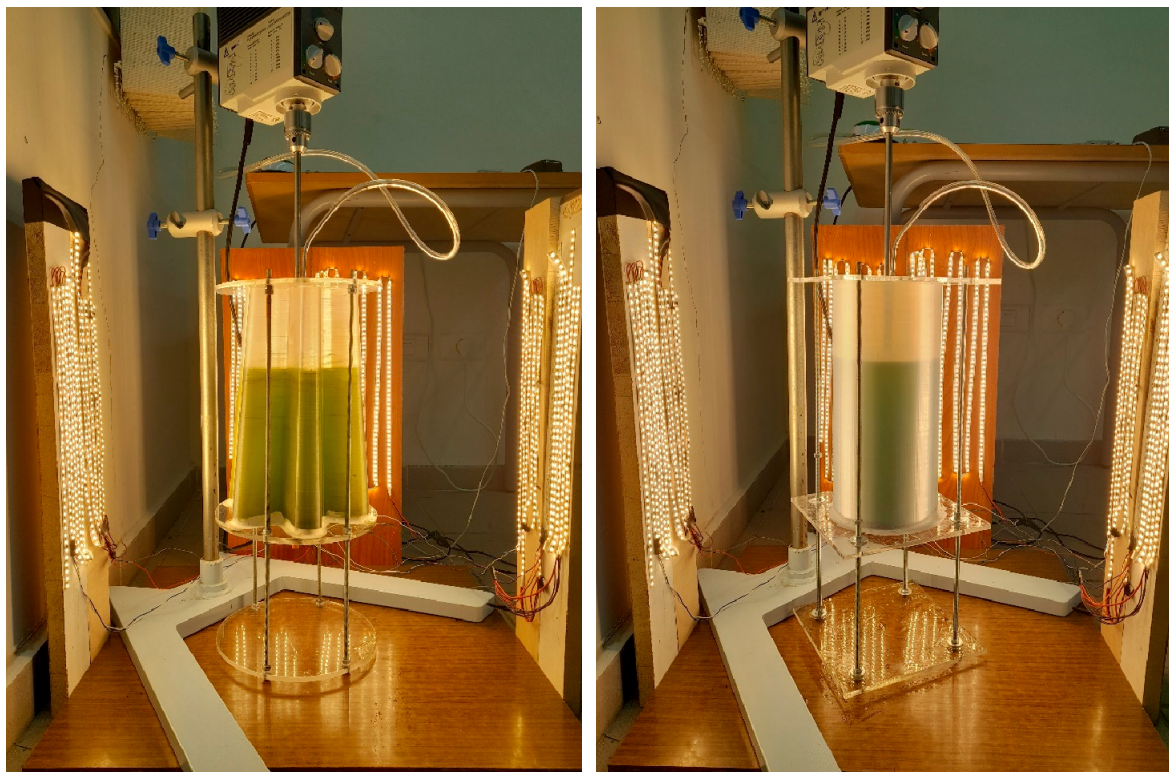


Figure 3. The Set-up of the cactus-like and the cylindrical PBRs.

2.2. Cultivation Experiment

The two algal strains identified for the present study were *Ankistrodesmum* sp. and *Chlorella* sp., provided by the Culture Collection of Microalgae at the Saint-Joseph University of Beirut, Lebanon. These two strains were selected due to their high lipid content, making them ideal for biodiesel production. Pre-cultures were prepared by inoculating microalgal colonies into 1000 mL Erlenmeyer flasks containing 300 mL of a modified synthetic BG11 medium [19]. The BG11 medium has the following composition: Na₂CO₃ 20 mg, NaNO₃ 1500 mg, K₂HPO₄ 40 mg, KH₂PO₄ 200 mg, Fe citrate 1mg, Citric acid 6 mg, EDTA 1mg per liter of solution, and an aliquot of 1 mL obtained from 1 liter of solution of a metallic stock solution containing 80 mg of CuSO₄, 20 mg of ZnSO₄, 80 mg of CO(NO₃)₂ and 1800 mg of MnSO₄, H₂O. After seven days of growth, the cultures were used as inoculum for the PBRs. Experiments in the two PBRs were performed under the following conditions. The microalgae strains were cultivated in a 2.7 L BG11 medium. 0.3 L of pre-culture was inoculated into the PBR [20]. The room temperature where the microalgae were grown was kept at 25 °C. Air was fed into the PBR at a flow rate of 2 L/min using an aquarium air pump (HAILEA, ACO-5501). The culture was agitated at 100 rpm with an anchor stirrer. The cultures were carried out for 14 days under five different light conditions, Condition 1: light intensity at 43 $\mu\text{mol photons/m}^2/\text{s}$, condition 2: light intensity at 57 $\mu\text{mol photons/m}^2/\text{s}$, condition 3: light intensity at 70 $\mu\text{mol photons/m}^2/\text{s}$, condition 4: light intensity at 100 $\mu\text{mol photons/m}^2/\text{s}$, condition 5: light intensity at 115 $\mu\text{mol photons/m}^2/\text{s}$, using SMD Led Flexible Strips of power: 9 W/m, color: GWW. In all five conditions, the photoperiod was established as 8 hours of light followed by 16 hours of darkness, indicated as an 8:16 (h:h) light-to-dark cycle.

2.3. Light Intensity Measurement

A digital lux meter (lx-1010B) was employed to measure light intensity at four different angles within the PBRs, and subsequently, an average value was calculated. The conversion from lux units to PPFD was carried out using an online converter considering a spectrum of high CRI LED 3000K [21].

$$PPFD(\mu\text{mol photons/m}^2/\text{s}) = 0.019 * Lux \quad (1)$$

2.4. Biomass Measurement

The progression of microalgae growth was systematically observed weekly. To quantify the biomass, the dry weight of the microalgae was determined through a meticulous process. Three 20 mL samples of the biomass were taken, and these samples underwent a drying procedure in an oven set at a constant temperature of 80 degrees Celsius. This drying process continued until a stable and consistent weight of the biomass was achieved, providing a reliable measure of its dry weight.

2.4.1. Specific Growth Rate

The specific growth rate (μ, d^{-1}) was calculated using Equation 2, [22,23] where DW_1 (g/L) and DW_2 (g/L) are dry biomass weights at t_1 and t_2 , respectively. The duration between t_1 and t_2 , which spans 14 days, represents the cultivation period.

$$\mu = \ln(DW_2/DW_1)/(t_2 - t_1) \quad (2)$$

2.4.2. Productivity

The productivity ($P, g.L^{-1}.d^{-1}$) was calculated using Equation 3, where DW_1 (g/L) and DW_2 (g/L) are dry biomass weights at t_2 and t_1 , respectively. The duration between t_1 and t_2 , which spans 14 days, represents the cultivation period.

$$P = (DW_2 - DW_1)/(t_2 - t_1) \quad (3)$$

2.4.3. Energy Efficiency

The energy efficiency ($\eta, g. d^{-1}. kWh^{-1}$) of electrical energy to biomass production was calculated using Equation 4, where DW_1 (g/L) and DW_2 (g/L) are dry biomass weight on the initial and the last

day of cultivation, respectively, V (L) is the volume of culture and E_e (kWh) is electrical energy consumed by LEDs during cultivation time t (days).

$$\eta = (DW_2 - DW_1) \cdot V / t \cdot E_e \quad (4)$$

2.5. Statistical Analysis

The experiments were conducted in triplicate, and the results are presented as mean values with standard deviations (mean $\pm$ standard deviation). Statistical analysis of the specific growth rates (μ , d⁻¹) was performed using Student's t-test, calculated using Microsoft Excel 2016, to ascertain the level of significance ($P \leq 0.05$).

3. Results and Discussion

3.1. Irradiance

The design of a PBR must allow the maximum possible light penetration with little unilluminated areas and uniform illumination over the reactor. The wavy shape of the new PBR's wall increased the SVR by two times compared with the cylindrical PBR as discussed earlier [24]. The light intensity inside the two PBRs was measured for each experimental condition using a lux meter. The lux level and the ratio between the values found inside the cactus-like PBR and the cylindrical PBR are shown in Figure 4. The cactus-like PBR exhibited an average of 29% higher light intensity inside its walls. The higher light intensity in the middle of the reactor could be linked to the shape of the reactor, which enhanced light penetration due to the reduction of the light path compared to the cylindrical (with an inner diameter of 8 and 11 cm versus 14 cm for the cylindrical PBR).

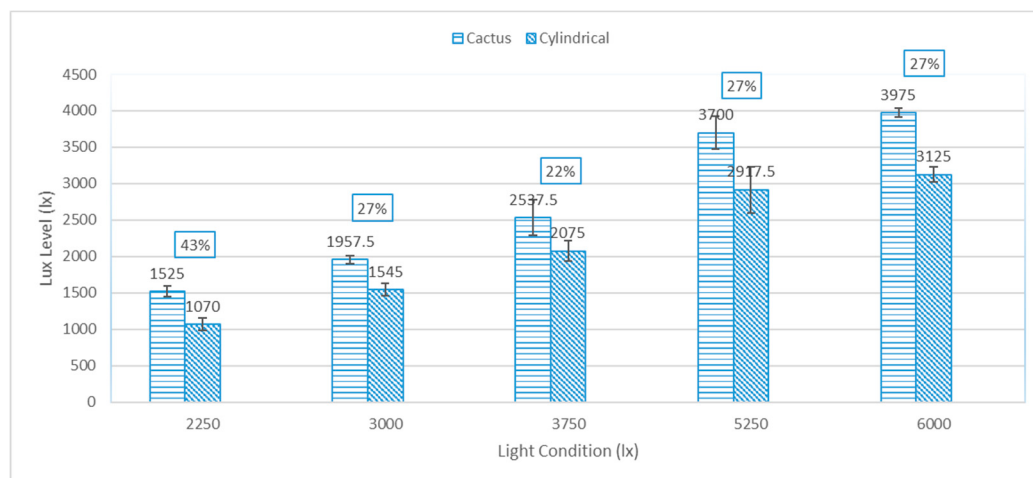


Figure 4. Lux level inside the two PBRs in Five Light Conditions.

3.2. Biomass Production

3.2.1. Specific Growth Rate

Light serves as the primary energy source and plays a crucial role in the process of photosynthesis, which in turn facilitates the multiplication of microalgae cells. The study calculated specific growth rates, productivity, and energy efficiency for two microalgae strains, *Ankistrodesmum sp.*, and *Chlorella sp.*, in a novel cactus-shaped PBR and a conventional cylindrical PBR under varying light intensities.

Figure 5 illustrates the specific growth rates of these two algal strains under five different light intensities. The lowest specific growth rate was observed under condition 1 (light intensity of 43 $\mu\text{mol photons/m}^2/\text{s}$) and condition 5 (light intensity of 115 $\mu\text{mol photons/m}^2/\text{s}$) for *Ankistrodesmum sp.* and *Chlorella sp.* respectively in both PBRs. Conversely, the highest specific growth rates were attained

under conditions 3 and 4 for *Ankistrodesmum sp.* and *Chlorella sp.*, respectively (light intensities of 70 and 100 $\mu\text{mol photons/m}^2/\text{s}$).

Insufficient irradiance can retard photosynthesis and diminish biomass yield, a condition known as light limitation [25]. Observations from Figure 5 reveal a significant surge in the specific growth rate when transitioning from a light intensity of 43 to 57 $\mu\text{moles/m}^2/\text{s}$. This increase amounts to approximately 2.5 for the Cactus-like PBR and 3.7 for the cylindrical PBR, for a 30% rise in light intensity. Thus, it can be inferred that a light intensity of 43 $\mu\text{moles/m}^2/\text{s}$ falls below the lower threshold to sustain a high growth rate of *Ankistrodesmum sp.* while 57 $\mu\text{moles/m}^2/\text{s}$ falls in the optimal threshold for this microalgae growth. This differentiation elucidates the notable surge in the specific growth rate observed between light intensities of 43 and 57 $\mu\text{moles/m}^2/\text{s}$.

For the *Chlorella sp.*, the evolution of the specific growth rate differs from that of *Ankistrodesmum sp.* This could be explained by the fact that microalgae species exhibit varying light requirements, with optimal light intensity varying from one strain to another [26]. Consequently, the optimal light conditions and light saturation point depend on the specific algal strain utilized.

It is important to note that higher light intensities (conditions 4 and 5 for *Ankistrodesmum sp.* and *Chlorella sp.*, respectively) resulted in light-induced photoinhibition. This aligns with many studies [27–34], indicating that the specific growth rate of microalgae correlates positively with light intensity, up to a saturation point.

Another notable observation is the significant decline in the specific growth rate observed in the cylindrical PBR when subjected to light intensities of 100 and 115 $\mu\text{moles/m}^2/\text{s}$ for both strains. Photoinhibition can be reduced by enhancing light/dark frequency [35]. As for microalgae cultivation, it is recognized that swirling conditions foster microalgae growth by enhancing light/dark frequency, prolonging air bubble residence time, facilitating mass transfer between phases, and mitigating thermal stratification. [36–38]. Therefore, the notable decline observed in the cylindrical PBR may be attributed to the superior mixing efficiency demonstrated by the cactus PBR, as evidenced by simulations anticipated to be detailed in a forthcoming publication.

Additionally, in all light conditions, the cactus PBR exhibited a higher specific growth rate than the cylindrical PBR. However, the increase in specific growth rate was particularly pronounced under condition 1 (light intensity of 43 $\mu\text{moles/m}^2/\text{s}$), representing low irradiance, and conditions 4 and 5 (light intensity of 100 and 115 $\mu\text{moles/m}^2/\text{s}$) for *Ankistrodesmum sp.* and *Chlorella sp.* respectively, corresponding to photoinhibition. These findings validate the superior light distribution and improved frequency of light/dark cycles in the cactus PBR, attributed to its enhanced mixing efficiency.

The highest values of specific growth rate attained are 0.1684 d^{-1} in the cactus PBR compared to 0.1446 d^{-1} in the cylindrical PBR for *Ankistrodesmum sp.* and 0.2300 d^{-1} in the cactus PBR compared to 0.2068 d^{-1} in the cylindrical PBR for *Chlorella sp.*, these values are comparable to those reported in the literature. Mohammed et al. [39,40] obtained a specific growth rate of 0.109 d^{-1} of a mixed microalgae culture grown in a pilot-scale red LED-illuminated stirred PBR. Also, Cerón-García et al. [41] produced oil-rich biomass from *Chlorella protothecoides* in a conventional 2-L stirred-tank bioreactor, and reported a specific growth rate of 0.15 d^{-1} .

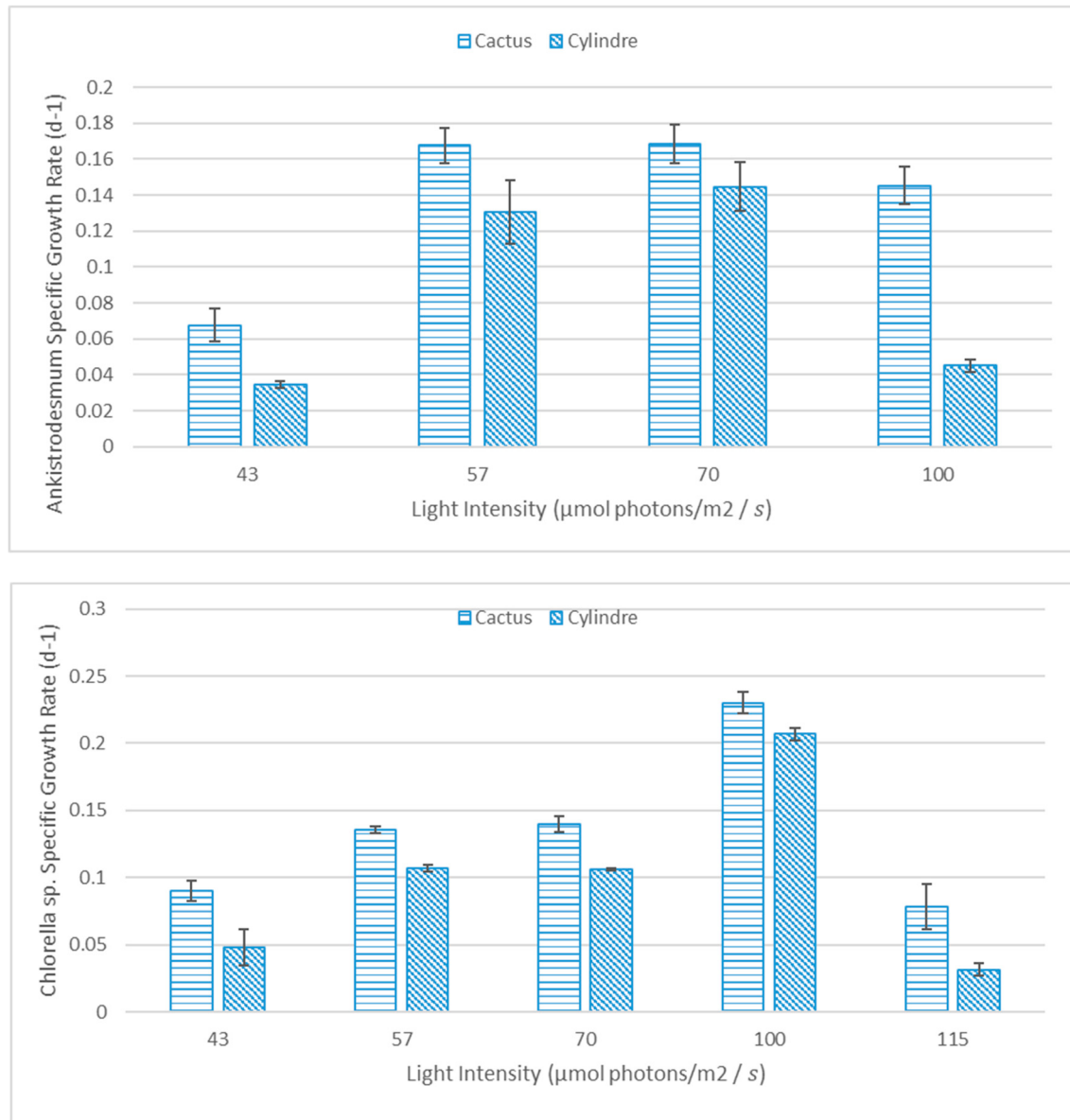


Figure 5. Specific growth rate of two microalgae strains inside the two PBRs in different light conditions.

3.2.2. Microalgae Productivity

The results in Table 1 demonstrate that varying light intensity from 43 $\mu\text{mol photons/m}^2/\text{s}$ to 100 $\mu\text{mol photons/m}^2/\text{s}$ resulted in an increase of 2.3-fold in the *Chlorella* sp. productivity, rising from 0.428 g/L/day to 0.999 g/L/day in the cactus-like PBR and from 0.321 g/L/day to 0.742 g/L/day in the cylindrical PBR. When exposed to 115 $\mu\text{mol photons/m}^2/\text{s}$, *Chlorella* sp. productivity decreased to 0.187 g/L/day in the cylindrical PBR and 0.239 g/L/day in the cactus PBR. While, *Ankistrodesmum* sp. productivity has shown a 1.6-fold increase, going from 0.588 g/L/day to 0.966 g/L/day in the cactus-like PBR and from 0.4122 g/L/day to 0.485 g/L/day in the cylindrical PBR when increasing light intensity from 43 $\mu\text{mol photons/m}^2/\text{s}$ to 70 $\mu\text{mol photons/m}^2/\text{s}$ and it decreased to 0.227 g/L/day in the cylindrical and 0.656 g/L/day in the cactus PBR when the light intensity was increased to 100 $\mu\text{mol photons/m}^2/\text{s}$.

These findings are in line with previous studies, such as that of Sankar et al. [29], who observed the effect of three light intensities: 2000, 6000, and 10000 lx on *C. minutissima* growth, they found that 6000 lx is optimal for microalgal growth and light intensities exceeding or falling below this value were found to be detrimental to the culture. Similarly, Khoeyi et al. [29] studied light intensity and

photoperiod’s effects on *Chlorella vulgaris* growth, finding that productivity increased with moderate light intensities from 37.5 to 62.5 $\mu\text{mol photons/m}^2/\text{s}$, but decreased at higher levels of 100 $\mu\text{mol photons/m}^2/\text{s}$. Elevated light intensity levels can lead to photobleaching of photosynthetic pigments, peroxidation of lipid membranes, and DNA damage [29]. Conversely, lower light intensities tend to increase chlorophyll and carotenoid content but reduce growth rate and cell density [30]. Lee and Pálsson [34] documented that *C. vulgaris* could be cultured under LED illumination at significantly greater light intensities (exceeding 400 W/m^2) without experiencing photoinhibition. Variations in results concerning the impact of light intensity on microalgal growth may stem from differences in light source type, PBR design and microalgal strains.

This study also found that *Chlorella sp.* could withstand higher light intensities compared to *Ankistrodesmum sp.* In conformity with several studies [42–44], *Chlorella sp.* is generally more tolerant of higher light intensities than *Ankistrodesmum sp.* *Chlorella sp.* is a versatile and adaptable microalgae species that can thrive under a wide range of light conditions, including high light levels. In contrast, *Ankistrodesmum sp.* is generally considered less light-tolerant and may be more sensitive to high light intensities [42].

Additionally, it is noteworthy that the productivity achieved in the cactus-shaped PBR consistently exceeded that of the cylindrical counterpart, showcasing a remarkable 2-fold increase for both strains. This heightened performance endured even when surpassing the photoinhibition threshold. The credit for this superiority can be ascribed to the more effective distribution and utilization of light within the cactus-shaped PBR, highlighting the robustness and efficiency inherent in its design. The results may also be associated with an enhancement in the hydrodynamic behavior of the novel PBR.

Table 1. Productivity, Specific Growth, and Energy Efficiency Rate of *Ankistrodesmum Sp.* and *Chlorella Sp.* Inside the Cactus-Like PBR and the Cylindrical PBR Under Different Light Conditions.

		Condition 1	Condition 2	Condition 3	Condition 4	Condition 5		
Ankistrodesmum	Productivity (g/L/d)	Cactus	0.5885 ± 0.0624	0.6888 ± 0.0452	0.9660 ± 0.0814	0.6566 ± 0.0630	-	
		Cylindrical	0.4122 ± 0.0192	0.4162 ± 0.0603	0.4858 ± 0.0040	0.2273 ± 0.0052	-	
	Specific growth rate (d-1)	Cactus	0.06766 ± 0.0090	0.1677 ± 0.0097	0.1684 ± 0.0106	0.1452 ± 0.0102	-	
		Cylindrical	0.0346 ± 0.0021	0.1305 ± 0.01758	0.1446 ± 0.0135	0.0450 ± 0.0037	-	
	Energy efficiency (g/d/kWh)	Cactus	0.3139 ± 0.0333	0.1837 ± 0.0120	0.1288 ± 0.0108	0.0437 ± 0.0042	-	
		Cylindrical	0.2199 ± 0.0102	0.1110 ± 0.0160	0.0649 ± 0.0035	0.0151 ± 0.0003	-	
	Chlorella	Productivity (g/L/d)	Cactus	0.4285 ± 0.0070	0.4898 ± 0.0182	0.5160 ± 0.0080	0.9994 ± 0.0322	0.2398 ± 0.0028
			Cylindrical	0.3219 ± 0.0072	0.2910 ± 0.0078	0.2777 ± 0.0031	0.7422 ± 0.0435	0.1879 ± 0.0125
Specific growth rate (d-1)		Cactus	0.0901 ± 0.0072	0.1353 ± 0.0024	0.1396 ± 0.0059	0.2300 ± 0.0082	0.0782 ± 0.0169	
		Cylindrical	0.0477 ± 0.0136	0.1069 ± 0.0025	0.1060 ± 0.0011	0.2068 ± 0.0044	0.0314 ± 0.0043	
Energy efficiency (g/d/kWh)		Cactus	0.2286 ± 0.0037	0.1306 ± 0.0048	0.0688 ± 0.0010	0.0666 ± 0.0021	0.0107 ± 0.0001	
		Cylindrical	0.1717 ± 0.0038	0.0776 ± 0.0020	0.0370 ± 0.0004	0.0494 ± 0.0029	0.0083 ± 0.0005	

3.2.3. Energy Efficiency

In the context of energy efficiency, as indicated in Table 1, the energy efficiency in the *Ankistrodesmum sp.* culture decreases with increasing light intensity. It is noteworthy that while productivity undergoes a 1.6-fold increase between Conditions 1 and 3, energy efficiency experiences a contrasting decrease by a factor of 2.4. Conversely, for *Chlorella sp.*, the energy efficiency registers a reduction by a factor of 3.4, accompanied by a 2.3-fold increase in productivity at Condition 4. The findings underscore that the optimal balance between biomass productivity and energy efficiency differs for *Ankistrodesmum sp.* and *Chlorella sp.*, being achieved under Conditions 3 and 4, respectively. Additionally, it is worth emphasizing that the energy efficiency in the cactus-shaped PBR consistently exceeds that of the traditional cylindrical PBR by a factor of two.

Finally, while productivity varies with species, light source, and PBR configuration, the productivity in the new PBR was comparable to that reported in the literature [39–48]. Nevertheless, the novel PBR, with twice the SVR of the conventional cylindrical PBR, exhibited superior performance for both microalgae strains. The productivity and energy efficiency obtained from the novel PBR were twice those of the cylindrical PBR.

4. Conclusions

This research aimed to investigate the impact of light intensity on microalgae growth, specifically focusing on productivity and energy efficiency. The study involved a comparative analysis between a newly designed PBR inspired by the cactus plant and a traditional cylindrical PBR. Both PBRs underwent meticulous design and were carefully examined using lux-metering to evaluate the extent of light penetration into their structures.

The experimental results revealed that the innovative cactus-inspired PBR surpassed the conventional cylindrical PBR in light penetration and biomass productivity. The cactus PBR demonstrated a remarkable 29% improvement in light penetration compared to the cylindrical PBR. Furthermore, it exhibited twice the productivity, highlighting its superior efficiency in cultivating microalgae.

However, it is important to note that while light penetration is a crucial factor influencing microalgae growth, other variables such as mixing and the hydrodynamic behavior of the innovative PBR may also play a role in fostering biomass productivity. These additional factors will be investigated in a future study using Computational Fluid Dynamics to provide a comprehensive understanding of the cactus-inspired PBR's performance.

Author Contributions: Conceptualization, R.H.; methodology, R.H.; writing—original draft preparation, R.H.; writing—review and editing, J.R.; supervision, J.R. and H.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Lebanese National Council for Scientific Research (CNRS-L) and the Research Council at the Saint Joseph University of Beirut.

Data availability statement: Data will be made available on request.

Acknowledgments: The authors thank the Lebanese National Council for Scientific Research (CNRS-L) and the Research Council at the Saint Joseph University of Beirut for their financial support.

Conflicts of Interest: The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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