Impact of Photosynthetically Active Radiation (PAR) on the cultivation of marine microalgae in open systems under tropical climatic conditions

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Abstract: Solar energy is the most cost-effective source for microalgae cultivation. Open-system biomass production enhances the sustainability of biofuel processes due to lower installation and operational costs. However, these systems are less efficient than closedsystems, as controlling light intensity and quality is challenging. This study evaluates the effect of photosynthetically active radiation (PAR) on marine microalgae cultivation in an open system under tropical climate conditions. The experiment was conducted in Mérida, Yucatán, using native microalgal strains to enhance adaptation. Throughout cultivation, PAR, nutrient concentrations, pH, and temperature were monitored to assess their interactions. Two trials were conducted in autumn (October–November) using three reactors exposed to different durations of solar radiation. Results indicate that the total daily PAR (30.6 mol/m²/day) exceeded the optimal growth range (20 mol/m²/day), leading to culture collapse within 14 days. Additionally, reactors exposed to longer sunlight exhibited greater temperature and pH fluctuations. No significant biomass accumulation or nutrient variation was observed. This study underscores the need for environmental monitoring in outdoor systems to optimize microalgae cultivation and better understand its applications and limitations.

Keywords: Photosynthetically active radiation, open pounds, microalgae

Introduction

Microalgae are photosynthetic autotrophs capable of utilizing solar or artificial light as an energy source to convert carbon dioxide (CO_2) and water into organic compounds, releasing oxygen (O_2) as a by-product. Their photosynthetic efficiency surpasses that of higher plants, as they can convert solar energy into biomass and other metabolites up to five times faster. This remarkable capacity for biomass production makes microalgae highly attractive for numerous biotechnological applications (Posten & Walter, 2012).

Among their most relevant applications, microalgae are widely used in bioremediation due to their ability to remove pollutants and toxic substances, often accumulating high concentrations of these compounds without impairing their physiological activity (Shao *et al*., 2022). They are also employed in the treatment of domestic, industrial, and livestock wastewater. Furthermore, microalgae represent a promising feedstock for biofuel production, offering a feasible alternative to the depletion of fossil fuel reserves (rChisti, 2016).

Microalgal biomass can be cultivated in open systems, exposed to outdoor environmental conditions, or in closed photobioreactors, where growth parameters can be tightly controlled. Although closed systems provide superior control, their large-scale implementation is limited by high operational costs, particularly those associated with artificial illumination and temperature regulation (Barceló-Villalobos *et al*., 2019). Consequently, assessing cultivation strategies that capitalize on natural solar radiation is essential, as is evaluating the influence of climatic and geographical factors on biomass productivity (González-Camejo *et al*., 2019). A key challenge in this context lies in identifying and selecting strains with high productivity under outdoor conditions. Additionally, tropical regions have been identified as optimal zones for microalgal biomass production, exhibiting the highest global productivity according to several studies (Dias *et al*., 2021).

Regardless of the cultivation system, region, or selected strain, parameters such as temperature, nutrient availability, and light intensity must be carefully managed, as they strongly influence growth kinetics and biochemical composition. Among these parameters, photosynthetically active radiation (PAR) plays a critical role, representing the fraction of the solar spectrum usable for photosynthesis. PAR spans wavelengths from 400 to 700 nm—approximately 50% of total solar radiation—with intensities typically ranging from 800 to 1000 W/m² (Dolganyuk *et al*., 2020). Although visible

light from blue to red wavelengths supports photosynthesis, radiation outside this range, such as ultraviolet or infrared, does not contribute to energy capture and may even damage photosynthetic cells.

Most microalgal species require between 5 and 20 mol/m²/day of PAR to achieve optimal growth. Lower doses restrict biomass accumulation, whereas higher doses increase the risk of photoinhibition, a light-induced reduction in photosynthetic efficiency. Therefore, quantifying PAR in outdoor cultures is essential for determining optimal solar exposure according to the physiological requirements of specific strains. This practice enhances photosynthetic efficiency, maximizes biomass productivity, and mitigates light-induced damage. Additionally, reliance on natural solar radiation significantly improves the economic and environmental sustainability of biomass production for biofuel applications. Nonetheless, open systems remain challenging due to the inherent difficulty of regulating solar radiation intensity and quality (Guedes *et al*., 2023).

In this context, the present study evaluates the influence of PAR on the cultivation of marine microalgae in an open system. The experiment was conducted under tropical climatic conditions in Mérida, Yucatán, Mexico, a region characterized by high solar irradiance, which is favorable for outdoor biomass production. Native microalgal strains from the Yucatán Peninsula were used, facilitating their adaptation to local environmental conditions. Throughout cultivation, biomass concentration, nutrient levels, pH, and temperature were monitored alongside PAR to determine its effect on these key variables.

Materials and Methods

Study Area

The study was conducted on the terrace of the Teaching Building at the National School of Higher Studies, Mérida Unit (Mexico). The region exhibits a bi-seasonal tropical climate consisting of a prolonged dry season and a summer rainy season. According to the Köppen classification modified by García *et al*. (2010), the climate is tropical with a mean annual temperature of 26 °C and maximum temperatures reaching 38 °C. Solar irradiance is consistently high; annual average radiation is 425.27 W/m², with monthly values exceeding 1000 W/m² between May and October (Morcillo Herrera, 2016).

Microalgae Cultivation

A marine microalgal consortium isolated from Sisal, Hunucmá, Yucatán, was cultivated in 4-L reactors. Each reactor included a volume indicator to detect evaporation losses. The culture medium consisted of a 50:50 mixture of seawater and distilled water supplemented with 47 ± 0.26 mg/L N-NO_3^- and 3.58 ± 0.25 mg/L P-PO_4^{3-}, with a pH of 7.32 and a salinity of 22.54 ± 0.41‰.

The experiment was performed during October and November, when the expected mean monthly solar radiation is approximately 425.27 W/m². Reactors were placed 2 meters apart near the environmental monitoring station and positioned to provide different daily sunlight exposures:

- Reactor I: sunrise–13:00 h
- Reactor II: sunrise–16:00 h
- Reactor III: sunrise–sunset (17:30–18:00 h)

Reactors were sealed with perforated lids to prevent insect intrusion while allowing adequate ventilation. Biomass concentration was determined as Total Suspended Solids (TSS) according to APHA (1992). Nutrient concentrations (P-PO_4^{3-} and N-NO_3^-) were measured using a dual-beam UV-visible spectrophotometer (Agilent Cary 60) following APHA (1992). Temperature and pH were monitored using an Extech EC500 multiparameter meter after calibration with standard solutions and homogenization of the cultures

PAR Monitoring

Photosynthetically Active Radiation (PAR) was measured using a monitoring station equipped with a pyranometer (S-LIB-M003) and a PAR sensor (S-LIA-M003), connected to a HOBO U30 datalogger. Instantaneous readings were collected every 30 seconds, and averaged values were logged every 1-minute internal. Data acquisition and retrieval were performed using HOBOware® software.

Results and Discussion

Two experimental assays were conducted. Figure 1 displays the growth curves and nutrient removal profiles obtained duringthe first assay. In all three reactors, microalgal cultures failed to survive beyond ten days. Nutrient concentrations ($P\text{-}PO_4^{3-}$ and $N\text{-}NO_3^-$) showed no significant decrease during the 14-day period, indicating minimal nutrient assimilation and absence of measurable biomass accumulation.

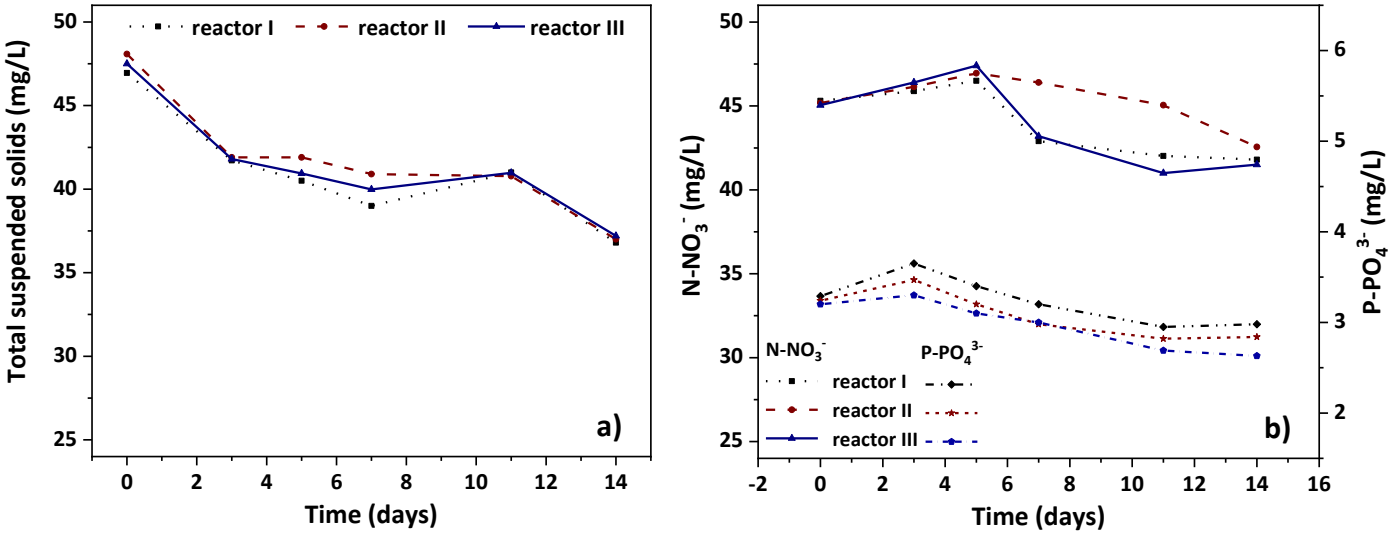

Figure 1. Growth dynamics (a) and nutrient removal profiles (b) of the marine microalgal consortium cultivated in an open system during the first experimental assay

These results suggest that the cultures experienced thermal stress caused by extended exposure to solar radiation. Reactors I, II, and III received approximately 8, 11, and 14 hours of direct sunlight per day, respectively. The presence of perforated lids and the placement of reactors on a concrete surface likely intensified heat retention, as concrete acts as a thermal mass and contributes to maintaining elevated temperatures within the reactors.

Temperature profiles shown in Figure 2a support this interpretation: reactor temperatures reached values as high as 35 °C, particularly in Reactors II and III, which were exposed to longer photoperiods. Correspondingly, Figure 2b shows notable pH fluctuations, primarily following periods of increased temperature, suggesting substantial physiological stress within the cultures.

Together, these findings indicate that excessive thermal load was the primary factor limiting culture survival, nutrient removal, and biomass production during the first experimental assay.

In the second experimental assay (Figure 3), reactor overheating was addressed by removing the plastic lids and covering the reactors with mosquito netting to maintain aeration while preventing contamination. Despite this modification, the cultures did not display measurable biomass accumulation; TSS values remained constant at approximately ~43 mg/L (Figure 3a). Consistent with the growth results, nutrient concentrations ($N\text{-}NO_3^-$ and $P\text{-}PO_4^{3-}$) showed no significant depletion over time, indicating a lack of measurable nutrient removal under these conditions.

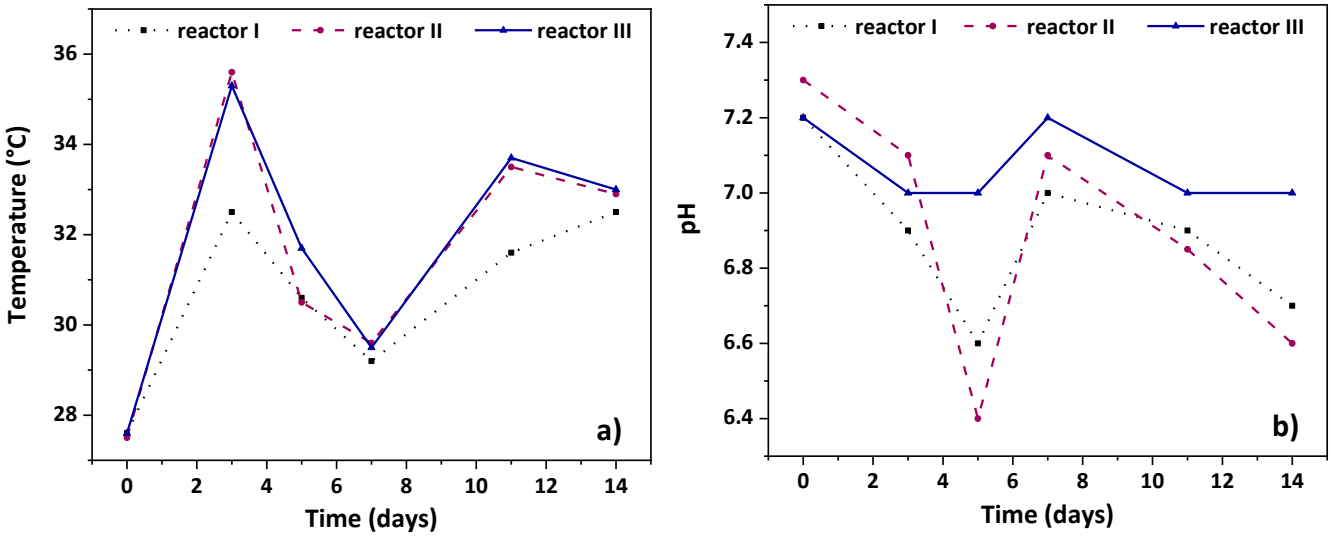

Figure 2. Solar exposure effects on (a) culture temperature and (b) pH in reactors I, II, and III during the first experimental assay

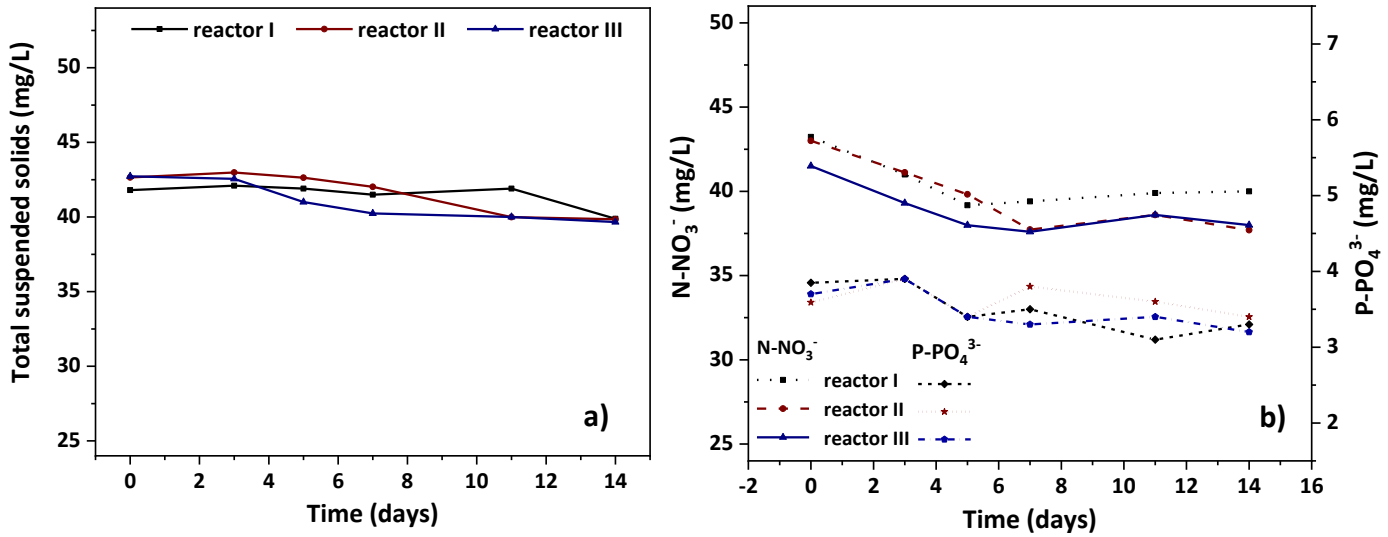

Figure 3. Growth dynamics (a) and nutrient removal profiles (b) of the microalgal consortium cultivated in an open system during the second experimental assay

Visual assessment of culture pigmentation revealed distinct responses among reactors, particularly after day 7. Reactor I, exposed to the least sunlight, displayed progressive pigment fading, suggesting insufficient irradiance to sustain optimal photosynthetic performance. Reactor II showed the most stable appearance, maintaining uniform dark green coloration throughout the first ten days, consistent with an intermediate and apparently favorable light regime. However, despite this stable pigmentation, no measurable biomass increases or exponential growth phase occurred. Following day 10, the culture in reactor II also collapsed, indicating that environmental stressors ultimately exceeded the consortium's tolerance threshold.

Reactor III exhibited marked pigment loss beginning on day 7, shifting from dark green to yellowish tones, indicative of chlorophyll degradation and photo stress. This response aligns with the extended solar exposure experienced by this reactor, the longest among the three. Despite this stress, the microalgal consortium—composed of native strains from the Yucatán Peninsula—survived more than ten days under high irradiance and elevated internal temperatures.

Routine inspection of reactor volume indicators revealed no detectable water loss, suggesting that temperatures did not reach levels sufficient to induce evaporation. Temperature dynamics (Figure 4a) showed a reduction immediately after replacing the plastic lids with mosquito netting. Temperature increases closely followed exposure duration:

reactor III reached values up to 2 °C above those in reactors I and II. pH remained comparatively stable, with smaller fluctuations than those observed in the first experimental assay.

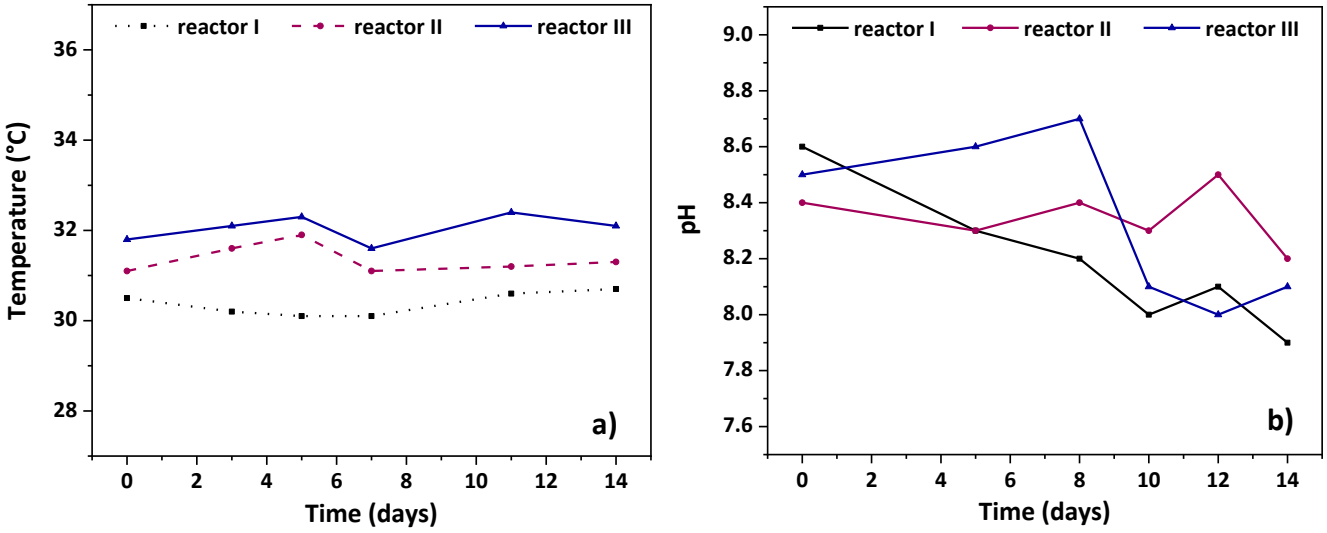

Figure 4. Influence of solar exposure on (a) culture temperature and (b) pH in reactors I, II, and III during the second experimental assay

PAR measurements (Figure 5) recorded between October 1 and November 15 revealed an average daily total of 30.6 mol/m²/day. This value substantially exceeded the optimal irradiance for microalgal growth (<20 mol/m²/day). The high radiation load is therefore identified as a major factor limiting culture persistence, as excessive irradiance can induce photoinhibition and severely compromise microalgal viability.

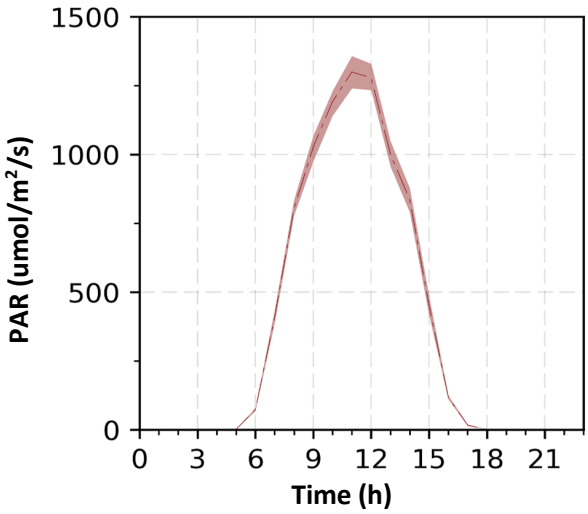

Figure 5. Diurnal PAR profile showing mean values (marron line) and the corresponding 95% confidence interval (shaded region)

The mean diurnal PAR pattern (Figure 5) is represented by a dotted line summarizing all measurements collected during the study period, along with a 95% confidence interval (shaded region). PAR values became positive shortly after 05:00 h and increased rapidly, surpassing 500 µmol/m²/s between 08:00 and 15:00 h. Peak irradiance exceeding 1000 µmol/m²/s occurred consistently from 09:00 to 14:00 h, a period of sustained high radiation that likely imposed substantial photo stress on reactor III due to its extended exposure duration.

The PAR time series (Figure 6) further illustrates pronounced diurnal variability, with instantaneous peaks occasionally exceeding 2000 µmol/m²/s near midday on several days. This pattern remained stable throughout the experiment, indicative of predominantly clear-sky conditions and limited atmospheric attenuation. These high-intensity events are

important when interpreting culture performance, as they represent acute irradiance levels capable of inducing photoinhibition.

Comparation of Figures 5 and 6 demonstrates the necessity of analyzing both averaged irradiance profiles and extreme events. While the mean diurnal curve in Figure 5 yields a smoothed pattern with a maximum near 1250 µmol/m²/s, the instantaneous measurements capture short-lived but intense spikes above 2000 µmol/m²/s, highlighting periods of potentially severe stress for the microalgae.

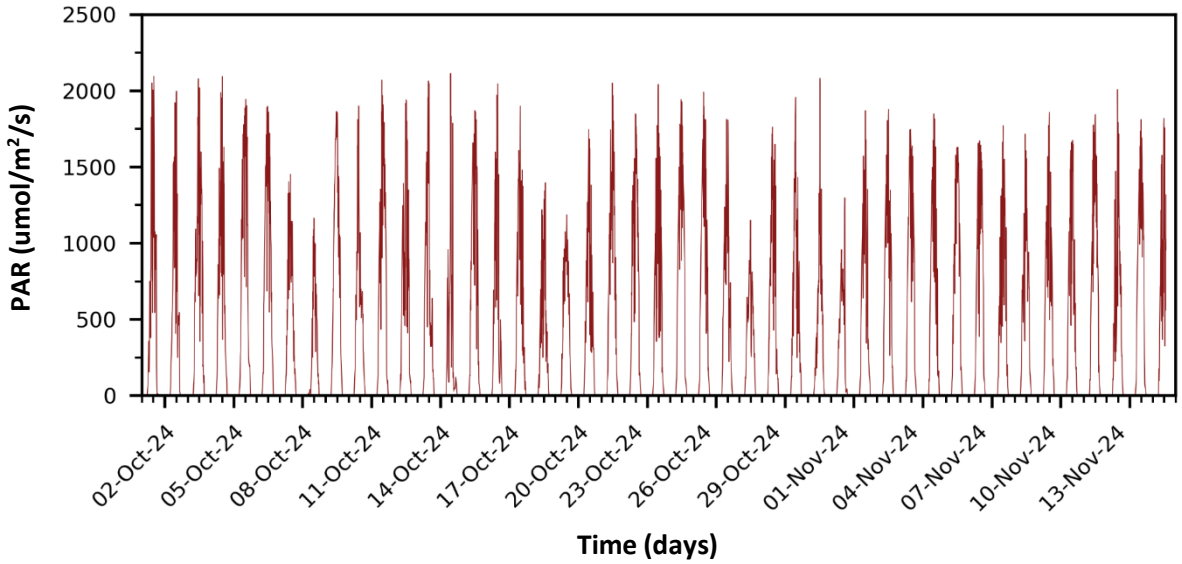

Figure 6. Time series of photosynthetically active radiation (PAR) measured in Mérida, Yucatán, between 1 October and 15 November 2024

Few studies have explicitly evaluated the role of PAR in outdoor microalgae cultivation systems. Consistent with findings by Guedes *et al*. (2023), our results reaffirm that solar irradiance is a viable and accessible energy source for microalgae production, particularly in regions with limited technological or economic resources.

Despite its advantages, reliance on natural sunlight introduces challenges due to the difficulty of controlling irradiance intensity and spectral quality—factors shown here to affect culture stability and performance. Nonetheless, these constraints can be partially addressed through system-level design interventions, including optimized reactor orientation, use of high-transmittance materials, PAR-triggered automated exposure control, and continuous monitoring of environmental parameters. Such measures could enhance biomass productivity while mitigating photo inhibitory stress. However, implementing these strategies requires careful management to ensure consistent operation and to avoid unintended environmental or physiological impacts on the cultures.

Conclusions

The findings of this study demonstrate that sunlight exposure time is a primary driver of the performance of the native microalgal consortium cultivated in open systems. The absence of detectable changes in nutrient concentration or biomass suggests that light availability—rather than nutrient limitation—was the dominant factor constraining growth. Both insufficient and excessive irradiance led to rapid culture decline, indicating a narrow operational window for maintaining stable biomass productivity. The combined effects of prolonged irradiance and temperature fluctuations appear to further influence culture viability, underscoring the strong coupling between light and thermal stress in outdoor environments.

Continuous PAR measurements provided critical insights into the relationship between environmental variability and culture dynamics. These data emphasize the value of sustained monitoring, which enables the identification of irradiance thresholds, informs system design, and strengthens reproducibility for future experiments.

Collectively, the results highlight the necessity of implementing robust environmental monitoring systems in outdoor cultivation platforms. Such systems not only support informed decision-making for process optimization but also clarify the practical limitations and potential of microalgal biomass production under natural irradiance regimes. This study therefore establishes an empirical basis for future research aimed at improving system resilience, optimizing light management strategies, and enhancing productivity in open microalgae cultivation systems.

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Author contributions: V.I.B.C.: data collection and analysis; J.C.Z.R.: funding acquisition, interpretation of data and editing; R.M.G.B.; conceptualization, writing and interpretation of data.

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