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Short Communication

Estimation of design parameters of the Fibonacci-type photobioreactor 5000 L

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ABSTRACT. The presented Fibonacci-type tubular photobioreactor represents a significant advancement over classical tubular photobioreactors. It exhibits notable flexibility in its geometric design with the ability to adapt its parameters to meet the specific photosynthetic requirements of microalgae, thereby achieving maximum efficiency. As a result, it emerges as a viable alternative to conventional tubular systems. Furthermore, the strategy utilized for optimizing the design of Fibonacci-type photobioreactors is also described. This strategy is applied to design a 5000 L reactor, serving as a potential approach to harnessing these reactors for the industrial-scale production of high-value microalgae with commercial significance.

Keywords: microalgae; production; photobioreactor; Fibonacci-type; biomass productivity

Microalgae represent a promising source of bioactive and nutritional compounds, offering significant economic potential for various applications in the food industry for human consumption, as well as in feed additives, pharmaceuticals, and nutraceuticals (Raja et al. 2008, Koller et al. 2014, Vigani et al. 2015, Mobin & Alam 2017). Recent advancements in photobioreactor engineering have led to a stronger focus on reducing production costs and recognizing the microalgae's ability to produce commercially valuable biomolecules (Assunção & Malcata 2020). In general, photobioreactors have been widely acknowledged as the most suitable cultivation systems for microalgae. Initially, open raceway ponds garnered significant attention due to their cost-effectiveness. However, these systems are fraught with limitations, including challenges in maintaining precise temperature control, susceptibility to water evaporation, and an elevated risk of contamination (Barceló-Villalobos et al. 2018). To address these limitations, closed cultivation systems emerged as a viable solution. These systems offer numerous advantages, including mitigating the risk of contamination, thereby providing microalgae with an optimal growth environment free from external influences (Masojídek & Torzillo 2014). Nevertheless, achieving industrial-scale production continues to pose a significant challenge, primarily attributed to the constraints imposed by conventional farming systems (Assunção & Malcata 2020).

The optimal design of a photobioreactor necessitates the consideration of specific parameters that facilitate growth control and versatility for cultivating various algae species, thereby presenting a significant challenge (Karimi et al. 2022). Key challenges include efficient gas exchange (CO_2, O_2) (Du et al. 2019), temperature regulation, pH maintenance, and nutrient distribution, collectively influencing microalgae growth within the reactor. Maximizing light availability is crucial, highlighting the importance of the photobioreactor's transparency and surface/volume ratio. These factors are essential in achieving elevated growth rates and enhanced productivity (Dixon et al. 2014, Xu et al. 2016, Díaz et al. 2019, Touloupakis et al. 2022).

Díaz et al. (2019) introduced a novel photobioreactor design known as the Fibonacci-type, which offers several advantages. This innovative photobioreactor captures approximately 1.4-1.6 times more solar radiation than a horizontal surface, creating optimal conditions for cultivating *Spirulina* and

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Dunaliella salina without refrigeration. Additionally, the design maximizes CO_2 utilization efficiency and prevents the excessive accumulation of dissolved oxygen.

The main objective of this study is to configure a 5000 L Fibonacci-type photobioreactor using the design experience of a 2500 L Fibonacci-type photobioreactor. Its volumetric productivity is estimated as a function of the length and diameter of the tube, maintaining the volume and surface ratio of the photobioreactor of 2500 L, which allows the optimization of the photosynthetic performance in the new photobioreactor.

The hyperbolic model was performed to compute both the oxygen production rate and the accumulation of dissolved oxygen within the cultures to evaluate the performance of the Fibonacci-type photobioreactor under various conditions (by altering the tube length and diameter). This model allows to estimate the oxygen production rate (PO_2) resulting from photosynthesis (Eq. 1) (Costache et al. 2013, Brindley et al. 2016) as a function of the maximal oxygen production rate (PO_2max = 2.45×10^{-2} mg O_2 L^{-1} s^{-1}), an exponential factor (n = 2), and the semi-saturation irradiance (I_k = 70 μmol photons m^{-2} s^{-1}). Determination of the maximal reactor length involved calculating the maximal dissolved oxygen concentration (DO_2) that the selected strain could withstand, utilizing Equation 2. This equation considers the increment in DO_2 resulting from photosynthesis for each length increment (L_i - L_{i-1}).

The ultimate DO_2 attained is also influenced by the liquid velocity (V_Q). The primary aim is to determine the maximum tube length that maintains the DO_2 below 200% Sat.($O_{2\ Max\ sat}$); simulations were conducted to achieve this, considering varying biomass concentrations, tube diameters, and reactor volumes. The intensity of the incident light varies over the entire surface of the photobioreactor, given the 3D shape and curvature of the tube. Equation 3 was corrected by a weighted average, where (%p) represents a percentage of an irradiance range at the reactor surface, and Io is averaged over that range and weighted by %p (Díaz et al. 2023). The specific growth rate (μ) (Molina-Grima et al. 1994), as a function of the specific maximal growth rate (μ_{max} = 0.75 L^{-1} d^{-1} theoretic), average irradiance (Iav), constant of the microalgae species, the culture conditions (Ki) and (n) exponent determined empirically, was calculated for each tube diameter using Equation 4, from which the volumetric biomass productivity (Pb) was then calculated Equation 5, as a function the biomass concentration (Cb).

$$\mathrm{PO}_2 = \frac{PO_{2\ max} \times Iav^n}{Ki^n + Iav^n} \quad (1)$$

$$\mathrm{DO}_2 = O_{2\ Max\ sat} = \sum_{i=1}^{imax} \frac{PO_2 \times (L_i - L_{i-1})}{V_Q} \quad (2)$$

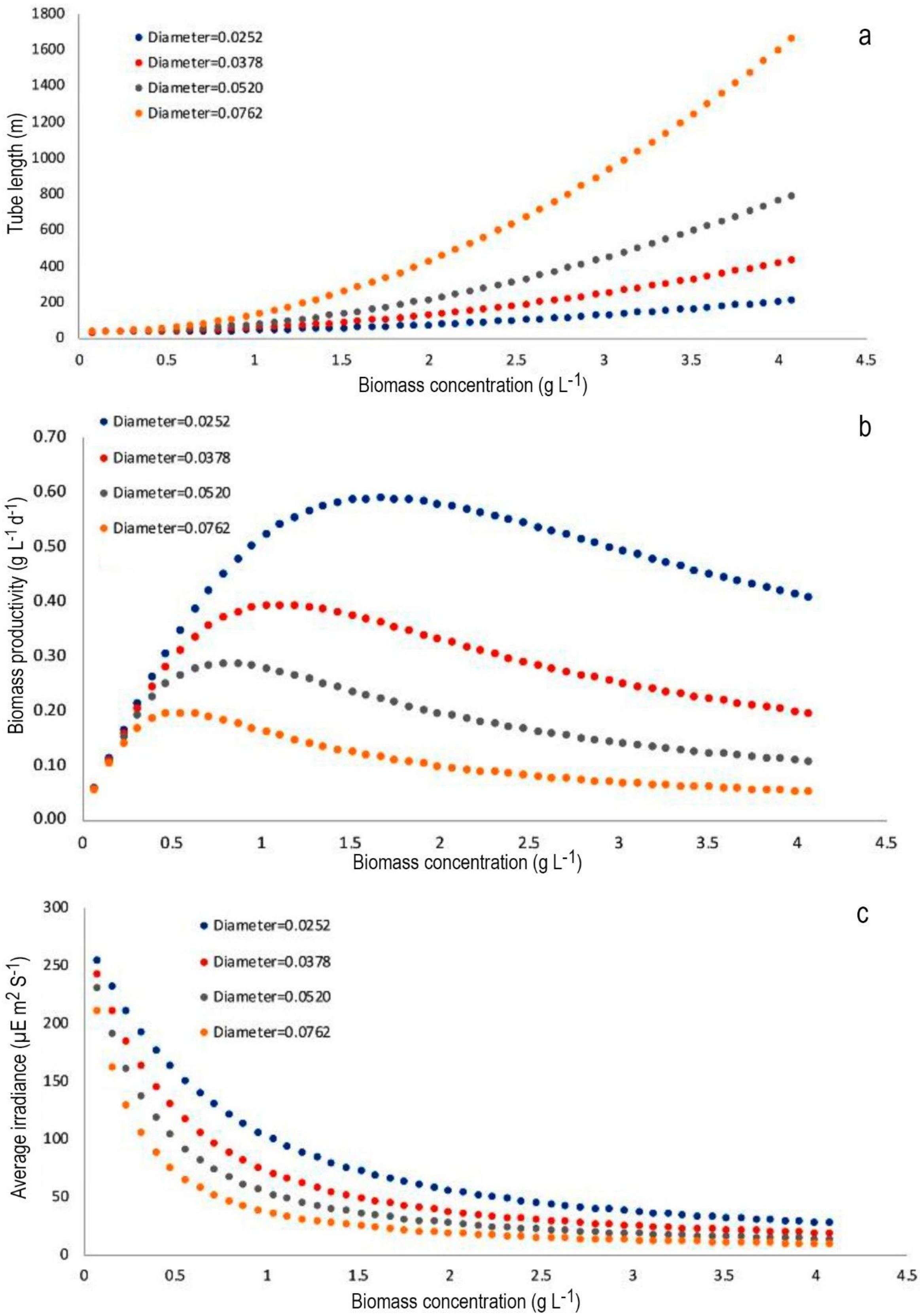
$$Iav = \left\{ \sum_{n=1}^{n} \frac{Io \times \%\mathrm{p}}{Ka \times Cb \times R} \left(1 exp(-Ka \times CbR)\right) \right\} n \quad (3)$$

$$\mu = \frac{\mu_{max} \times Iav^n}{Ki^n + Iav^n} \quad (4)$$

$$\mathrm{P}_b = C_b \times \mu\ \mathrm{P}_b \quad (5)$$

The scale-up process of this system demands a systematic approach based on rational criteria. Therefore, we conducted simulations to assess the impact of both tube diameter and biomass concentration on determining the maximum feasible length of the tube. By considering the daily solar radiation available during the summer (280 μmol photons m^{-2} s^{-1}) and fixing a maximal dissolved oxygen level of 200% of saturation (Molina-Grima et al. 1997, Richmond 2004, Acién et al. 2013), the maximal length of the tube was calculated using the oxygen production rate model (Eq. 1-2). The data illustrates a direct correlation between the maximal tube length and both the biomass concentration and tube diameter, primarily due to decreased light availability within the tube and subsequent reduction in the PO_2 (Fig. 1a). For instance, when a biomass concentration of 4.0 g L^{-1} is considered, the maximal tube length increases from 200 to 1600 m as the tube diameter increases from 0.025 to 0.076 m. Furthermore, the data reveals that the average irradiance declines from its initial value of 280 μmol photons m^{-2} s^{-1} to values below 30 μmol photons m^{-2} s^{-1} for biomass concentrations of 4 g L^{-1} (Fig. 1c). The optimal performance of the cultures is achieved when the average irradiance is equal to the semi-saturation irradiance (I_k) of 70 μmol photons m^{-2} s^{-1}. The biomass concentration must be in the range of 0.5 to 1.5 g L^{-1} to achieve this value when the tube diameter increases from 0.025 to 0.076 m. Average irradiance also determines the growth rate of the strain. In addition to the biomass concentration, the biomass productivity is calculated (Eq. 5). The data demonstrates that biomass productivity reaches its peak when the average irradiance equals the irradiance semi-saturation, highlighting the crucial role of these factors in achieving optimal biomass concentration and maximal biomass productivity (Fig. 1b). For instance, with a higher tube diameter of 0.076 m, the optimal biomass concentration is 0.5 g L^{-1}, but this results in relatively low biomass productivity of 0.2 g L^{-1} d^{-1}.

Conversely, with a lower tube diameter of 0.025 m, the optimal biomass concentration is 1.5 g L^{-1}, leading to a significantly higher biomass productivity of up to


a
Diameter=0.0252
Diameter=0.0378
Diameter=0.0520
Diameter=0.0762
Tube length (m)
0
200
400
600
800
1000
1200
1400
1600
1800
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5
Biomass concentration (g L-1)
b
Diameter=0.0252
Diameter=0.0378
Diameter=0.0520
Diameter=0.0762
Biomass productivity (g L-1 d-1)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5
Biomass concentration (g L-1)
c
Diameter=0.0252
Diameter=0.0378
Diameter=0.0520
Diameter=0.0762
Average irradiance (μE m2 S-1)
0
50
100
150
200
250
300
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5
Biomass concentration (g L-1)

Continuation

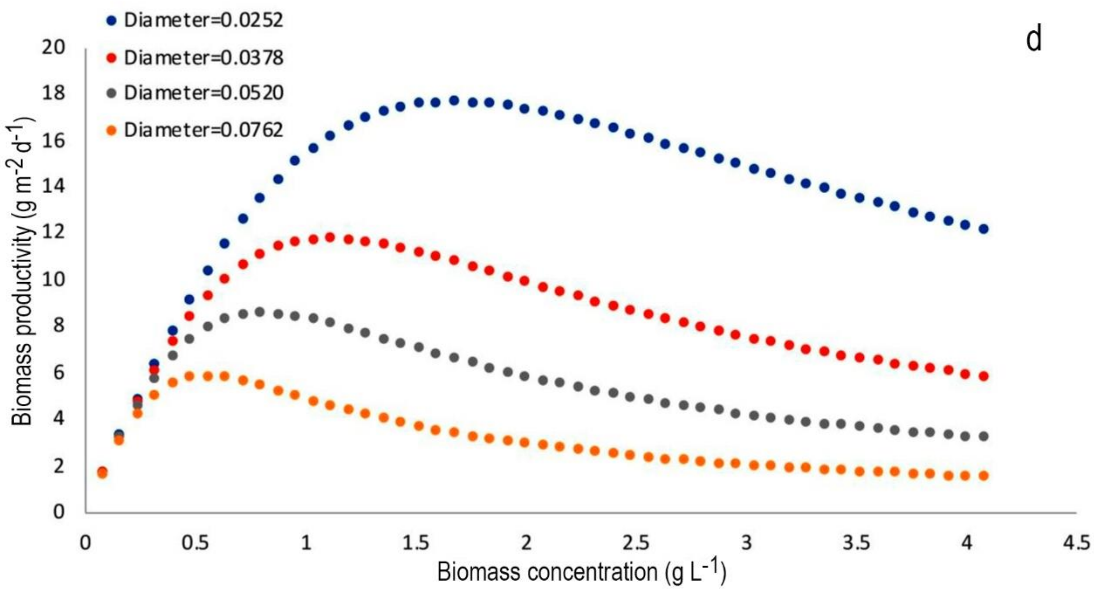


Figure 1. a) Influence of tube diameter on the design of Fibonacci-type photobioreactor, b) influence of tube diameter and biomass concentration on the maximal tube length, c) variation of volumetric biomass productivity s a function of tube diameter and biomass concentration, d) variation of biomass productivity per surface unit as a function of tube diameter and biomass concentration.

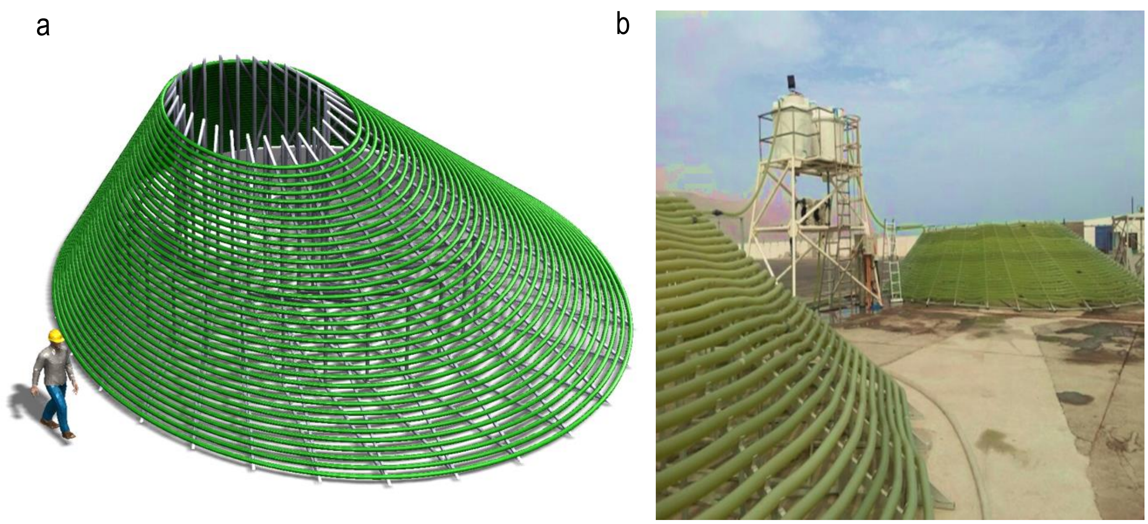


Figure 2. a) Three-dimensional view of Fibonacci-type photobioreactor 5000 L. b) Pilot scale 2500 L Fibonacci-type photobioreactor.

0.6 g L^{-1} d^{-1}. Similar findings were reported in studies involving tubular photobioreactors, where an increase in tube diameter reduced biomass productivity (Acién-Fernández et al. 2001, Torzillo et al. 2015). Considering that the tube diameter and length influence the overall culture volume per surface area, these values can also be translated into areal productivity, demonstrating a comparable trend (Fig. 1d).

The results demonstrate a wide range of maximal areal biomass productivity, ranging from 6 to 18 g m^{-2} d^{-1}, for the previously investigated biomass concentrations and tube diameters. It is important to note that

Table 1. Design parameters of the Fibonacci-type photobioreactor 2500 and 5000 L.

Parameters	2500 L	5000 L	Unity
Tube diameter	0.052	0.0762	m
Long tube (Lt)	841	792	m
Land length (L)	10	10	m
Land width (Lw)	9	9	m
Surface tube exposed to light (St)	96.6	125.6	m^2
Land occupied (S)	90.0	90	m^2
Volume (V)	2.50	5	m^3
S/V	36	18	m^{-1}
V/S	27.8	55.6	$L\ m^{-2}$
St/V	39	25.1	m^{-1}
Volume tube (V)	1.68	3.57	m^3
Volume degassing tank	0.82	1.43	m^3
Photobioreactor height	2.2	2.84	m

these results are specific to the particular location and environmental conditions studied. When considering other scenarios, it becomes essential to recalculate the optimal design. However, the proposed strategy remains consistent and applicable regardless of the scenario (Fig. 2, Table 1).

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