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Model-based feasibility assessment of a deep solar photobioreactor for microalgae culturing

M. Castrillo*, R. Díez-Montero, I. Tejero

Group of Environmental Engineering, Department of Water and Environmental Sciences and Technologies, University of Cantabria, Avda. Los Castros s/n, 39005 Santander, Spain

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ABSTRACT

A deep photobioreactor (PBR) based on cone-shaped light guides was conceived to improve the solar light utilization efficiency of microalgae cultures, optimizing light distribution over the culture surface and thus minimizing photoinhibition and photosaturation occurrence. A preliminary model based on local light intensities and local growth rates was developed in order to check its viability. The model was applied to a conceptual PBR unit using irradiance data of Santander (Spain). Areal biomass productivities of 15.17 and 34.57 $g\,m^{-2}\,d^{-1}$ were predicted for the most unfavorable and favorable months respectively, both under monthly average cloud cover. These results are, in average, 2.72 times higher than predicted values for an open pond PBR under identical irradiance conditions. A procedure to scale-up the deep PBR in any location was developed. The procedure provides the optimal arrangement of the light guides and its operational parameters as a function of the surface incident light intensity. According to the obtained results, the novel configuration is highly efficient in land use, providing a low surface requirement solution.

1. Introduction

In the last few decades the culture of microalgae has awakened scientific and commercial interest since these microorganisms have been seen as an attractive source of valuable biomass. A wide variety of applications have been attributed to algal biomass and its byproducts. Its utilization with environmental purposes like bioremediation and CO_2 fixation, as well as with commercial purposes in different industrial sectors, has been reported [1]. However its production at large scale is still limited. The cost of producing 1 kg of biomass in raceway ponds, tubular reactors and flat panels is estimated in 4.95, 4.15 and 5.96 € respectively (100 ha plants), which could be reduced to 1.28, 0.70 and 0.68 € kg biomass^{-1} by implementing improvements in the location, the mixing, the photosynthetic efficiency and the source of CO_2 and water [2]. A way to reduce its cost is to couple wastewater treatment based on microalgae with other purposes like biomass production for lipids extraction [3].

Microalgae are cultivated in production facilities called photobioreactors (PBR), which make use of light to produce biomass and byproducts. The design of large scale efficient PBRs is an issue that remains unsolved, mainly due to the nature of light that is attenuated while passing through the culture [4,5]. Illuminated surface to volume ratio (S_I/V) is a key parameter in PBR design, and with this idea a wide variety of devices, mainly consisting on narrow channels or panels, have been developed [6]. Nowadays there is a trend to reduce the reactors depth in order to increase light availability and therefore biomass productivity. It has been reported that reducing the water depth in raceways from 30 to 5 cm, can increase biomass productivity up to 72% [7]. However, reducing the water depth entails higher surface requirements.

On the way to find an effective utilization of light energy, systems that include internal light sources have been proposed. Also for scaling-up reasons, they are viewed as the only feasible configuration [8,9]. As conventional closed PBR, they are characterized by having a high S_I/V ratio, but additionally they allow for more compact designs [10]. Recently, PBR with internal LED have been found as a suitable configuration with remarkable advantages like the possibility to scale-up in a three-dimensional way and to avoid overheating [11].

Considering solar light, an efficient utilization of the sunlight hitting the PBR surface is the key factor to achieve sustainable designs [12]. In a given geographical location, the amount of light that a culturing device receives is determined by the surface exposed to solar irradiance, therefore PBR must be designed to maximize its conversion efficiency. With this purpose, light harvesting and distributing methods have been proposed, especially by making use of Fresnel lenses and optical fiber [13–15]. More recently, systems driving the light deep into the reactor

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* Corresponding author.
E-mail addresses: castrillom@unican.es (M. Castrillo), ruben.diezmontero@unican.es (R. Díez-Montero), tejeroi@unican.es (I. Tejero).

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Abbreviations

A	ground occupied surface of the PBR unit, m^2
Az	Azimuth angle, °
b	distance between the apex of the cone and the pivot joint, m
C	cord of the base of the cone in the direction that they tilt, m
C_b	culture biomass concentration, $kg\ m^{-3}$
D	cone base diameter, m
F	minimum distance between contiguous cones, m
F_β	minimum distance between two contiguous cones in the direction of β, m
$F_{N\text{-}S}$	minimum distance between two contiguous cones in the N-S direction, m
$F_{W\text{-}E}$	minimum distance between two contiguous cones in the W-E direction, m
I	direct light intensity over the cones' base, $\mu E\ m^{-2}\ s^{-1}$
I′	direct light intensity over the internal surface of the cones, $\mu E\ m^{-2}\ s^{-1}$
I_l	local light intensity in a point of the culture volume, $\mu E\ m^{-2}\ s^{-1}$
LPFD	Local Photon Flux Density
K_a	light extinction coefficient, $m^2\ kg^{-1}$
K_i	half-saturation constant, $\mu E\ m^{-2}\ s^{-1}$
n_1	air refractive index, dimensionless
n_2	cone's material refractive index, dimensionless
n_3	culture suspension refractive index, dimensionless
$L_{R(n)}$	depth of the cone where reflected radiation hits, m
$L_{R(n-1)}$	depth of the cone where the previous reflection hits, m
q	height of the cones above the water level to avoid splashing, m
Q	height of the cones above the water level to avoid submersion, m
R	reflected light
S	specular factor, %
S_I	illuminated surface, m^2
S_I/V	illuminated surface to volume ratio, $m^2\ m^{-3}$
T	transmitted light
Tr	transmittance, %
Y_x	biomass yield, (g biomass/mol PAR photons)
z	distance between the wall of the cone and a point P(x,y), m
α	inclination angle of the cones to the horizontal, in any direction, °
α_S	maximum inclination angle of the cones in the South direction, °
α_{min}	maximum inclination angle of the cones in any direction, °
β	half of the rhombus angle in the grid formed by the cones, °
μ_{max}	maximum growth rate, d^{-1}
θ_i	incident angle, °
θt	refractive angle, °
φ	half aperture angle of the cones, °

by means of vertical plastic light guides or empty chambers have been employed [16–18].

The use of solar light implies a big challenge in PBR design, since it is a non-scalable parameter that follows cyclical variations, but it is also affected by the weather and atmospheric conditions. In nutrient-limited systems, the limiting factor is a component of the medium, so it can be controlled by varying the dilution rate, but in light-limited systems, the limiting factor is not directly dependent on the dilution rate and cannot be assumed to be homogeneously distributed in the PBR volume [19]. Ideally, in a PBR the light inhibition and the complete dark zones should be avoided or at least minimized, keeping the light intensity between the critical and the saturation intensities. Then, the challenge consists on modulate the irradiance over the culture surface by varying its geometry or orientation in order to achieve a 'light dilution effect', with dilution factors ranging from 5 to 10 [20]. According to Posten [21], the answer of process engineering is to design vertically mounted PBR with a large surface, where the sunlight falling on a given ground area is spread over a larger reactor surface. As a guidance value, it is reported that the surface to ground area ratio should be 10 or higher.

Solar tracking systems can help to achieve solar light capture optimization. Its use has been mainly applied to flat panels. It has been shown that using solar tracking systems enables a higher irradiance in winter days by facing the panel perpendicular to the solar beams, thus increasing the overall productivity. On the contrary, at low cell densities or at high irradiances it is possible to provide lower irradiance over the culture by adjusting the tilt angle of the panel. According to the work of Hindersin et al. [22], the main advantages of using solar tracking systems are: (i) the possibility to decrease photoinhibition of photosynthesis in a microalgal culture of low density, by reducing the irradiance; (ii) enhancing the irradiance beyond 100% of the horizontal irradiance in high cell density cultures by exposure of the reactor perpendicular to the sun light and (iii) regulating culture temperature by adjusting the irradiance or cooling to avoid heat stress.

Large scale PBR optimization and modelling is governed by two main types of phenomena: on the one hand the biokinetics of the species to be cultured, and on the other hand the PBR physical structure that determines the radiant light transport. At the same time, when designing a solar based PBR, two main types of factors must be taken into account. Firstly, the shape and geometry of the PBR, like its exposed surface and the presence of shadowing elements, and secondly geographical factors like the latitude and the relative position of the Sun. In non-sun tracking PBR, direct irradiance over the reactor surface depends on the incident angle, which depends on the solar position. However, sun tracking PBR are usually designed to receive the optimal radiation over the time, thus their geometry and dimensions must be designed and calculated according to the different positions of the Sun from the sunrise to the sunset through the year. Since daily Sun path varies along the year, especially in high latitudes, the optimized design must satisfy the global maximum productivity, thus averaged irradiance values should be avoided.

Knowing the angle of incidence of the direct light beams all over the day becomes essential to calculate light gradients inside the culture and to avoid heterogeneously irradiated surfaces. The study of the tilt angle for optimal year-round energy collection and, when possible, the adjustment of this angle through the year has been recognized to result in an enhancement of the overall annual productivity [23,24].

Many approaches can be found in scientific literature to model volumetric or areal productivity of microalgae. As a first classification, two border cases can be distinguished: models that predict the photosynthetic activity according to the local conditions of a cell at a given position inside the PBR and models that use averaged parameters. Secondly, within each group, the light dependence can be calculated in different ways although the most common approach is to consider that light dependence follows Monod-type kinetics. Among the models that use averaged parameters, the most basic approach is to consider the light intensity in the PBR as the average of all the local intensities within the same. The average irradiance can be defined as the irradiance experienced by a single cell randomly moving inside the culture [25]. However, average irradiance is not a sufficient criterion of culture performance because it considers only the total length of the dark and the light periods, not their frequency and reactors presenting identical averaged irradiances can show different productivity [10,26], so more