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Hydrodynamic and mass transfer characterization of flat-panel airlift photobioreactors for the cultivation of a photosynthetic microbial consortium

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ABSTRACT

The design and build of industrial photobioreactors are critical steps for the production of photoautotrophic microorganisms. Flat-panel airlift photobioreactors (PBRs) of 50 L and 150 L were built; hydrodynamics (gas hold-up (ε), mixing time (t_m) and Reynolds number (Re)) and mass transfer properties were characterized in the two flat-panel airlift PBRs (50 and 150 L). The geometric ratio (illuminated area: operation volume (A/V) ratio) selected for building the 150 L PBR was adequate to carry out biomass production of a microbial consortium (MC). A high CO_2 utilization efficiency in the PBRs was obtained. Finally, the experimental results of k_La were correlated mathematically to describe the influences of the considered factors (the overall power input and density) on the studied superficial gas velocity range. The predicted k_La values yielded acceptable results compared to the experimental results.

1. Introduction

Cyanobacteria are oxygenic phototrophic organisms that are able to form consortia and to produce compounds with high added value for different biotechnological areas [1]; hence, its laboratory or pilot scale production is achieved in closed systems called photobioreactors. These systems present diverse advantages; among them are procurement of high cellular density, better temperature and pH control, etc. [2,3]. Despite the known usefulness of these production systems, they still have some limitations for their industrial scaling; therefore, photobioreactors of diverse forms have been designed, such as tubular, flat panel, stirred-tank fermenter, etc., aimed at providing the necessary conditions for the growth of the selected cyanobacterium [4].

Due to the scaling limitation presented by photobioreactors in their different configurations, it is necessary to select a reference parameter for their design and operation such as the mass transfer coefficient (k_La). This parameter is affected by diverse factors of the system like agitation, airflow, air pressure, temperature, geometry of the reactor, properties of the fluid (density, viscosity, etc.), presence of anti-foaming agents, concentration, and presence of a third phase (density, particle size, etc.), among others [5,6].

Another of the parameters considered for the design of photobioreactors is the transfer of light for which the relation illuminated area: operation volume (A/V) has to be increased; to comply with this, the flat panel photobioreactors were designed specifically to favor the optimal use of light by microalgae and cyanobacteria; however, scaling, using this parameter, still presents several limitations, because there is no universal criterion that determines the optimal characteristics of this type of reactors [7–9].

Likewise, it is important to characterize hydrodynamics and mass transfer of the photobioreactors aimed at knowing the optimal operational conditions needed for the growth of microorganisms. For this, it is necessary to determine diverse parameters, such as k_La, mixing time, velocity of the liquid, velocity of the gas bubbles and the gas hold-up [10]. In aerated photobioreactors, one of the main used parameters for their characterization is oxygen transfer, which depends on many factors, like the tank

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design, the rheological properties of the fluid, the hydrodynamic properties of the system, and the presence of suspended solids, as for example biomass. In addition, in this type of photobioreactors, the level of dissolved oxygen and the power provided by aeration are factors that limit their scaling; therefore, it is important to use different mathematical correlations to help us understand the relation among the microorganism and the hydrodynamic and mass transfer properties in photobioreactors [11,12].

The first attempts to achieve a large scale production of microalgae were made in the 60′s in Japan using *Chlorella* [13]. Afterwards large scale production of diverse microalgal species was reported in flat panel airlift photobioreactors of 100 and 400 L by modifying the A/V relation and the light path to improve productivity of *Phaeodactylum tricornutum, Thalassiosira pseudonana*, and *Chlorella* sp. [14,15].

In this context, our working team isolated, propagated, and characterized a photosynthetic microbial consortium (MC), constituted mainly by nitrogen-fixing filamentous cyanobacteria, hence its potential to be used as biofertilizer has been proposed [16]. Besides, the design and characterization of a 50 L flat panel airlift photobioreactor (PBR) was achieved with a high light path used for the production of photosynthetic microorganisms, revealing a high mass transfer and an excellent light distribution [17].

Due to the biotechnological interest posed by this MC it is necessary to perform a detailed study of its large scale production in PBRs, under controlled light and temperature conditions. The objective of this study was to construct a PBR of 150 L, keeping the A/V relation of the 50 L PBR, to characterize its hydrodynamic and mass transfer properties in a biphasic (air-water) and a triphasic (CM-culture medium-air) system, using a photosynthetic microbial consortium as study model. In addition, we are proposing a mathematical model to correlate the volumetric coefficient of mass transfer with superficial velocity of the gas and the power supplied to the 150 L PBR.

2. Materials and methods

2.1. Flat-panel airlift photobioreactor (PBR)

Our work group had previously characterized the hydrodynamics and mass transfer properties of a flat-panel airlift photobioreactor of 50 L (working volume) in biphasic and triphasic systems using the cyanobacterium *Spirulina* sp. as a study model. The minimum and maximum superficial gas velocities (U_G) assayed were 5×10^{-5} and 8.4×10^{-3} m s^{-1}, respectively. The maximum values of k_La and ε were 20.34 h^{-1} and 0.033 in the biphasic system and 31.27 h^{-1} and 0.065 in the triphasic system, respectively [17]. Since production of photoautotrophic microorganism in this PBR type had been studied previously, a 150 L PBR was built in the present work, which was characterized in terms of hydrodynamics and mass transfer and used to evaluate the production of a photosynthetic microbial consortium, as this MC has potential to be used as a biofertilizer for its nitrogen fixing capability [16,18].

For building the PBR, the photobioreactor configuration described by Reyna-Velarde et al. [17] was maintained, using as geometric relationship the A/V ratio of 7.3 m^{-1}. The PBR was constructed with acrylic plates, having a working volume of 150 L, length of 1.56 m, height of 0.78 m, and width (light-path) of 0.14 m. The central plate measured 0.61 m and was placed 0.04 m above the base of the PBR. The air was fed to the PBR through a stainless-steel tube (with a length of 1.56 m) with 26 holes of 0.002 m in diameter, which was placed as close as possible to the frontal plate, along the base of the PBR. Airflow was controlled with a stainless-steel float flowmeter (Key Instruments, USA). Airflow pressure was controlled with a Wilkerson 2001 pressure regulator (0–28 kg cm^{-2}). The PBR had a downcomer-to-riser cross-sectional area ratio (Ad/Ar) of 1. In addition, hydrodynamics and mass transfer properties of the photobioreactor reported by Reyna-Velarde et al. [17] was characterized in the triphasic system using the photosynthetic MC as a study model. This was done to compare the performance of the 50 L and 150 L PBRs and confirm that hydrodynamic and mass transfer features of the 150 L PBR are suitable for the growth of the MC.

2.2. Microorganism and culture conditions

For a triphasic system, the MC previously isolated and characterized [18] was used as study model. MC production kinetics was assessed in batch mode in both PBRs (50 L and 150 L) using a mineral medium ($BG11_0$) without a nitrogen source for propagation [19]. The operating conditions of each PBR are mentioned below.

In the 50 L PBR, 16 L of inoculum and 34 L of culture medium were used. The airflow supplied to the PBR was 25 L min^{-1} (equivalent to a U_G of 0.0042 m s^{-1}). The culture was maintained at a temperature of 21 ± 2 °C, illuminated on the front panel by an arrangement of white lamps (Sylvania, USA) with a flux of 80 μmol photons m^{-2} s^{-1} and a light:darkness photoperiod of 12 h:12 h.

In the 150 L PBR, 50 L of inoculum and 100 L of culture medium were used. The airflow supplied to the PBR was 90 L min^{-1} (equivalent to a U_G of 0.0068 m s^{-1}). The culture was maintained at a temperature of 21 ± 2 °C in a closed space with air conditioner, illuminated on the front panel by an arrangement of white lamps (Sylvania, USA) with a flux of 80 μmol photons m^{-2} s^{-1} and a light:darkness photoperiod of 12 h:12 h.

Batch culture reached the stationary phase on day 14 in both PBRs (50 and 150 L). After this incubation time, the hydrodynamic and mass transfer characterization was performed for each PBR (in the triphasic system).

After hydrodynamic and mass transfer characteristics of the 150 L PBR were studied, growth kinetics of the MC in batch culture for 14 d was assessed using different airflow rates, namely 50, 60, 70, 80, 90, and 100 L min^{-1} (U_G equivalent to 0.0038, 0.0046, 0.0053, 0.0061, 0.0068, and 0.0076 m s^{-1}, respectively), under the same conditions of light and temperature previously mentioned. Airflow studies were performed to evaluate the effect of the fluid dynamics based on the Reynolds number on overall biomass production.

The dry biomass concentration in both PBRs was determined, using the technique described by Tredici et al. [7], in all batch cultures. The liquid density (ρ) in the biphasic and triphasic systems was determined by the method described by Mott [20].

The Reynolds number (*Re*) for non-circular cross-sections was determined by Eq. (1), proposed by Mott [20]:

$$Re = \frac{\rho v(4R)}{\mu} \quad (1)$$

Where: μ is the liquid viscosity [kg m^{-1} s^{-1}], ρ is the liquid density [kg m^{-3}], v is the liquid average speed [m s^{-1}], and R is the hydraulic radius determined by Eq. (2):

$$R = \frac{La}{2a + 2L} \quad (2)$$

Where: L is the length and a is the width of the PBR [m].

2.3. Hydrodynamic and mass transfer characterization

Hydrodynamic and mass transfer characteristics of the PBRs using the biphasic and triphasic systems were determined at 21 ± 2 °C (dry bulb temperature), with relative humidity of 45% and at Mexico City's atmospheric pressure (585 mm Hg). Both PBRs were operated with the same volume of air per volume of medium per minute (0.06–1 vvm). The minimum and maximum U_G evalu-