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Characterization of split cylinder airlift photobioreactors for efficient microalgae cultivation

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HIGHLIGHTS

- A novel photobioreactor (SCAPBR) was developed.
- SCAPBR has up to 53% more illuminated area comparing to a bubble column.
- Mass transference in SCAPBR was very efficient (K_La up to 0.003 s^{-1}).
- Maximum biomass productivity was obtained in SCAPBR 50 at U_{Gr}=0.004 m s^{-1}.

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ABSTRACT

An extensive characterization of photobioreactors (PBRs) must be made in order to optimize their operational conditions, operate design improvements and perform scale-up. In this work, a hydrodynamic characterization of liquid and gas phases was performed, as well as the determination of the mass transfer coefficient of three different PBRs (bubble column – BC – and two Split Cylinder Airlift Photobioreactors – SCAPBRs – featuring two different riser-to-downcomer cross sectional area ratios: SCAPBR 75 and SCAPBR 50). The effect of these parameters on biomass productivity was also evaluated. The developed SCAPBRs proved to be extremely suitable for microalgae cultivation. The design of the PBR, particularly the designed gas sparger, allowed meeting the needs of microalgae in terms of mixing and mass transfer (efficient supply and removal of CO_2 and O_2, respectively). SCAPBR 50 (with a superficial gas velocity of 0.0044 m s^{-1}) showed, among the tested PBRs, the highest value of biomass volumetric productivity (0.75 g L^{-1} d^{-1}). This result is probably due to a higher PBR illuminated surface area, and a more regular flow pattern between the illuminated and dark zones verified in SCAPBR 50, which allows exposing cells to regular light–dark periods.

1. Introduction

The driving force for the development of microalgae-related technology is the ability of these microorganisms to efficiently convert solar energy to chemical energy via carbon dioxide (CO_2) fixation. In recent years microalgae became one of the most promising feedstocks for biofuel, bioplastics, cosmetics, pharmaceutical and human nutrition markets. In spite of the huge interest in microalgae cultivation, the economic aspects of the process are still not satisfactorily solved, especially at large-scale. Assuming that the best microalgal specie for the process is identified and selected, the next quest remaining is an optimal design of the microalgae cultivation system to increase cultivation productivity as a whole, reducing the cost of the production process.

In general, the cultivation systems that have been proposed or used for microalgae growth are, inefficient, complex or too costly to be applied in large-scale production. Enclosed photobioreactors (PBRs) have several advantages over open pond production and these advantages are even more important if the desired product is to be used in pharmaceutical applications or if the microalgae require a culture environment that is not highly selective (Mirón et al., 2003) and consequently liable to contaminations. Generally, closed PBRs can be divided in horizontal and vertical PBRs.

Vertical PBR orientation has been proposed to enhance productivity by reducing the photosaturation (Cuaresma et al., 2011). This photosaturation reduction is achieved by an effect of light dilution, since the sunlight falling on a given ground area is spread over a larger reactor surface area when the PBRs are placed vertically. As a result, more algae are exposed to lower intensities,

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being able to maximize their photosynthetic efficiency (Posten and Schaub, 2009). Cuaresma et al. (2011) tested outdoor vertical and horizontal PBRs and concluded that the highest photosynthetic efficiency was found for the vertical simulation, 1.3 g of biomass produced per mol of PAR photons supplied, against 0.85 g mol^{-1} of horizontal PBR and the theoretical maximal yield (1.8 g mol^{-1}). In addition, it is known that under low light intensity a vertical orientation captures more reflected light (Sánchez Mirón et al., 1999). The same authors also concluded that vertical PBRs performed better than horizontal PBRs because they are supposedly more suited for scale-up, require less energy for cooling because of the low surface to volume ratio, and overall outperform horizontal reactors throughout the year. Moreover, vertical column PBRs are characterized by their high volumetric gas transfer coefficients. This is caused by the bubbling of gas from the bottom, which enables not only efficient CO_2 utilization, but also optimal O_2 removal (Wang et al., 2012). The main factor that affects microalgae growth in vertical PBRs is the limited efficiency of light utilization.

It is well known that both the quantity and the quality of the light delivered to the cells are significant to the cells' growth (Fernandes et al., 2010). For dense cultures, in certain periods of the day, the regions close to the surface are subject to high light intensities. These are often greater than the saturation value of the main microalgae species causing photoinibition (Wu and Merchuk, 2004). On the other hand some zones in the reactor may remain in the dark due to optical absorption and self-shading of the cells, causing photolimitation. Thus, it is necessary to prevent high residence time of microalgae cells under these conditions, which is achieved through a constant but regular cell circulation. It is known that the conversion of light energy to biomass can be enhanced if microalgal cells are made to repeatedly move between the well-lit exterior and the dimly lit interior of the photobioreactor (Janssen et al., 2003). Ordered mixing forces the cells to experience periodical light/dark cycles. The effect of the light/dark cycles has been studied previously (Merchuk et al., 1998), and it was found that periodical light/dark cycles might enhance growth (Wu and Merchuk, 2004). However, random mixing does not appear to enhance productivity as much as a regular light–dark cycle (Degen et al., 2001). According to Janssen et al. (2003) fast light/dark cycles on a microsecond–millisecond scale improve microalgal photosynthetic efficiencies. The same authors state that photosynthetic efficiencies can be increased with light/dark cycles of 1–4 s, but these improvements were less evident at the longest cycles. On the other hand, utilization of light/dark cycles of several seconds to tens of seconds does not appear to result in an improvement of the photosynthetic efficiency. Therefore the microalgal photosynthetic efficiency seems to be influenced by the frequency of light/dark cycles, which is determined by liquid circulation velocity, which in turn depends on reactor design and superficial gas velocity (Janssen et al., 2003).

According to Wang et al. (2012), airlift PBRs can sustain better biomass production of different microalgae in comparison to other vertical column PBRs. This might be due to this regular mixing, as opposed to random mixing found in bubble columns. The concentric tube airlift is the most commonly used airlift for microalgae cultivation. However some limitations are evidenced, such as difficult temperature control and large fraction of dark zones inside the PBR, mainly due to the presence of the internal column, which limits light penetration.

In this work a novel Split Column Airlift Photobioreactor (SCAPBR) is proposed as a very promising microalgae cultivation system. The novel SCAPBR has the potential to overcome the limitations of the concentric tube airlift (integrated temperature control system and transport of light to the centre), while maintaining all the benefits inherent to an airlift PBR. In order to provide the best conditions for microalgae growth in SCAPBR, it is of interest to determine and optimize all the parameters that characterize SCAPBR operation. At this stage it is necessary to prove some of the assumptions on which the design was based. SCAPBRs characterization in terms of hydrodynamics and mass transfer characteristics includes the determination of: mass transfer coefficient (K_La), mixing time, liquid velocity, gas bubble velocity and gas hold-up. The nutritional and light requirements of photosynthetic microorganisms may be covered in PBRs with larger light paths, if hydrodynamic and mass transfer conditions are optimized in these PBRs. Only taking into account this point it will also allow predicting the effects of scale-up on the performance of the SCAPBR. In this work a full characterization of two different SCAPBRs designs (SCAPBR 50 and SCAPBR 75) and a bubble column (BC) (used as a control PBR) will be carried out, as well as the evaluation of the effect of the hydrodynamic characteristics and design on biomass productivity.

2. Material and methods

2.1. Photobioreactors

In the proposed SCAPBRs (Fig. 1), a flat plate splits the diameter of the column and separates the column into two parts (riser and downcomer), acting also as a heat exchanger and an internal light guide. The choice for a SCAPBR and the options made in the project design had as main objective to overcome some of the limitations of existing microalgae cultivation systems.

The flat plate that splits the column is made of a transparent material and fully filled with water and acts as a light conductor and distributor inside the SCAPBR (Fig. 1). Therefore the PBR illuminated surface significantly increases. Thus, the central area of the PBR which normally would be completely devoid of light (especially for higher cell concentrations) will have a continuous supply of light. The presence of this central baffle also allows using diameters in the SCAPBR scale-up that would be otherwise unviable due to a substantial increase of dark zones within the PBR. Finally the central wall of the PBR also functions as heat exchanger (Fig. 1), ensuring an efficient cooling of the medium without the need of a large technical apparatus nor the use of large amounts of water.

Considering all the characteristics presented, the SCAPBR proposed has the potential to provide conditions for an ideal microalgae cultivation: proper exposure to light energy, good mass exchange between gas and liquid, flow mixing, low shear stress over the cells and a proper temperature control.

Three different PBRs were tested: a bubble column (BC) and two different SCAPBRs, as shown schematically in Fig. 1.

All vessels were made of 3.8 mm thick, transparent poly (methyl methacrylate) with 90 mm of internal diameter. The liquid height was 600 mm, for a working volume of 3.7 L. All the three PBRs have a total height of 700 mm. The riser-to-downcomer cross sectional area ratio was 1.0 for the SCAPBR 50 and 3.0 for the SCAPBR 75. The baffles, with 4.0 mm of thickness, were located 50 mm from the bottom of the PBRs and 50 mm below the liquid level and were also made of transparent poly(methyl methacrylate) to allow light penetration (Fig. 1).

2.1.1. Aeration system

To ensure an efficient mass transfer inside the SCAPBR an aeration system was developed. The fluid was mixed by sparging CO_2-enriched air (2% v/v CO_2) through a sparger composed by 45, 26 and 19 uniformly spaced needles (with an inner diameter (d_n) of 0.25 mm) in the BC, SCAPBR 75 and SCAPBR 50, respectively. In all the spargers, needles were placed with a spacing (L_n) of