Microalgae bio-fixation efficiency of carbon dioxide through innovative planar photobioreactor

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Abstract The high anthropogenic activity of recent centuries has led to an urgent need to improve CO_2 capture and sequestration technologies. In this context, microalgae systems have gained importance, thanks to their high photosynthetic efficiency and the many applications to which they can be destined. For this reason, a new photobioreactor prototype was developed, consisting of two interconnected units: a photostage loop, composed by fluorescent lamps and two parallel alveolar flat-panel, and an obscured tank in which culture mixing is achieved. The photobioreactor is also equipped with a system of sensors that allows to control all the growth parameters of the culture and a system to control the CO_2 flow rate introduced. In this study a series of parameters were monitored to characterize the photobioreactor both as regards the hydraulic and the luminous parts. Furthermore, a series of biological tests were carried out using the alga *Acutodesmus obliquus* to verify the growth system under different hydraulic conditions (4÷18 L min^{-1}) and the CO_2 removal efficiency of this microalgal species.
The next phase will be to try to optimize the photobioreactor from an energy point of view in order to maximize the efficiency of the entire system.
Keywords: *Acutodesmus obliquus, photobioreactor, CO2 biofixation, artificial light.*

1. Introduction

During the 20th and the first part of the 21st century, the concentration of greenhouse gases in the atmosphere continued to increase, mainly related to the anthropogenic activities. In order to mitigate this human footprint, there is greater attention to CO_2 removal/capture techniques. In this context, microalgae-based refinery concepts have gained importance. In fact, these microorganisms are more photosynthetically efficient than terrestrial plants (10-50 higher than land plant) thanks to their simple cellular structure, large surface-to-volume ratio and aquatic life-style that allow an easy access to water, CO_2 and other nutrients. Moreover, microalgal biomass is considered promising for multiples applications, such as nutraceuticals, cosmetics, food and animal feed additives and biofuels. Since, they have the ability to accumulate significant amounts of different compounds, such as pigments, vitamins, lipids, carbohydrates and proteins.

Algal cultivation methods are classified in open and closed systems. The formers are the most frequently used for commercial production of microalgae because they have very low investment and management costs. However, they have several disadvantages such us low biomass productivities, low CO_2 mass transfer, high risk of contamination and high consumption of water. Whereas, the latter systems allow easier control of the operating conditions and higher biomass productivities, but this implies significantly investment and operation costs.

In particular, closed flat panels photobioreactor (PBR) systems are currently the most common configuration at industrial scale for microalgae cultivation, mainly related to the high photosynthetic efficiencies that can be reached. However, this kind of closed PBR, still present some limitations due to the air bubbled mixing system, directly from the bottom of the panels, which brings to high energy expenditures, very low efficiency of mixing and can lead to the occurrence of serious phenomena of biofouling.

In this study, it is presented the design and characterization of a new and innovative alveolar flat panel photobioreactor prototype. This new PBR has a pump-assisted hydraulic circuit, that transport the microalgae inside a pressurized serpentine, directly exposed to the artificial light source. It represents a new and highly efficient CO_2 supply strategy. In order to characterize the performance of the PBR, different biological tests were carrying out in batch mode, using the microalgae: *Acutodesmus obliquus*.

2. Materials and Methods

2.1. The flat-panels photobioreactor

The photobioreactor prototype is made up of a hydraulic part, which includes two parallel alveolar flat-panels, a closed mixing tank and a hydraulic circulator, which transports the culture from the tank into the flat-panels. Between the panels there is the luminous part, composed

by seven fluorescent lamps. The PBR is equipped with several sensors, able to monitor constantly dissolved oxygen, pH, dissolved carbon dioxide, temperature and conductivity levels. The CO_2 introduction in the PBR is controlled with a thermal mass flow, able to finely regulated carbon dioxide flow rate, and to account the volume introduced during the entire test.

2.2. Microalgae cultivation conditions

Acutodesmus obliquus is a green microalga that lives in freshwater environments, which has a typical eye shape. During the biological test the microalgae were maintained at constant conditions: temperature (23°C ± 2), pH 7, and under constant light intensity (120 µmol m-2 s-1). Each test started with an initial cell concentration of 0.25 g L^{-1} of dry weight, using BG-11. The injection of CO_2 was carried out at three different flow rates, keeping constant the carbon dioxide concentration in the PBR at 25 mg L^{-1} using a solenoid valve in conjunction of a thermal mass flow.

2.3. Biomass concentration measurements

Microalgae growth was quantified with a spectrophotometric method, which measured the optical density of the cell culture at wavelengths of 680 nm (OD680) using a scan spectrophotometer. Moreover, the biomass concentration was also measured by the dry weight (DW). In this method 10-20 mL of culture was filtered using pre-weighted 1.5 µm pore size glass fiber filters. The filters were then dried using a thermobalance and weighted with an analytical balance.

2.4. Hydraulic parameters

The PBR was characterized by three hydraulic parameters: hydraulic flow rate, CO_2 mass transfer coefficient (k_La) and mixing time. The hydraulic circulator installed on the PBR allows to choose between three hydraulic flows, corresponding to levels I, II and III. The value of the flow rates was measured by an electromagnetic flow meter. All measurements were carried out by placing the meter at the outlet of the hydraulic panels.

The $k_La(CO_2)$ was measured without microalgal cells, using 60 L of distilled water at ambient temperature and atmospheric pressure (25 °C and 101.325 Pa). The tests were conducted by blowing a constant and continuous CO_2 flow rate inside the PBR and monitoring the carbon dioxide concentration. For each circulation level, the k_La value was identified for different carbon dioxide flow rates.

The mixing time [t_M] was evaluated by a pH tracing test. A 5 mL volume of 10^{-3} M hydrochloric acid is instantaneously injected into the system, and the value of pH was recorded every minute. The t_M was determined as the time required to reach the 95% of complete homogeneity after the injection of HCl.

2.5. Light parameters

The PBR uses an artificial lighting system, composed of seven fluorescent tubes placed between the two flat-panels. In order to characterized the systems also the homogeneity of the incident light intensity was determined by a PAR spectrophotoradiometer on different points along the optical guide. Moreover, the light intensity on all points of the surface was calculated using an interpolation method developped with the software Matlab®.

2.6. Energetic measurements

The energy consumption of the most important components of the system (hydraulic circulator and lighting system) was measured using an amperometric clapper. The power input was calculated multiplying the voltage and current intensity measured for each unit.

2.7. CO_2 fixation yield (ηCO_2)

At the end of the biological tests, the CO_2 bio-fixation yield (ηCO_2) of the culture was calculated as the ratio between the kilograms of carbon accumulated within the algal biomass and the kg of carbon supplied to the microalgae through the injection of a certain CO_2 flow rate.

3. Results and Discussions

In order to characterize the photobioreactor from the fluid-dynamic point of view, the three hydraulic flow rates available on the circulator used were measured. Moreover, it was also observed their influence on the mixing time and the CO_2 volumetric mass transfer coefficient at various carbon dioxide injection flows. The data of the hydraulic flow rates obtained, without any gas injection, are respectively 4 L min^{-1} for the lower configuration of the circulator, 14 L min^{-1} for the medium level and 18 L min^{-1} for higher level. However, since the CO_2 is injected immediately upstream the circulator, as the injected CO_2 flow increases, a reduction in the hydraulic flow occurs. A CO_2 flow rate of 0.06 L min^{-1} reduces by 10% the hydraulic flow at level I. At level II a CO_2 flow of 0.48 L min^{-1} is required to obtain the same reduction in the hydraulic flow. While, at level III of the circulator there is no significant reduction up to values higher than 1.08 L min^{-1} of CO_2.

The other fluidodynmic parameters measured is the time mixing t_M. The values of the t_M obtained are 13.57, 4.10 and 3.23 min, respectively for the hydraulic flow rate 4, 14 and 18 L min^{-1}. This result suggests that it is no convenient to operate this PBR at level I because it would provoke poor mixing conditions and likely favor the formation of microalgae sediments. While, evaluating the energy consumption of the circulator that are 46, 26 and 38 W m^{-3} h^{-1}, respectively for the three levels. It is clear how operating at level III of the circulator, with the highest liquid speed, is energetically disadvantageous.

Since microalgae carbon bio-fixation rate is one of the main targets of this PBR system, the CO_2 transfer coefficient (k_La CO_2) was investigated. As shown in Table 1, k_{La} values were not measured for the carbon dioxide flow rates that decrease the hydraulic flow below the 90%. The data obtained show that the k_La CO_2 values increase linearly with the increase of the CO_2 flow injected, in each conditions of the hydraulic flow rate. Moreover, as already observed in the case of the mixing time parameter, it is not convenient to operate at level I and increasing the

hydraulic flow from level II to III does not result in an increase of k_La, further suggesting that it is not energetically convenient to operate the PBR at level III.

Table 1. CO_2 mass transfer coefficient as a function of the hydraulic and CO_2 flow rate.

	k_La CO_2 [s^{-1}]		
CO_2 flow rate [nL min^{-1}]	**Circulator level I**	**Circulator level II**	**Circulator level III**
0.06	1.21 · 10-5	1.89 · 10-5	1.64 · 10-5
0.12	1.47 · 10-5	3.43 · 10-5	-
0.48	-	1.30 · 10-4	1.24 · 10-4
0.60	-	-	-
0.84	-	-	-
1.08	-	-	2.99 · 10-4

The lighting system provides a mean incident light intensity of ~ 120 µmol m^{-2} s^{-1} with a light uniformity coefficient UI of 40%. The trend of light distribution presents the peaks corresponding to the fluorescent tubes positioning along the surface of the optical guide. The low UI value and the trend of distribution implicate that culture is exposed to a fluctuating light intensity along the path, which might cause a loss of photosynthetic productivity. Moreover, the energetic consumption of the lightning system, about 400 Wh, is still too high and decreases the global efficiencies of the process.

The biological tests were carried out using the level II of the circulator since, based on the results obtained from the previous parameters, represents the best condition. The tests were conducted with 3 different CO_2 flow rates, respectively 0.06, 0.12 and 0.48 L min^{-1}. Monitoring the dry weight value daily, growth curves were created, Figure 1. Observing the curves, it is possible to notice that the trends are very similar to each other, especially for the two largest CO_2 flows.

The CO_2 bio-fixation rate (ηCO_2) was calculated at the end of each biological test. The values obtained are 52, 67 and 63 %, respectively for the injected CO_2 flow rate 0.06, 0.12 e 0.48 L min^{-1}. Therefore, it can be observed, through the growth curves and the CO_2 bio-fixation values obtained, how the optimal configuration is a carbon dioxide flow equal to 0.12 L min^{-1}.

4. Conclusions

The photobioreactor represent a new and innovative microalgae cultivation system, that uses a hydraulic circulation systems to mix and transport the biomass. Although the hydraulic parameters, that characterize the PBR, are comparable with the ones observed in literature, there are still some elements, such as the lighting system, which need to be optimized. However, biological tests have shown that the average productivity obtained is 0.208, 0.223 and 0.219 g L^{-1} d^{-1}, respectively for 0.06, 0.12 and 0.48 L min^{-1} of CO_2 flow rate. Moreover, the microalgae are able to reach 52, 67 and 63 % of CO_2 biofixation efficiency.

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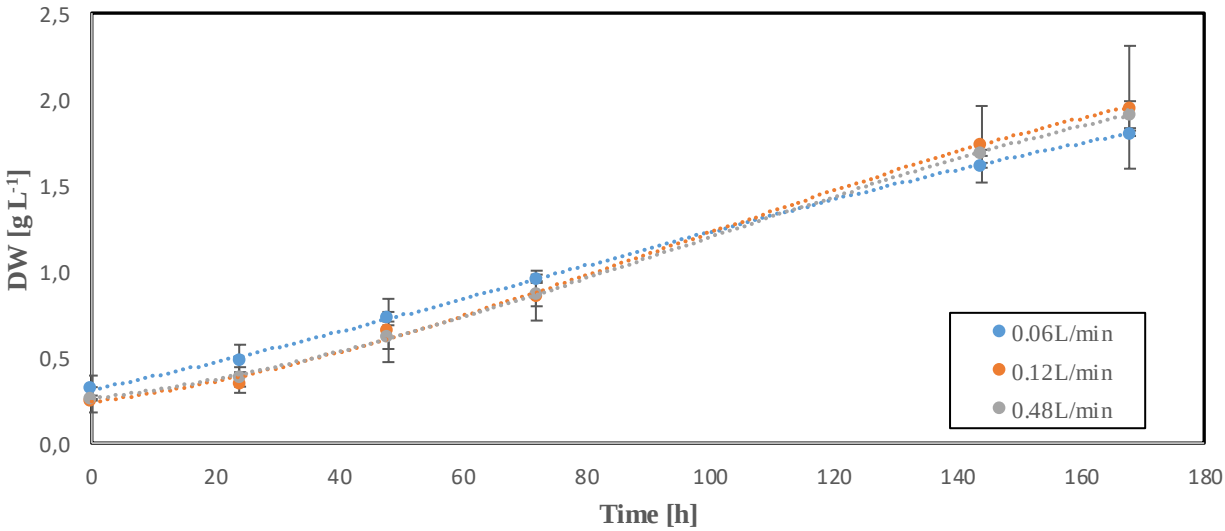

Figure 1: Growth curves of the biological test carried out with a three different CO2 flow rate.

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