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New ultra-flat photobioreactor for intensive microalgal production: The effect of light irradiance

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ABSTRACT

One of the main bottlenecks for the exploitation of microalgae is the low biomass concentration of the cultures: high harvesting costs and large cultivation area are always required. This bottleneck is partly due to a low light availability along the optical path of photobioreactors. An ultra-thin flat photobioreactor (UFP) (3 mm thickness) was proposed to increase both biomass concentration and productivity. The performance of the UFP was investigated: the effects of incident light intensity - from 50 and 1000 $\mu mol_{Photons}\, m^{-2}\, s^{-1}$ - on cell growth, photosynthesis rate, and biochemical composition of *Chlorella sorokiniana* were characterized. The maximum microalgal concentration and the maximum areal productivity were $24\, kg\, m^{-3}$ and $1.34\, g\, m^{-2}\, h^{-1}$, respectively. The cell specific growth rate reached $0.1\, h^{-1}$ at $1000\, \mu mol\, m^{-2}\, s^{-1}$. The biochemical composition of the microalgal biomass changed with the light irradiance. Protein content increased from 35 up to 53% of DW with increasing the light intensity. The concentration of storage compounds, such as starch and lipids, decreased from 30 to 16% and from 30 to 10%, respectively, with increasing the light intensity. A limit in the maximum biomass concentration achievable was identified. Several hypotheses have been discussed. A light transfer model was applied to assess the presence of light limitation. Other hypotheses were analyzed in depth and the most feasible explanations were found to be a) the damage to the photosystem when exposed for long period to continuous and high light irradiances, b) nutrient limitation due to salt precipitation or c) gas-liquid transfer of the CO_2. Finally, benefits and drawbacks of the ultra-thin culture system were discussed.

1. Introduction

The potential of microalgal cultures has led to applications in many industrial fields. Dozens of enterprises have been founded in the recent years with the aim to produce sustainable bioproducts: renewable oils for more sustainable fuels, ingredients for healthy foods and industrial products for personal care [1]. It was proved that microalgae are a source of proteins characterized by high nutritional value and emulsifying properties [2,3]. The lipid fraction includes omega-3 and other polyunsatured fatty acids, that can be used as food additives. Instead TAG (triglycerides) can be used as feedstock for biodiesel production [4]. Pigments, such as chlorophylls, are used as food colorants [5]. Moreover, valuable pigments such as β-carotene, lutein, tocopherols and astaxanthin are also exploited in cosmetics and pharmaceutics [6]. Carbohydrate fractions are proposed for fermentation and bio-ethanol production [7] or as bulk chemicals [8].

The market of bioproducts from microalgae is currently limited and one of the main reasons is the low biomass concentration and productivity during microalgal cultivation. Although microalgal productivity far exceeds crop cultures, the facility and the processing costs still negatively affect the economy of the process [9,10] and confine microalgal productions to high value compounds only. The low biomass concentration is mainly caused by low light availability in the large-scale culture systems. Indeed, when the biomass concentration in a photobioreactor (PBR) increases, a more extended inner dark zone establishes. The energy associated with the low light irradiance in this zone becomes even smaller than the energy required for the maintenance of the cells and the photosynthetic efficiency of the culture is affected [11]. In order to avoid light limitation, flat-panel PBRs [12–15] and open thin-layer pounds [16] have been proposed by several research groups. These culture systems are characterized by a short optical path (≤ 1 cm) that reduces the PBR volume for the unit irradiated area and the shadowing effect among microalgal cells. The concentration and productivity of microalgae achieved in these culture systems

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are quite high. Moreover, the flat-panel PBRs are easy to scale up and some applications as building-integrated PBR have already been proposed [17].

The current configurations of flat PBR systems are characterized by thickness larger than 7 mm [12,14]. In this study a new ultra-flat PBR has been developed. The innovation is the extremely reduced optical path of 3 mm aimed to increase the microalgal concentration and productivity. The performance of the proposed PBR has been characterized with reference to a robust microalgal strain *Chlorella sorokiniana* [18]. The effects of light intensity on growth, photosynthesis, and biochemical composition of the strain in the proposed PBR have been investigated. The light transfer model proposed by Pruvost and Cornet [19] was applied to assess the light availability in the ultra-flat PBR. Benefits and issues of this PBR are discussed and potential solutions for advancement in the ultra-flat technology are proposed.

2. Materials and methods

2.1. Ultra-flat photobioreactor system

The experimental apparatus consisted in an ultra-flat photobioreactor (UFP), an irradiance system, a cooling system, and a gas feeding system.

The diagram and the photo of the UFP are reported in Fig. 1. It consists of three Plexiglass panels (86 × 18 cm × 0.5 mm) spaced out by two silicone sheets, characterized by a thickness of 3 mm, conveniently cut out to outline the reactor. Two compartments – front and back – were formed by the sandwich structure panel-sheet-panel-sheet-panel. Each panel globally absorbed 1% of the incident irradiance (measured by light sensor Li-cor). The front-compartment was exposed to the light and housed the microalgal culture. The final volume of the culture was 0.3 L. The back-compartment was the cooling jacket equipped with four ports (two at the top and two at the bottom of the panel) for the circulation of cooling water. A gas stream was sparged into the culture from the bottom of the photobioreactor through four 1 mm orifices. The head of the PBR was equipped with four ports for sampling and venting. The reactor was chemically sterilized by 2% Steril-C sterilizing solution.

The irradiance system was made of two indoor LED floodlight lamps (Tech-mar, Prince 4) able to irradiate up to 3500 $\mu mol\ m^{-2}\ s^{-1}$. The lamps irradiated the front of the PBR. The irradiation was continuous (24/24 h) and the average light irradiance was set at different values between 50 and 1000 $\mu mol\ m^{-2}\ s^{-1}$.

The temperature of the PBR was kept at 25 ± 2 °C by using an external thermo-cryostat connected to the cooling jacket.

The gas feeding system consisted of: air and pure CO_2 from a pressurized vessel; a gas mixer device (Bronkhorst, model: El-flow Select Series); a hydrophobic filter (0.2 μm) to sterilize the gas stream fed to the PBR. The gas flow rate was set at 4 vvm. The initial CO_2 concentration was set at 2% of the gas flow (0.08 vvm of pure CO_2). As the culture concentration increased, the CO_2 concentration in the gas stream has been increased up to 18% (0.72 vvm of pure CO_2) in order to control the pH of the culture at 7 and avoid carbon limitation. The final gas flow rate was maintained constant at 4 vvm.

2.2. Strain and nutrients

The microalgal strain was *Chlorella sorokiniana* Shihiraet Krauss

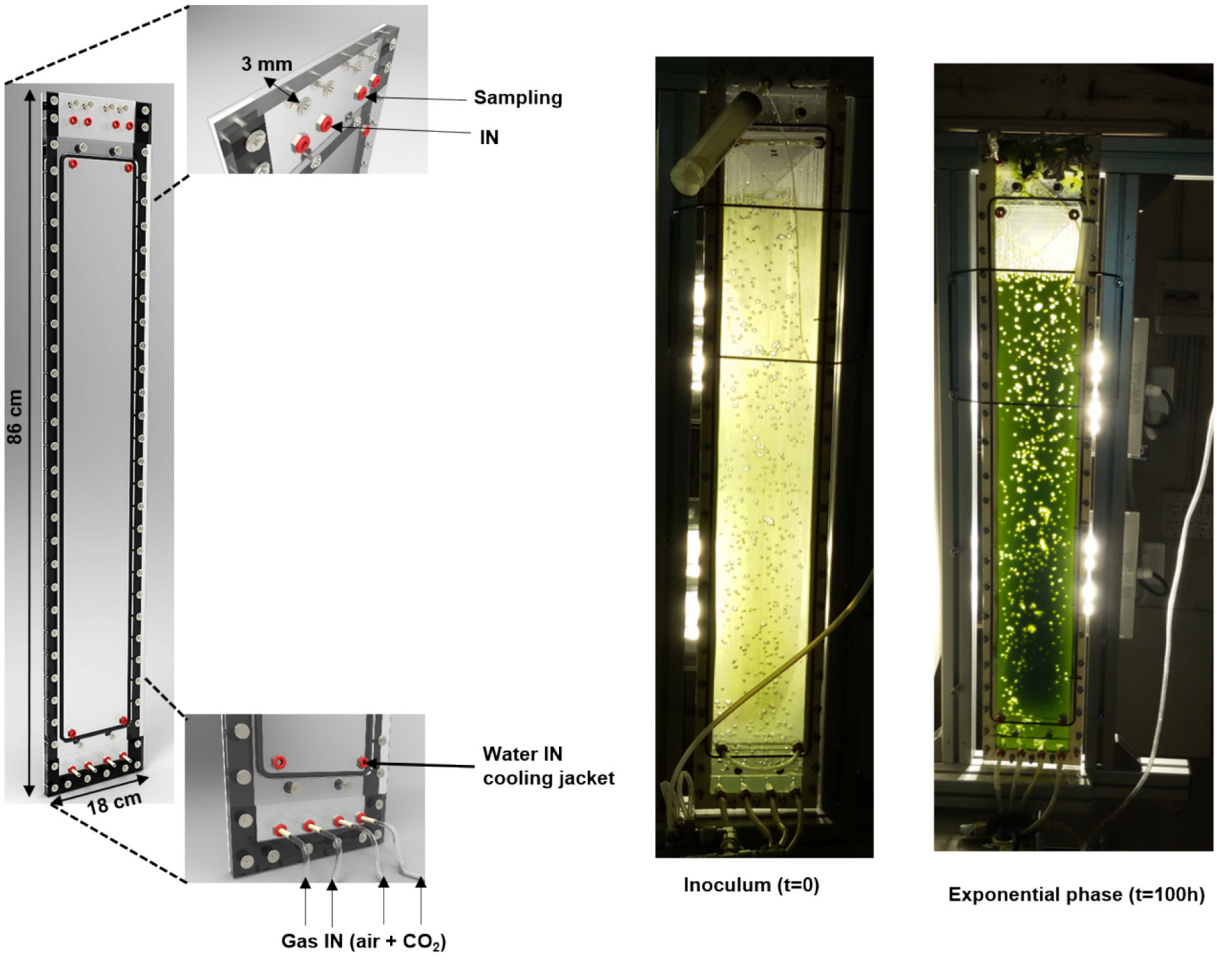

Fig. 1. Diagram and photos of the UFP.