Bioresource Technology 239 (2017) 211–218

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Development of an X-Shape airlift photobioreactor for increasing algal biomass and biodiesel production

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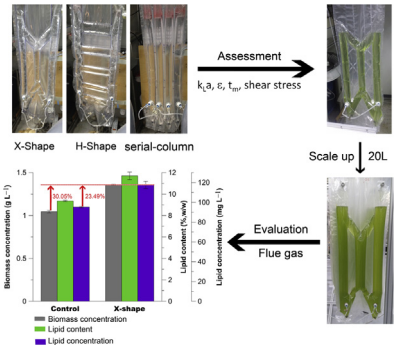
HIGHLIGHTS

- X-Shape airlift PBR was suitable for high production of algal biomass and lipid.
- Biomass and lipid production in X-Shape raised 30.05% and 23.49%, respectively.
- X-Shape induced high MUFAs which are suitable for high quality of algal biofuel.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 31 March 2017
Received in revised form 4 May 2017
Accepted 5 May 2017
Available online 8 May 2017

Keywords:
Photobioreactor
Hydrodynamic properties
Mass transfer coefficient
Microalgae
Biomass and biodiesel production

ABSTRACT

The aim of this work was to develop a high efficient photobioreactor for increasing biomass and lipid production in microalgae by assessment of the hydrodynamic properties and k_La which are important parameters for improving the algal cultivation efficiency. We designed three different photobioreactors (H-Shape, X-Shape and serial-column). Among them, X-Shape showed the highest hydrodynamic properties and k_La for algal cultivation. Thus, we evaluated the biomass and the lipid production in a 20 L scale-up X-Shape photobioreactor. The biomass and lipid production from X-Shape photobioreactor are 1.359 ± 0.007 g L^{-1} and 117.624 ± 3.522 mg L^{-1}, respectively; which are 30.05% and 23.49% higher than those from the control photobioreactor. Finally, we observed the lipid from X-Shape had high MUFAs, CN and low IV, which is suitable for high quality of biodiesel, suggesting that it can be practicably utilized for mass production of algal biofuel.

1. Introduction

CO_2 gas from the combustion of fossil fuel is one of the major factors that contribute to the greenhouse effect. The two main approaches considered to reduce CO_2 emission are (*i*) CO_2 capturing through chemical reaction and (*ii*) biological fixation of CO_2 by microalgae (Wang et al., 2008). The former consists of cyclic carbonation and de-carbonation by producing metal carbonates via reaction of CO_2 with metal oxides (Gupta and Fan, 2002). The latter depends on the photosynthesis process, which consumes CO_2 and releases O_2 into the atmosphere. The microalgae-based biomass is one of the sources of biofuels. More and more research on cultivation of microalgae has been conducted in order to recognize the dominants of using microalgae to capture CO_2 and produce biofuel (Li et al., 2008; Huang et al., 2010; Razzak et al., 2013).

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http://dx.doi.org/10.1016/j.biortech.2017.05.030
0960-8524/

Microalgae are photosynthetic microorganisms that enable to convert carbon dioxide into useful biomaterials such as biofuel, food, pharmaceuticals, and have a rapid growth compared to the plant due to their simple structure (Li et al., 2008). Approaches are used to enhance biomass and biomaterials production in microalgae such as modified culture media and condition (Kong et al., 2010; Holcomb et al., 2011; Cai et al., 2016; Cho et al., 2017), or droplet-based microfluidic system for algal strain selection (Pan et al., 2011; Dewan et al., 2012; Sung et al., 2016). The main purpose of these approaches is to select the best strains and conditions for mass cultivation of microalgae in industrial fields.

In the mass production, microalgae can be grown either in opened culture systems or in closed systems (photobioreactors, PBRs). Recently reports show that closed systems have attracted much interest to cultivate algal biomass because of the disadvantages of the opened systems (Chisti, 2007). Closed PBRs can achieve higher biomass productivities and easily prevent contamination from external environment. Airlift and bubble column reactors are more considered to algal cultivation due to their simple structure, compact and easy to operate axenically. In comparison, airlift reactors outperformed bubble column reactors because of several major advantages such as homogeneous flow pattern, good mixing, high mass transfer coefficient, and low operating costs. The mixing inside airlift reactor could reduce the shear force in the liquid flow, which could restrict the algal growth. Furthermore, the well-defined fluid flow pattern in the airlift reactor could help increase light utilization for the high cell density systems (Merchuk et al., 1996, 1998; Xu et al., 2009).

Although a number of PBRs have been studied, only few of them can be feasibly utilized in outdoor cultivation of microalgae. One of the main setbacks is the inefficient PBRs used for outdoor cultivation. A thorough understanding of the hydrodynamic and the mass transfer of PBRs is required to achieve higher efficient PBRs for microalgal cultivation. Recent research on PBR hydrodynamic generally focused on gas hold-up, mass transfer coefficient (k_La), effect of shear stress on algal growth and mixing time assessment.

In this paper, for the first time, we developed an airlift thin-film made of low-cost polypropylene beside other designs and characterized the hydrodynamic properties, volumetric mass transfer coefficient of the new geometric designs. The most efficient design was scaled up for large scale production of biomass in model alga, *Chlamydomonas reinhardtii*, as well as assessed its lipid production in comparison with the previous design that is already applied in outdoor cultivation using flue gas.

2. Materials and methods

2.1. Schematic design of photobioreactor

The designs of three new geometric photobioreactors (PBRs) were generated using AutoCAD as showed in Fig. 1. Those PBRs were made of low-cost polypropylene-based (CPP) film due to the transparence and high durability of the material. Baffles were sealed with the vacuum sealer machine (Intrise Co. Ltd., Danwon-gu, Ansan-si, Gyeonggi-do, Korea). The working volume of these PBRs were 5 L each and the column diameter was 5 cm. Stone sparger was used to input gases into the PBRs. The number of sparger used was 2 spargers for X-Shape and H-Shape, and 4 spargers for serial-column (Fig. SI1).

2.2. Photobioreactor characterization parameters

2.2.1. Gas hold-up (ε)

ε was calculated by the ratio between the difference of the height of liquid after sparging gas to the liquid media and was calculated by the Equation (Chisti, 1989):

$$\varepsilon = (H_G - H_L)/H_L \quad (1)$$

where H_L and H_G are the height of liquid and (gas + liquid) in the PBR, respectively.

2.2.2. Mixing time (t_m)

t_m was measured by the pH tracer method (Chisti, 1989). In detail, 2 mL of 2 M NaOH was added at the bottom of the PBR. A pH electrode probe (Hanna, South Korea) was located at the top of the PBR to record the change of the pH in the liquid until the change reaches 5% deviation from fully homogeneity liquid (Fig. SI2). The time needed to reach that change in different PBRs was noted and compared.

2.2.3. Gas liquid mass transfer coefficient (k_La)

Dynamic method was used to determine the k_La (Kargi and Moo-Young, 1985). An electrode DO sensor (DO-5512SD, Lutron, Taiwan) was placed at the top of the PBR to measure the dissolved oxygen (Fig. SI2). To measure the k_La, dissolved oxygen was first removed by nitrogen sparging to the reactor until the dissolved oxygen reached stable at near zero. Then, air was sparged to the reactor until dissolved oxygen concentration approached the saturation point. The slope of the graph was calculated by the equation:

$$\ln\left(\frac{C^* - C_0}{C^* - C}\right) = k_L a(t - t_0) \quad (2)$$

where C^* is the saturated dissolved oxygen concentration, C_0 is the initial dissolved oxygen concentration at time t_0, and C is the dissolved oxygen concentration at time t. The left hand side of this equation was plotted against time $(t - t_0)$ in order to obtain k_La as the slope. k_La was then applied a temperature correction to 20 °C using the relation (Bouaifi and Roustan, 1998):

$$(k_L a)_{20\,^\circ C} = 1.024^{(20-T)}(k_L a)_T \quad (3)$$

where T is the water temperature during the experiment.

2.2.4. Shear stress effect

In the same operation conditions (*i.e.* light intensity, high gas flow rate) the reduction of biomass in each type of PBRs can indirectly indicate the shear stress effect on the cell growth. Xu et al. (2009) has demonstrated that when increasing the gas flow rate, the higher shear stress observed and probably resulted in the cell corruption. Therefore, in this study, the shear stress effect of each PBR was indirectly evaluated by the comparison of the biomass production of each type of PBRs at high gas flow rate (0.3 vvm).

2.3. Microalgae cultivation

2.3.1. Microalga strain and pre-culture condition

Chlamydomonas reinhardtii strain CC125 was obtained from Chlamydomonas Resource Center at the University of Minnesota. TP medium (pH = 7.0) (Kim et al., 2016) was used to culture cells. The strain was grown photoautotrophically under 100 $\mu E\ m^{-2}\ s^{-1}$ of LED light intensity in a 500 mL flask containing 200 mL culture media and incubated in the shaking incubation at 150 rpm, 25 °C while being provided with 5% CO_2 enriched air supply. LI-250 quantum photometer (Lambda Instrument Corp., Lincoln, Nebraska, USA) was used to measure the light intensity.

2.3.2. Culture condition

For the indoor 5 L working volume, cells were inoculated to the PBRs with the initial OD at 800 nm (OD_{800}) was 0.1. Cells were cultured with flue gas containing 5% CO_2 (v/v) at different flow rate ranged from 0.1 to 0.3 vvm and at a continuous 350 $\mu E\ m^{-2}\ s^{-1}$ light intensity. For the outdoor 20 L working volume, pre-cultured cells were inoculated to the PBRs (OD_{800} = 0.1). The