Biochemical Engineering Journal 134 (2018) 60–68

Contents lists available at ScienceDirect

Biochemical Engineering Journal

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

Regular article

Increasing microalgal lipid productivity for conversion into biodiesel by using a non-energy consuming light guide

Nekoo Seyed Hosseini, Helen Shang, John Ashley Scott*

Bharti School of Engineering, Laurentian University, Sudbury, ON, Canada

ARTICLE INFO

Article history:
Received 30 October 2017
Received in revised form 1 February 2018
Accepted 10 March 2018
Available online 11 March 2018

Keywords:
Microalgae
Gas-lift
Optimization
Light guide
Areal productivity
Biodiesel

ABSTRACT

Mass cultivation of photosynthetic microalgae combined with mitigation of carbon dioxide (CO_2) emissions from industrial off-gases to produce lipids as a biodiesel feedstock can help environmental sustainability. However, traditional open microalgae mass cultivation systems that use sunlight are typically no more than 30 cm deep due to light attenuation and self-shading by the mircroalgae and, therefore, have low CO_2 uptake efficiency due to their shallow depth. To address this issue, a non-energy consuming light guide was employed to diffuse light deep into a top-lit, 120 cm deep open gas-lift cultivation system. This gas-lift system has been already shown to increase areal biomass productivity by 60%. Without any increase in supplied light energy, the light guide enhanced light penetration into the bioreactor and resulted in further increases in biomass and lipid productivities per unit area of 33% and 16%, respectively. The factors influencing light and CO_2 absorption rates were investigated with a Plackett-Burman experimental design. Mathematical models for predicting biomass and lipid production as well as optimal bioreactor configurations for maximizing lipid production and minimizing production costs were then determined by applying response surface methodology. The optimum configuration of operational parameters identified by the optimization function was then verified in the gas-lift bioreactor equipped with the light guide and resulted in areal biomass productivity of 34.4 g_{dw}/m^2day and areal lipid production of 223.9 g_{Lipid}/m^2.

1. Introduction

Lipids produced by photosynthetic microalgae show great potential as a feedstock for biodiesel and other bioactive value-added compounds [1]. In addition, microalgae can potentially sequester sparged in carbon dioxide (CO_2) [2], such as found in industrial off-gas [3], thereby reducing green house gas emissions. Studies have, therefore, evaluated the absorption rate of CO_2 from actual and simulated off-gases in order to assess its influence on algal growth rates and biochemical composition of biomass [4–6].

For light energy as the driving force of photosynthetic reactions, sunlight and artificial lights have been both utilized to stimulate the algal growth. Light delivery [7], intensity [8], spectra [9], light-dark photoperiods [10], frequency [11], and light-exposed surface area [12] have been all reported to have significant impact on microalgal biomass formation rate. They can also influence the biochemical content, including lipids, carbohydrates, proteins, vitamins, pigments and antioxidants [13].

Baer et al. [14] for example, studied the effects of spectral light quality on biomass and phycobiliprotein productivities. Wu et al. [15] reported the variation of pigment and chlorophyll composition and antioxidant activities under light stress. The effect of light and nitrogen availability on growth and carotenoid accumulation in *Scenedesmus* sp. was studied by Pribyl et al. [8]. Furthermore, for specifically lipid production, nutrient deficiency [16], nutrient replete [17], off-gas CO_2 content [18], CO_2 supply strategy [19], pH [20], lighting duration [21], temperature [22], and hydrodynamic shear stress [23] showed having an impact.

The effectiveness of any microalgal-sourced process depends on maintaining low production costs whilst achieving the highest level of desired biochemical content [11]. Production costs include the operation and maintenance of cultivation systems, labor, raw materials and supplied energy. Cultivation of microalgae can be carried out in either open or closed systems. Open systems such as raceways or tanks need less capital investment and labor, and have lower operation and maintenance costs compared to closed systems [2]. To reduce the cost of construction and operation, open systems are usually buried in the ground and rely on sunlight to

* Corresponding author at: Bharti Schoot of Engineering, Laurentian University 935 Ramsey Lake Road Sudbury, ON, P3E 2C6, Canada.
E-mail address: jascott@laurentian.ca (J.A. Scott).

https://doi.org/10.1016/j.bej.2018.03.006
1369-703X/

avoid artificial lighting. However, due to their shallow operational depths of 15–30 cm or less due to self-shading by the microalgae [24], poor utilization rates of light and CO_2 have been reported as drawbacks compared to closed systems [25].

A one-meter deep, top-lit gas-lift open bioreactor has been proposed to improve CO_2 transfer rates by increasing the depth and consequently the gas-liquid contact time, as well as reducing the physical footprint of the algal cultivation system [26]. The surface of a top-lit culture receives the highest light intensity (such as by sunlight), which decreases exponentially with depth. However, the optimal conditions for growing microalgae require that only 20% of the system cycle be in the dark region and efficiency decreases significantly when this is above 50% [27]. The use of a gas-lift system in the deep bioreactor provided vertical circulation of algal cells from dark to light zones, thereby avoiding the expense of additional artificial lighting. Microalgal cells in the light zone convert light energy to chemical energy for carbon fixation and biomass production. Furthermore, biomass and lipid productivities were enhanced significantly due to light and hydrodynamic stresses [26].

Currently the solution to increase light exposure and thereby be able to use deeper cultivation tanks is to use sub-surface artificial lighting [24], such as optical fibers [28], and submerged LEDs [29], planner scattering light waveguides [30], and light guides [31]. Sun et al. [32] used 3 cm long cylindrical hollow tubes, horizontally fixed at the front wall of a flat plate photobioreactor and showed a 23% increase in biomass production. Castrillo et al. [33] studied feasibility of using cone-shaped light guides in a conceptual photobioreactors to improve light utilization efficiency. Fu et al. [34] reported an application of a horizontal light guide plate to improve biofilm formation in the photobioreactor. Zijffers et al. [35,36] proposed and simulated the use of frensel lenses and triangular-shaped light guides in a flat panel photobioreactor to focus and distribute light into algal culture. Biofouling, mixing impairment, high cost, and complexity, however, have been also reported [29]. For example, Miyake et al. [37] reported a high production cost and difficulty in cleaning with a fiber glass light diffuser used to distribute light into the deep part of a bioreactor.

To avoid the additional costs of installing, running and maintaining sub-surface artificial lighting in a deep bioreactor, a new kind of a non-energy-consuming light guide in a 120 cm deep, open gas-lift bioreactor is examined in this study. The light guide was a water-filled tansparent tube inserted vertically in the center of the draft tuble. As microalgal cells are not present in the light guide, the light can diffuse deeper into the bioreactor without being blocked due to the shadow effect. Turbulance created by the rising bubbles inside the draft tube was also found to prevent biofouling on the walls of the light guide.

The performance of the light guide was evaluated for growth of *Scenedesmus dimorphus* and optimized through a two step, screening-optimization method focused on lipid production per unit area occupied by the bioreactor. In the factor screening step, the influence of operational parameters on lipid production were evaluated through application of a Plackett-Burman design. In the optimization step, the configuration of the significant operational parameters that maximize the lipid productivity was obtained through applying a response surface methodology. The result of the optimization process was then verified with the top-lit gas-lift bioreactor equipped with the light guide.

2. Material and methods

2.1. Microalgae strain and media

The green microalgae *Scenedesmus dimorphus* were obtained from the University of Texas, Austin collection (1237 UTEX collection). Bold's Basal medium (BBM) [38] was used for photoautotrophic cultivation. The stock culture was incubated at 25 °C and 125 rpm. It was illuminated at 80 μmol/m^2s on a photoperiod of 12 h light/12 h dark and fed with Bold's Basal growth medium every three weeks.

2.2. The bioreactors setup

The bioreactor used in this study was a concentric draft-tube, gas-lift column modified from a previous study [6]. A draft tube with an internal diameter of 13 cm and height of 80 cm, was secured in a 20 cm-diameter outer column and placed 5 cm above the sparger (Fig. 1A). They were fabricated out of transparent Plexiglas with a wall thickness of 5 mm. Air mixed with carbon dioxide to simulate off-gas was sparged through a 10 cm diameter ceramic sparger with a mean pore size of 15 μm (Refractron Technologies Corp., NY, USA). The bioreactor had side ports at 5 cm and 50 cm from the base for taking samples. The depth of the bioreactor was varied by changing the dispersion height (Δh), which is the distance from top of the draft tube to the surface of the culture. The flow rate was controlled using rotameters (±5%) (Omega Engineering Ltd., QC, Canada).

As an open algal cultivation system, the bioreactor would be buried outside and light can not penetrate from the sides. In the laboratory setting, therefore, the outside of the bioreactor was covered with a layer of black plastic sheet on top of a white plastic sheet to block light entrance from the side. Light energy for the photosynthesis was provided only from the top of the bioreactor to simulate buried open systems on an industrial site, which is top lit by sunlight only. A 90 W circular grow light (UFO grow quad band (red, blue, orange, white), Ledwholesalers Inc., CA, USA) was used to provide a light/dark photoperiod. The photosynthetic active radiation at the surface of the culture was kept around 1000 μmol/m^2s by changing the distance between the light source and culture surface at different depths.

The light guide made of transparent Plexiglas with a 5 cm diameter was inserted in the center of the draft tube (Fig. 1B). The light guide was filled with water in order to increase the refraction of light. The presence of the light guide in the center of the draft tube changed the mixing pattern and turbulence. In order to evaluate its effect on productivity, the results were compared to a bioreactor where the light guide was covered with black plastic (dark guide) to prevent light transmission while replicating the turbulence produced by the light guide (Fig. 1C).

The light intensity was measured with a light meter (±0.4%) (LI–250 A, LI-COR Biosciences, NE, USA) equipped with a quantum sensor (±5%) (LI-193SA, LI-COR Biosciences, NE, USA). The light intensity was measured at increments of known distances below the surface to identify the transition from the light zone to the dark zone. An intensity of 50 μmol/m^2s was considered the minimum intensity for the light zone [39] to estimate light fraction (ε) as a ratio of the time algal cells spend in the light zone (t_l) over the mean circulation time (t_c) (Eq. (1)).

$$\varepsilon = t_l/t_c \quad (1)$$

The mean circulation time was calculated by measuring the time taken for a 5 mm colored tracer bead (Engineering Laboratories, NJ, USA) with the same density as water to circulate one cycle through an arbitrarily chosen horizontal reference plane in the bioreactor [6]. Make up water was supplied every day to compensate for evaporative losses and experiments were carried out at 22 ± 2 °C.

2.3. Experimental design

The design of the experiment consisted of two steps. The first step, factor screening, employed a five-factor two-level