Bioresource Technology 192 (2015) 432–440

Contents lists available at ScienceDirect

Bioresource Technology

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

Microalgae cultivation in a novel top-lit gas-lift open bioreactor

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HIGHLIGHTS

- We have devised a top-lit gas-lift open top microalgae bioreactor.
- It operates successfully with a water column depth of 1 m.
- Biomass volumetric productivities are comparable to traditional raceways.
- Areal productivities are significantly higher than traditional raceways.
- Use of CO_2 enhanced gas increases lipid productivity.

ARTICLE INFO

Article history:
Received 3 April 2015
Received in revised form 24 May 2015
Accepted 25 May 2015
Available online 29 May 2015

Keywords:
Microalgae
Gas-lift bioreactor
Top lit
Enhanced CO_2
Lipids

ABSTRACT

This work investigated a top-lit open microalgae bioreactor that uses a gas-lift system to enable deeper production depths, thereby significantly reducing the footprint. Growth of *Scenedesmus* sp. in a one-meter deep system by sparged with 6% CO_2-enhanced air was evaluated. The results gave comparable volumetric biomass productivity ($0.06\ g_{dw}\ L^{-1}\ day^{-1}$), but around three-times higher areal productivity ($60.0\ g_{dw}\ m^{-2}\ day^{-1}$) than reported for traditional raceways. The lipid content of the *Scenedesmus* sp. was increased by 27% with an enhanced level of CO_2 in the sparging gas.

1. Introduction

Due to dwindling reserves of fossil fuels and the impact on the global environment that their consumption can cause, alternative energy sources are needed. Specific species of microalgae with high photosynthetic rates and lipid content have the potential to provide one such alternative liquid fuel, biodiesel (Chisti, 2007). Furthermore, through microalgae photosynthesis there is opportunity to fix anthropogenic carbon dioxide (CO_2) from industrial point sources to both improve productivity and mitigate greenhouse gas emissions.

The diffusion of CO_2 from the atmosphere into a microalgal culture limits biomass productivity due to the low CO_2 content of air (around 380 ppmv) and the high surface tension of water (Zimmerman et al., 2011). Enhancing the supply of algae accessible carbon could, therefore, improve biomass density (Zhao and Su, 2014) and hence the economics of biodiesel production. However, adding inorganic carbon as bicarbonate salts or compressed CO_2 involves a relatively large cost. Therefore, the use of CO_2 bearing off-gas from industrial process is seen as an attractive economic option. Bounaceur et al. (2006) reported the CO_2 concentration in the off-gas from natural gas combustion, coal-fired power plants, steel and iron production as 9%, 10% and 30%, respectively. The CO_2 content of cement production off-gas has been reported as 15–25% and as 6–7% in smelter furnace off-gas (Laamanen et al., 2014). In addition, industrial off-gases released to the environment contain significant amount of waste heat that could be utilized to maintain the temperature of open ponds in cold climate regions (Shang and Scott, 2011).

Among various methods proposed for large-scale cultivation of microalgae (Zhao and Su, 2014) open oval raceways circulated by use of a paddlewheel are currently the most economic option for commercial scale production due to relatively low capital, maintenance and operation costs (Chisti, 2007). They are typically located in regions with warm temperature and also have intensive light

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http://dx.doi.org/10.1016/j.biortech.2015.05.092
0960-8524/

intensities, which can cause considerable evaporation losses and possible photoinhibition (Chisti, 2007). These regions are often semi-arid and suffer from lack of freshwater. Whereas regions that are rich in freshwater generally experience seasonal cold climates and consequently are not considered for outdoor algal production unless sources of "free" heat, such as that contained within off-gas can be utilized (Shang and Scott, 2011).

Open commercial raceways lit by sunlight only typically have large surface areas (e.g., 978 m^2/pond (Chisti, 2007)), but only operate at a water depth of 15–35 cm (Zhao and Su, 2014). Providing an appropriate large land space close to a fixed off-gas source may, therefore, prove difficult on an industrial site and distribution piping costs to transfer off-gas to remote algal farms will contribute significantly in the cost of cultivation (Putt et al., 2011). If the costs of supplementary below the surface lighting is to be avoided, then the depth is limited due to restricted sunlight penetration. However, if off-gas is to be bubbled through, the shallow depth is likely to lead to reduced CO_2 (and where applicable heat) transfer due to a short residence time. Weissman et al. (1988) reported 80–90% loss of CO_2 to the atmosphere. Overall, these limitations have led to low utilization of CO_2 and areal productivity (20 $g_{dw}\ m^{-2}\ day^{-1}$) in traditional raceway ponds.

Alternative designs have been presented to increase productivity and CO_2 capture efficiency in traditional raceways such as: using single or multiple sumps with/without baffles (Weissman et al., 1988; de Godos et al., 2014), a carbonation column system to circulate the culture through an absorption column (Putt et al., 2011), a carbon supplying device fixed at the bottom of the pond (Su et al., 2008) and an airlift-driven raceway design as a replacement of the current paddlewheel-driven design (Ketheesan and Nirmalakhandan, 2012). Although proposed configurations have provided enhanced CO_2 transfer efficiency, the reported areal productivities were not significantly improved.

Poor mixing, dark zones and inefficient light utilization are other factors inhibiting the productivity of open systems. Paddlewheel technology, which is relatively simple and inexpensive, is currently used for mixing raceways and provides a 0.1–0.3 $m\ s^{-1}$ horizontal liquid velocity, but limited vertical agitation. Increasing mechanical energy to achieve good turbulent mixing would markedly affect operation costs as well as potentially damage or stress microalgal cells.

A more desirable approach to utilizing CO_2 from off-gas to achieve longer gas–liquid transfer times, as well as providing greater per area (areal) productivity on industrial sites would be to have deeper ponds. In order to make the ponds deeper and avoid the cost of artificial lighting, gas-lift systems could be employed to provide vertical circulation of the microalgae. Gas-lift columns have gained acceptance for gas–liquid contacting applications in bioprocessing due to efficient mixing with low stress, high volumetric gas transfer and a lack of microbial growth on the walls (Kumar and Das, 2012).

There have been studies on deep vertical photobioreactors for algal biomass product (Barbosa et al., 2003; Luo and Al-Dahhan, 2011), but they have been generally restricted to enclosed bioreactors that are lit from the sides and the top. The use of a gas-lift system in large-scale open ponds has not, however, been widely studied. Furthermore, if relatively cost-effective open system designs are to be used with off-gas bubbled through, lighting will be restricted to solar radiation from the top. Otherwise the additional expense of installing, running and maintaining sub-surface lighting will be needed.

In this study, we have evaluated the feasibility of cultivating microalgae in a one-meter deep top-lit open bioreactor coupled with a gas-lift system. The volumetric and areal productivities, CO_2 sequestration rate and power requirement of the proposed configuration are reported and compared with traditional raceways and photobioreactors. In addition, the impact on lipid content of the *Scenedesmus* sp. was assessed.

2. Methods

2.1. Microalgae and culture medium

Scenedesmus dimorphus obtained from the University of Texas, Austin collection (1237 UTEX collection) was used for all experiments. The *Scenedesmus* species has been shown to out produce other microalgae, such as *Chlorella* sp. and *Chlorococcum* sp., with respect to percentage lipid content produced (Vidyashankar et al., 2013) and ability to grow under a wide range of CO_2 concentrations (Tang et al., 2011). The seed culture was grown in freshwater Bold's Basal medium (Andersen, 2005) in covered 180 L (120 × 30 × 50 cm) glass tanks at 22 ± 2 °C under cool white fluorescent light (approximately 60 $\mu mol\ m^{-2}\ s^{-1}$) and on a 12 h light/dark photoperiod. The cultures were continuously sparged with air for agitation and supplied with fresh Bold's Basal growth media every three weeks.

2.2. Laboratory scale bioreactor

The gas-lift bioreactors were constructed out of clear plexiglas tube with an internal diameter of 20 cm and wall thickness of 5 mm (Fig. 1). For operation as a gas-lift reactor, a concentric draft

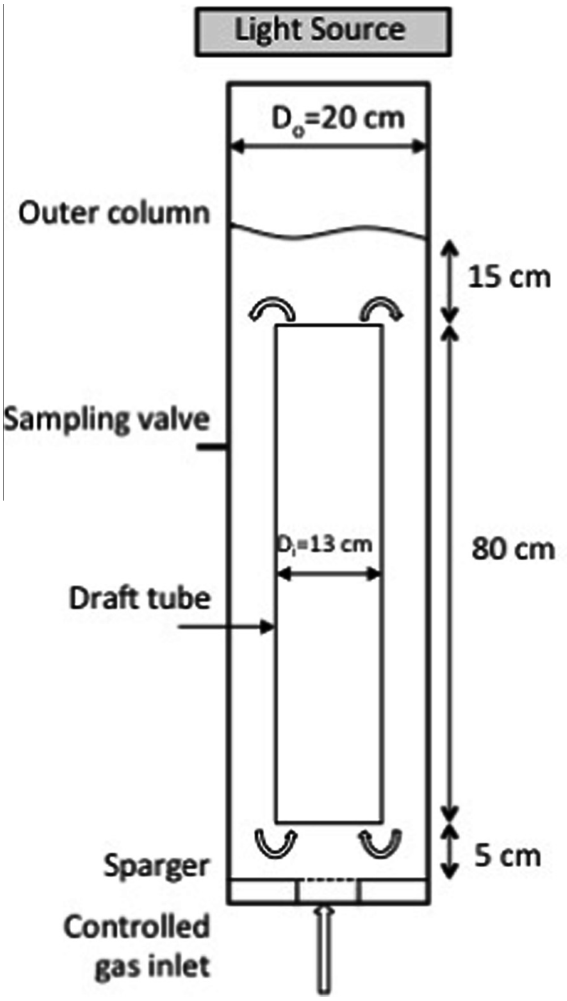

Fig. 1. Schematic diagram of the top-lit gas-lift bioreactor