Algal Research 21 (2017) 9–15

Contents lists available at ScienceDirect

Algal Research

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

Enhanced biomass/biofuel production and nutrient removal in an algal biofilm airlift photobioreactor

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ARTICLE INFO

Article history:
Received 12 June 2016
Received in revised form 23 October 2016
Accepted 7 November 2016
Available online xxxx

Keywords:
Microalgal biomass
Biofuel
Algal biofilm
Nutrient uptake
Photobioreactor

ABSTRACT

The production of algal biofuel has received increasing attention in recent years but is still not economically feasible due to a lack of reliable and cost-effective microalgal cultivation systems. In this study, a unique algal biofilm airlift photobioreactor (ABA-PBR) was developed for attached growth of the alga *Chlorella vulgaris* on a culture medium consisting of treated sewage. When the ABA-PBR is aerated, solid carriers suspended in the reactor are dispersed throughout the reactor via fluid circulation. A portion of the algal cells in the reactor are able to attach to and grow on the carriers. Prior to ABA-PBR experiments, batch adsorption experiments were performed to choose the best solid carrier for the ABA-PBR. The carriers were named C-1, C-2 and C-3 and were made of fiber, plastic and terylene respectively. The highest microalgal adsorption capacity was observed for Carrier C-1, which exhibited a biomass adsorption capacity of 32.9 mg (g carrier)$^{-1}$. Carrier C-1 was therefore added to the ABA-PBR for algal cell attachment. Compared to a conventional photobioreactor (C-PBR) without solid carriers, the ABA-PBR achieved a higher volumetric biomass productivity (15.93 mg L^{-1} d^{-1}), and a higher algal lipid productivity (4.09 mg L^{-1} d^{-1}), as the solid carriers in the ABA-PBR facilitate the development of the algal biofilm system in the reactor. An aerial biomass productivity of 0.82 g m^{-2} d^{-1} was also achieved with the developed algal biofilm in the ABA-PBR. Furthermore, improved nutrient removal rates (1.00 and 0.20 mg L^{-1} d^{-1} for N and P, respectively) were also achieved in ABA-PBR due to the higher algal biomass productivity of the reactor.

1. Introduction

Microalgal-based biodiesel is an extremely promising renewable resource and has attracted increasing attention in the past decade [1–5]. However, current production of biofuels from microalgal biomass is hampered by a lack of reliable and cost-effective methods to produce and harvest algal feedstocks [6]. To offset the cost of fertilizers and freshwater required for the cultivation of microalgae, many recent studies have suggested that algal biomass production be incorporated with wastewater treatment and recycling [7–10]. This incorporation of algal biomass production with wastewater treatment is also beneficial for wastewater purification [11–13]. The nutrient assimilation abilities of microalgal cells can reduce the nitrogen and phosphorus contents of the wastewater to relatively low level to meet the increasing strict discharge standard of nutrients [14,15]. Furthermore, not only are the nutrients in the wastewater removed, but the nutrients are also captured by the microalgae and can be returned to the environment as agricultural fertilizers. Another advantage of microalgae-based wastewater treatment is the fixation of the greenhouse gas CO_2 via photosynthesis by the algal cells. To date, microalgae cultivations have been widely used for wastewater treatment and have demonstrated the ability to remove nutrients from many kinds of wastewater, including municipal wastewater [16,17], livestock wastewater [18,19], aquaculture wastewater [11], and industrial wastewater [20,21]. In most cases, >80% of the nutrients in the wastewater are removed, demonstrating the potential of combining wastewater treatment with algal biomass production.

To date, most of the information regarding microalgae cultivation with wastewater has focused on suspended culture systems, such as open pond and traditional photobioreactors. Algal biofilm culture systems, an alternative to traditional suspended culture systems, have received increasing attention in recent years. Algal biofilm culture systems can reduce the costs related to harvesting of algal biomass [22–24]. In addition to facilitating harvesting, algal biofilm culture systems involve the immobilization of algal cells within an algal biofilm that can be separated from the liquid medium. The microalgal biomass content of the system can therefore be maintained at a high level [25–27]. High concentrations of microalgae in photobioreactors are usually regarded as beneficial not only for algal biomass production but also for nutrient removal in microalgae-based wastewater treatment systems [22,27]. Moreover, attachment-based cultivation allows the

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http://dx.doi.org/10.1016/j.algal.2016.11.004
2211-9264/

hydraulic retention time (HRT) and the biomass retention time (BRT) of the culture system to be effectively separated [27–29]. This separation particularly beneficial for wastewater treatment, where a high BRT:HRT ratio is typically required.

Recently, various novel algal biofilm systems that integrate the cultivation and harvest of microalgae have been developed. In Gross's research, a rotating algal biofilm (RAB) system was developed to produce and harvest algal biomass. The attachment material in the RAB system was partially submerged in a nutrient-rich medium; and rotated between an air phase and the liquid medium [30]. Another of RAB system, in which ropes are wrapped around a cylinder that rotates between an air phase and a liquid phase, was designed by Christenson. In this system, algal biomass on a rope can be harvested by passing the rope through an adjustable-diameter scraper [22]. Johnson et al. developed a rocker algal biofilm system by placing a chamber on a rocking shaker. The attachment material which is located on the bottom of the chamber is alternatively submerged in culture medium for algal growth and then exposed to illumination for algal photosynthesis [25]. Liu et al. developed a vertical plate-attached algal biofilm system. In this system, microalgal cells attach and grow on the surface of a vertically oriented artificial support material [24]. These various algal biofilm systems showed great promise in producing concentrated algal biomass and minimizing harvesting costs. However, at present, the development of algal biofilm systems is still in its infancy when compared to suspended culture systems. The development of an efficient, inexpensive and scalable algal biofilm system will transform biofilm-based algal culture systems into economically viable alternatives for algal cultivation.

In this study, a unique algal biofilm airlift photobioreactor (ABA-PBR) equipped with suspended solid carriers is proposed for attached microalgae cultivation and nutrient removal from wastewater. In an ABA-PBR, suspended solid carriers act as supporting material for the cultivation of algal biofilms. When the ABA-PBR is aerated, the solid carriers are dispersed throughout the reactor via fluid flow. In this submerged algal biofilm system, the attachment materials are simply dispersed in the culture medium. Moreover, the structure of the reactor is also very simple. The performance of the ABA-PBR was evaluated in terms of algal biomass and lipid production as well as nutrient removal from treated sewage, and compared to that of a conventional photobioreactor (C-PBR). The results of this study suggest that the ABA-PBR algal biofilm system has great potential for use at large scales.

2. Materials and methods

2.1. Algal strain

The algal strain *Chlorella vulgaris* from the Culture Collection of Algae (Institute of Hydrobiology, Chinese Academy of Sciences) was used in this study. *Chlorella vulgaris* microalgae were pre-cultured in 500 mL flasks with BG11 culture medium under stationary conditions at 25 °C with continuous white fluorescent light illumination (161.1 μmol m^{-2} s^{-1}) and shaking at 100 rpm.

2.2. Batch adsorption experiments

Before performing ABA-PBR experiments, batch adsorption experiments were performed with several solid carriers to determine the algal biomass adsorption performance of each carrier. The results of the batch adsorption experiments were used to determine a suitable carrier for use in the ABA-PBR. For batch adsorption experiments, *Chlorella vulgaris* cells were first cultured to stationary phase in BG11 medium with the culture conditions described in Section 2.1. The cells were then transferred to 250 mL conical flasks, each containing 200 mL of culture liquor. The initial microalgae concentration in each flask was approximately 0.35 g L^{-1}. Equal weights (2.0 g) of three different kinds of solid carriers were added to different conical flasks. These carriers, named C-1, C-2 and C-3, were made of fiber, plastic and terylene, respectively. All of these carriers are widely used in traditional activated sludge biofilm processes for wastewater treatment. The properties of the solid carriers tested in this study are listed in Table 1. Three replicate conical flasks were used for each carrier. All conical flasks were incubated for 5 days with shaking at 120 rpm and 25 °C under continuous light illumination (161.1 μmol m^{-2} s^{-1}) from a white fluorescent light. After adsorption, the biomass contents of suspended algal cells were determined. Algal cells attached on carriers were then completely desorbed in water using an ultrasonic cleaner (500 W, 40 KHz, 30 min) [23]. The amounts of algal biomass in water were determined, and the algal adsorption capacity (mg biomass (g carrier)$^{-1}$) and algal adsorption percentages (%) of each solid carrier were calculated as follows:

$$\text{Adsorption capacity } (\text{mg g}^{-1}) = \frac{DW_a}{DW_c} \quad (1)$$

$$\text{Adsorption percentage } (\%) = \frac{DW_a}{DW_a + DW_s} \quad (2)$$

where DW_a and DW_s are the dry weights of the attached and suspended algal biomass in conical flasks, respectively. DW_c is the dry weight of the solid carrier (2.0 g).

2.3. Lab-scale reactor

Two lab-scale flat-plate ABA-PBRs with dimensions of 39 cm (L) × 26 cm (W) × 32 cm (H) were constructed out of plexiglass as shown in Fig. 1. The water depth in each reactor was maintained at 20 cm, and the working volume of the reactor was 20.3 L. On both sides of each reactor, two LED lamps (9 W, red/blue light ratio of 4:1) were placed 2 cm from the 39 cm (L) × 26 cm (W) wall. The maximum light intensity at the reactor wall was 120.8 μmol m^{-2} s^{-1}. The solid carrier that exhibited the highest adsorption capacity as determined by batch adsorption experiments was added to the reactor for algal cell attachment. At the bottom of each reactor, 4 perforated pipes were installed. Two pipes were installed on each side close to the 26 cm (W) × 32 cm (H) reactor wall. Air was pumped into the reactor through these pipes, forming the bubbles that drive circumrotation within the reactor. When aerated, the solid carriers are dispersed throughout the reactor via fluid circulation (Fig. 1). Algal cells suspended in the reactor can then continually attach to the solid carriers. At the end of the culture, suspended solid carriers can be easily captured for microalgae harvesting.

As a control, two C-PBRs without solid carriers were also constructed. All other properties of the C-PBR mirrored that of the ABA-PBR.

2.4. Treated sewage

The treated sewage that used as the cultivation medium in this study was collected from the outlet of a batch-scale sequencing batch reactor (SBR) used to treat municipal wastewater. Before use, the wastewater was filtered using 0.45 μm pore size GF/C glass microfiber filters (Whatman Co.) to remove particles and microorganisms such as bacteria, fungi and microalgae. The mean concentrations of the principal chemical compounds in the wastewater were (except for pH, values are in mg L^{-1}): NH_4^+-N, 0.04 ± 0.03; NO_3^--N, 15.81 ± 3.37; NO_2^--N, below 0.001; dissolved inorganic phosphorus (DIP), 3.07 ± 0.67; COD, 21.26 ± 4.84; total nitrogen (TN), 16.43 ± 3.12; total phosphorus (TP), 3.25 ± 0.71; pH 7.5 ± 0.3. The average concentration of dissolved inorganic nitrogen (DIN, NH_4^+-N + NO_3^--N + NO_2^--N) in the treated sewage was 15.86 mg L^{-1}, which accounted for 96.5% of the TN in the sewage. The ratio of DIP to TP in the treated sewage was 94.5%. Therefore, DIN and DIP are the main nutrients present in the sewage. DIN and DIP concentrations were therefore monitored and used to determine the nutrient removal performance of the reactors investigated in this study.