Chemical Engineering Journal 332 (2018) 277–285

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

Algal biofilm-assisted microbial fuel cell to enhance domestic wastewater treatment: Nutrient, organics removal and bioenergy production

Zhigang Yang[a], Haiyan Pei[a,b,*], Qingjie Hou[a], Liqun Jiang[a], Lijie Zhang[a], Changliang Nie[a]

[a] School of Environmental Science and Engineering, Shandong University, No. 27 Shanda Nan Road, Jinan 250100, China
[b] Shandong Provincial Engineering Centre on Environmental Science and Technology, No. 17923 Jingshi Road, Jinan 250061, China

ARTICLE INFO

Keywords:
Algae biofilm microbial fuel cell
Algal biofilm
Domestic wastewater
Microbial community
Biofuel

ABSTRACT

An algae biofilm microbial fuel cell (ABMFC) was established by integrating an algal biofilm (AB) with a microbial fuel cell (MFC) to facilitate the system's operation for nutrient removal and bioenergy generation. In batch mode, the removal efficiencies of TN, TP and COD in the ABMFC reached 96.0%, 91.5% and 80.2%, respectively, which performed much better than MFC or AB alone. The highest power density of the ABMFC (62.93 $mW{\cdot}m^{-2}$) was 18% higher than that of the MFC (52.33 $mW{\cdot}m^{-2}$), and a lipid productivity of 6.26 $mg{\cdot}L^{-1}{\cdot}d^{-1}$ could be obtained simultaneously. High-throughput sequencing revealed that Chlorobia and Deltaproteobacteria grew well in the symbiotic ABMFC system. Betaproteobacteria, versatile in organic pollutant degradation, was inhibited by algal biofilm; it may be due to the nutrients competitions between algae and Betaproteobacteria. It was proved that the ABMFC system was able to handle real, complex, variable wastewater in the continuous flow trials and a total energy of 0.094 kWh·per m^3 of wastewater was obtained in the process. This study not only developed a wastewater treatment and energy recovery method but also explored a better understanding of the mechanisms for the algae-bacteria system.

1. Introduction

The problems of water pollution and resource shortage have led us to treat and utilize wastewater with energy-efficient and resource-recovering technologies [1]. It was estimated that the chemical energy of municipal wastewater is at least 13 kJ/g-COD, which is about 9 times more than the current demand for its treatment [2]. The microbial fuel cell (MFC) is an emerging technology that directly generates energy from organics in wastewater, and is also an energy-saving technology with reduced or nil aeration and lower sludge production than aerobic activated sludge [1]. MFCs can effectively remove various biodegradable organics, like acetate, glucose, starch, and proteins, from waste streams such as brewery wastewater, dye wastewater and domestic wastewater [3]. However, MFCs alone have little ability to remove phosphorus and the rate of nitrogen removal was limited without specially designed removal processes [4,5].

An integrated process, which combines struvite with a MFC, successfully recovered 94% phosphorus from urine [6]. But the struvite precipitation performance greatly depends on the water composition, including pH and ammonium concentration [4]. Nitrate can be used as an electron acceptor at the cathode, allowing for simultaneous removal of carbon (anode) and nitrogen (cathode) [7]. Generally, nitrogen is present in domestic wastewater in the form of NH_4^+-N, so aeration to oxidize ammonium is necessary for simultaneous nitrification and denitrification in MFCs [7].

In order to overcome these disadvantages, MFCs were designed to incorporate microalgae, which could assimilate nutrients from wastewater efficiently for biomass synthesis, to establish an energy-efficient and resource-recovering technology [8]. On top of this, microalgae are deemed one of the promising feedstocks for biofuel production [9]. Many researchers have attempted to build a cathode compartment containing algae and separate it from the anode compartment by a cation exchange membrane. In that case, special designs were required to achieve the exchange of CO_2 and effluent between the anode and cathode compartments, resulting in the increase in the establishment and operation costs [10,7]. A symbiotic MFC system that mixed suspended algae with electrochemically active bacteria was established; it accomplished the simultaneous removal of nitrogen, phosphorus and organic carbon [5]. However, sedimentation of algae in the anode compartment would adversely affect the anode reaction, and the suspension of algae limits the practical application for continuous operation and harvest of algae for biofuels.

Recently, several studies indicated that the algae biofilm systems surpassed the suspended systems in regard to biomass productivity and

* Corresponding author at: School of Environmental Science and Engineering, Shandong University, 27 Shanda Nan Road, Jinan 250100, China.
E-mail address: haiyanhup@126.com (H. Pei).

http://dx.doi.org/10.1016/j.cej.2017.09.096
Received 8 July 2017; Received in revised form 14 September 2017; Accepted 15 September 2017
Available online 18 September 2017
1385-8947/

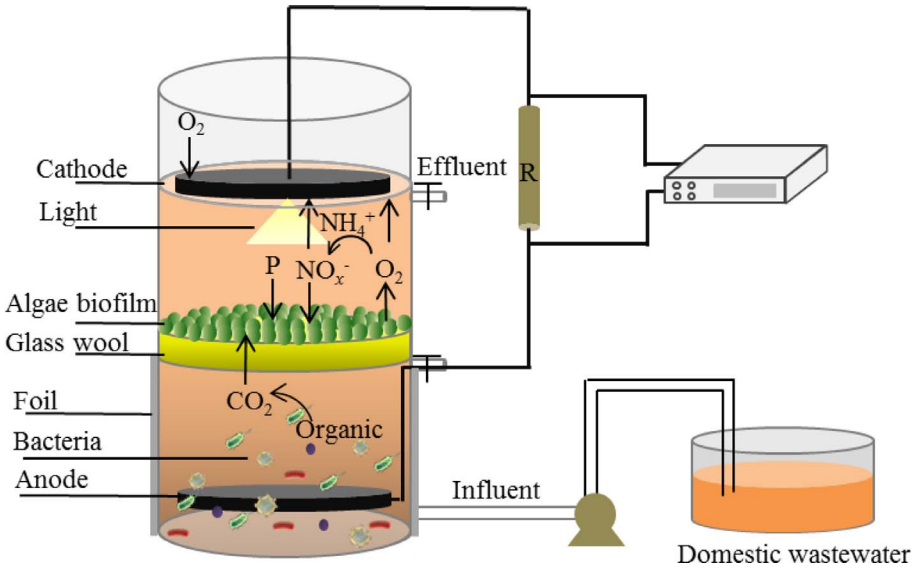

Fig. 1. Experimental set up of algal biofilm microbial fuel cell (ABMFC).

nutrients recovery [11]. However, algae biofilm alone cannot removal the organics efficiently. To address these problems, a microalgal biofilm was introduced to the MFC to establish an innovative ABMFC. The bacteria at the anode can use organic carbon to release electrons and CO_2, while the algae at the cathode can use the CO_2 for photosynthesis and take up nitrogen and phosphorus at the same time. Through these processes, organics and nutrients can be removed simultaneously, while power generation and growth of microalgae will be mutually promoted by one another. Additionally, the presence of an algal biofilm not only alleviates adverse effects between algae and electrochemically active bacteria, but also makes the harvest of algae convenient [11]. Meanwhile, in terms of practical application, microalgal biofilms can reduce the biomass losses and algae pollution from effluent in long-term continuous operation.

In this study, the performance of C, N and P removal, power generation, and lipid production were investigated in both batch operation and continuous operation. The identification and biometry of the microbial communities in MFCs were well-studied in previous research work, and were seen to vary greatly in response to different conditions, such as substrate and architecture [12]. However, no exhaustive information was available about microbial communities in algae-assisted MFCs, aside from the reports that focused on the cathode [4,13]. Therefore, the influence of algal biofilm on the microbial community structure at the anode was explored in this study in order to better understand the mechanisms of power generation and contaminant removal.

In a nutshell, exploitation of a comprehensive wastewater treatment and energy recovery process that integrates MFC and microalgal biofilms was elucidated in this study.

2. Materials and methods

2.1. Setup and operation of MFC

Before the ABMFC start-up, the MFC was built firstly in a Plexiglas cylinder (diameter 110 mm, height 250 mm). As anode electrodes, a piece of carbon cloth which (diameter 90 mm, thickness 8 mm) was interwoven with titanium wire was placed in the lower chamber of the MFC. A Plexiglas annulus (thickness 5 mm) was fixed in the middle of the cylinder as a supporting material for a piece of compressed glass wool (thickness 20 mm, diameter 110 mm), and also to establish an interface between the upper chamber and lower chamber of the MFC. A carbon cloth cathode (diameter 90 mm, thickness 8 mm) which was woven with titanium was placed on the water surface. The lower chamber of the MFC was wrapped with foil to prevent the growth of algae after inoculating the algal biofilm into the upper chamber. The reactors were fed domestic wastewater (obtained from the sewer at Shandong University, and filtered through gauze to remove solid granules) and operated with an external resistance of 1000 Ω at 25 ± 1 °C for 2 months to generate a stable voltage (about 510 mV).

2.2. ABMFC construction and operation

Scenedesmus quadricauda SDEC-8 (GenBank: KF999643) isolated from a local lake was acclimatized in domestic wastewater under continuous irradiation (135 $\mu mol \cdot m^{-3} \cdot s^{-1}$) at room temperature (25 ± 1 °C). The concentration and number of cells were estimated by optical density (OD) at 680 nm according to a correlation curve (Fig. S1).

To form a microalgal biofilm, the microalgae was preprocessed by centrifugation (3000*g*, 10 min) and then resuspended with domestic wastewater. The suspension was diluted with wastewater to form a 225 $mg \cdot L^{-1}$ (dry mass) microalgae solution. Glass wool (diameter 110 mm, thickness 20 mm) was placed in the bottom of a 1 L beaker containing 500 mL of microalgae solution. After cultivating for 10 days (135 $\mu mol \cdot m^{-3} \cdot s^{-1}$, 25 ± 1 °C), most algae covered the glass wool. The unattached algae were washed off by DI water. This process was repeated three times to form stable algal biofilm. Additional triplicate microalgal biofilms were cultivated and processed simultaneously to estimate the initial biomass of the microalgal biofilm. Before inoculation, possible residues of the substrates in the MFC were removed by washing the reactor with DI water. Then the prepared microalgal biofilm was placed on the annular Plexiglas which was fixed at the middle of the MFC to construct the ABMFC. A waterproof light bulb was fixed under the cathode electrode to achieve an illumination of 135 $\mu mol \cdot m^{-3} \cdot s^{-1}$ on the top of the biofilm (Fig. 1). Eventually, the effective volume of these systems was about 1.6 L.

This study was operated in batch mode firstly. For comparison, two control groups were included

I. MFC (wastewater treated by MFC): a MFC operated without algal biofilm under closed circuit conditions;
II. Algal Biofilm (AB) (wastewater treated by algal biofilm): a ABMFC operated under open circuit conditions.

After start-up, these reactors were refilled with the domestic wastewater, and operated with an external resistor of 1000 Ω under continuous irradiation (135 $\mu mol \cdot m^{-3} \cdot s^{-1}$) at room temperature