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Effects of electrode material and substrate concentration on the bioenergy output and wastewater treatment in air-cathode microbial fuel cell integrating with constructed wetland

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ABSTRACT

In the study, the effects of electrode material and substrate concentration on the bioelectricity generation and wastewater treatment performances in air-cathode microbial fuel cell coupled with constructed wetland (CW-ACMFC) systems were investigated. Four materials including carbon fiber felt (CFF), stainless steel mesh (SSM), graphite rod (GR), and foamed nickel (FN) were used as air-cathode and anode for each system. The obtained maximum power densities of Systems 1, 2, 3 and 4 were 4.80, 2.30, 3.35, and 5.11 mW m^{-2}, respectively. In addition, a relative higher NO_3-N removal efficiency was observed in four reactors, However, average COD removal percentages of Systems 1, 2, 3, and 4 were 42.30%, 37.42%, 48.78%, and 35.73%, respectively. The relative abundance of autotrophic denitrifying bacteria in the FN system was relatively higher. In summary, CFF and FN can be used as the electrode materials in the CW-ACMFCs system for wastewater treatment and bioelectricity generation simultaneously.

1. Introduction

Microbial fuel cells (MFCs) have been widely applied in bioelectricity generation from organic matters in the presence of electrochemically active bacteria (EAB) under mild reaction conditions (Du et al., 2007; Venkata Mohan et al., 2008). Compared with the suboptimal biochemical wastewater treatment or a wastewater polishing process, the membrane-free single chamber air-cathode MFCs (ACMFCs) with the advantages of low-cost operation and maintenance and sustainable and high power output (Fang et al., 2013; Zhao et al., 2013) are considered as one of the most viable configurations for large-scale applications in the future (Yuan et al., 2013; Liu et al., 2015). In an ACMFC, the proton exchange membrane (PEM) is not required and protons produced by the EAB can directly enter the cathode chamber (Yadav et al., 2012; Zhao et al., 2013). Electrons are transferred to the cathode and then combined with the protons and oxygen (a high redox electron acceptor) to form water (Logan et al., 2006; Corbella et al., 2014). One of the most important applications for MFCs is wastewater treatment because it can harvest bioenergy during the wastewater treatment (Abrevaya et al., 2015; Liao et al., 2015; Tian et al., 2015).

Constructed wetlands (CWs) have been received widely attention on their application in domestic sewage treatment in many small communities due to their advantages of easy maintenance and high self-purification capacity (Villasenor et al., 2013; Oon et al., 2015). In the wastewater treatment system, CWs are used to manage domestic or industrial wastewater under different conditions (Dunne et al., 2005). The dissolved oxygen (DO) concentration in CWs varies with the depth of wetlands and CWs provide natural habitats for a wide range of microorganisms (Ciria et al., 2005; Ojeda et al., 2008). Both CWs and MFCs possess aerobic and anaerobic zones, where the processes of oxidation and reduction reactions occur respectively (Liu et al., 2014). Therefore, a well-designed CW could simulate an MFC in situ for wastewater treatment and bioelectricity generation (Doherty et al., 2015).

In recent novel power generation technologies, MFCs are integrated with constructed wetlands (CW-MFCs) and significant progresses have been made (Yadav et al., 2012; Liu et al., 2014; Fang et al., 2015). It was reported that the maximum power density (15.73 mW m^{-2}) and current density (69.75 mA m^{-2}) were obtained with wastewater containing 1000 mg L^{-1} dye (Yadav et al., 2012). Similarly, after integrating MFC into a CW with a

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granular activated carbon and stainless steel mesh (GAC-SSM) biocathode, Liu et al. (2014) achieved the maximum power density of 55.05 mW m^{-2}. Recently, Fang et al. (2015) developed a CW-MFC to treat Azo dye wastewater and realized the highest power density of 852 mW m^{-2} and the decolorization rate of 95.6%. Fang et al. (2013) implied that the closed circuit in a CW-MFC was conducive to the growth of EAB especially autotrophs such as *Geobacter sulfurreducens* and *Betaproteobacteria* (Cha et al., 2010). However, it is impossible to maintain the high power generation in the CW-MFCs operated under the sequencing batch mode. In our previous study, the average voltage of CW-ACMFCs was significantly higher than that of the CW-MFCs systems under the sequencing batch mode. Therefore, the ACMFCs might be incorporated into CW systems. Unfortunately, CW-ACMFCs are not applied in wastewater treatment or bioelectricity generation because of the obstacles in engineering operation and economic electrode material.

In the CW-ACMFCs systems, substrate concentration and hydraulic retention time (HRT) are important influencing factors of their performances because they can affect other operation parameters (Nam et al., 2010; Pant et al., 2010). In this paper, we utilized carbon fiber felt (CFF), stainless steel mesh (SSM), graphite rod (GR), and foamed nickel (FN) as the cathode and anode materials of each CW-ACMFC, which were operated under the same organic load. These CW-ACMFCs with different materials were compared in terms of harnessing renewable energy, and the polarization characteristics of every ACMFC were also assessed at the end of each stage. In order to evaluate the contaminant removal efficiency of each microcosm, we investigated dissolved oxygen (DO), chemical oxygen demand (COD), and NO_3-N concentrations in each influent and effluent sample. Finally, the biomass density around the anode of each reactor was also measured.

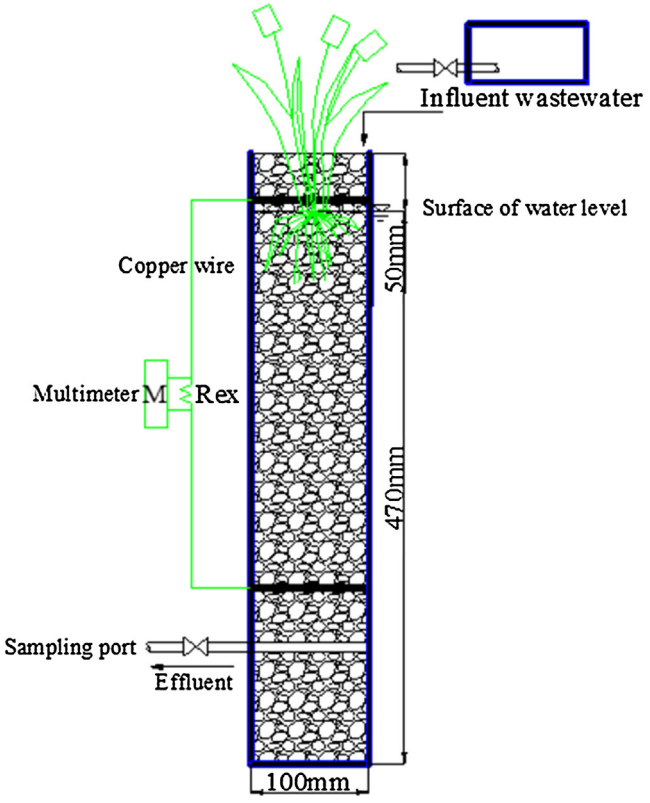

Fig. 1. Schematic diagram of the CW-ACMFC system.

2. Materials and methods

2.1. CW-ACMFC construction

As schematically shown in Fig. 1, CW-ACMFC systems with an analogous configuration of multiple porous filter bed column (10 cm in diameter) and different electrode materials were constructed. These four polyvinyl chloride units were filled with 0.52-m thick quartz sand with a grain size (4–6 mm in diameter). Disease-free *Canna indica* plant species were transplanted in CWs (2 rhizomes per unit) and the initial stem length was 35 ± 4 cm. The plant roots of each *Canna* were placed on the upper part of anodic compartment. Carbon fiber felt (CFF, diameter of 8 cm, thickness of 3 mm, Beijing Jixingshengan Industry & Trade Co., Ltd. China), stainless steel mesh (SSM, diameter of 8 cm, working surface area of 31.8 cm^2), graphite rod (GR, diameter of 1 cm, length of 8 cm, Beijing Jixingshengan Industry & Trade Co., Ltd. China), and foamed nickel (FN, diameter of 8 cm, thickness of 3 mm, Hebei Anpingxian Huirui Wire Mesh Factory, China) were used as the electrode materials in 4 reactors. The anode was 12 cm above the bottom of the microcosm and the cathode was embedded in the position at the surface water level (5 cm below the top of microcosm). The external electrical resistor (1000 Ω) was connected between the anode and cathode. Each external circuit was connected with copper conductors and the distance between the two electrodes was 35 cm. Sample ports of the anode compartment of each CW-ACMFC were 7 cm above the bottom of the wetlands. The total volume of the four CW-ACMFCs was 4.08 L with a liquid volume of 1.43 L.

2.2. CW-ACMFC operation

The anodic compartment of each CW-ACMFC was inoculated with the same volume of concentrated activated sludge (4.0 L), which was collected from a wastewater treatment plant in Songjiang District, Shanghai, China and then diluted with tap water. To evaluate the effect of contaminant concentrations on the wastewater treatment and bioelectricity generation performance of CW-ACMFCs, three types of simulated wastewater was prepared with glucose, KH_2PO_4, Na_2HPO_4, $MgCl_2$, $ZnCl_2$, $CaCl_2$, CH_3COONa, $CuSO_4$, $NaNO_3$, and tap water. The wetlands were operated under the same conditions and in the sequencing batch mode (during March to June, 90 days) and the contaminant concentration varied from 215 to 813 mg L^{-1} in the three consecutive periods. Synthetic wastewater was fed into the four CW-ACMFCs from the top and then discharged via perforated pipes at the bottom of the wetlands. In Period 1 (during March to May, 50 days), Period 2 (during May to June, 20 days), and Period 3 (during June, 20 days), three types of synthetic wastewater (1, 2, and 3, see Table S1) was respectively adopted as the influent water and the hydraulic retention time (HRT) in the three periods (Periods 1, 2, and 3) was respectively 24 h, 48 h, and 96 h. The longer first period was the start-up stage (30 days) for acclimation of wetland plants and the biofilm growth. In this study, the pH value of wastewater approximately varied from 7.2 to 7.5 and the air temperature ranged from 20 °C to 32 °C.

2.3. Bioelectricity monitoring and analysis

Cell voltages of the CW-ACMFCs across the external electrical resistance were recorded every 2 min with an automatic recorder intelligent instrument (UGA 22, Hangzhou Bright Technology Co., Ltd., China). To obtain the polarization curves of four CW-ACMFCs during the three periods, the current (I) and voltage (U) of external circuit were measured with a data acquisition module (VICTOR 86E, Shenzhen, China) through changing the external electrical resistance (R_{ex}) from 0 to 80000 Ω at the end of each period. The power density (P, mW m^{-2}) and the current density (J, mA m^{-2}) were cal-