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Electricity production and sludge reduction by integrating microbial fuel cells in anoxic-oxic process

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ABSTRACT

To produce energy and reduce sludge production from the treatment of municipal wastewater, four identical microbial fuel cells (MFCs) were constructed in an anoxic–oxic (A/O) process (MFCs-A/O system). Experimental results indicated that this system enhance the removals of chemical oxygen demand (COD) and total nitrogen (TN). The electricity produced by each MFC were ranged from 0.371 to 0.477 V (voltage) and from 138 to 227 mW/m^3 (power density) at the stable stage, when the external resistance was fixed at 1000 Ω. The coulombic efficiency of the MFCs-A/O system ranged from 0.31% to 1.68% (mean = 0.72%) at the stable stage, respectively. The removals of COD and TN in the MFCs-A/O system were slightly higher than those in the control system. Compared with the control system, the MFCs-A/O system can reduce waste activated sludge production and sludge yield by 24.0% and 24.2%, respectively. The experimental results indicated that the MFC constructed in A/O system improves wastewater treatment and the MFCs-A/O system can produce electricity while reducing sludge production and increasing wastewater treatment efficiency.

1. Introduction

Fossil fuels currently account for over 80% of the primary energy consumed worldwide (Bardhan et al., 2015) and their extensive utilization has led to serious energy crisis and numerous global environmental problems (Kumar et al., 2016; Qi et al., 2016). The need to mitigate these ongoing issues is urgent; therefore, new, renewable, and environmentally friendly sources of energy need to be developed (Kumar et al., 2016; Qi et al., 2016). Electricity production using a microbial fuel cell (MFC) is one promising method (Logan and Rabaey, 2012; Mohan et al., 2014; Moqsud et al., 2013). MFC is a biochemical-catalyzed electrochemical system that converts chemical energy to electrical energy by oxidizing biodegradable organic matter via the catalytic reaction of microorganisms (Logan and Rabaey, 2012; Mohan et al., 2014; Moqsud et al., 2013). MFC provides a new opportunity for direct electricity generation from renewable and biodegradable materials using active microorganisms. Furthermore, it is considered as a promising sustainable technology to meet increasing energy needs and uses the organic contaminants in wastewater as substrates (Logan and Rabaey, 2012; Mohan et al., 2014; Li et al., 2014; Moqsud et al., 2013). MFC is regarded as a highly adaptable technology for sustainable wastewater treatment for several reasons: (1) electric energy is directly produced and value-added products are generated; (2) the process produces good quality effluent with a low environmental footprint; (3) the process provides real-time monitoring and control; and (4) there is operation stability (Li et al., 2014).

However, to make it suitable for real-world applications, the MFC has to be combined with various wastewater treatment processes or systems (Li et al., 2014). Some wastewater treatment processes have been combined with MFC including activated sludge process (Li et al., 2014), anaerobic digestion (Li et al., 2014), membrane bioreactor (Li et al., 2014), anoxic-oxic (A/O) process (Chang et al., 2014; You et al., 2010), anaerobic-anoxic-oxic (A2/O) process (Xie et al., 2014, 2016). The A/O process is a common wastewater treatment process, which has been applied to treating a wide range of municipal and industrial wastewaters by removing chemical oxygen demand (COD), ammonium (NH_4^+-N), total nitrogen (TN), and suspended solids (SS) (Chan et al., 2009; Chang et al., 2014; Rasool et al., 2014). The A/O process has two stages, the anoxic stage and oxic stage, which are separated and distinguished by

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different dissolved oxygen (DO) levels (Chan et al., 2009). The DO in the anoxic stage is lower than 0.2 mg/L and is 2–4 mg/L in the oxic stage. In a two-chamber MFC, a typical type of MFC, the anode chamber is an anaerobic, or anoxic environment while the cathode chamber is an aerobic (oxic) environment. The two chambers are separated by a proton exchange membrane (PEM) or other types of membranes (Madani et al., 2015). Therefore, the environmental conditions of a two-chamber MFC are similar to those of the A/O process and it can be integrated in the A/O process. Researchers have been studying the combined MFC and A/O process system (MFC-A/O system). For example, Chang et al. (2014) studied the treatment of pharmaceutical and personal care product (PPCP)-containing sewage with a pilot-scale MFC-A/O system, and You et al. (2010) studied the treatment of saline seafood wastewater and electricity generation in a U-tube MFC-A/O system.

Sludge is an important by-product of the activated sludge process, which is the process applied in the oxic stage of A/O. The sludge yield in normal activated sludge process is approximately 0.3–0.5 g VSS (volatile suspended solids)/g COD or 0.5–0.8 g SS/g COD (SS/VSS = 0.6) (Metcalf and Eddy, 2003). The improper treatment and disposal of sludge will lead to some environmental issues, such as greenhouse gas emissions and secondary pollution (Li et al., 2015). Although sludge can be used to produce energy materials such as methane (Xiao et al., 2014), hydrogen (Sun et al., 2014), and electricity (Xiao et al., 2014), its treatment and disposal costs are still high (Guo et al., 2013). Because of its mass-yield, sludge treatment and disposal has become an important issue for many wastewater treatment plants, and reducing sludge production in the wastewater treatment is very significant (Guo et al., 2013). Sludge production is expected to be low in the wastewater treatment using MFCs because part of organic matter energy is converted into electricity by electricity-producing microorganisms (electricigens). The cell yield of electricigen (0.07–0.16 g VSS/g COD) is much less than that of normal activated sludge microorganisms (Huggins et al., 2013; Logan and Rabaey, 2012; Logan et al., 2015). Research has been conducted on reducing sludge production in wastewater treatment using MFCs (Gajaraj and Hu, 2014; Su et al., 2013). For instance, Su et al. (2013) reported the sludge production could be reduced by approximately 5.1% in a system combining a MFC and a membrane bioreactor. Later, Gajaraj and Hu (2014) noted that the combination of activated sludge processes with MFCs could reduce sludge production by approximately 6–11%. To date, however, the reduction of sludge production in wastewater treatment systems integrated with MFCs is still low, and no studies have been conducted so far on sludge production in the MFC-A/O process.

It is possible to simultaneously produce electricity, treat wastewater and reduce sludge production by integrating MFCs in the A/O process. Meanwhile, it is very important to produce electricity with practical meaning sludge reduction for applying MFC in practical wastewater treatment. The novelty of this study is to obtain practical meaning sludge reduction in wastewater treatment by enhancing the conversion of organic matters to electricity of integrating MFC. Therefore, the aims of this study are to investigate electricity production from practical municipal wastewater using the MFC-A/O process, as well as reduction of sludge production and wastewater treatment efficiencies of this process.

2. Material and methods

2.1. Municipal wastewater

The municipal wastewater, used in this study, was collected from a residential quarter of Beijing, China. The characteristics of this wastewater are summarized in Table 1.

Table 1
The characteristics of municipal wastewater used in the test.

Index	Range	Average
COD (mg/L)	108–371	203
pH	7.4–8.4	7.8
SS (mg/L)	24–451	165
NH_4^+-N (mg/L)	71.7–90.8	79.8
TN (mg/L)	73.8–93.3	82.8
C/N	1.3–4.7	2.5

2.2. MFC-A/O system

Two A/O process apparatuses, which were made of polyvinyl chloride, were used in the test. One A/O process apparatus was constructed with four identical MFCs with external resistances (MFCs-A/O), while and the other, used as control system, was constructed with four MFCs without external resistances (i.e., open MFC). The work volumes of the two A/O process tanks were 1 L (10 × 10 × 10 cm, anoxic tank) and 4 L (25 × 20 × 10 cm less 10 × 10 × 10 cm, oxic tank). To fully use the working volume of A/O process, the anoxic tank was placed in the oxic tank, and the four identical MFCs were constructed in the A/O process as follows (Fig. 1). Four carbon felt brushes were placed in the anoxic tank and used as the MFC anodes. Four carbon felt brushes, were placed in the oxic tank and used as the cathodes. Four PEMs (Ø = 5 cm) were installed in each of the four walls of anoxic tank. Then copper wires were used to connect the four external circuits with four fixed external resistances (1000 Ω) in the MFCs-A/O system. The anode carbon felt brushes were made of four carbon felt pieces (6 × 2 × 1 cm), which were fixed on a graphite rod (0.8 cm in diameter by 12.0 cm in length). The cathode carbon felt brushes were made of four carbon felt pieces (6 × 1 × 1 cm) which also fixed on a graphite rod (0.8 cm in diameter by 12.0 cm in length). The two electrodes were placed 2 cm apart for each of the four MFCs.

2.3. Wastewater treatment and electricity production

The wastewater was continuously pumped into the anoxic tank of systems with a flow velocity of approximately 9.26 ml/min using a peristaltic pump (Lange Co., China). The anoxic tank was mixed with a slow-speed stirrer to maintain low DO levels between 0.2 and 0.5 mg/L. To maintain an aerobic environment, the oxic tank was aerated with an aerator to maintain approximately 2.0 mg/L of DO. The settled sludge from the settlement tank was returned to both the anoxic and oxic tanks. The sludge return rates for the two tanks were 25%, with a flow velocity of about 2.31 ml/min, in the anoxic tank, and 75%, with a flow velocity of about 6.94 ml/min, in the oxic tank. The wastewater hydraulic retention times in the anoxic and oxic tanks were 1.8 h and 7.2 h, respectively. The activated sludge in the oxic tanks of two systems was periodically discharged as waste activated sludge (WAS) to maintain a stable sludge concentration (2.0–3.0 g SS/L).

2.4. Analytical methods and calculation of electrical parameters

The soluble COD (SCOD) and total COD (TCOD) of the influent and effluent for the two systems were quantified using a COD measurement system (HACH DR2800, USA) and COD kit (HACH 20–1500 mg COD/L, USA). The samples were filtered using 0.45 μm membranes before determining their SCOD. The pH of the wastewater was measured with a pH meter (Sartorius PB-10, Germany). The sludge concentrations (SS and VSS) were measured using the weight method, and NH_4^+-N and TN were measured using the spectrophotometric method (APHA, 1998). Wastewater TC was