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Long-term investigation of microbial fuel cells treating primary sludge or digested sludge

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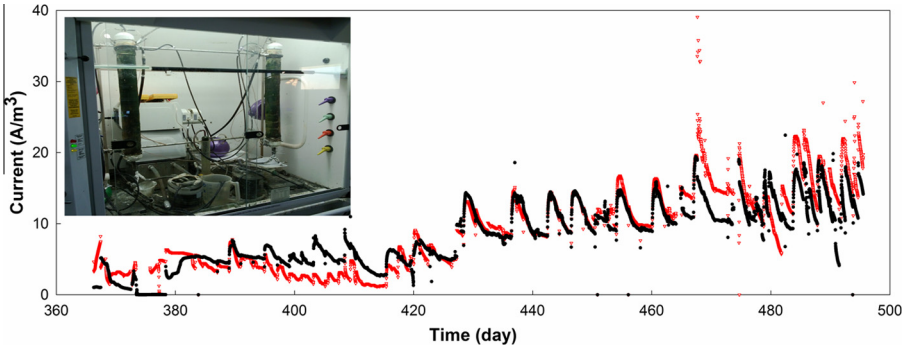
HIGHLIGHTS

- Two 1.8-L MFCs were operated on sewage sludge for almost 500 days.
- The MFCs achieved better treatment of primary sludge than digested sludge.
- Biogas production was produced from primary sludge and quantified.
- Total energy production in MFCs could be comparable to anaerobic digesters.
- Direct electricity generation had a minor contribution to total energy production.

GRAPHICAL ABSTRACT



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ABSTRACT

The long-term performance of sludge treatment in microbial fuel cells (MFCs) was examined by operating two MFCs for almost 500 days. In Phase I, one MFC fed with primary sludge removed 69.8 ± 24.1% of total chemical oxygen demand (TCOD) and 68.4 ± 17.9% of volatile suspended solids (VSS); the other MFC with digested sludge reduced 36.2 ± 24.4% of TCOD and 46.1 ± 19.2% of VSS. In Phase II, both MFCs were operated as a two-stage system that removed 60% of TCOD and 70% of VSS from the primary sludge. An energy analysis revealed that, although the total energy in the MFC system was comparable with that of anaerobic digesters, the electric energy had a minor contribution and methane gas still dominated the total energy production. The results suggest that MFCs may not be suitable for treating primary sludge for energy recovery, but could potentially be used to polish the effluent from anaerobic digesters.

1. Introduction

Sewage sludge is a byproduct of municipal wastewater treatment and generated from primary and secondary sedimentation. In municipal wastewater treatment plants, the treatment and disposal of sewage sludge can comprise up to 50% of the operation costs (Appels et al., 2008). There are several approaches for treating sludge to reduce solid contents and to stabilize biomass; however, anaerobic digestion (AD) is generally preferred because of its cost-effectiveness and bioenergy production. Digested sludge can be further composted for agriculture uses, and biogas can be converted into electricity and/or heat through combustion and thus compensate for some energy use in a wastewater treatment plant. Because of a large amount of organic contents, primary sludge contains about 66% of the energy content of wastewater (Ting and Lee, 2007), and about 81% of biodegradable organic energy may be converted to methane (McCarty et al., 2011). Despite the great energy potential with biogas production, several issues limit successful AD application; for instance, electric generators and their maintenance are costly, and biogas may need pre-treatment to remove contaminants such as hydrogen sulfide (Appels et al., 2008). In addition,

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energy will be lost during methane conversion, because the common efficiency of methane-to-electricity is about 33%. Therefore, it is of great interest to explore alternative technologies for sludge treatment and energy recovery.

The use of microbial fuel cells (MFCs) is a promising approach for direct production of electric energy or other energy carriers such as hydrogen gas from various organic substrates (Logan et al., 2006; Pant et al., 2010). Sewage sludge has also been studied in MFCs for electricity generation. A single-chamber MFC with a baffle inside its anode compartment generated low power from anaerobic sludge due to a large internal resistance caused by the baffle (Hu, 2008). Because hydrolysis is considered to be a limiting step in AD (Halalsheh et al., 2011), appropriate pretreatment is expected to improve the contents of soluble and small-particle organics that can be better used by microorganisms. The ultrasonic and alkaline pretreatment of sludge improved its degradability and resulted in a higher power output of 12.5 W/m^3, with 61.0% and 62.9% reduction of total chemical oxygen demand (TCOD) and volatile solids (VS), respectively (Jiang et al., 2009, 2010). Likewise, improved power output and solid production was observed in an MFC after pretreatment with sterilization and alkalization (Xiao et al., 2011). When an MFC was linked to an anaerobic digester to form an integrated recirculation loop, it was found that methane production was higher than the digester alone (Inglesby and Fisher, 2012), because a high concentration of ammonium/ammonia will inhibit methanogenic activity (Sung and Liu, 2003). The improved biogas production, resulting from the use of a recirculation loop, was likely due to the migration of ammonium ions from the digester to the cathode compartment of the MFC driven by electricity generation in the MFC, which was also demonstrated previously (Kim et al., 2008). A recent study reported the performance of MFCs in treating a fermentation solution from primary sludge, in which higher power production was obtained when treating a mixture of fermentation supernatant and primary effluent, because of elevated concentrations of soluble COD and volatile fatty acids after the fermentation process (Yang et al., 2013).

In general, previous research on using MFCs to treat sludge focused on the short-term performance of power production and COD removal, and few studies have examined biogas production and solid reduction in great detail. Furthermore, no studies have really shown the production of electric energy (in kWh) from sludge; power is not an energy parameter (He, 2013). In this study, we conducted a long-term (almost 500 days) investigation of MFCs treating sewage sludge for energy production, organics removal, and solid reduction. The experiment consisted of two phases: in Phase I, two tubular MFCs were operated with primary sludge and digested sludge, respectively, for more than 10 months; in Phase II, both MFCs were operated as a two-stage system to treat primary sludge for about 6 months. We examined biogas production in the MFCs and compared energy production between MFCs and anaerobic digesters. The results helped to better understand the application niche of MFC technology in wastewater treatment.

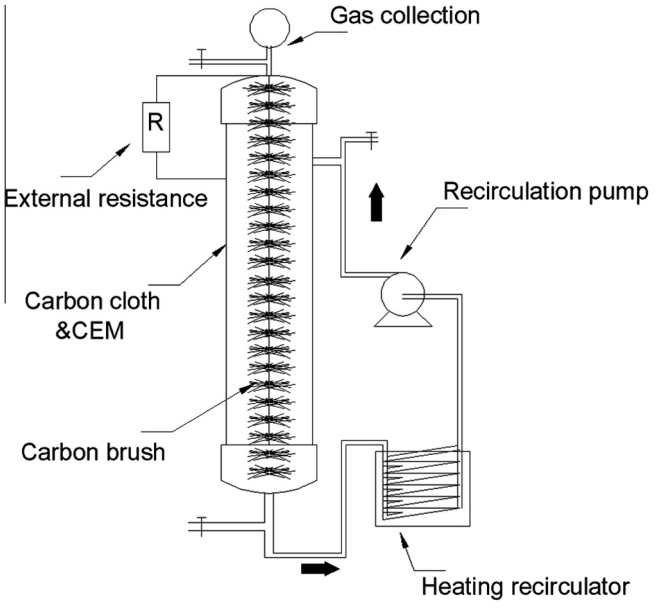

Fig. 1. Schematic of the tubular MFC used for sludge treatment.

2. Methods

2.1. MFCs setup

Two identical tubular MFCs were constructed based on a tube made of cation exchange membrane (Ultrex CMI7000, Membranes International, Inc., Glen Rock, NJ, USA) (Fig. 1). The membrane tube had a diameter of 6 cm and a height of 70 cm. A carbon brush (Gordon Brush Mfg. Co., Inc., Commerce, CA, USA) was used as an anode electrode and installed inside the membrane tube, resulting in an anode liquid volume of 1.8 L. The cathode electrode was carbon cloth (PANEX® 30-PW03, Zoltek, Corporation, St. Louis, MO, USA) coated with Pt/Carbon catalyst (0.2 mg Pt/cm^2). The cathode electrode wrapped the membrane tube and connected to the anode electrode by titanium wire and copper wire across a resistance decade box.

2.2. MFCs operation

Both MFCs (MFC-1 and MFC-2) were inoculated with raw sludge from a primary sedimentation tank (South Shore Water Reclamation Facility, Milwaukee, WI, USA). In Phase I, two MFCs were operated at an HRT of 9 days in each reactor: MFC-1 used the primary sludge as an anode substrate, while MFC-2 was fed with the digested sludge from the anaerobic digesters at South Shore Water Reclamation Facility. In Phase 1, the large particles in the sludge were removed using a 4-mm sieve before feeding. In Phase II, the two MFCs formed a two-stage MFC system, in which the primary sludge was first fed into MFC-1, and then the treated effluent of MFC-1 was transferred into MFC-2. Each MFC had an HRT of 7 days, resulting in a total HRT of 14 days in the two-stage MFC system. An electric blender was used to break the large particles in the primary sludge, and then the sludge was screened through a 3.3-mm sieve. To buffer the pH of the anolytes in the two MFCs, 1.68–3.36 g of $NaHCO_3$ was added at the beginning of each feed cycle. The anolytes were recirculated at 150 and 100 mL/min in Phase I and II, respectively. The temperature of the anolytes was maintained around 35 °C by using a heating recirculator (Model 1104; VWR International, LLC, USA), which heated a water bath housing the recirculation of the anolyte. The acidified tap water (pH = 2, adjusted using sulfuric acid) was recirculated at ~45 mL/min as the catholyte for both MFCs.

2.3. Measurement and analysis

The MFC voltage across an external resistor was measured using a multimeter (Model 2700; Keithley Instruments, Inc.). Biogas was collected and measured by the water replacement method. The composition of biogas (mainly CO_2 and CH_4) was analyzed by using a gas chromatography (Focus GC, Thermo Fisher Scientific, Waltham, MA, USA). TCOD concentrations were measured using a COD digester and colorimeter according to the manufacturer's instructions (Hach Company, Loveland, CO, USA). Total suspended