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Evaluation of electricity generation from ultrasonic and heat/alkaline pretreatment of different sludge types using microbial fuel cells

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HIGHLIGHTS

- Sludge pretreatment methods were compared for electricity production in MFCs.
- Various types of sludge were compared for pretreatment and MFCs operation.
- PS and ES were more susceptible to ultrasonic pretreatment than ADS.
- Electricity generation was proportional to SCOD removal with all sludge types.

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ABSTRACT

This study investigated the effects of different sludge pretreatment methods (ultrasonic vs. combined heat/alkali) with varied sources of municipal sewage sludge (primary sludge (PS), secondary excess sludge (ES), anaerobic digestion sludge (ADS)) on electricity generation in microbial fuel cells (MFCs). Introduction of ultrasonically pretreated sludge (PS, ES, ADS) to MFCs generated maximum power densities of 13.59, 9.78 and 12.67 mW/m^2 and soluble COD (SCOD) removal efficiencies of 87%, 90% and 57%, respectively. The sludge pretreated by combined heat/alkali (0.04 N NaOH at 120 °C for 1 h) produced maximum power densities of 10.03, 5.21 and 12.53 mW/m^2 and SCOD removal efficiencies of 83%, 75% and 74% with PS, ES and ADS samples, respectively. Higher SCOD by sludge pretreatment enhanced performance of the MFCs and the electricity generation was linearly proportional to the SCOD removal, especially for ES.

1. Introduction

The growing demand for energy, depletion of fossil fuels and increasing concerns of environmental issues have challenged researchers to develop new technological processes to generate clean and sustainable energy mainly through the utilization of renewable energy sources (Cai et al., 2013; Liu et al., 2014; Logan et al., 2006). Recently, microbial fuel cell (MFC) technology has emerged as a promising sustainable technology to meet increasing energy demand that can utilize organic materials as a fuel (Pant et al., 2010; Yusoff et al., 2013). MFCs are bio-electrochemical devices capable of converting biochemical energy into electrical energy through the catalytic reaction of microorganisms (Logan et al., 2006; Pant et al., 2010; Yusoff et al., 2013). MFCs have remarkable electron-donor versatility as the microbes use wastewater as substrates to generate electricity and simultaneously accomplish wastewater treatment (Oh and Logan, 2005; Lu et al., 2009; Pant et al., 2010).

Production of unmanageable quantity of sewage sludge from wastewater treatment plants is the major issue in terms of capital and environmental burden. This costs 60% of the total plant capital cost, and its disposal has become problematic due to stringent sludge disposal laws (Canales et al., 1994; Pilli et al., 2011; Xiao et al., 2013). MFC technology provides new opportunities for the sustainable wastewater treatment by converting waste into energy, which may offset the operational costs of wastewater treatment plant (Lu et al., 2009). High concentrations of organic matter, mainly protein and carbohydrate can be found in sewage sludge (Wang et al., 2006; Xiao et al., 2013). Wang et al. (2006) reported the total protein and carbohydrate in sludge to be 12,036 mg/L and 2109 mg/L respectively. However, it is known that generation of power during the MFC process might be influenced by the efficient degradation of biomass in MFCs (Bougrier et al., 2008; Yusoff et al., 2013). To make these persistent biomaterials (protein and

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carbohydrate) more susceptible to efficient microbial degradation, pretreatment of sludge is absolutely required (Kim and Lee, 2012; Kim et al., 2013; Kim, 2013). Pretreatment of sludge might promote value-added productivity into the sludge and subsequently increase the overall performance of MFCs (Bougrier et al., 2008).

Various pretreatment methods such as ultrasound pretreatment (Jiang et al., 2010), alkaline pretreatment (Lin et al., 1997; Jiang et al., 2010; Xiao et al., 2013), thermal pretreatment (Xiao et al., 2011), ozonation (Yusoff et al., 2013), microwave digestion (Yusoff et al., 2013) and aerobic digestion (Xiao et al., 2011) have been used to improve the power generation from sludge in MFCs. Jiang et al. (2010) studied the effect of ultrasonic and alkaline pretreatment on sludge degradation and found that both methods led to efficient sludge disintegration, which correspondingly increased sludge soluble chemical oxygen demand (SCOD). Xiao et al. (2011) reported that power generation from sewage sludge could be enhanced by alkaline pretreatment; the voltage output increased from 0.28–0.31 V to 0.41–0.43 V. This is due to the process of alkaline pretreatment that disintegrate cell membrane and solubilize organic matters in the sludge to increase microbial availability of organic substances in the solution (Kim et al., 2009; Zhang et al., 2011).

Although many researchers have investigated sludge pretreatment for power generation, yet there are uncertainties about the Coulomb production from sludge in MFCs. On top of this, in most of the sludge pretreatment only one type of sludge sample is being used. Therefore, in this study, ultrasound and combined heat/alkali treatments were investigated and compared as the pretreatment methods of primary sludge (PS), secondary excess sludge (ES) and anaerobic digestion sludge (ADS) for electricity generation in MFCs. The effect of pretreatment processes on the sludge was evaluated by investigating voltage, power density and Coulomb generation in MFCs.

2. Methods

2.1. Microbial fuel cell construction

The MFCs used in this study were fabricated by joining two media glass bottles (working volume = 240 mL) as described before (Oh et al., 2004). The anode and cathode compartments were separated by a proton exchange membrane (PEM) (Nafion117®, Dupont Co., Delaware, USA), clamped between the flattened ends of the glass tubes fitted with two O-ring rubber gaskets. The two compartments were positioned and held together by a bolt. Both the anode and cathode electrodes were consisted of a graphite rod (ID: 6.15 mm, length: 55 mm, Alfa Aesar, USA) with the surface area of 0.004278 m^2.

The anode chamber was purged with N_2 gas for 5 min to eliminate oxygen and then sealed using a septum. The cathode chamber was continuously aerated with an air pump. The MFC experiment was carried out in a BOD incubator at 30 °C. The electrodes were connected through copper wire to form the full electric circuit (loaded with an external resistance of 1000 Ω).

2.2. Inocula and substrates used for the MFCs

Anaerobic digestion sludge was used as the inoculum of the anode chamber. The inoculum was prepared by mixing anaerobic digested sludge and nutrient minerals buffer solution in the ratio of 1:1. The composition of the minerals used in this study was as follows (mg/L): 310 (NH_4Cl), 2690 ($NaH_2PO_4.H_2O$), 4330 (Na_2HPO_4), 130 (KCl), 18.75 ($C_6H_9NO_6$), 37.5 ($MgSO_4$), 6.25 ($MnSO_4.H_2O$), 12.5 (NaCl), 1.25 ($FeSO_4.7H_2O$), 1.25 ($CaCl_2.2H_2O$), 1.25 ($CoCl_2.6H_2O$), 1.625 ($ZnCl_2$), 0.125 ($CuSO_4.5H_2O$), 0.125 (H_3BO_3), 3.125 (Na_2MoO_4), 0.3 ($NiCl_2.6H_2O$), 0.313 ($Na_2WO_4.2H_2O$). The mixed solution of digested sludge and minerals was supplemented with 100 mM acetate. The mixture was then cultured at 30 °C in a shaking incubator (30 °C, 180 rpm) for 24 h. This produced 10 mL of the supernatant and was inoculated into the anode chamber.

During the start-up, the MFCs were fed with 1 mM acetate and 1 mM glucose consecutively. When a stable voltage was generated in the MFCs, the concentrations of acetate and glucose were kept up to 0.1 mM. Then two types of substrates were used in this study as follows: the untreated sludge which divides into primary sludge-PS, secondary excess sludge-ES and anaerobic digestion sludge-ADS and the treated sludge (PS, ES and ADS).

In order to study the effects of sludge pretreatments, the sludge samples were ultrasonicated or pretreated with a combination of heat/alkali before being fed into the anode chambers of the MFCs. The sludge ultrasonication was performed by an ultrasonic cell disintegrator (VC-750, Sonics & Materials Inc., USA). The disintegrator was equipped with a probe (or horn), which was operated at a fixed frequency of 20 kHz and ultrasonic power intensity of 100 W. Six 0.5 L of sludge sample were taken in a 1 L beaker and then each sample was sonicated for 5, 10, 15, 20, 30, 60 min applying the total energy of 60, 120, 180, 240, 360, 720 kJ/L respectively. During the ultrasonic pretreatment of the sludge, the ultrasonication process was repeatedly operated by turning the system on for 20 s and off for 10 s to prevent the system from overheating. In this study, combined heat/alkali pretreatment was carried out in an autoclave set at 120 °C for 60 min with 0.04 N NaOH as a reference (Lin et al., 1997). The pH of the heat/alkali pretreated sludge was adjusted to 7.0–7.2 by the addition of 2 N HCl.

The pretreated sludge was centrifuged (2140*g*) for 15 min leaving 60 mL of the supernatant, and this was mixed with 180 mL of mineral solution to give the total volume of 240 mL in the anode chamber. The degree of sludge solubilization based on COD (SS_{COD}) was calculated based on the following formula (Cui and Jahng, 2006):

$$\text{Sludge solubilization } (\%) = \frac{\text{SCOD} - \text{SCODo}}{\text{TCODo} - \text{SCODo}} \times 100$$

where SCOD and $SCOD_O$ values are soluble chemical oxygen demand of the treated and raw sludge samples, respectively. $TCOD_O$ represents the total initial chemical oxygen demand. Tests of each MFC with particular substrate were conducted in duplicate and all the results presented were the means of replicate analyses.

2.3. Analysis and calculations

Each MFC system was monitored using a precision multi-meter and a data acquisition system (2700, Keithley, OH, USA) with a voltage across resistor recorded every 20 min intervals. Power output (P) from the MFC was calculated according to Ohm's Law, i.e., P = IV (I = V/R), where I (A) is the current, V (V) is the voltage, and R (Ω) is the external load or resistance. Maximum power density was calculated as previously described by Logan et al. (2006), in which the power output is normalized to the projected surface area of the electrode. Coulombic efficiency (CE) (%) was calculated as explained earlier in the report (Rittmann and McCarty, 2002; Oh et al., 2004). Polarization curves were obtained by measuring the voltages obtained with different external resistors (10 Ω–1 M Ω), after the voltage had stabilized.

The TCOD and SCOD of the sludge samples were determined using a HACH COD measurement system and kit (HACH, C., USA). Prior to the measurement of SCOD, the sludge samples were filtered using 0.45 μm membranes. The pH and electrical conductivity of the sludge samples were measured with a multi-parameter analyzer (C861, Consort, Germany). The Total Suspended Solids (TSS) and the Volatile Suspended Solids (VSS) were measured