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Optimizing the performance of microbial fuel cells fed a combination of different synthetic organic fractions in municipal solid waste

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A B S T R A C T

The objective of this study was to establish the impact of different steam exploded organic fractions in municipal solid waste (MSW) on electricity production using microbial fuel cells (MFCs). In particular, the influence of individual steam exploded liquefied waste components (food waste (FW), paper–cardboard waste (PCW) and garden waste (GW)) and their blends on chemical oxygen demand (COD) removal, columbic efficiency (CE) and microbial diversity was examined using a mixture design. Maximum power densities from 0.56 to 0.83 W m^{-2} were observed for MFCs fed with different feedstocks. The maximum COD removed and minimum CE were observed for a GW feed. However, a reverse trend (minimum COD removed and maximum CE) was observed for the FW feed. A maximum COD removal (78%) accompanied with a maximum CE (24%) was observed for a combined feed of FW, PCW plus GW in a 1:1:1 ratio. Lactate, the major byproduct detected, was unutilized by the anodic biofilm community. The organic fraction of municipal solid waste (OFMSW) could serve as a potential feedstock for electricity generation in MFCs; however, elevated protein levels will lead to reduced COD removal. The microbial communities in cultures fed FW and PCW was highly diversified; however, the communities in cultures fed FW or a feed mixture containing high FW levels were similar and dominated by *Bacteroidetes* and *β-proteobacteria*.

1. Introduction

The availability of inexpensive electron donor feedstocks is an important factor in developing an economical microbial fuel cell (MFC) technology. Low value organic substrates in municipal solid waste (MSW) are potential sources of electron donors for MFCs. The global quantity of MSW produced annually in 2010 of approximately 1.3 billion tonnes is expected to increase to 2.2 billion tonnes by 2025 (Gardner, 2002). In Canada, the quantity of MSW generated annually in 2008 reached 34 million tonnes (Statistics Canada, 2008) whereas in the United States (U.S.), the quantity generated in 2011 was estimated at 250 million tonnes (USEPA, 2011). Based on the organic fraction content, approximately 110–170 million tonnes of organic municipal solid waste (OMSW) is produced annually in Canada and the U.S. (37–55 million tonnes of paper and cardboard waste (PCW), 53–80 million tonnes of food waste (FW) and 21–32 million tonnes of garden waste (GW)) (Statistics Canada, 2008; USEPA, 2011).

Because of the large quantities of MSW generated globally, efficient management practices must be implemented to protect human health, reduce environmental impacts and preserve natural resources. Common practices used to manage MSW include materials or energy recovery by recycling, composting, land filling, anaerobic digestion and combustion with energy recovery. Negative impacts caused by the disposal of MSW in landfills include leachate production and uncontrolled greenhouse gas (methane) emissions. According to the United States Environmental Protection Agency (USEPA), the annual global quantity of landfill methane produce in Asia, Latin America and Africa is equivalent to 37 million tonnes of carbon dioxide equivalent (USEPA, 2002).

An alternative approach to manage MSW is to develop and/or improve existing technologies which can produce value added products from the organic fraction of municipal solid waste (OFMSW). Existing treatment processes include heat, combustion, gasification, pyrolization, landfill gas (LFG) recovery and anaerobic

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digestion (UNEP, 2005). Commercially available technologies such as combustion and anaerobic digestion (AD) are widely used to produce electricity and biogas, respectively, from OFMSW. In both processes, steam and biogas intermediates are converted into electricity using a steam/biogas powered electric generator. An alternative technology, which does not produce biogas nor require biogas combustion to produce electricity, is a microbial fuel cell (MFC) (Harnisch and Freguia, 2012). In MFCs, organic matter degradation can occur at temperatures below 20 °C and at lower substrate concentration; however, AD operating these conditions usually fails because of slow reaction rates (Nimje et al., 2012). In comparison to AD, MFCs are able to convert biodegradable substrates directly into electricity. Based on work reported by Venkata Mohan et al. (2010), Jia et al. (2013) and El-Chakhtoura et al. (2014), the percent COD removed from MSW fed to MFCs can range from approximately 60–85%. According to Jia et al. (2013), single-chamber air cathode MFCs fed a food waste were able to achieved a current density and CE of 556 mW m^{-2} and 23.5%, respectively.

Electricity production from renewable organic biomass using MFCs is a rapidly growing research area which has received widespread attention as an alternative energy producing technology. Converting the biodegradable fraction of OFMSW into bioelectricity is a novel waste-to-energy approach which is carbon neutral because the carbon as CO_2 produced from biomass undergoing degradation is recycled and converted into biomass via photosynthesis.

MFCs are able to produce electricity using pure and mixed microbial cultures. Using a mixed microbial community as a culture source in MFCs is advantageous for many reasons. Mixed consortiums are adaptable to a variety of complex substrates. In addition, these microorganisms interact syntrophically, they exhibit stress resistance and they are able to produce higher currents and power densities when compared to pure cultures (Nimje et al., 2012). Mixed microbial cultures are robust and able to degrade a wide variety of substrates (Ren et al., 2007) such as short chain fatty acids (Kumar et al., 2008), starch and cellulose (Spets et al., 2008), organic wastes (Moqsud et al., 2013), corn stover (Zuo et al., 2006) and organic chemicals in wastewater effluents (Harnisch and Freguia, 2012; Velasquez-Orta et al., 2011).

Organic municipal solid waste (OMSW) could serve as a potential feedstock because it is available in large quantities and it contains easily degradable substrates. Typically OMSW has an energy value of approximately 11.6 GJ $tonne^{-1}$ (Wise, 1994). Assuming the total quantity of OMSW generated in the U.S. and Canada is approximately 280 million tonnes, the annual energy content of this waste is 3.25 EJ (3.25×10^{18} J) or 531 MBOE (million barrel of oil equivalent). Assuming the energy output from an MFC of 8700 MJ $tonne^{-1}$ (2425 kW h $tonne^{-1}$) of waste (Goud et al., 2011), approximately 190 terawatt hours can be produced from 280 million tonnes of waste.

Obtaining a well-defined uniform OMSW as a feedstock for MFCs is impractical because temporal and spatial changes cause non-uniform compositions. The composite nature of OMSW containing carbohydrates, proteins and fats can influence the treatment efficiency of MFCs. If OMSW is to be considered as a feedstock for MFCs, then it is critical to understand the impact of compositional variations on microbial structural and functional diversity as well as electricity production. Hence, the objectives of this study are to prepare different feedstock compositions using a mixture design and to predict the impact of feeding different mixtures on electricity production using an air cathode MFC. The third objective is to interpret the relative contribution, possible interactions between microbial diversity, columbic efficiency and substrate consumption (chemical oxygen demand (COD) removal)) using response surface methodology (RSM).

2. Materials and methods

2.1. Preparation of different feedstocks

A synthetic food waste (FW) was used to minimize compositional variation in the feedstock. Following the Canada Food Guide (Health Canada, 2011), vegetables, carbohydrates, protein and fat were the major components in the synthetic FW. The main constituents (wt% wet solids) were cooked rice (13), cooked pasta (13), bread (10), ground lean meat (18), potato (10), lettuce (8), broccoli (8), apple (10) and banana (10). The FW slurry was prepared by homogenizing the components. The PCW slurry and GW slurries were prepared by homogenizing mixtures containing 50 g paper plus 50 g corrugated cardboard in 1.5 L water and 50 g grass and 250 g wood shavings in 3.0 L water, respectively. The slurries were heat treated in a steam explosion reactor operating in batch mode with a working volume of 2 L. Based on the materials characteristics, the steam explosion time was varied (0.5–1 h) to minimize the formation of furans and to achieve higher COD levels. The FW slurry was heated at 160 °C for 0.5 h while the PCW and GW slurries were heated for 1 h at 160 °C.

2.2. MFC construction

Single-chamber MFCs were constructed in accordance with work reported by Liu and Logan (2004). The cylindrical Plexiglas MFCs (empty bed volume 28 mL) were 4 cm long and 3 cm in diameter. The graphite fiber brush anodes (2.5 cm diameter $\times$ 2.5 cm long; fiber type PANEX 33 160 K, ZOLTEK) were heat treated at 450 °C for 30 min to enhance the power production (Liu and Logan, 2004; Feng et al., 2010). The cathodes were constructed using wet proofed carbon cloth (7 cm^2) containing a Pt catalyst (0.5 mg cm^{-2}) on the water side (inside) and four polytetrafluoroethylene (PTFE®) layers (4 mg cm^{-2} of PTFE per coating) on the air side (outside) (Cheng et al., 2006).

2.3. MFCs operation

The MFCs were inoculated with flocculated anaerobic inoculum (10 g VSS L^{-1}) which was obtained from a municipal wastewater treatment plant (Chatham, ON). The reactors were fed a medium containing 2 g COD L^{-1} feedstock as per Table 1 plus the following (per liter): 310 mg NH_4Cl; 130 mg KCl; 4.97 g $NaH_2PO_4 \cdot H_2O$; 2.75 g $Na_2HPO_4 \cdot H_2O$ and a mineral solution (10 mL) plus a vitamin solution (10 mL) (Lovley and Phillips, 1988). The MFCs were operated repeatedly by decanting and filling with media until a biofilm was formed on the carbon brush anode and a maximum stable voltage was observed. During repeated operation, the MFC was refilled with media and substrate when the voltage decreased to less than 50 mV (1 KΩ resistor). The MFCs were operated for 70 cycles (feed, reaction and decant) to achieve stable conditions. All experiments were conducted in duplicate at 37 °C and an initial pH of 7.1.

2.4. Data acquisition, calculations and electrochemical analysis

The voltage (V) across an external resistor (1 KΩ) in the MFCs circuit was monitored at 10 min intervals using a data logger (Agilent Instruments, OH) configured to a personal computer. Maximum current densities were evaluated by measuring the current per m^2 of the cathode using linear sweep voltammetry (LSV) at a scan rate of 0.1 mV s^{-1} from open circuit voltage (OCV) to 100 mV (Logan et al., 2006). The maximum power density was calculated using Eq. (1).

$$P = IV/A. \quad (1)$$