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Electricity generation and microbial community structure of air-cathode microbial fuel cells powered with the organic fraction of municipal solid waste and inoculated with different seeds

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ABSTRACT

The organic fraction of municipal solid waste (OFMSW), normally exceeding 60% of the waste stream in developing countries, could constitute a valuable source of feed for microbial fuel cells (MFCs). This study tested the start-up of two sets of OFMSW-fed air-cathode MFCs inoculated with wastewater sludge or cattle manure. The maximum power density obtained was 123 ± 41 mW m^{-2} in the manure-seeded MFCs and 116 ± 29 mW m^{-2} in the wastewater-seeded MFCs. Coulombic efficiencies ranged between 24 ± 5% (manure-seeded MFCs) and 23 ± 2% (wastewater-seeded MFCs). Chemical oxygen demand removal was >86% in all the MFCs and carbohydrate removal >98%. Microbial community analysis using 16S rRNA gene pyrosequencing demonstrated the dominance of the phylum *Firmicutes* (67%) on the anode suggesting the possible role of members of this phylum in electricity generation. Principal coordinate analysis showed that the microbial community structure in replicate MFCs converged regardless of the inoculum source. This study demonstrates efficient electricity production coupled with organic treatment in OFMSW-fueled MFCs inoculated with manure or wastewater.

1. Introduction

In recent years, there has been an increased interest in harvesting energy from biomass (e.g. cellulosic biomass and residual biomass from human activities) [1,2]. The organic fraction of municipal solid waste (OFMSW), which constitutes a mixture of carbohydrates, proteins, lipids and fibers (cellulose, hemicellulose and lignin), represents an attractive source of biomass energy, particularly in developing countries where the organic fraction can exceed 60% of the waste stream [3]. The anaerobic digestion (AD) of OFMSW has succeeded in many regions at both research and commercial scales, but lack of suitable inocula has hindered reliable start-up of this technology in developing nations [4]. Furthermore, despite the environmental and economic benefits of AD, the

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biogas produced is often poor in quality, difficult to store and must be combusted for electric energy generation [5].

A microbial fuel cell (MFC) is a bioelectrochemical system inoculated with microorganisms that mediate the conversion of chemical energy stored in organic matter into electricity [6,7]. In MFCs, exoelectrogenic bacteria (pure or mixed cultures) catalyze the degradation of organic matter and transfer electrons to the anode, producing an electric current [8,9]. The electrons flow through an electric circuit containing a load onto a cathode where they combine with electron acceptors such as oxygen. A wide variety of substrates supports bioelectricity generation in MFCs, ranging from soluble, simple substrates such as acetate [10,11] and glucose [12] to particulate, complex substrates such as chitin [13] and cellulose [14,15]. Residual, low-value biomass has also been tested extensively as a feed, e.g. wheat or rice straw hydrolysate [6,16,17], straw [18], raw corn stover [19] and algae powders [20]. The OFMSW contains easily biodegradable organic matter with a lignin mass fraction <2.4% [3] and may represent a valuable source of feed for electricity production in MFCs. However, bioelectricity generation in MFCs using the OFMSW has been rarely reported [21].

With complex substrates, a synergistic consortium of hydrolytic, fermentative microorganisms and fermentation product-utilizing, electrochemically active bacteria is usually needed [14,22]. Different inoculum sources have been used to start-up MFCs treating complex substrates. Wastewater microorganisms have been efficient in starting up MFCs treating complex substrates such as carbohydrates and proteins [6,20]. Manure sludge was shown to generate electricity in an MFC [23] indicating the presence of certain exoelectrogenic bacteria, although power output was low (5–10 mW m^{-2}). To the best of the authors' knowledge, the effect of different inoculum sources on the start-up, performance and microbial community structure in MFCs fed with the OFMSW has not been previously reported.

The objectives of this study were to (i) test different inoculum sources (wastewater sludge or cattle manure) for the start-up and performance (voltage, power density, Coulombic efficiency and organic matter removal) of replicate single-chamber air-cathode MFCs fed with the OFMSW; and (ii) characterize the microbial community structure that develops on the anodes, cathodes and in suspension. Bacterial communities were examined using high-throughput 16S ribosomal RNA (16S rRNA) gene pyrosequencing.

2. Materials and methods

2.1. Reactor construction

Six single-chamber, cube-shaped, air-cathode MFCs (4 cm long by 3 cm in diameter; empty bed volume of 28 cm^3) were constructed from Plexiglas as previously described [10]. Two sampling ports were drilled on top of the MFCs and a plastic cap fitted in one of them to create a headspace for gas accumulation. The ports were sealed with rubber stoppers. The anodes were made of non-wet-proofed carbon cloth (type A; E-TEK, USA). The cathodes were made of wet-proofed (30% mass fraction) carbon cloth (type B-1/B; E-TEK, USA), treated with four polytetrafluoroethylene (PTFE) diffusion layers and a platinum catalyst (5 g m^{-2}) [12]. The anode and cathode were pressed by rubber gaskets on opposite sides of the chamber with a solid plate covering the anode side while the cathode side was covered by a flat plate with a 3 cm diameter hole.

2.2. Feed preparation

Source-sorted OFMSW was collected from households. It was moistened with distilled water and ground using a blender to augment biodegradation surfaces [3]. It was then sieved to obtain a feed with particles of size 300–850 μm to avoid reduced power densities with large particles [13]. The OFMSW was analyzed for relevant parameters: pH, conductivity, total solids (TS), total volatile solids (TVS), chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), phosphorus, total Kjeldahl nitrogen (TKN), proteins and carbohydrates. The homogenized waste was then stored at −20 °C until used in order to maintain its stability. Prior to use, the OFMSW was diluted to a COD concentration of 1.178 kg m^{-3}. The OFMSW was diluted with (per liter of deionized water) a medium consisting of 5 cm^3 vitamins, 12.5 cm^3 trace minerals [24] and phosphate buffer (Na_2HPO_4, 4.56 kg m^{-3}; NaH_2PO_4, 2.45 kg m^{-3}; NH_4Cl, 0.31 kg m^{-3}; KCl, 0.13 kg m^{-3}) [22]. The characteristics of the OFMSW before dilution are presented in Table 1.

2.3. Seed preparation

Two different seeds were tested. Wastewater sludge was collected from the aeration basin of a local (Baalbek, Lebanon) municipal wastewater treatment plant and stored at 4 °C until used. Fresh, moist manure was procured from a local (Beit-Chabab, Lebanon) cattle-rearing farm, transported in a sealed plastic bag and added to the reactors within a few hours without any modification.

2.4. Reactor operation

The reactors were first fed with glucose (1 kg m^{-3}) as the sole substrate for approximately 10 days to enrich for exoelectrogens and fermentative bacteria. During the enrichment phase, two sets of MFCs (triplicate MFCs per set), inoculated

Table 1 – Characteristics of the ground and sieved OFMSW used as substrate.

Parameters	Value
pH (at 25 °C)	4.12
Conductivity (mS cm^{-1} at 25 °C)	4.38
TS (g kg^{-1})	78.00
TVS mass fraction of TS (%)	97.40
Total COD (kg m^{-3})	128.60
Soluble COD (kg m^{-3})	39.30
Ammonia nitrogen (g m^{-3} NH_3-N)	165.00
Total phosphorus (g m^{-3} PO_4^{3-})	870.00
Soluble phosphorus (g m^{-3} PO_4^{3-})	598.00
TKN (% mass fraction)	0.27
Proteins (% mass fraction)	1.66
Total carbohydrates (kg m^{-3})	21.91
Soluble carbohydrates (kg m^{-3})	13.14