Bioelectricity Production from Fermentable Household Waste in a Dual-Chamber Microbial Fuel Cell

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Abstract

The use of a Microbial fuel cell (MFC) was studied as an alternative novel solution to convert a **F**ood **R**esidue **B**iomass (**FORBI)** product into Bioelectricity. FORBI was produced by drying and shredding the pre-sorted fermentable fraction of household food waste collected door-to-door in the Municipality of Halandri. In this study, the possibility of bioelectricity production from a FORBI extract was investigated in an MFC. Different organic loading rates (OLR) (0.7, 0.9, 1.4, 2.8, 6 g COD/L) were examined. It was observed that the increase of the initial concentration of the final extract resulted in a corresponding increase in the operating time. The best performance of the cell was observed at the highest concentration of the final extract tested (6 g COD/L) corresponding to a maximum power density (normalized to the geometric area of the anodic electrode, which was 21.6 cm^2) of approximately 30 mW/m^2 corresponding to a current density of 88 mA/m^2. The results demonstrate that readily biodegradable substrates such as FORBI can be effectively used for enhanced bioelectricity harvesting in an MFC.

Keywords: Microbial fuel cells; Power density; Bioelectricity; fermentable household waste; Food Residue Biomass product.

1. Introduction

Due to the large quantities of Municipal Solid Waste (MSW) generated globally, different waste management practices must be implemented to reduce environmental and health impacts and preserve natural resources. Common practices used to manage MSW include materials or energy recovery by recycling, composting, land filling, incineration, anaerobic digestion etc. (Pendyala *et al.* 2016). It was reported by the Food and Agricultural Organization that one third of the food produced in the world for human consumption (1.3 billion tons per year) is wasted (FAO, 2012). Health and Environmental negative impacts caused by landfilling MSW include leachate production and uncontrolled greenhouse gas (methane) emissions (USEPA, 2002; 2011). An alternative approach to manage MSW is to develop and improve alternative technologies, in order to produce value-added products

from the fermentable fraction of municipal solid waste. Electricity production from fermentable household biomass using MFCs is an interesting waste-to-energy producing technology which has received attention as an alternative. Recently, some researches on the MFC which directly employ food waste as substrate have been reported (Goud *et al.* 2011; Jia *et al.,* 2013; Jia *et al.,*2013; Moqsud *et al.*, 2013, 2014; Hui *et al.*, 2016; Colombo *et al.,* 2017). Colombo *et al.,* 2017, studied the electrical signals produced by MFCs during anaerobic biodegradation of four different types of wastes: citrus pulp, fishery waste, cheese whey and kitchen waste. Coulombic Efficiency (CE) and soluble COD (sCOD) removal were monitored for 100 days. The maximum CE for kitchen waste was 9.91%, with a sCOD removal of 64.25%. Also Li *et al.* (2016) proposed MFC for recovering electricity from canteen based food waste. A maximum power density of 5.6 W/m^3 and an average output voltage of 0.51 V were obtained. The present work is in the framework of Waste4Think, a Horizon 2020 project, which proposes source separation and separate collection of the Fermentable Household Waste (FHW) in the Municipality of Halandri, followed by drying and shredding at the Municipality level, aiming to evaluate the generated product, called FORBI (Food Residue Biomass), as a potential feedstock for the production of electricity with MFC, among various valorization alternatives. FORBI is a high quality homogenized and dry biomass product with a weight approximately 25% of the original food waste, which may be stored for prolonged periods of time without deterioration.

2. Materials and Methods

2.1. MFC set up

All experiments were performed in an H-type dual chamber MFC, consisting of two 310 ml glass cylindrical bottles connected via a glass tube (Tremouli *et al.* 2013, (Antonopoulou *et al.*, 2010). The solutions in the two bottles, where the two electrodes of the MFC were immersed, were kept in electrolytic contact via a proton-exchange membrane (PEM, Nafion 117). The solutions in both bottles were mixed using magnetic stirrers and their temperature in all experiments was maintained at 35$^\text{o}$C by

performing the experiments in a temperature-controlled box. Carbon fiber paper (Toray, 10 wt% wet proofing) was used as the anode electrode and carbon cloth coated with a Pt catalyst (E-Tek, 0.5 mg/cm^2) as the cathode electrode. The electrodes, each with dimensions 4 cm x 2.7 cm, having an apparent surface area A= 2 x 10.8 = 21.6 cm^2, were connected via silver wires with a 100 Ω external resistor (unless stated otherwise), forming a closed electrical circuit. The calculation of current densities was based on the aforementioned apparent surface area of each electrode (21.6 cm^2).

2.2. Reactor operation

In this study, the liquid phase of a separation process of FORBI was added to a nutrient solution in the anode chamber and different initial concentrations (ranging from 0.7 to 6 g COD/L) were examined. The nutrient solution (250 mL) contained (per L): 5.29 g NaH$_2$PO$_4$ 2H$_2$O, 3.45 g Na$_2$HPO$_4$·2H$_2$O, 0.16 g KCl, 5 g NaHCO$_3$ and 10 mL of a trace elements solution (Skiadas and Lyberatos, 1998). The NaH$_2$PO$_4$ ·2H$_2$O and Na$_2$HPO4 ·2H$_2$O contained in the nutrient solution buffered the pH to a value close to 7. A 2 mm sieve was used to achieve the desired particle size of the dry mixture of fermentable household food waste (FORBI). In order to remove solids, a solids/liquid separation step was used as pretreatment. Initially, FORBI was suspended in water and was vigorously stirred for 30 minutes. Then the slurry was filtered under pressure using a cloth filter. The liquid extract retained 95% of the dissolved organic content of the waste. Prior to the use extract was filtered using sequential Whatman filters of pore sizes 1.2 μm to 0.7 μm. The final extract, having an initial COD value of 6.92 g/L was diluted to different extents giving solutions ranging from 0.7 to 6 g COD/L and these were used as energy source for electricity production in the microbial fuel cell.

Characteristics	Value
pH	6.43
Conductivity (mS/cm)	2.31
Total COD (g/L)	9.98
Dissolved COD (g/L)	6.92
Total Carbohydrates (g/L)	8.02
Soluble Carbohydrates (g/L)	6.12
Total Suspended Solids – TSS (g/L)	2.36
Volatile Suspended Solids – VSS (g/L)	2.29
Total Solids – TS (g/L)	9.83
Volatile Solids – VS (g/L)	8.04
Total Kjeldahl nitrogen (TKN) (g/L)	0.22
Total phosphorus (g/L)	0.06

Figure 1.Main characteristics of the FORBI extract

All cycles were conducted in batch mode. The anolyte and the catholyte were replaced after the MFC voltage dropped to approximately zero, designating the end of a cycle (substrate consumption). The cathodic chamber was continuously aerated via an air-pump, while the anodic chamber was sealed with a rubber stopper and the anolyte was sparged with a gaseous mixture of N$_2$/CO$_2$ in order to ensure anaerobic conditions. The cathodic chamber was filled with a buffer solution (5.29 g/L NaH$_2$PO$_4$ · 2H$_2$O and 3.45 g/L Na$_2$HPO$_4$ · 2H$_2$O), where KCL (0.16 g/L) was added. The external load of the MFC was regulated using a resistance decade box (RS, No. 211 – 159). The current, MFC voltage and temperature were continuously monitored, while COD, pH and conductivity were measured at selected time intervals after the addition of substrate.

2.3. Analytical Methods and Calculations

The measurements of dissolved and total COD, TSS and VSS, total Kjeldahl nitrogen (TKN) and total phosphorus were carried out according to Standard Methods (APHA, 1998). The dissolved and total carbohydrates were measured according to (Josefsson, 1983), pH and conductivity were measured using a digital pH-meter (WTW INOLAB PH720) and a conductivity meter (WTW INOLAB), respectively. The fuel cell voltage U_{cell} was monitored and recorded at 50 s intervals, using a data acquisition system (Advantech ADAM-4019+), connected to a personal computer, while the current I passing through

the cell was measured using a precision multimeter (Mastech MY 61). The produced power density was calculated using the equation:

$$P = \frac{I \cdot U_{cell}}{A} \qquad (1)$$

where, I denotes the current, U_{cell} the cell voltage, and A the geometric surface area of the anode ($A=21.6$ cm^2).

Polarization curves were obtained after adding the fresh substrate and establishing a constant power output, by varying the external resistance (external load) in the range of 0.1-1000 kΩ and recording the corresponding quasi–steady–state MFC voltage and current values. The Coulombic Efficiency (CE) was calculated using Eq. (2) (Logan *et al.*, 2006):

$$CE = \frac{M \cdot \int_0^t I dt}{F\, b\, V\, \Delta(COD)} \qquad (2)$$

where, M is the molecular weight of oxygen (= 32), F is Faraday's constant (= 96,485 C / mol), b is the number of electrons exchanged per mol of oxygen (= 4), V is the volume of liquid in the anode compartment and $\Delta(COD)$ is the change in dissolved COD over time. The internal resistance R_{in} of the MFC was calculated by the power density peak method (Logan, 2008), according to which, at maximum power output the internal resistance is equal to the external resistance, i.e., R_{in} is equal to the external resistance (load) R_{ext} that must be connected to the MFC to obtain the maximum power output.

3. Results and discussion

3.1 MFC operation using FORBI extract

The final extract was used as substrate in the anode chamber, in concentrations ranging from 0.7 – 6 g COD/L. The MFC voltage (R_{ext} = 100 Ω) and the COD consumption versus time for the different initial final extract concentrations are shown in Fig.1. The final extract concentration was sequentially increased, by addition in the anolyte of the proper amount of final extract after the end of each operation cycle. As shown in Figure 1, the duration of the operation cycle increased with increasing initial concentration of the substrate. Moreover, the MFC potential before the abrupt decrease was higher for higher initial concentrations of the final extract, increasing by approximately 10 mV as the concentration was increased from 0.7 to 6 g COD/L. The substrate removal efficiency at the end of each operation cycle was relatively high, ranging from 71% - 83%. As far as the CE (R_{ext} = 100 Ω) is concerned, it was very low, averaging at a value of 2% for all initial concentrations of final extract. The low CE implies that most of the COD was removed by methanogens or other non-electrogenic microbes established in the anode rather than by electron transfer bacteria (He *et al.*, 2005).

3.2. Effect of final extract concentration on the polarization performance of the MFC

Fig.2 shows the dependence of the MFC voltage U_{cell} and the produced power density, P, on the current density passing through the MFC, at different final extract concentrations. The data were obtained after the MFC voltage had leveled off to a practically constant value, following the addition of the substrate in the anolyte. As shown in Fig.2, the increase of the final extract initial concentration from 0.7 (1st cycle) to 6 (12th cycle) g COD/L, results in an increase of the maximum power density from 20.4 to 29.6 mW/m2 (ca.9.2% increase). The internal resistance of the MFC, operating with final extract as substrate at concentrations 0.7 to 6 g COD/L, as determined by the power density peak method for the data presented in Fig.2, was 1.8 kΩ. Moreover, the almost constant slope of the polarization curves (Fig.2) indicates the very significant contribution of ohmic losses (ohmic overpotential) in the dual chamber MFC of the present study.
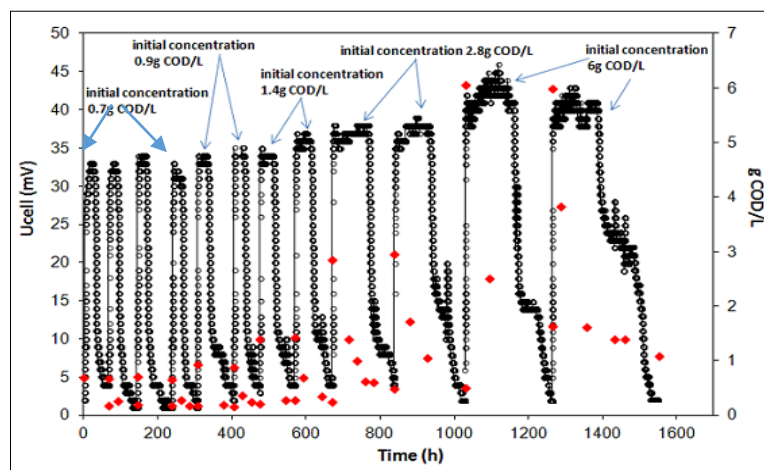

Figure 1: MFC voltage U_{cell} and dCOD consumption versus time using the final extract as substrate at different initial concentrations. External resistance R_{ext} = 100 Ω.
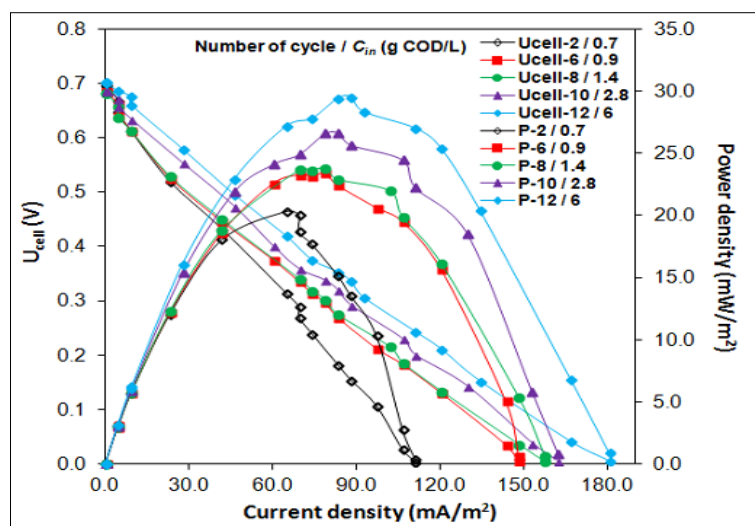
Figure 2: MFC voltage U_{cell} and power density versus current density when using the final extract as substrate at different initial concentrations C_{in}.

4. Conclusion

It was shown that power generation is possible using filtered FORBI as substrate in a two-chamber MFC. The highest power density obtained was 29.6 mW/m² (2.96 mW/m²·g FORBI). The COD removal was in the range of 71% - 83%. The experiments showed that the period of time needed to degrade the final extract increases with the increase of final extract concentration. In order to optimize the process an improved configuration should be designed, mainly aiming to minimization of the ohmic losses.

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