Condensate originating from household food waste as a substrate for Microbial Fuel Cells

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Abstract A microbial fuel cell (MFC) is a bioreactor that converts the chemical energy of the bonds of organic compounds to electrical energy, through the catalytic reactions of microorganisms. Under anaerobic conditions various substrates have been examined using MFC technology. This study examines the potential use of the liquid fraction of fermentable household waste (source-sorted food waste), which results from condensation of the vapors generated during drying, as a feed to the MFC. The main characteristics of this substrate are: 13 g COD/L, pH=3.5, conductivity=262 μS/cm. Condensate was fed to two single-chamber air cathode MFCs, using mullite and GoreTex as cathodic electrodes, respectively. The oxygen reduction catalyst was MnO_2 in both cases, while graphite granules were used as anodic electrodes. The units were operated in batch mode. Linear sweep voltammetry was carried out in order to conduct electrochemical characterization. The maximum power output was 0.52 $\mu W/m^3$ for the mullite cell and 0.28 $\mu W/m^3$ for the GoreTex cell, respectively. High COD removal efficiencies (>75%) were achieved for both cells.

Keywords: Microbial Fuel Cell, Condensate, Household food waste, Wastewater treatment, Energy production

1. Introduction

Efficient municipal waste management (MW) is a key factor that contributes to the overall waste management [European Commission Proposal 2015]. Although the amount of MW is not the same across EU countries [EUROSTAT 2017], food waste is the major fraction of MW [European Parliament News 2017], 53 % of which is produced in households [Stenmark 2016]. Food waste (FW) is rich in various substances with high energetic and nutritional content [Antonopoulou et al 2019], making an excellent supply for many biological processes [Ng et al 2020]. In the municipality of Halandri, in Attica, Greece, an innovative FW valorization approach has been developed and implemented at pilot-scale within the framework of the Horizon 2020 project WASTE4think [Antonopoulou et al 2019, Tremouli et al. 2019, Lytras et al. 2020]. The implemented waste management scheme included the source-separated collection of the household FW from 250 households. The collected FW was then led to a drying/shredding facility of the Municipality. The produced condensate is rich in organic carbon but poor in nitrogen which limits its biological treatment. An exploitation approach of condensate is its mixing with waste activated sludge as a feed for an anaerobic digester, in order to enhance the methane yield [Lytras et al. 2020].

Another approach of condensate exploitation is bioelectricity production using the microbial fuel cell (MFC) technology. This is an innovative approach to wastewater treatment with direct electricity output [Logan 2009]. The MFC is comprised of an anode and a cathode compartment. In the anode the effluent is oxidized by bacteria, under anaerobic conditions. The produced electrons are collected through the anodic electrode and transferred to the cathodic electrode by an external resistance. The produced protons are transferred through the separator to the cathodic chamber. On the cathodic electrode an electron acceptor is reduced [Obileke et al. 2021]. Depending on the acceptor the presence of a catalyst may be needed; such is the case of O_2. The separator between the anode and the cathode may increase the cost of the system, especially when membranes are used [Daud et al. 2015]. More feasible options than membranes have been researched and provided comparable results at lower costs, such as ceramic electrodes [Winfield et al. 2016] and GoreTex cloth [Tremouli et al. 2019].

In this study, the performance of two single chamber MFCs with alternative cathode assemblies (ceramic and GoreTex) was studied. Two MFCs were acclimated and operated using raw condensate as the substrate.

2. **Materials and Methods**

Two similar Plexiglas single chamber MFCs were constructed, as described elsewhere [Tremouli et al. 2021]. Each cell had four tubes running through the anodic compartment. The same anode electrode setup was used for both cells, graphite granules (250 g) and an embedded graphite rod. Different cathode electrodes were used for the two cells. For the first cell, four cathodic electrodes with GoreTex cloth were assembled as specified in Tremouli *et al*. [2019]. For the second cell, the four cathodic mullite electrodes were internally coated with the oxygen reduction catalyst by mixing graphite paint (12 g), xylene (3 ml), ethanol (3 ml) and 3 g MnO_2. An external resistance set at 100 Ω was connected between the anode and the cathode electrodes.

The cells were operated in batch mode, each filled up with 150 cm^3 anodic liquid. The cells were placed in a temperature-controlled room, at 27 ºC. During the acclimation period both cells were fed with synthetic wastewater consisting of phosphate buffer (3.67 g/L NaH_2PO_4 and 3.45 g/L Na_2HPO_4), potassium chloride (0.16 g/L KCl), sodium bicarbonate (5 g/L $NaHCO_3$), trace elements (1% v/v, described elsewhere [Skiadas & Lyberatos 1998]) and glucose (1.5 g COD/L) as the electron donor. During the first three acclimation cycles the cells were inoculated with anaerobic sludge (10 % v/v) obtained from the Likovrisi, Athens, Greece sewage treatment plant.

Following the acclimation period, glucose was replaced with condensate. Condensate was produced by condensing the vapors that are generated during the drying and shredding of the pre-sorted fermentable fraction of household food waste collected door-to-door in the Municipality of Halandri, Greece [Ntaikou et al 2018]. The characteristics of condensate were 13 g COD/L, pH=3.5, conductivity=262 μS/cm cm and contained the following volatile fatty acids (VFAs) acetic 1008 ± 720 mg/L, propionic 75 ± 25 mg/L, iso-butyric 40 ± 28 mg/L, butyric 144 ± 68 mg/L and iso-valeric 13 ± 4 mg/L. The VFAs concentrations are the average values of four different feed samples. In order to improve the low conductivity and pH, phosphate buffer was added in the raw condensate. After the mixing the improved pH and conductivity were 4.9 and 6.6 mS/cm, respectively. The condensate feeding presented fluctuations because it originated from gathered HFW, which varied each batch.

The voltage of the cells was recorded every two minutes by a Keysight LXI Data Acquisition. Linear sweep voltammetry was conducted by a Potentiostat – Galvanostat (PGSTAT128N – AUTOLAB) with an Ag/AgCl reference electrode. The pH and conductivity were measured by digital instruments (WTW INOLAB PH720) and (WTW INOLAB) respectively. Soluble COD was measured according to the standard methods [Standard Methods 2012]. For the quantification of VFAs, 1 ml of sample acidified with 30 μL of 20% H2SO4 was analyzed via a gas chromatograph (SHIMADZU GC-2010 plus) equipped with a flame ionization detector and a capillary column (Agilent technologies, 30m x 0.53mm ID x1 μm film, HP-FFAP) using an auto sampler (SHIMADZU AOC-20s).

Coulombic efficiency (CE) was calculated according to Eq.1. CE is the charge produced to the charge that is contained in the substrate and is calculated by [Logan 2009]:

$$CE=\frac{M_{O2}\cdot\int_0^t Idt}{F\cdot b\cdot V\cdot \Delta COD} \quad \text{Eq. 1}$$

M_{O2} is the molar weight of Oxygen (=32), F is the Faraday constant (=96485 C/mol), b is number of electrons per O_2 mole (=4), V is the effective volume of the cell (=150 ml) and ΔCOD is the difference between the initial and the final COD measurements for each batch cycle.

3. **Results**

3.1. GoreTex cell operation

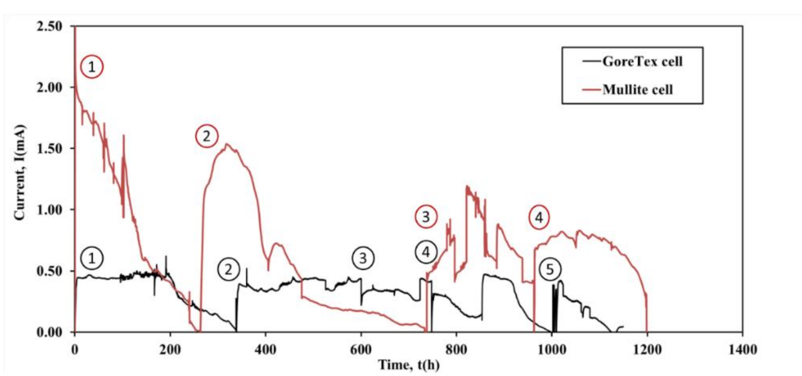

Figure 1: Current output versus time during operation of the two cells (Black = GoreTex cell, Red = mullite cell). The cycles have been numbered with the respective colors.

The duration of the acclimation period of the GoreTex cell was 660 h. For the acclimation to be considered complete, there had to be repeatable current peaks and high COD removal, implying development of the electrogenic active biofilm. The maximum current output for the acclimation cycles was 0.5 mA.

Following the acclimation period, the glucose synthetic feed was replaced with raw condensate and the results are presented in Figure 1. Five cycles were carried out; the detailed results of each cycle are presented in Table 1. The current output was comparable to the maximum current achieved during the acclimation, approximately 0.5 mA. However, the maximum current output was decreased over time, 1st cycle 0.62 mA and 4th cycle 0.42 mA.

Table 1: Measurements and calculations of the GoreTex cell operation.

Cycle #	CODin (g/L)	Inlet pH	Imax (mA)	COD Removal (%)
1st	9.9	5.9	0.62	95%
2nd	9.2	4.0	0.52	96%
3rd	12.7	4.9	0.44	94%
4th	14.7	3.8	0.47	92%
5th	13.8	4.3	0.42	77%

The GoreTex cell achieved high COD removal (>92%) in all five cycles, but a decrease was observed in the last cycle (77%). The inlet characteristics in terms of COD and pH have possibly affected the performance of the cell, as the inlet COD is increased and the pH is lowered through the cycles. The maximum current output (0.62 mA) was achieved in the first cycle, where both a low inlet COD (9.9 mg/L) and highest pH (5.9) were measured. Coulombic efficiencies calculated for the five cycles were very low, approximately 2%.

3.2. Mullite cell operation

The duration of the acclimation of the mullite cell was 2010 h. The maximum current output for the acclimation cycles was 2.28 mA. Following the acclimation period, the synthetic glucose feed was replaced with raw condensate and the results are presented in Figure 1. Four cycles were carried out, the detailed results of each cycle being presented in Table 2. In particular, the maximum current output achieved was 2.02 mA, similar to the acclimation maximum current output (2.28 mA). However, the maximum current output decreased with time, as it can be seen in Figure 1 and Table 2 (current output for the 1st cycle 2.02 mA and 0.83 mA for the 4th cycle, respectively). As it can be seen from Figure 1, during the 3rd cycle the current output of the mullite cell (red line) presented fluctuations which are attributed to the electrical connection issues.

Table 2: Measurements and calculations of the mullite cell operation.

Cycle #	CODin (g/L)	Inlet pH	Imax (mA)	COD Removal (%)
1st	10.9	5.9	2.02	96%
2nd	6.2	6.1	1.54	91%
3rd	10.5	4.8	1.26	95%
4th	12.5	3.8	0.83	94%

The COD removal (>91%) was high for the mullite cell. The maximum current output is affected by the low pH and the high COD of the raw condensate while a drop is observed in its maximum value during time (2.02 mA 1st cycle, 1.54 mA 2nd cycle, 1.26 mA 3rd cycle and 0.83 mA 4th cycle). Coulombic efficiencies calculated for the four cycles ranged between 4% - 9%.

The VFAs were almost completely consumed by the microorganisms, leading to an increase in the pH in both cells at the end of every cycle (e.g. GoreTex cell 1st cycle inlet pH=5.9, outlet pH=7.13, mullite cell 4th cycle inlet pH 3.8, outlet pH=4.36).

3.3 Electrochemical Characterization

Figure 2 presents the polarization curves of the two cells. The maximum power output was achieved by the GoreTex cell P_{max} = 0.52 W/m^3, while the mullite cell achieved P_{max} = 0.3 W/m^3. The OCVs (open circuit voltages) obtained were 0.228 V and 0.452 V for the GoreTex and mullite cell, respectively. The voltage versus volumetric current density curves indicate that, in both cells, ohmic resistances dominated, but were greater for the GoreTex cell, due to a higher slope (698 Ω internal GoreTex cell resistance, 211 Ω internal mullite cell resistance). Despite the facts that acclimation was not as fast and the OCV was not as high as for the GoreTex cell, the mulite cell overall performed better in terms of power output, waste treatment efficiency and coulombic efficiency.

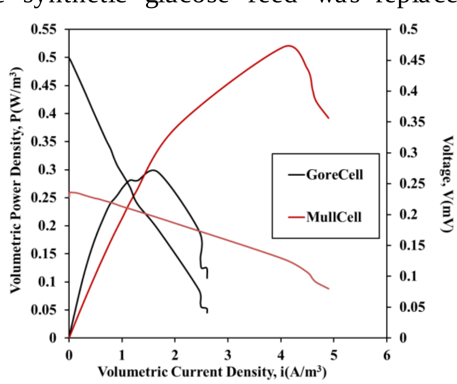

Figure 2: Volumetric power density versus volumetric current density versus voltage as extracted by LSV experiment on the two cells. (Black = GoreTex cell, Red = mullite cell)

4. Conclusion

The liquid fraction of dried fermentable household waste was treated using two single chamber MFCs using different cathode assemblies (GoreTex and mullite assembly, respectively). The mullite cell performed better than the GoreTex cell in terms of COD removal and power output. The results indicated that both cells had difficulty treating the raw condensate wastewater, because of its high COD 13 g/L and low pH 3.5 and conductivity 2.62 mS/cm.

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