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Electricity generation potential of poultry droppings wastewater in microbial fuel cell using rice husk charcoal electrodes

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Abstract

Background: Poultry droppings from poultry farms and rice husks obtained from rice milling process are generally considered as wastes and discarded in Nigeria. Although many studies have shown that microbial fuel cells (MFCs) can generate electricity from organic wastes, little or no study have examined MFCs for generating electricity from poultry droppings and rice husk as electrode material.

Findings: Laboratory-scale double-chamber MFCs were inoculated with concentrations of poultry droppings wastewater and supplied with rice husk charcoal as anode and cathode electrodes for electricity generation. Power outputs and dissolved organic carbon (DOC) removal efficiencies were compared between MFCs using rice husk charcoal (RHCE) as electrode and those using carbon cloth (CCE) as electrodes. The RHCE-MFC 2 containing 477 mg L^{-1} dissolved organic carbon produced a volumetric power density of 6.9 ± 3.1 W m^{-3} which was higher than the control and the CCE-MFCs by a factor of 2 and achieved at DOC removal efficiencies of $40 \pm 1.2\%$.

Conclusions: The results suggest that poultry droppings wastewater is a feasible feedstock for generating electricity in MFCs. The findings also suggest that rice husk charcoal is a potentially useful electrode material in MFCs.

Keywords: Poultry droppings wastewater, Microbial fuel cell, Power density, Rice husk charcoal electrodes

Background

It is estimated that 932.5 metric tons of commercial poultry droppings manure are generated in Nigeria annually (Musa et al. 2012). Currently, they are mostly considered to contribute to environmental pollution and aesthetic nuisance and thus discarded in Nigeria.

Microbial fuel cells (MFCs) are devices that use living microbes as anode catalysts for generating electricity from organic matter and have attracted social attention due to their ability to generate electricity from waste biomass and wastewater (Logan et al. 2006). In MFCs, substrate is regarded as one of the most important biological factors affecting electricity generation (Liu et al. 2009). Substrate is a key parameter that influences the integral composition of the bacterial community in the anode biofilm, and the MFC performance including the power density and Coulombic efficiency (Pant et al. 2010). Diverse metabolites such as formate, succinate, lactate, acetate and propionate, are produced during glucose oxidation in MFC due to its fermentative nature but acetate has been identified as the dominant and most effectively utilized (Kim et al. 2011). Further, acetate has been categorized as the end product of several metabolic pathways for higher order carbon sources including the Entner–Doudoroff pathway for glucose metabolism (Biffinger et al. 2008).

Microbial fuel cells have been examined for electricity generation from swine wastewater (Min et al. 2005), cattle manure (Inoue et al. 2013), and rice bran (Takahashi et al. 2016). However, no study has examined the potential of poultry droppings wastewater (PDWW) as MFC feedstock; hence no threshold level of PDWW concentration has been reported.

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Furthermore, electrode materials are key components of an MFC. The bio-anode where microorganisms grow as a biofilm functions as living biocatalysts. The MFC performance largely depends on this living biofilm and a robust electrochemically active biofilm (EAB) should be developed at the anode (Kalathil et al. 2017). Carbon-based materials are most frequently used as both anode and cathode electrodes. Carbon-based electrodes are commonly employed in MFCs due to their biocompatibility, long durability, good conductivity, and low cost (Li et al. 2017). Several studies have examined the use of carbon-based electrodes as components for electron transfers in MFCs. These include carbon cloth (Ishi et al. 2012), graphite fibre brush (Yang et al. 2013), and graphite felt (Jong et al. 2011). However, no study has examined the potential of rice husk as a workable source of electrode material for electricity generation in MFCs. In the present study, MFCs were operated with varying concentrations of poultry droppings wastewater (PDWW) as the feedstock, and rice husk charcoal as electrodes. The power outputs as affected by the concentration of PDWW and the nature of electrodes were compared.

Methods

Construction of reactors used in experiments

Two sets of two-chamber MFCs, constructed with Perspex™ acrylic bottles of 200 mL working volume were used (Fig. 1). The electrodes in both chambers were made

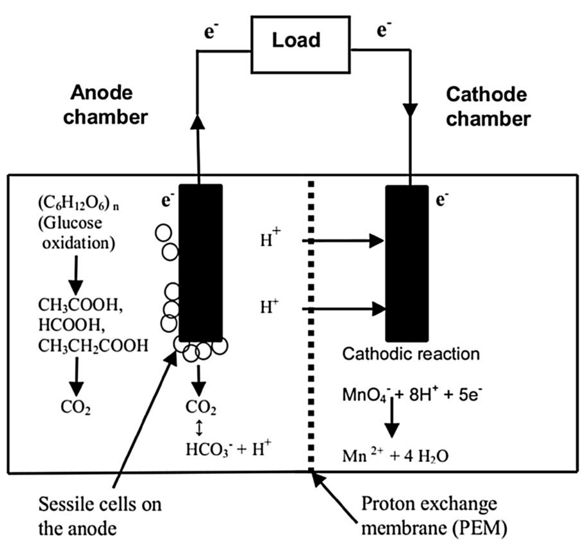

Fig. 1 A schematic diagram of a double-chamber PDWW. Electron flows from anode to cathode are through external load as indicated with arrows. Black bars in chambers are the electrodes. Oxidation reaction of PDWW in the anode was shown at the anode while the reduction reaction in the cathode was shown at the cathode. The directions of the flow of protons from anode to cathode through PEM were shown by arrows

Table 1 Selected characteristics of poultry droppings wastewater

Parameter (mg L^{-1})	Value (mean ± SD)
DOC	954 ± 37.1
TSS	1056 ± 59.7
Phosphate	7.7 ± 2.3
Sulphate	64 ± 13.8
Nitrate	3.3 ± 1.2
Nitrite	839 ± 56.5
Microbial count (cells mL^{-1})	5.8×10^8

from RHCE for one set of four (4) reactors. For comparison of electrode performance, CCE were used for the second set of two (2) reactors. The operating room temperature was 25 ± 2 °C. The anode and cathode were connected via epoxy encapsulated copper wires, and the circuit was completed using an external resistor fixed at 1 kΩ. After pre-treatment, 40 g of rice husk were carbonized at 400 °C for 1 h in a muffle furnace (Barnstead, USA) in order to produce charcoal as described earlier (Hanum et al. 2017). Charcoal samples were crushed with blender and sieved to a finely granulated charcoal and glued together using an electrically conductive carbon epoxy A (World Precision Instruments, Inc. Sarasota FL, USA) in an adhesive mix of 1:1 ratio and reshaped to form rods (8 cm by 3 cm by 1 cm, or 48 cm^2 of total projected surface area per electrode).

Poultry dropping samples were collected from Nigeria and transported in sealed plastic bags to Japan. Samples were stored in cold room (4 °C) before use. Wastewater was prepared by weighing (per litre) 500 g slurry concentrations of poultry dropping as feedstock. Table 1 shows the characteristics of the wastewater.

Chemical analysis/evaluation of DOC removal

Dissolved organic carbon analysis was carried out using total organic carbon analyzer (Shimadzu, Japan). Total suspended solids (TSS) concentration was determined by standard methods (APHA 1998). The presence and concentrations of the following dissolved ions: PO_4^{3-}, SO_4^{2-}, NO_3^- and NO_2^- in PDWW were determined using an ion chromatograph (IC-2010, Tosoh Science, Japan). Gases (CH_4, CO_2 and H_2) were analysed within the anode chamber headspace using a gas chromatograph (GC-2014, Shimadzu, Kyoto Japan) equipped with a thermal conductivity detector (TCD) and a molecular sieve 5A 60–80/Porapack Q 80–100 column as described elsewhere (Ishi et al. 2005). The column, injection, and detector temperatures were 50, 100, and 80 °C respectively. Argon gas was used as the carrier gas. Daily headspace gas volumes were recorded. DOC removal efficiency was calculated as percentage decrease in DOC.

Evaluation of electricity generation in MFCs

Current (*I*, A) and voltage (*V*) were monitored. Current density (CD, A m^{-3}) was calculated based on the volume of anolyte. Voltage was converted to power density (PD, W m^{-3}) according to an equation $P = IV$/volume of anolyte.

Start-up of operation

Dissolved organic carbons (DOCs) in feedstock were varied by diluting with Milli-Q into (per litre): 954 mg (undiluted control), 477, 95.4, and 9.54 mg and designated as MFC 1, MFC 2, MFC 3, and MFC 4, respectively. Cathodic buffer with pre-determined concentration of 500 μM (pH 6.8) was prepared with analytical-grade potassium permanganate ($KMnO_4$) as an oxidant. For inoculation, 1 mL of PDWWs was injected into the anode chambers. The operation was initiated by connecting the anode and the cathode via the external resistor and current (A) across the resistor was monitored using a data-acquisition system Agilent HP 34790 (Agilent Technologies, Loveland, USA) connected to a personal computer. When the current dropped down to below 0.005 mA, the solution was supplemented with 1 mL of undiluted PDWW as the sole organic substrate to recover current output.

Operation of MFC reactors

After a successful start-up which lasted for 10 days, a synthetic medium containing 5 mM of glucose as the sole electron donor and the following nutrients (per litre): 50 mM K_2HPO_4, 10 mM KH_2PO_4, 0.1 mM $(NH_4)_2SO_4$, 0.25 mM $MgCl_2 \cdot 6H_2O$, 0.25 mM $CaCl_2$, 100 μL trace element solution, and 100 μL vitamin solution was used to sustain the continuous electricity production in MFCs. Vitamins solution contained (per litre): 1 mg biotin, 1 mg folic acid, 8 mg pyridoxine, 3 mg HCl, 3 mg thiamine $HCl \cdot 2H_2O$, 2 mg riboflavin, 2 mg nicotinic acid, 2 mg calcium D-pantothenate, 0.1 mg vitamin B_{12}, 2 mg *p*-aminobezoic acid, and 2 mg lipoic acid. Trace elements contained (per litre): 0.5 g $FeCl_3 \cdot 6H_2O$, 0.1 g $MnCl_2 \cdot 4H_2O$, 0.01 g $CaCl_2$, 0.1 g $CoCl_2 \cdot 6H_2O$, 0.1 g $ZnSO_4 \cdot 7H_2O$, 0.1 g $CuCl_2 \cdot 2H_2O$, 2 mg H_3BO, 0.01 g Na_2MoO_4, and 0.02 g $NiCl_2 \cdot 6H_2O$.

Once a stable current was observed, the synthetic medium was switched to the desired PDWW concentration buffered with 50 mM KH_2PO_4, pH 7.0 (Jiang et al. 2009), and MFCs were operated in continuous mode for 60 days. Anolyte was continuously recycled using an adjustable peristaltic pump (Pump II, Model 3385 Thomas Inc, Swedesboro, New J. USA) at a flow rate of 0.27 mL Min^{-1}, corresponding to a hydraulic retention time (HRT) of 12 h. The samples were kept anoxic by purging with N_2-CO_2 (80:20 v/v) for 10 min and placed at 4 °C prior to use. The anolytes were subjected to continuous stirring using magnetic stirring bars.

Determination of anodic biomass density

In order to determine the total microbial density on the anode surface, protein contents in anode biofilms, was extracted as described previously (Ishi et al. 2012). Cyclic voltammetry (CV) was carried out to investigate the electrochemical activities of anode samples as described previously (Chung and Okabe 2009). Anode samples were taken on day 40 from the MFC 1, MFC 2, and MFC 3 for CV analysis. At the end of the experiments, the viable bacterial cell count on anode was determined as described previously (Friman et al. 2013). Current densities and DOCs were routinely calculated.

Results

Electricity generation in MFCs

Figure 2a shows a typical current density evolution. The acclimatization periods were compared between RHCE-MFC 2 and CCE-MFC 2, showing that RHCE-MFC 2 generated a significantly higher ($p < 0.05$) stable current density (0.01–2.2 A m^{-3}) in a shorter time of ~10 days compared to CCE-MFC 2.

Evaluation of methane production in MFCs

The values of methane production were compared between CCE-MFCs and RHCE-MFCs (Fig. 2b), showing that CCE-MFCs generated significantly higher methane concentration suggesting prolific activities of archaea on the anodes. In our recent study, methane gas production was found to be directly proportional to methanogenic population and methanogens identified as electron scavengers (Oyiwona et al. 2016). A positive correlation ($r^2 = 0.95$, $p < 0.05$) exists between the number of methanogens and the daily methane production (Ding et al. 2012).

Biomass density

The average biomass density for CCE-MFCs was 6.5 (±1.5) mg BSA cm^{-2} and this was significantly higher than that of RHCE-MFCs.

Cyclic voltammetry

Cyclic voltammograms (Fig. 3) show that the magnitudes of peak areas amongst the MFC treatments followed the hierarchical order: RHCE-MFC 2 (*red line*) > RHCE-MFC 3 (*blue line*) > RHCE-MFC 1 (*black line*) > CCE-MFC 2 (*green line*). The peak redox areas of RHCE-MFC 1 (*black line*) and CCE-MFC 2 (*green line*) showed poor

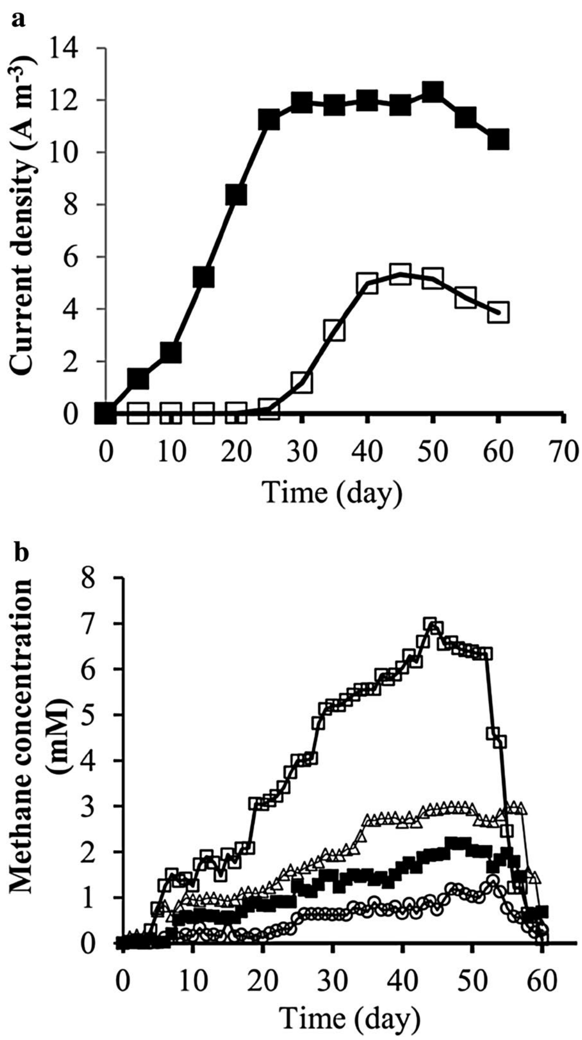

Fig. 2 Effect of dilution of raw wastewater on current density and CH_4 gas evolutions. **a** Current density evolution in MFC 2. Electrodes: (black square) RHCE, (white square) CCE; **b** methane gas production in MFCs. CCE; (white square) MFC 1, (Greek capital letter delta) MFC 2. RHCE; (black square) MFC 1, (white circle) MFC 2. The peak volumetric current density observed for RHCE-MFC 2 was 12.3 A m^{-3} while the peak current density for CCE-MFC 2 was 5.3 A m^{-3} (**a**). The peak methane gas concentration for CCE-MFC 2 was 2.9 mM while that of RHCE-MFC 2 was 1.2 mM (**b**)

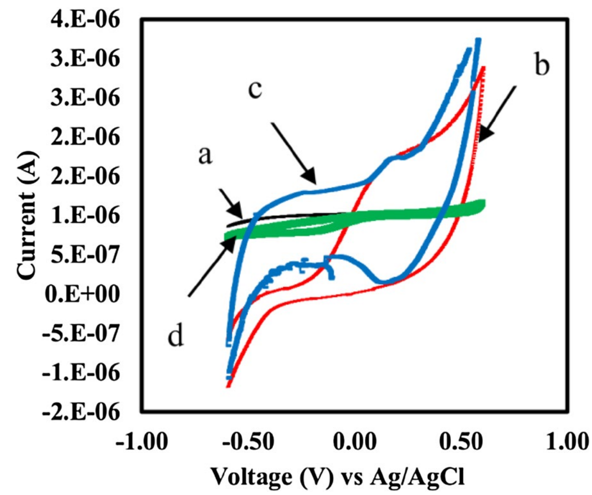

Fig. 3 Cyclic voltammograms of anodic biofilms of MFCs on day 40. RHCE: (black line) MFC 1, (red line) MFC 2, (blue line) MFC 3. CCE: (green line) MFC 2. The peak areas, amongst the MFC treatments are shown in the following order: RHCE- MFC 2 (red line) > RHCE-MFC 3 (blue line) > RHCE-MFC 1 (black line) > CCE-MFC 2 (green line). The peak redox areas of RHCE-MFC 1 (black line) and CCE-MFC 2 (green line) showed poor electrochemical activities

electrochemical activities. The redox peaks disappeared completely in both compared to the biofilms of MFC 2 and MFC 3.

We found that in 60 days of operation, there were decreases in DOC removal efficiencies coincidence with decreases in the concentrations of the slurry (Tables 1, 2). Power density values did not follow the same trend. In RHCE-MFC 2, the power density increased to 6.9 ± 3.1 W m^{-3}. The DOC removal efficiencies followed the order: MFC 1 (44 ± 4.9) % > MFC 2 (40 ± 1.2) % > MFC 3 (20 ± 1.2) % > MFC 4 (14 ± 3.8) % in line with substrate concentrations. This is consistent with the report of Min et al. (2005) that DOC removal efficiencies for glucose-fed MFC treating wastewater were directly proportional to substrate concentrations. The average power densities however were in the following order: MFC 2 (6.9 ± 3.1) W m^{-3} > MFC 3 (4.1 ± 2.1) W m^{-3} > MFC 1 (3.7 ± 1.5) W m^{-3} > MFC 4 (2.7 ± 1.7) W m^{-3}. This suggests that twofold dilution of raw PDWW yielded the highest average power density, which was approximately twofold higher than the control.

Discussion

It is noteworthy that RHCE-MFC 2 generated a significantly higher peak current density output (12.3 A m^{-3}) compared to CCE-MFC 2 (5.3 A m^{-3}) suggesting that rice husk is a feasible electrode material in MFCs. The nature of this CD difference is unclear at present. However, it is postulated that the higher biomass density on CCE-MFCs compared to RHCE-MFCs may be responsible. The affinity of archaea for CCE compared to RHCE amongst the treatments was most likely due to the differences in the microbial growth and particle size spectra of the organic substrates (Li et al. 2014). The results suggest that more current density was evolved under a comparatively lower methanogenic population in RHCE.

It was conjectured that moribund, unproductive biomass, unavailable for electricity generation accumulated in CCE-MFCs. The current/cell ratio was higher in CCE-MFCs than in RHCE-MFCs (data not shown). This

Table 2 Performance of poultry droppings-fed MFC at different substrate concentrations under continuous operation

MFC (rice husk charcoal electrode)	PDWW Concentration (mg L^{-1})	Average power density (Wm^{-3})	DOC removal efficiency (%)
1 (control)	954	3.7 ± 1.5	44 ± 4.9
2	477	6.9 ± 3.1	40 ± 1.2
3	95.5	4.1 ± 2.1	20 ± 1.2
4	9.54	2.7 ± 1.7	14 ± 3.8
MFC (carbon cloth electrode)			
1 (control)	954	2.5 ± 1.2	50 ± 2.3
2	477	3.5 ± 2.6	45 ± 6.2

suggests that electricity generating microorganisms on CCE-MFCs diverted more of electron flow to cell synthesis rather than to current. This agrees with the findings of Ieropolous et al. (2010), Lee et al. (2008), and Reguera et al. (2005) that increase in anodic biomass brings with it an increase in non-conductive cellular components and enhances mass transfer resistance which are limiting factors in current production.

In MFCs, microbes oxidize organic matter and release electrons that are transferred to anodes, resulting in electricity generation (Watanabe 2008). Substrate is important for any biological process as it serves as carbon (nutrient) and energy source. The efficiency and economic viability of converting organic wastes to bioenergy depend on the characteristics and components of the waste material (Pant et al. 2010). The present study shows that chicken droppings are a potent organic substrate in MFCs. In addition, it is likely that PDWW dilution factor may influence the growth of microbes involved in electricity generation in MFCs. We were interested in determining the most potent PDWW dilution threshold favourable for microorganisms involved in electricity generation.

Current in the voltammogram is a visual signal of the release of e^- produced from the oxidation of substrate in the bacterial cell. A higher current observed can be correlated to higher electron discharge (Wang et al. 2014). The results of cyclic voltammetry from this study agreed well with the findings of Chung et al. (2011) that electrochemical activities in MFCs could be detected from peak areas.

The comparatively higher DOC removal efficiency of biofilms on CCE-MFCs did not translate to a prolific current and power densities. This confirms that consumption of DOCs in CCE-MFCs was majorly not associated with power generation because electrons were apparently diverted from current production. This is consistent with the report of Asai et al. (2017) that a possible reason for inconsistency in trends between the COD removal and maximum power density would be that microbial terminal electron-accepting reactions other than current generation also contributed to the COD removal.

Conclusions

The present study comparatively evaluated CCE-MFCs and RHCE-MFCs using different concentrations of poultry droppings wastewater, suggesting that poultry droppings wastewater are feasible fuel for electricity generation in MFCs. Rice husk charcoal can also be considered as doable electrode materials in MFCs since substantial outputs were generated in rice husk microbial fuel cells. This study has addressed one of the recommendations of Asai et al. (2017) on the need for further studies on the development of technologies for the production of cheap electrodes. In future studies, the utility of rice husk charcoal will be further evaluated in large-scale MFC reactors with different configurations and substrates.

Authors' contributions

GEO performed the experiments, JCO laid the guideline and designed the experiment, CUA edited the manuscript, and SO gave a general advice. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

All data generated or analysed during this study are included in this article for open access.

Ethics approval and consent to participate

The authors have read and approved to submit it to Bioresources and Bioprocessing.

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