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Effect of C/N ratio and salinity on power generation in compost microbial fuel cells

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In this work, compost Microbial Fuel Cells (cMFCs) were used to generate electricity from a mix of fruit and vegetable wastes, and soil with different C/N ratios and salinities. Experiments were carried out in 500 mL cMFCs equipped with carbon felt anodes and manganese dioxide cathodes. The cMFCs were loaded with fresh compost and operated at 20–23 °C for up to 97 days. The low C/N ratio (C/N 24) had a greater power production with a maximum power density of 5.29 mW/m^2 (71.43 mW/m^3), indicating a more favorable condition for microbial growth. High-saline cMFCs produced lower power, suggesting that their level of salinity (10 g/L of NaCl) inhibited electricigenic microorganisms. The closed-circuit cMFC showed an improved degradation of organic matter by 6% to 8% compared to the control MFC operated in an open circuit mode (no external resistor attached).

1. Introduction

Solid organic wastes represent a significant source of environmental pollution worldwide (Otten, 2001; Bingemer and Crutzen, 1987; Gupta et al., 1998) and when left unprocessed, emit greenhouse gases (GHGs) such as carbon dioxide (CO_2) and methane (CH_4) into the atmosphere. Reduction of GHG emissions can be realized when organic wastes are composted or anaerobically digested and the end products are utilized for energy and as bio-fertilizer, rather than being uncontrollably discharged into landfills. A proper waste management is critical because landfills without efficient gas capture systems result in methane release. CH_4 is the second most important greenhouse gas, which is 25 times more potent as a heat-trapping gas than CO_2 (Forster et al., 2007).

On a global perspective, organic waste should be considered as a valuable resource that can be profitable, and comply with the waste-to-energy concept (APO, 2007). The buildup of large quantities of agricultural and municipal solid wastes must be addressed even though it may be demanding to resolve (Hinrichs and Merlin, 2006). Urban areas could have a greater impact on the environment due to the amount of organic waste produced per capita (Curry and Pillay, 2012). For instance, Canada produced 777 kg per capita of annual municipal waste in 2008, two times as much as Japan, and has been steadily increasing since 1990 (Municipal Waste Generation, 2013). For this reason, studies on several alternative technologies such as anaerobic digestion (Mata-Alvarez, 2003), gasification (Arena, 2012), and pyrolysis (Chen et al., 2014) have been conducted on municipal solid waste disposal to address the increasing amount of organic wastes produced due to economic growth and massive urbanization (Gupta et al., 1998; Curry and Pillay, 2012; Cheng and Hu, 2010).

Conventional composting requires air supply by either turning or aeration in order for decomposition to occur under aerobic conditions. Therefore, depending on the process, composting can occur in aerobic and anaerobic conditions. In the absence of air (O_2) supply, it becomes "anaerobic composting" (more commonly known as anaerobic digestion) which describes the process of breaking down organic matter by reduction (Compost Fundamentals, 2015; Yu et al., 2015). For example, transformation of organic materials such as acetic acid in anaerobic condition produces methane and carbon dioxide ($CH_3COOH \rightarrow CH_4 + CO_2$).

Microbial Fuel Cell (MFC) is a device in which electricigenic (anodophilic) microorganisms generate electricity from carbon source under anaerobic conditions. Oxidization of organic matter in the anodic chamber releases electrons and protons. Most of the released electrons are conveyed to the anode, and the transfer can be accomplished by three possible mechanisms such as direct electron transport, nanowires, and electron shuttling via self-produced mediators (Logan, 2009). From the anode, these electrons are directed to the cathode through an external circuit, whereas the protons are transported to the cathode through a separator.

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At the cathode, electrons and protons are combined with the electron acceptor (oxygen) to produce H_2O. A complete reaction in a closed circuit MFC produces electricity. Several advantages of MFCs over other energy technologies utilizing organic matter include the in-situ conversion to electricity that allows a high conversion efficiency, the ability to operate at ambient temperatures and below, and its potential to be used in remote locations lacking electrical infrastructures (Rabaey and Verstraete, 2005).

MFCs can be classified to be either liquid-phase or solid-phase, depending on the state of the carbon source. Because of low internal resistance and simplicity of carbon delivery in liquid-phase, most MFCs use dissolved sources of carbon. In particular, MFCs are often operated using municipal and agricultural wastewaters (Zhang et al., 2013; Min et al., 2005; Min and Logan, 2004; Liu et al., 2004). However, solid-phase MFCs are typically operated on such carbon sources from solid municipal or agricultural wastes (Moqsud et al., 2014; Wang et al., 2013; Lee and Nirmalakhandan, 2011), contaminated soil (Huang et al., 2011) and lignocellulosic waste (Huang and Logan, 2008; Catal et al., 2008). Despite the fact that solid-phase MFCs may not produce as much electricity as those fed with liquid wastes (Lee and Nirmalakhandan, 2011), the approach of developing solid-phase MFCs still can be valuable because solid organic wastes are rich in organic matter (Wang et al., 2013).

There is only a limited number of studies has been dedicated to the solid-state organic waste degradation in microbial fuel cells. In 2011, Mohan and Chandrasekhar (2011) utilized canteen-based food waste (mainly boiled rice and vegetable) as a fuel in a single chamber MFC (450 mL working volume) with air-cathode and graphite plate electrodes and obtained 170.81 mW/m^2. Wang et al. (2013) experimented with household organic matter (bean residue, ground coffee waste, fallen leaves, and rice hull) with different carbon-to-nitrogen (C/N) ratios. They used a single-chamber MFC (200 mL working volume) with carbon felt for both electrodes and found a compost C/N ratio of 31:1 resulting in optimal electrical performance, and also by adding bio-enzyme, a maximum power output of 264 mW/m^2 was achieved. Recently, Yu et al. (2015) attempted to enhance the composting of dewatered sludge that they used as the anode fuel. Using a double chamber (anodic compartment 780 mL and cathodic compartment 350 mL) and graphite fiber brushes for both electrodes, they demonstrated the MFC accelerated anaerobic composting process and enhanced composting maturity in comparison with the traditional anaerobic composting. In that study, a power output of 5.6 W/m^3 was observed.

By proposing a different configuration from previous studies, this study investigated the potential of combining anaerobic digestion of solid organic wastes i.e. anaerobic composting with MFC technology, which enables electricity generation from degradation of complex organic materials. In cMFCs, both the C/N ratio and salinity factors might affect power output. The C/N ratio is expected to have an effect on cMFC performance because it might influence microbial metabolism, and thus the power production in MFCs. As for salinity factor, it is expected that a high salinity can increase mobility of protons in the anodic chamber i.e. to help boost proton transport to the cathode, thereby resulting in a greater power production. The experiments were performed in two series: set A was designed to study the impact of electrical connection on cMFCs, and set B was to study the effect of C/N ratio and salinity on cMFCs performance. We also demonstrated the flexibility of operating MFCs at ambient temperature.

2. Materials and methods

2.1. C/N ratio and salinity concentration selection

Generally, an optimum C/N ratio for composting is within the range of 19 to 40 parts available carbon to 1 part available nitrogen, depending on the substrate (Golueke and Diaz, 1990; Golueke, 1991). Therefore, this work studied two different C/N ratios: 24:1 (denoted as C/N 24) and 31:1 (C/N 31). C/N 24 was selected considering it as the ideal microbial diet to feed soil microbes (USDA-NRCS, 2011), and this ratio is close to C/N 25 which is acknowledged theoretically as the optimum ratio for microbial growth (Heal et al., 1997). Although C/N 30 is widely known as the ideal ratio for general composting, we used C/N 31 due to the previous study (Wang et al., 2013), which found C/N 31 to exhibit the best power density.

Salt (NaCl) concentration of 10 g/L was chosen based on a similar study (De Schamphelaire et al., 2010) reporting that a maximum power MFC could be achieved within the range of 5–15 g/L NaCl. Furthermore, *Geobacter* spp. have demonstrated the tolerance up to 10 g/L NaCl (Nevin et al., 2005). Beyond 20 g/L NaCl, MFC performance was observed to have decreased (Lefebvre et al., 2012).

2.2. Compost preparation

Table 1 gives the compost recipe used for this study. The compost consisted of a mix of apples, lettuce, green beans, and soil (potting mix). The raw material sample was finely ground, weighed, and wrapped in an aluminum capsule before being placed in the NC Soil Analyzer (Flash 1112 Series EA, Thermo Finnigan, Italy). The C/N ratio of each raw material was then substituted into Eq. (1) (Richard and Trautmann, 1996) to determine the required amounts of each organic matter to prepare C/N 24 and 31.

$$R = \frac{Q_1(C_1 \times (100 - M_1) + Q_2(C_2 \times (100 - M_2) + Q_3(C_3 \times (100 - M_3) + Q_4(C_4 \times (100 - M_4)}{Q_1(N_1 \times (100 - M_1) + Q_2(N_2 \times (100 - M_2) + Q_3(N_3 \times (100 - M_3) + Q_4(N_4 \times (100 - M_4)} \quad (1)$$

where R is the C/N ratio, Q_n the mass of material n, C_n the carbon (% in dry basis) of material n, N_n the nitrogen (% in dry basis) of material n, M_n the moisture content (% in wet basis) of material n, and index n = 1, 2, 3, 4 refers to apples, green beans, lettuce, and soil, respectively.

The moisture content was obtained by drying materials in a hot air vacuum oven at 105 °C until a constant mass was reached (Sluiter et al., 2004). The formula to calculate moisture content as in Eq. (2):

Table 1
Fresh compost composition.

Ingredient	Moisture content (%)	Carbon (%)	Nitrogen (%)	Mass (kg)	C/N ratio	Mass (kg)	C/N ratio
Apple	79	50.6	0	0.54	31:1	0.18	24:1
Green beans	73	49.6	3.4	0.27		0.27	
Lettuce	81	43.7	1.7	0.35		0.35	
Potting soil	10	35.1	1.4	0.15		0.1	

$$M_n = \frac{(W_w - W_d)}{W_w} \times 100 \quad (2)$$

where M_n is the moisture content (%) of material n, W_w is the wet mass of the sample, and W_d is the mass of the sample after drying.

2.3. Construction, design, and operation of compost MFCs

Fig. 1A provides a schematic diagram of the compost MFC (cMFC). An air-cathode cMFC was constructed using a 500 mL high-density polyethylene (HDPE) bottle (Fisher Scientific, ON, Canada) with 105 holes having a diameter of 8.72 mm each. Accordingly, the total cathode area was $6.27 \times 10^{-3}\ m^2$. A $23 \times 10\ cm^2$ piece of MnO_2 carbon paper cathode (Electric Fuel Ltd., Bet Shemesh, Israel) was glued to the outside surface of the bottle by using Loctite Superflex Clear RTV Silicone Adhesive Sealant (Henkel Corporation, CT, USA). Carbon felt anode (SGL Canada, Kitchener, ON, Canada) with a dimension of $22 \times 10\ cm^2$ was placed inside the bottle along the wall.

Distance between anode and cathode was approximately 1.6 mm (Fig. 1B). The anodic compartment (12 cm height; 7 cm diameter) was in anaerobic conditions. The water level was manually adjusted in set A and controlled by water supply in set B. Table 2 shows two sets of experiments containing six cMFCs constructed and loaded with fresh compost. In set A, four cMFCs were operated for 97 days with two factors: C/N ratio and salinity levels. Next, two cMFCs in set B were operated for 71 days using a single C/N ratio and salinity level. One of these cMFCs was a closed circuit cMFC ($cMFC_{cc}$) and the open circuit ($cMFC_{oc}$) was used as a control. All experiments were conducted at room temperature (20–23 °C).

Table 2
Compost MFC used in two sets A and B experiments.

Set	cMFC	NaCl in water solution (g/L)	C/N ratio
A	NS24	0	24:1
	NS31		31:1
	S24	10	24:1
	S31		31:1
B	cMFCcc	0	24:1
	cMFCoc		

Notations S (saline) denotes cMFCs provided with NaCl solution, and NS (non-saline) denotes cMFCs with only distilled water i.e. no salt added. The numbers correspond to the C/N ratio (24:1 or 31:1). cMFCcc is the cMFC operated in closed circuit (with electrical load), cMFCoc is the cMFC operated in open circuit mode (no electrical load).

2.4. Analytical methods

The effects of the C/N ratio and salinity on cMFC performance in the set A were examined by the electrical properties (voltage, internal resistance, power generation) and analyses of suspended solids (SS), volatile suspended solids (VSS), C/N ratio, electrical conductivity (EC), and pH. Voltage output in set A was monitored automatically every 15 min on a daily basis using a data acquisition system (Agilent 34970A) interfaced with BenchLink Data Logger Version 3.04 (Agilent Technologies, Santa Clara, CA, USA). Data were sent to and stored on a desktop PC.

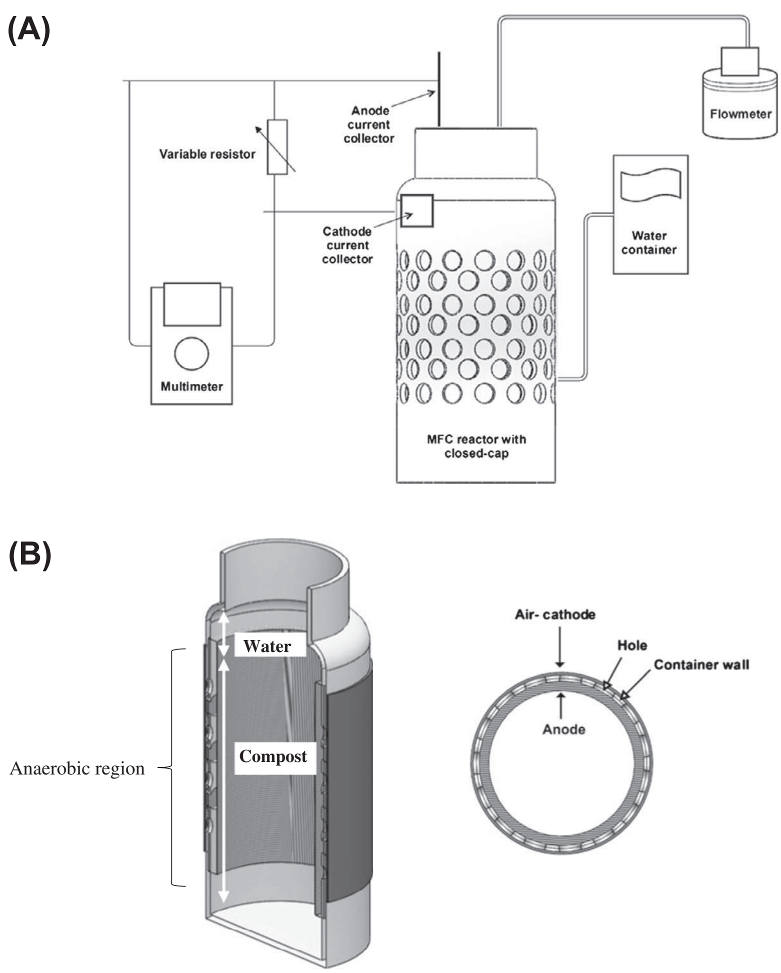

Fig. 1. (A) Schematic diagram of the compost MFC used in set B experiments and (B) cross section of the cMFC container.

In order to ensure that the MFC was consistently operating under optimal conditions, polarization tests were conducted on a weekly basis using Vee Pro 8.0 software (Agilent Technologies, Santa Clara, CA, USA). The test began with an open circuit voltage (V_{OCV}) for 30 min and then voltages were measured using 5000, 2000, 1000, 500, 250, 150, 100, 50 Ω in descending order in a 5-min step and repeated in reverse. After each test, the external resistance (R_{ext}) was set close to the estimation of internal resistance (R_{int}).

The SS and VSS measurements were carried out at the beginning and the end of the experiment in both set A and set B using Standard Methods (Association, 1995). SS represents the amount of solid matter in the sample, whereas VSS is an estimation of the biodegradable organic matter present in the sample. The decomposition of organic matter is indicated by the difference between the initial and final VSS.

Electrical conductivity (EC) and pH were measured using an electrical conductivity meter (EC 110, Spectrum Technologies, IL, USA) and a soil pH meter (FieldScout SoilStik ProMeter, Spectrum Technologies, IL, USA), respectively. Measurements were conducted on a weekly basis. Statistical analysis was done by Design-Expert® software version 9 (Stat-Ease, Inc., Minneapolis, MN, USA).

Additionally, set B cMFCs were equipped with a flow meter (Milligascounter, Ritter Apparatus, Bochum, Germany) to record off-gas production throughout the experiment. The composition of off-gas in the set B cMFCs was analyzed periodically and measured using an HP 6890 gas chromatograph (Hewlett Packard, Palo Alto, CA, USA) equipped with a thermal conductivity detector and a 5 m × 2.1 mm Carboxen-1000 column (Supelco, Bellafonte, PA, USA). Argon was used as the carrier gas.

To summarize, the feasibility of bioelectrochemically enhanced composting was evaluated in two series of tests. In the first set, the factorial design approach was adopted to study the impact of C/N ratio and salinity on MFC performance. In the second experiment, the impact of electrical connection on organic matter degradation and thereby MFC performance were assessed by measuring SS and VSS reduction in active MFC and comparing it with a control system lacking bioelectrochemical reactions.

3. Results and discussion

3.1. SS and VSS reduction

Table 3 compares SS and VSS values of fresh compost with the corresponding values at the end of each test. Set A cMFCs has shown a greater VSS reduction in the higher C/N ratio cMFC, supporting the finding from a previous study showing the maximum VSS reduction occurred at the highest C/N ratio when using green wastes (Kumar et al., 2010). Moreover, the greater VSS reduction in the saline cMFCs (S24 and S31) suggests the effect of NaCl solution used as the electrolyte.

The reduction of VSS in set B $cMFC_{oc}$ was the lowest among all other cMFCs with 8–12% less, implying that fewer decomposition of biodegradable organic matter occurred in the cMFC operated in an open circuit mode. Biodegradation in $cMFC_{cc}$ was observed to be 6–8% higher compared to $cMFC_{oc}$. This finding suggests that operating MFC in a closed circuit was more conducive for the growth of microbial community in the anodic chamber (Huang et al., 2014) thereby improving the composting process. This result is in agreement with a study (Ma et al., 2014) conducted on organic matter recovered from real municipal wastewater which found greater SS and VSS reduction in the working MFC with 56.9% and 62.1%, respectively, compared to the control MFC which had decreased by only 31.7% in SS and 31.9% in VSS.

3.2. C/N ratio and salinity impact on energy production

Fig. 2 shows the changes in the power density of the cMFCs in set A over the 97-day experiment. Several abrupt voltage changes were observed. The voltage drop phenomenon occurred because the carbon source limited the metabolism of bacteria within the anaerobic zone of the MFC. In other words, whenever the organic matters start depleting, the electricity generation would subside due to the low microbial metabolism occurring in the MFC (Barua and Deka, 2010). Fluctuations in power density were also observed with several upward trends and sharp falls as seen in NS24, for instance. These fluctuations can be attributed to a number of factors such as periodic adjustments of R_{ext} done to maintain the R_{ext} close to its optimal values ($R_{ext} \sim R_{int}$), changes in the cMFC microbial community, and pH. The saline cMFCs were observed to have fewer variations in the power output, although this could be associated with lower power production in these cMFCs. For this

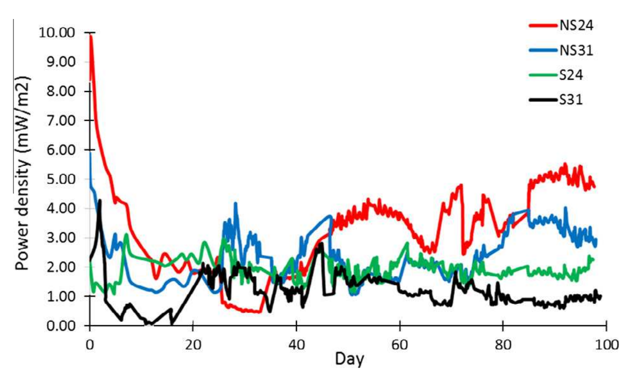

Fig. 2. Changes in power densities over time of cMFCs operated with different C/N ratios and salinities (set A experiment).

Table 3
SS and VSS values of fresh compost and compost at the end of cMFC operation.

Set A	Compost sample	SS (g/kg)	Reduction (%)	VSS (g/kg)	Reduction (%)
Fresh	24:1	130.87 ± 4.02	–	120.49 ± 4.02	–
Final	NS24	86.91 ± 1.21	33.60	76.73 ± 1.21	36.32
	S24	88.66 ± 2.09	32.25	71.96 ± 1.92	40.28
Fresh	31:1	133.45 ± 1.66	–	124.02 ± 1.69	–
Final	NS31	87.62 ± 3.04	34.34	77.92 ± 2.89	37.17
	S31	109.11 ± 10.33	18.24	75.30 ± 1.28	39.28
Set B	**Compost sample**	**SS (g/kg)**	**Reduction (%)**	**VSS (g/kg)**	**Reduction (%)**
Fresh	24:1	117.45 ± 1.36	–	107.51 ± 1.32	–
Final	$cMFC_{cc}$	78.38 ± 0.78	33.27	68.63 ± 0.97	36.16
	$cMFC_{oc}$	86.08 ± 1.50	26.71	77.39 ± 1.42	28.02

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reason, power outputs were also compared based on the steady state performance and, thus, data for the last 12 days were used. During this period, NS24 clearly demonstrated the highest power density followed by NS31, S24 and S31 with a range of 0.73–5.29 mW/m^2.

Fig. 3 presents a regression model-based analysis of power outputs during steady state cMFC operation and power output relating to the two model terms: C/N ratio and salinity. Analysis of variance shows that model terms in this study were significant ($p < 0.05$). The p-value of lack-of-fit was calculated to be 0.086 for $p > 0.05$, which indicated that the model was acceptable. The analysis also demonstrates that the coefficient estimate of C/N ratio was −0.22 while that of salinity level was −0.44, which was indicative of adverse effects of both factors on power density.

The maximum power density (P_D) and current density (C_D) normalized to the cathode surface area during the steady state were obtained from NS24 with 5.29 mW/m^2 (or 71.43 mW/m^3 in term of working volume), and 28.73 mA/m^2, respectively. In brief, NS24 showed that the lower the C/N ratio, the higher the power produced. P_D for Fig. 3 can be expressed mathematically by the following equation:

$$P_D = \left(3.77 - 0.06\frac{C}{N}\text{ratio} - 0.09\text{Salinity}\right)^2 \quad (3)$$

With regard to the statistical analysis, the regression model analysis suggests that for a C/N ratio of 24 to 31 and salinity from 0 to 10 g/L of NaCl, the optimum condition to achieve the maximum P_D is C/N ratio of 24 with no salt added. Its desirability is 0.947 giving an extrapolated power density of 5.05 mW/m^2.

The changes in C/N ratio of compost samples over time are shown in Table 4. While generally C/N ratio decreases over time, NS24 had no significant change in C/N ratio, suggesting that the decomposition of carbon and nitrogen in NS24 had occurred at a similar rate. Put differently, the decomposition process in NS24 had taken place as shown in the VSS reduction (36.32%) without affecting its final value of C/N ratio. The loss in S24 was only 8.0%, and this could be attributed to the smaller amount of potting mix used in the compost of C/N 24 compared to C/N 31. In contrast to C/N 24, the final composts of C/N 31 had greater percentage losses. For example, the final ratio of S31 (C/N 31) decreased to C/N 22.4 by 27.8% and NS31 decreased to C/N 25.6 by 17.3%. The decrease in the final C/N ratio is consistent with a study reporting the decline of the C/N ratio of the compost from 32 to 20 after 60 days of composting (Lin, 2008).

Table 4
Comparison of C/N ratio of the compost samples.

cMFC	C/N initial	C/N final	Difference (%)
NS24	24.0	24.3	1.2
S24	24.0	22.1	−8.0
NS31	31.0	25.6	−17.3
S31	31.0	22.4	−27.8

Although the addition of NaCl increased solution conductivity and supposedly reduced internal resistance, this increased conductivity was not translated into higher power output in our experiments. It is contrary to the recommendation (Lefebvre et al., 2012) to add up to 20 g/L of NaCl to increase the performance of MFC. The negative impact of increased salinity is in agreement with the previously observed changes in the Coulombic efficiency, which started to decrease at 10 g/L of NaCl, although the power production showed an increase (De Schamphelaire et al., 2010). Hence, the salt intake should be regulated and sufficient adaptation time might be required to develop a salt tolerant microbial community which is beneficial to MFC performance. Further investigation on MFCs for soils with high salinity may consider a recent finding (Miyahara et al., 2015) on the abundance of a salt-tolerant strain of *Geobacter* spp. found on the anodes with 0 to 0.1 M (5.84 g/L) NaCl, but decreased significantly above 0.3 M NaCl (17.53 g/L). At a concentration of 0.3 M NaCl, bacteria affiliated with *Gammaproteobacteria* and *Bacilli* were abundantly detected.

In summary, our findings have shown C/N 24 produced higher power density, suggesting that although the carbon source in C/N 24 is lower than C/N 31, this ratio is more favorable for the microbes in the cMFC, confirming the optimum C/N ratio for microbial growth (Heal et al., 1997). In addition, lower power output in high-saline cMFCs, suggesting that the salinity, at least, in

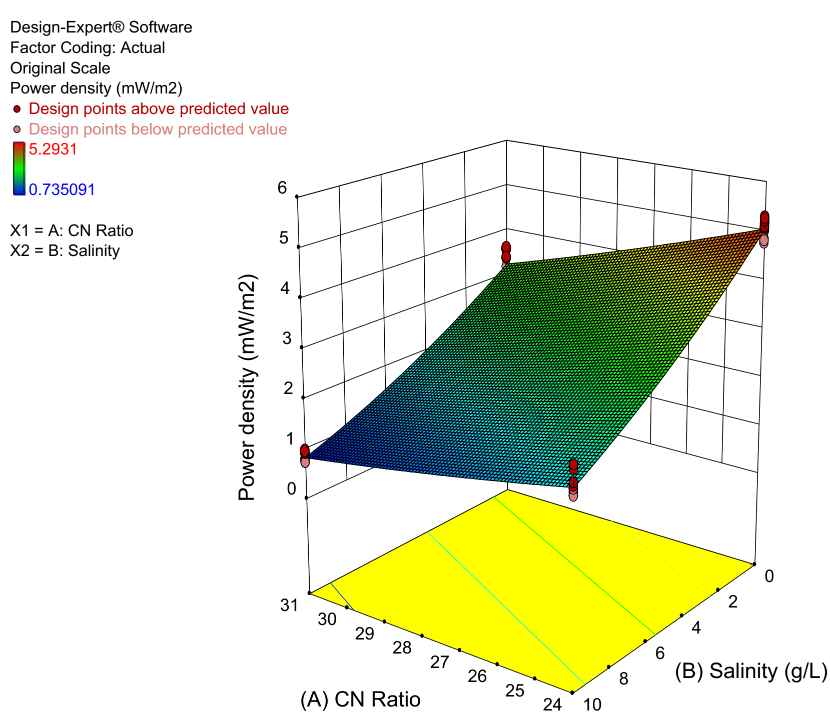

Fig. 3. The effect of C/N ratio and salinity on cMFC power output.

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this case, was not beneficial. Microorganisms in the anodic chambers were salt sensitive at this concentration and were negatively affected. It can be suggested that a longer adaptation period or specific salt-tolerant bacteria such as *Geobacter* spp. might be inoculated to take advantage of increased conductivity.

3.3. Polarization tests

The idea of performing polarization test was to estimate the maximum MFC power by estimating the R_{int}, and to adjust R_{ext} values accordingly. Fig. 4 shows the voltage and power density (P) values obtained in polarization tests conducted on a particular day (day 74 for set A and day 64 for set B experiments). P_{max} was highest in cMFC$_{oc}$ (6.34 mW/m^2), followed in descending order by NS24 (4.29 mW/m^2), NS31 (3.84 mW/m^2), S24 (3.70 mW/m^2), S31 (2.02 mW/m^2) and cMFC$_{cc}$ (1.24 mW/m^2). The highest power output observed in cMFC$_{oc}$ suggests that the open circuit MFC exhibited energy accumulation within the anodic biofilm. It also shows that during the short period when cMFC$_{oc}$ was connected to an external resistor, the MFC was capable of exhibiting a power burst as a result of the oxidization of respiratory enzymes and electron carriers holding electrons. In open-circuit MFC the anode potential becomes more negative, and whenever the circuit is reconnected with a load, the anode potential becomes less negative resulting in the greater power output and lower energy capture by bacteria (Logan, 2009).

A comparison of polarization tests in set A cMFCs in terms of the maximum power output (P_{max}), estimation of internal resistance (R_{int}), and open circuit voltage (V_{ocv}) between cMFCs is presented in Fig. 5. Most of P_{max} values of S24 were greater than NS24 although the P_D of NS24 during the normal operation was higher compared to S24 (Fig. 2) suggesting the high-saline cMFC to have higher capacity to accumulate charge during the open circuit mode period (30 min) of the polarization test. Moreover, the R_{int} of NS24 increased over time indicating the depletion of carbon source in it. The constant trend of high open circuit voltages (V_{ocv}) in NS24 has shown that NS24 was better than S24 which observed a decrease in V_{ocv} after the 7th polarization test. S31 was observed to undergo a consistent trend of high R_{int}, low P_{max} and low V_{ocv} throughout the experiment which implies that the higher C/N ratio in saline conditions was not an advantage to produce high power density.

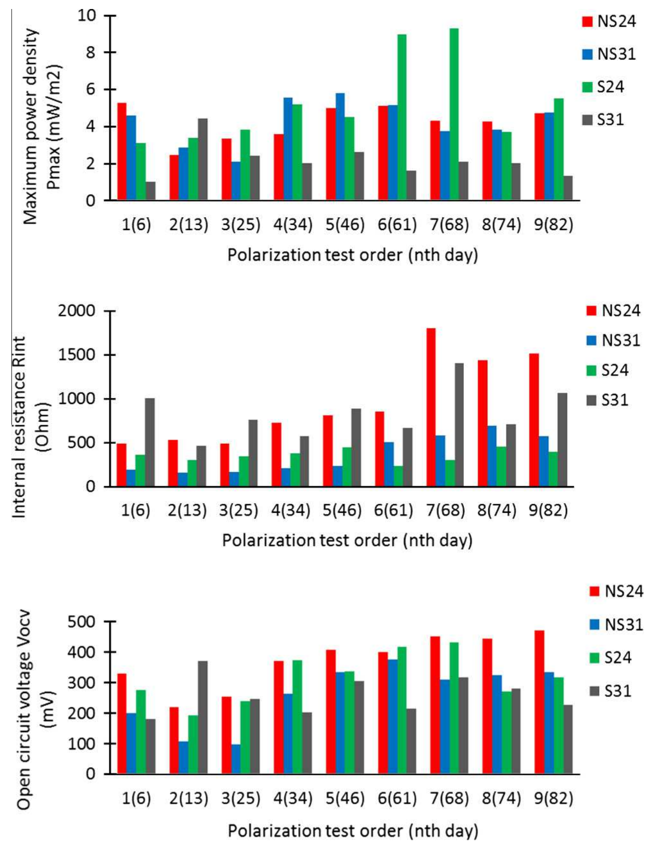

Fig. 5. A comparison of P_{max}, estimated R_{int} and V_{ocv} from polarization tests throughout the operation of set A. Number in brackets denotes particularly the day of which the polarization test was conducted.

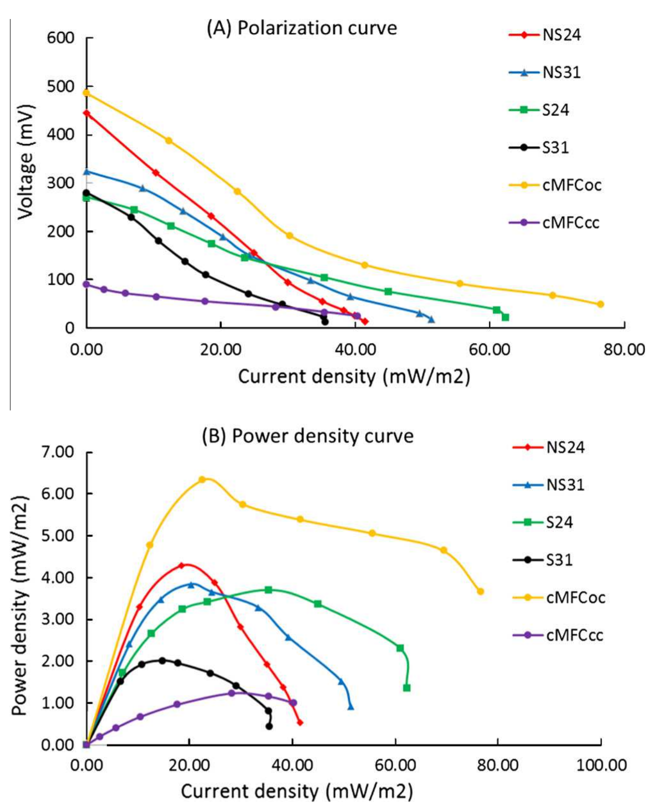

Fig. 4. Polarization (A) and power density (B) curves obtained in polarization tests performed on day 74 and 64 for set A and set B, respectively.

3.4. Electrical conductivity (EC) and pH changes

NS cMFCs demonstrated relatively consistent EC with a mean of 5.74 ± 0.44 mS/cm for NS31 and 5.33 ± 0.40 mS/cm for NS24. Obviously, these values were lower than those of the saline cMFCs, 16.22 ± 4.48 and 9.59 ± 1.63 mS/cm for S31 and S24 due to the accumulation of NaCl in the anodic chambers. Initially, the pH of the fresh compost was at approximately pH 4 as shown in Fig. 6, apparently due to low pH of apples (pH 3.3). The acidic conditions might be favorable for a breakdown of lignin and cellulose. At the end of the experiment, the pH of cMFCs became less acidic and reached near-neutral values of 6.33–7.54. These results corroborate commonly observed gradual neutralization of pH due to microbial degradation of proteins, which releases ammonium resulting in a pH increase (Tuomela et al., 2000; Haug, 1993).

3.5. Off-gas production and composition

During the set B experiment, a total of 22.96 and 35.64 mL of off-gas were produced and collected from cMFC$_{cc}$ and cMFC$_{oc}$, respectively. Furthermore, after the first ten days of experiment, gas production decreased to near zero values. The off-gas composition from each cMFC$_{cc}$ and cMFC$_{oc}$ was analyzed three times in the

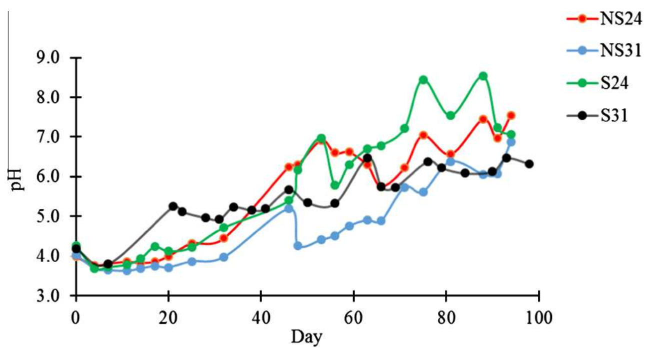

Fig. 6. Change in pH over time during set A experiment.

course of the experiment with off-gas consisting of N_2 and CO_2. Total production of CO_2 in $cMFC_{cc}$ decreased from 1.15 to 0.83 mL while that of $cMFC_{oc}$ declined from 1.89 to 1.21 mL. Although CH_4 production was expected in both cMFCs, it was not detected in the off-gas analysis.

It can be hypothesized that the absence of CH_4 in both $cMFC_{cc}$ and $cMFC_{oc}$ as well as the observed differences in total biogas production were due to gas exchange through the porous cathode allowing for influx of oxygen to the soil matrix and the outflow of CO_2 and CH_4. The influx of O_2 will cause aerobic or microaerobic conditions to occur in the soil matrix. The presence of oxygen will suppress methanogenic activity as well as enable methanotrophic microorganisms in the anodic chamber to oxidize methane (Amils, 2011). Although the attempt to measure off-gas composition was not fully conclusive, it can be speculated that greenhouse gas emissions in the working MFC might be lower as compared to the control due to reduced methanogenic activity.

4. Conclusion

The results of this study show a greater VSS reduction in cMFCs as compared to the control system operated in open circuit mode, thereby giving an insight into the applicability of employing cMFC to enhance biodegradation of organic wastes. Findings from our study demonstrated that the cMFCs with lower C/N ratio and lower salinity produced higher power. C/N 24 appears to be more favorable for microbial metabolism, hence, producing a greater power, in contrast to the additional 10 g/L of NaCl treatment which was adverse to the power production. The normalized maximum power density (P_D) during the steady state observed in cMFC NS24 was 71.43 mW/m^3 (per working volume) or 5.29 mW/m^2. This relatively low energy can be used to power small electronic devices, such as environmental sensors.

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