Effect of substrate type and concentration on the performance of a double chamber microbial fuel cell

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ABSTRACT

The microbial fuel cell (MFC) provides new opportunities for energy generation and wastewater treatment through conversion of organic matter into electricity by electrogenic bacteria. This study investigates the effect of different types and concentrations of substrates on the performance of a double chamber microbial fuel cell (DCMFC). Three mediator-less laboratory-scale DCMFCs were used in this study, which were equipped with graphite electrode and cation exchange membrane. The MFCs were fed with three different types of substrates (glucose, acetate and sucrose) at a chemical oxygen demand (COD) concentration of 1,000 mg/L. The selected substrate (acetate) was studied for three different concentrations of 500, 2,000 and 3,000 mg/L of COD. Results demonstrated that acetate was the best substrate among the three different substrates with maximum power density and COD removal of 91 mW/m^2 and 77%, respectively. Concentration of 2,000 mg/L was the best concentration in terms of performance with maximum power density and COD removal of 114 mW/m^2 and 79%, respectively. The polarization curve shows that ohmic losses were dominant in DCMFCs established for all three substrates and concentrations.

Key words | COD removal, double chamber microbial fuel cell, power density, wastewater

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INTRODUCTION

The microbial fuel cell (MFC) has been widely regarded as one of the promising approaches for sustainable energy production from a variety of organic wastes and biomass. It utilizes the catalytic activity of microorganisms to convert organic matters to electricity generation. Searching new renewable energy resources to replace fossil fuels has been the focus in recent times. MFCs have received significant consideration owing to their potential to achieve partial treatment of a wide range of wastewaters while producing electrical energy at the same time.

In the past, the MFC has been considered as a promising alternative technology for the biological reactor of conventional municipal wastewater treatment plants. It has been considered applicable for highly loaded industrial wastewater treatment as well (Cusick *et al.* 2010). Recently, MFCs have received considerable attention to be used as a substitute for the conventional activated sludge process because they can treat wastewater while generating electricity at the same time (Zhang *et al.* 2013). MFCs have clearly an upper hand over the existing wastewater treatment systems and can replace these energy-intensive systems. They degrade waste and at the same time reclaim energy for further use at the plant. It has been shown in the past that MFCs could reduce 50–90% of the organic matter by using wastewater as substrate (Min & Logan 2004). At small scale, the results have been encouraging but the scale-up exposure of MFCs is facing a huge obstacle at the present time and a lot of work has to be done in the coming years to overcome it effectively.

There are two configurations of MFCs on the basis of number of chambers: (i) single chamber microbial fuel cell (SCMFC) and (ii) double chamber microbial fuel cell (DCMFC). The SCMFCs can be fabricated by eliminating the cathode compartment and keeping the cathode in direct contact with air. This design of an MFC does not need any membrane, which makes it simple and economical. However, the major challenge for a membrane-less MFC is the consumption of substrate to oxygen diffused through the cathode. These problems could be resolved by a DCMFC, which can diminish the oxygen diffusion without affecting the power density and increasing the internal resistance of the cell. The conventional design of DCMFCs

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comprises two chambers, anaerobic (anode) and aerobic (cathode) chamber, which are joined by a bridge and are separated by a cation exchange membrane (CEM). This design is commonly run in fed-batch and batch mode. The main purpose of the CEM is to allow protons to flow from anode to cathode while physically separating the liquids in each chamber (Logan *et al.* 2006).

Several other structural and operational aspects have been studied to enhance the performance of MFCs, including inoculums, electrode material, ion exchange membrane, solution ionic strength, temperature and use of various types of real wastewater or synthetic solutions as substrates (Cheng *et al.* 2006; Lee *et al.* 2015). The use of synthetic solutions as substrates has a great significance because this kind of energy conversion device is not the best choice for general environmental applications, as researched in the last few years (Rodrigo *et al.* 2009). In fact, the greater and real opportunity could be the supply of power for remote applications with low requirement of energy. Within this context, yielding energy from different organic matters in a synthetic fuel, manufactured only for this purpose, can be a possible approach to optimize this technology. The synthetic wastewater used in an MFC should not only comprise a carbon source to provide energy but have sufficient ratios of nutrients as well to fulfil metabolic requirements of microorganisms, so that they do not become the limiting components of the process, which is the case with different types of wastewater typically fed to these systems (Asensio *et al.* 2016). Various organic substrates can be utilized as potential fuels for MFCs. Simple and easily biodegradable molecules may result in a more effective process. An initial step of hydrolysis and fermentation is required for the complex substrate to break macromolecules to simpler ones and then convert them to other readily biodegradable substrates like acetate, which is then degraded by anode respiring bacteria (ARB) (Kiely *et al.* 2011). The redox mediators and/or redox transfer enzymes involved in the metabolism of simple substrates like alcohol and sugar proceed through very different pathways, which should reveal the efficiency of an MFC.

Due to the potential of wastewater treatment and energy recovery with MFCs, several wastewater types have been used as substrates till now. Mohan and his co-workers evaluated the feasibility of composite vegetables waste as substrate in a single chambered mediator-less MFC (Mohan *et al.* 2010). The MFC used in that study resulted in maximum power density of 57 mW/m^2 with effective chemical oxygen demand (COD) removal of 62%. Liu *et al.* (2005) reported maximum power density of 305 and 506 mW/m^2 with butyrate- and acetate-fed MFCs, respectively. Energy conversion efficiencies have also been evaluated with the most frequently used fermentable (glucose) and non-fermentable (acetate) types of substrates in several studies. Min & Logan (2004) have applied ferricyanide as catholyte and continuous mode of operation and produced maximum power density of 286 and 212 mW/m^2 by using acetate and glucose as substrates respectively. In one other study, Rabaey *et al.* (2005) reported maximum power output of 90 and 66 W/m^3 with acetate- and glucose-fed MFCs, respectively.

It is important to know which of these substrates delivers a higher efficiency. Besides this, the substrate concentration also plays a key role in evaluating the performance. Many researchers have been focusing on the use of pure cultures, and various MFC systems operate mainly with pure substrates as a sole carbon source. The growth medium having the necessary micronutrients and a carbon source (pure substrate) is generally stated as synthetic wastewater. It is interesting to explore the new dimensions of this technology with different types of synthetic wastewaters and in various concentrations, so as to find the fuel with the best performance.

With this background, the main purpose of the present study has been to evaluate the effect of different types and concentrations of substrate on performance of a double chamber mediator-less MFC.

MATERIAL AND METHODS

Design of DCMFCs

Three identical laboratory-scale DCMFCs were constructed with transparent acrylic sheets with a working volume of 1.9 L for each chamber. MFCs were constructed in an H-shaped design with both chambers separated by a CEM (CMI-7000, Membranes International, Inc.) as shown in Figure 1. The CEM surface area was 64 cm^2, and it had been soaked in 5% NaCl solution for 12 hours before use to allow for hydration and expansion. The reason for using CMI-7000 was its excellent proton conductivity, and thermal and chemical stability with much less water permeability (Liu 2008). Two equal sized uncoated rods of graphite were used as electrodes for each chamber. The effective length and diameter of graphite rods were 7.3 and 0.9 cm respectively resulting in a surface area of 22 cm^2 (0.0022 m^2). The graphite rods were abraded by sand paper before the installation to enhance the bacterial attachment. A copper wire was connected to each electrode and stretched outside each chamber to simply develop an electrical circuit for electron transport.

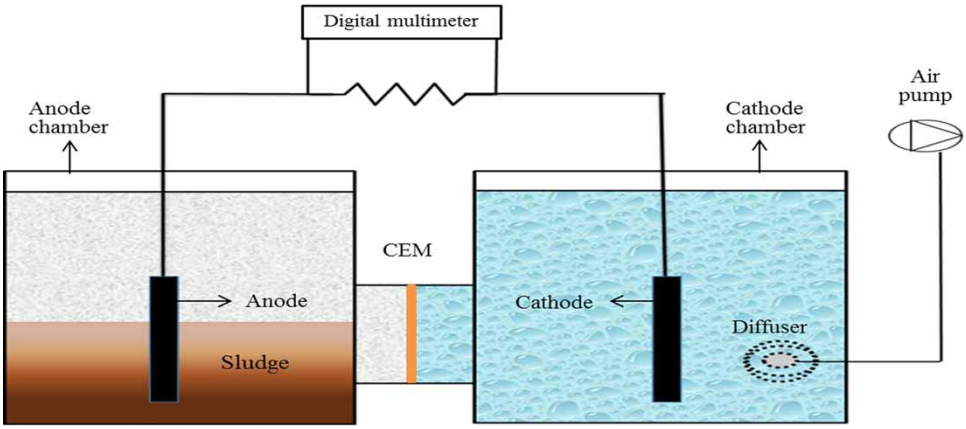

Figure 1 | Schematic diagram of double chamber MFC.

DCMFC inoculation and synthetic wastewater

Activated sludge from the wastewater treatment plant of the National University of Sciences and Technology, Islamabad, Pakistan, was used as the inoculum for the anodic chamber. Before the use of activated sludge in MFCs, it was kept in the three different containers for 3 days without aeration in a ratio of 1:2 to support the establishment of a mixed culture of anaerobic microorganisms. During this period, no synthetic wastewater was fed to the inoculum source (Asensio *et al.* 2016). After this duration, synthetic wastewater with different carbon based substrates at concentration of 1,000 mg/L was fed for 2 months to the MFCs for acclimation purposes. Inorganic compounds were the same for all substrates.

The synthetic wastewater fed to each MFC in the first experiment consisted of glucose, sucrose or sodium acetate as a sole carbon source with the concentration of 1,000 mg/L COD. In the second experiment, synthetic wastewater fed to each MFC consisted of acetate as a sole carbon source but with different concentrations of 500, 2,000 and 3,000 mg/L COD. The synthetic wastewater was prepared in phosphate buffer of 50 mM (pH 7) and it consisted of 191 mg/L of NH_4Cl, 87 mg/L of KH_2PO_4, 2 mg/L of $MnCl_2.4H_2O$, 10 mg/L of $CaCl_2$, 3 mg/L of $FeCl_3$ and 10 mg/L of $MgSO_4.7H_2O$, and $NaHCO_3$ was also added to adjust pH.

Operation of DCMFCs

The MFCs were operated in batch mode at 30 °C temperature. The anode chamber was filled with substrate solution. The anode chamber of each MFC was sparged with N_2 gas at the start of every batch, which reduced the chances of electron loss to O_2. The MFCs were operated at hydraulic retention time of 96 hours. All the tests were conducted in a 30 °C temperature-controlled water bath. The cathode compartment was filled with 100 mM phosphate buffer solution of pH 7 and was constantly aerated with a fishery pump (3.5 L/min) to supply oxygen.

Electrochemical and chemical measurements

A digital multimeter (Mastech-8217) was used to continuously monitor the value of the cell potential (V) across the external load of 1,000 Ω. COD was determined using closed reflux titrimetric method (APHA *et al.* 2005) and pH was measured with a Hach multimeter (Model-156). Power generation of the MFCs at different external loads was determined using polarization measurements. Polarization curves were obtained by varying the resistance across the cell from 100 kΩ to 10 Ω in decreasing order using a decade resistance box (Extech-380400).

Current and power output of the cell were determined from Ohm's law (Equations (1) and (2)).

$$I = E/R_{ext} \quad (1)$$

$$P = E^2/R_{ext} \quad (2)$$

where E is the voltage drop across a resistor (V), R_{ext} is the external resistor (Ω), I is the current (A) and P is the power output (W).

Current and power densities were obtained by normalizing Equations (1) and (2) with anode surface area.

$$C.D = E/(R_{ext}.A) \quad (3)$$

$$P.D = E^2/(R_{ext}.A) \quad (4)$$

where $C.D$ is the current density (A/m^2), $P.D$ is the power density (W/m^2) and A is the area of anode electrode (m^2).

COD removal efficiency was calculated based on concentration before and after treatment.

Coulombic efficiency (CE) was determined by Equation (5) as stated in Montpart *et al.* (2015).

$$CE = \int I(t)dt/(F.b.V.\Delta S) \quad (5)$$

where t is time (s), F is Faraday's constant (96,485 C per mol of electrons), b is the number of electrons exchanged per mol of oxygen (i.e. 4 electrons/mol of oxygen), V is the liquid volume (L) and ΔS is the substrate consumption in terms of COD (mol O_2/L).

Internal resistance is calculated from the slope of the polarization curve (Equation (6)).

$$R_{int} = \Delta E/\Delta I \quad (6)$$

where ΔE is change in potential, ΔI is change in current and R_{int} is the internal resistance.

RESULTS

Open circuit voltage of DCMFC with different substrate types

Initially all MFCs were operated under open circuit condition to assess their performance when no load was applied. The open circuit voltage (OCV) was recorded at a time interval of 2 h and the recorded data was averaged for every 24 h. Three distinct phases were observed from the variations of OCVs with time, as shown in Figure 2(a). The upsurge during the initial phase of the operation indicates the formation of the microbial community. A fairly steady phase followed this phase where the microbial growth in the system saturates the anode and maximum OCVs were achieved in the three reactors. As we have used already acclimatized sludge, the first phase lasted for a short time and peak of the phase came quite quickly. The maximum OCVs of 710, 721 and 781 mV across the anode and cathode were obtained for the reactors with a substrate of glucose, sucrose and acetate, respectively, during the second phase of operation. From the trend, decline in MFC performance can be observed in the third phase, which is the indication of substantial decrease in nutrient concentration.

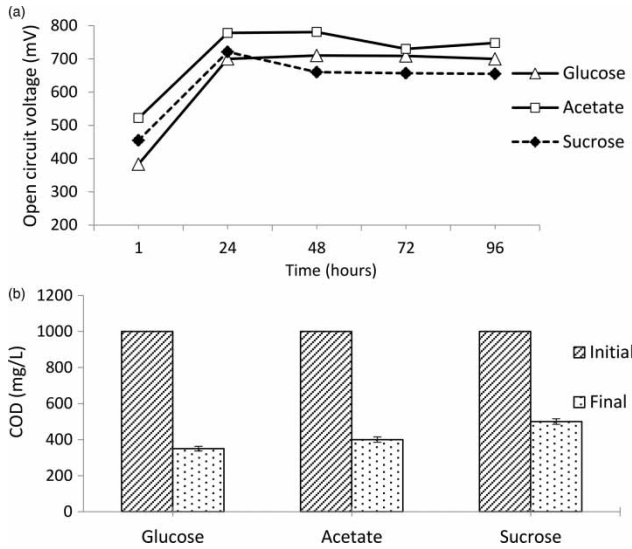

Figure 2 | (a) Variation in electrode potential with time and (b) COD removal for different substrates under open circuit condition.

Another very interesting point under open circuit condition is the consumption of the organic load. Figure 2(b) shows the amount of COD at the start and end of batch for all three substrates. With the same initial COD of 1,000 mg/L, final COD of 350, 400 and 500 mg/L was achieved, which corresponded to the removal efficiencies of 65, 60 and 50% for glucose, acetate and sucrose respectively.

Performance evaluation of DCMFC using different types of substrates

To find the effect of different substrates on the performance of the DCMFC, three types of substrate – glucose, acetate and sucrose – were used. MFCs were operated using the subject substrates under closed circuit condition at fixed load of 1,000 Ω; the performance is provided in the following sub-sections.

Voltage and power generation

Following the OCV measurement, a resistor of 1,000 Ω was connected between the anode and cathode to close the circuit and the voltage was recorded at a time interval of 2 hours. The recorded data was averaged for every 12 h, unlike the open circuit where it was recorded for 24 h. The system developed here was able to continuously generate electricity from the organic matter in the wastewater while accomplishing wastewater treatment. A similar trend to that of OCVs was observed, where maximum voltage

was achieved after initial development of the microbial community, and a relatively steady state followed this phase. Maximum voltages of 262, 343 and 339 mV (Figure 3(a)) corresponding to maximum power densities of 31, 53.4 and 52.3 mW/m^2 (Figure 3(b)) were achieved for glucose, acetate and sucrose respectively.

COD removal and coulombic efficiency

The COD removal and CE are two important parameters used in the evaluation of MFC performance. The COD test in an MFC is performed for the determination of the availability of converting fuels (substrate), to either generate electricity or form competitive reactions with other electron acceptors (e.g., oxygen, sulfate and nitrate) or growth of biomass. The CE was determined based on the utilization of total substrate into current. In this study, 60–80% of COD was removed for all substrates; however, CE was only in the range of 0.7–1.3% (Figure 4) indicating that a significant amount of electrons was lost.

Polarization and power curve

The polarization curve was plotted as a factor of electrode potential against current or current density of MFCs. The yielding data is obtained by varying the external resistance from 10 to 100,000 Ω in decreasing order after a steady state of operation as shown in Figure 5, which shows

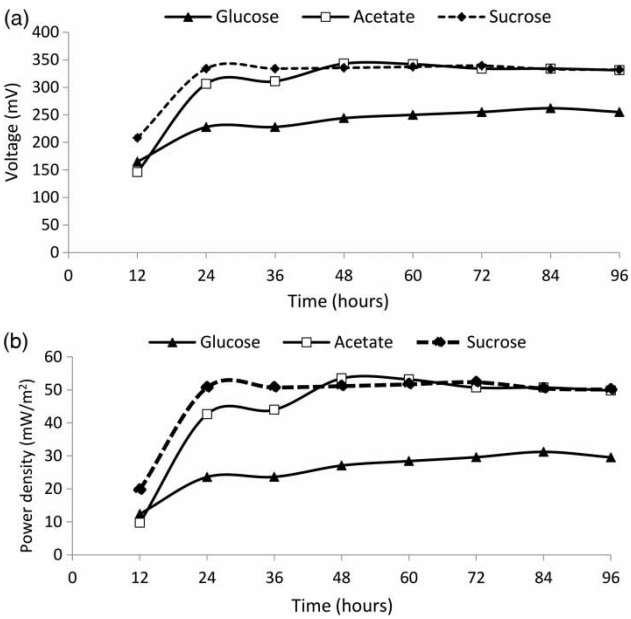

Figure 3 | (a) Variation in voltage generated with time and (b) power density versus time for different substrates under closed circuit.

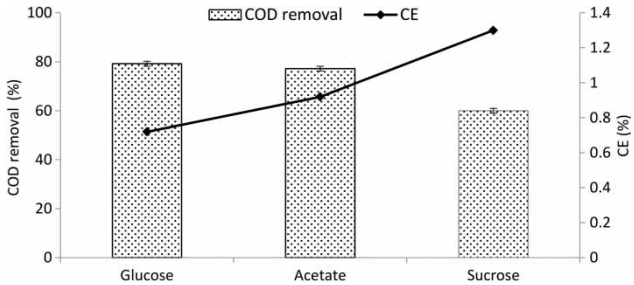

Figure 4 | COD removal and coulombic efficiency for all substrates.

polarization curve as a factor of current density against potential at different resistance. Figure 5 shows that potential decreases and current density increases with increase in external resistance. Maximum current densities of 378, 863 and 591 mA/m^2 were achieved for glucose, acetate and sucrose based MFCs, respectively. There was a sudden drop of cell potential at lower external resistance and relatively higher current in all polarization tests. Internal resistance was estimated from the slope of the curve (Logan *et al.* 2006), and it was observed to be 705, 472 and 280 Ω for glucose, sucrose and acetate based MFCs, respectively.

The power curve helps in finding the maximum achievable power in an MFC. It is calculated from polarization data and plotted as a function of power density against current density. Figure 5 shows the power curve for all substrates, obtained during steady state. The figure shows that maximum power densities of 91, 64, and 51 mW/m^2 were obtained for acetate, sucrose and glucose, respectively.

Performance evaluation of DCMFC for different concentrations of acetate

After studying the effect of different types of substrate, performance of DCMFC was evaluated for different concentrations of the substrate that proved best among the three in the first experiment. Acetate was selected based

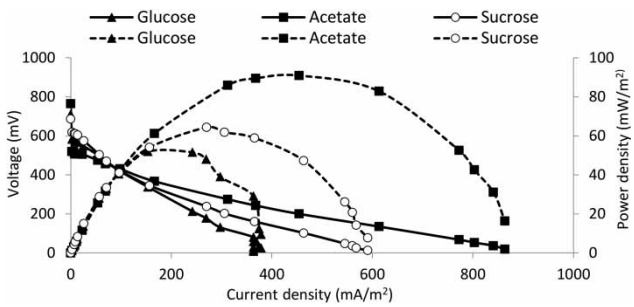

Figure 5 | Steady-state polarization (solid line) and power (dotted line) curve for all substrates.

on the performance and was used at three different concentrations of 500, 2,000 and 3,000 mg/L of COD to assess the performance of the DCMFC, which is given in the following sub-sections.

Voltage and power generation at different concentrations of acetate

Figure 6(a) and 6(b) show the voltage and power density generation for three different concentrations of acetate. The system was operated under the same closed conditions of 1,000 ohms. As shown in the figure, variation in voltage and power density is dependent on the concentration of acetate in the MFC. The maximum voltages of 273, 378 and 435 mV were achieved for MFCs operated at concentrations of 500, 2,000 and 3,000 mg/L of COD, respectively. The maximum power densities achieved for 500, 2,000 and 3,000 mg/L of COD were 34, 65 and 86 mW/m^2, respectively.

The reactor operated at COD of 500 mg/L reached maximum output rather quickly, that is, within the first 36 hours, before it started to decline, whereas reactors with COD of 2,000 and 3,000 mg/L reached the highest value within 50–60 hours on average, after which their output started to decrease. Although this does give useful information about the pattern of voltage and power density, COD consumption and, to some extent, the maximum value of voltage and power, the actual maximum value can be found from polarization and power curves with variable resistors.

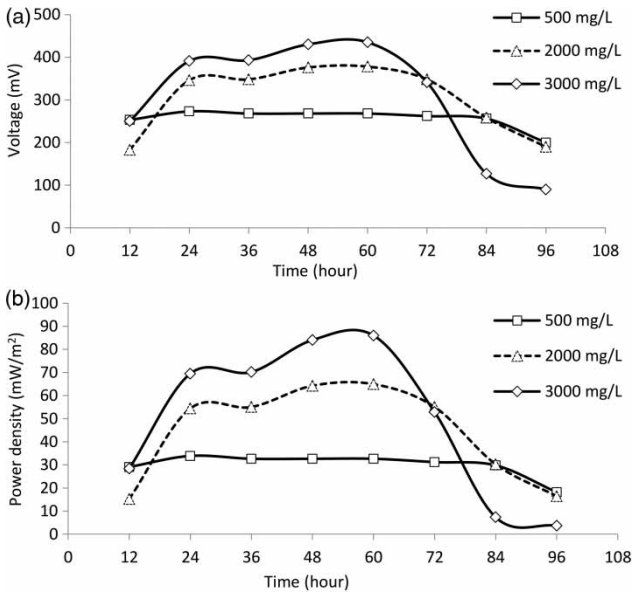

Figure 6 | (a) Variation in voltage generated with time and (b) variation in power density versus time for different concentrations of acetate.

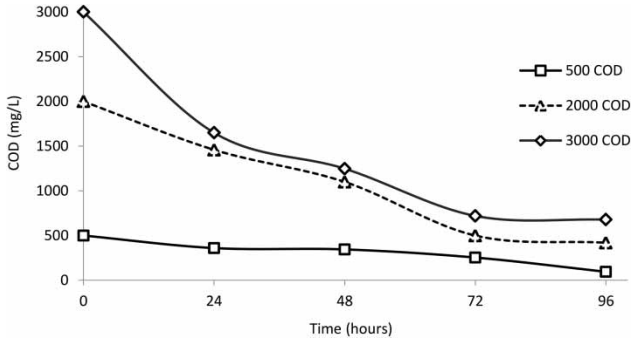

Figure 7 | Variation in COD with time for different acetate concentrations.

COD removal efficiency at different concentrations of acetate

Figure 7 shows the COD reduction profile of three concentrations of acetate with time. Results show that the reactor fed with COD of 500, 2,000 and 3,000 mg/L ended up with 95, 420 and 678 mg/L with COD removal efficiency of 81, 79 and 77%, respectively. COD consumption rate was 101 mg/L/d for 500 mg/L COD, 395 mg/L/d for 2,000 mg/L COD and 580 mg/L/d for 3,000 mg/L COD during the 4 day batch.

Polarization and power curve for different concentrations of acetate

The polarization curve was obtained for all three concentrations in the same way as previously obtained for different types of substrates. Figure 8 shows polarization

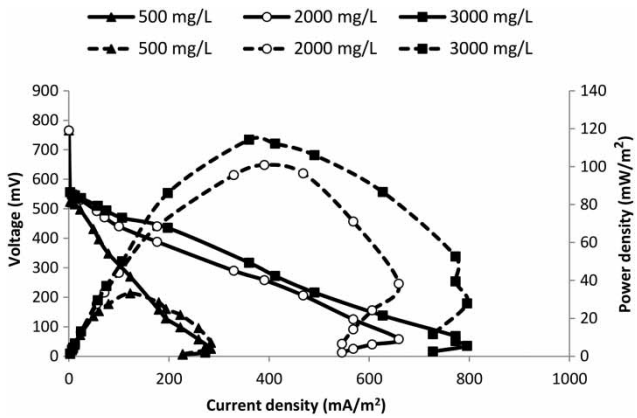

Figure 8 | Steady-state polarization (solid line) and power (dotted line) curve for different concentrations of COD.

and power curves for three different concentrations of substrates, that is, 500, 2,000 and 3,000 mg/L of COD. Maximum current density was found to be dependent on substrates concentration. Maximum current density of 284, 659 and 795 mA/m^2 was achieved for MFCs operated at concentration of 500, 2,000 and 3,000 mg/L of COD respectively. Internal resistance, estimated from the slope of the curve, was found to be 871 Ω for MFC with COD of 500 mg/L, 370 Ω for MFC with COD of 2,000 mg/L and 301 Ω for MFC with COD of 3,000 mg/L.

Figure 8 shows power curves obtained in steady state for all three concentrations of acetate. The figure shows that maximum power densities of 33, 101 and 114 mW/m^2 were achieved for MFCs operated at concentration of 500, 2,000 and 3,000 mg/L of COD, respectively. In this particular case maximum power density point is not exactly equal but near to the external resistance. For MFC with COD of 500 mg/L, maximum power density of 33 mW/m^2 was achieved at external resistance of 1,000 Ω which corresponded to the internal resistance of 871 Ω. For MFC with COD of 2,000 mg/L, maximum power density of 101 mW/m^2 was achieved at external resistance of 300 Ω which is corresponding to the internal resistance of 370 Ω. In the same way, for COD of 3,000 mg/L, maximum power density of 114 mW/m^2 was achieved at external resistance of 400 Ω which was corresponding to the internal resistance of 301 Ω.

DISCUSSION

he experiments presented and evaluated in this research have provided insight into the effect of substrate type and concentration on the performance of a DCMFC. The first part of the first experiment, that is, based on OCV measurement, was carried out to assess the maximum voltage an MFC can generate. In this case, the maximum OCVs of 710, 721 and 781 mV were obtained for substrate of glucose, sucrose and acetate, respectively. Conventionally, OCV of MFC systems ranges from 0.5 to 0.8 V (Liu 2008). The COD removal rate was not very different for various substrates. Results from this study demonstrate that substrate consumption in MFCs was enhanced under closed circuit as compared to the open-circuit condition, in which the typical anaerobic metabolism prevailed. In this study, the COD removal efficiency increased by 13% on average in closed circuit as compared to open circuit for all substrates. Luo *et al.* (2009) earlier observed that the degradation rate of phenol in the MFC increased about 15% with 1,000 Ω resistor as compared to the open-circuit. This is simply explained in terms of coexistence of both types of microorganisms, electrogenic and non-electrogenic, in the mixed microbial culture contained in the anodic chamber (Lobato *et al.* 2013).

The second part of the first experiment was carried out to find the effect of substrate type on the performance of the DCMFC. Unlike the first part, this was carried out under closed circuit with fixed resistance. Regardless of the generally similar trends, Figure 3(a) and 3(b) show that patterns of voltage and power generation with time were distinctly different for fermentable and non-fermentable substrates. In the acetate-fed reactor, maximum values of voltage and power were achieved quickly between 36 and 48 hours and then started to decline. Lee *et al.* (2008) have also reported that in glucose- and sucrose-fed MFCs, voltage and power reached maximum value rather slowly and lower maximum values were achieved.

The CE is not directly related to power density due to the fact that it is not a kinetic factor. Thus, due to space competition in the anode biofilm, low density of ARB could be the reason associated with low CE which may result in low power density. Moreover, COD removal is inversely proportional to CE. Previous studies have shown that lower CE with higher COD removal was potentially caused by bacteria in the solution with non-electrogenic characteristics, which utilize the electron in other metabolic processes (Liu *et al.* 2005). The loss of electron can be caused by many factors, including the substrate utilization for bacterial growth, fermentation, methanogenesis and transfer of electron from substrate to other electron acceptors, such as oxygen, sulfate and nitrate in solution (Prestigiacomo *et al.* 2016; Ismail & Habeeb 2017).

The polarization curve is usually divided into three regions, which gives an idea about the type of losses in the MFC. In the first region, voltage of the MFC drops sharply as a result of activation losses. In the second region, voltage drops fairly linearly with current and more slowly, which is the indication of ohmic losses. In the third region, rapid fall of voltage at higher current occurs due to the concentration losses (Rismani-Yazdi *et al.* 2008). In this study, the internal resistance is mainly due to the ohmic losses as the linear portion of voltage and current is dominant. The main reason for ohmic losses is possibly the uncoated electrode (Zhou *et al.* 2011).

As shown here and consistent with a previous study, a higher power density in an acetate-fed MFC than in a glucose-fed MFC was found from the power curve (Lee *et al.* 2008), which reinforces the fact that non-fermentable compounds, acetate in particular, are more effective in

MFCs for power generation. Moreover, the greater the internal resistance, the lower will be the power density because a substantial amount of electrons will be lost to overcome the internal resistance (Khater *et al.* 2015). A power curve of symmetrical semi-cycle nature is typically obtained for an MFC of high internal resistance, which is limited by ohmic losses rather than limited by mass transfer. The maximum power point in a symmetrical semi-cycle power curve will take place at a point on the curve where internal resistance of the MFC is corresponding to external resistance, i.e. $R_{ext} = R_{int}$ (Cheng *et al.* 2006).

The second experiment was carried out to evaluate the performance of DCMFC for different concentrations of substrate (acetate). Maximum voltages of 273, 378 and 435 mV were produced at acetate concentration of 500, 2,000 and 3,000 mg/L respectively, while it was 343 mV at 1,000 mg/L of acetate in the first experiment. It shows that substrate concentrations have a substantial effect on maximum voltage and power generation. Results from this and previous studies show that electricity generation increases with substrate concentration (Khater *et al.* 2015; Asensio *et al.* 2016).

Results for COD consumption show that the higher the concentration of substrate, the higher the observed removal rate, with a very clear first order kinetic behaviour in which substrates consumption depends linearly on initial concentration of COD. It is worth mentioning that COD changes give information about the localized metabolism of the bacteria that are present in the anode chamber; however, these changes do not provide information about the consumption of COD by electrogenic microorganisms because non-electrogenic microorganisms are also anticipated to consume it. Asensio *et al.* (2016) reported similarly the dominance of substrate with high concentration over low concentration.

There was a sudden drop of cell potential at lower external resistance and relatively higher current in all polarization tests. The same three phases of voltage loss can be observed in the curves. In the first region, there is an initial steep decrease of voltage due to the activation losses. Voltage then dropped more slowly and fairly linearly with current, which was the indication of ohmic losses. In the third region, rapid fall of voltage at higher current occurred due to the concentration losses (Logan *et al.* 2006). It can be concluded from the results that internal resistance decreases with increase in COD. Khater *et al.* (2015) have a similar type of observation for glucose used as substrate in a single chamber MFC. Some other researchers have also reported that an increase in COD led to decrease in internal resistance and increase in current production. However, high substrate concentrations were found to inhibit power production in MFCs (Liu *et al.* 2009; Khater *et al.* 2017).

Results from the power curve of different concentrations show the maximum power density of 33, 101 and 114 mW/m^2 at acetate concentration of 500, 2,000 and 3,000 mg/L respectively, while it was 91 mW/m^2 at acetate concentration of 1,000 mg/L as observed in the first experiment. These results reinforce the fact that power density increases with substrate concentration. They also emphasize the fact that the greater the internal resistance, the lower will be the power density because a substantial amount of electrons will be lost to overcome the internal resistance (Nam *et al.* 2010). In this particular type of curve, the maximum power point will take place at a point on the curve where the internal resistance is equal to external resistance (Fan *et al.* 2008).

CONCLUSIONS

There is a clear effect of the type of organic substrate on the performance of the MFC. For the same organic load, acetate is the most efficient substrate in comparison to glucose (single sugar) and sucrose (double sugar). Regardless of the generally similar trends, the patterns of voltage and power generation with time were distinctly different for fermentable and non-fermentable substrates. In the acetate-fed MFC, voltage and power reached a maximum point sooner and higher than glucose- and sucrose-fed MFCs. COD removal of 60–80% was achieved with maximum power density of 51–91 mW/m^2, which indicates that electric current was the least significant electron sink in all MFCs. The polarization curve shows that ohmic losses were dominant.

The performance of the MFC was found to be affected by the concentration of substrates. For a system fed with different concentrations of acetate solution, electricity production increased with COD concentration. The MFC with 2,000 mg/L of COD turned out to be the best concentration among all three, based on maximum power density, COD removal and internal resistance. COD removal efficiency of 77–81% was achieved for different concentrations. Internal resistance decreased with increase in COD concentration.

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