PERFORMANCE OF A SINGLE CHAMBER SOIL MICROBIAL FUEL CELL ACROSS VARIED EXTERNAL LOADS FOR POWER GENERATION.

[1]Simeon M. I., [2]Raji O. A., [1]Agidi Gbabo., [1]Adeoye P. A.

[1] *Department of Agricultural and Bioresources Engineering, Federal University of Technology, Minna, Nigeria*
[2] *Department of Agricultural and Environmental Engineering University Of Ibadan, Nigeria*

ABSTRACT
The soil is beginning to receive attention as suitable inoculums for Microbial Fuel Cells (MFCs) designed for remediation and for electricity generation because of its high microbial load. However, not much has been done in this aspect beyond laboratory based experiment. This study is aimed at generating electricity from agricultural soil, utilizing the microorganisms already present and the soil nutrients as the sole substrates and to investigate the performance of the soil Microbial Fuel Cell (MFC) across varied external loads. The study used the mud watt MFC kit inoculated with mud prepared from topsoil, collected from a garden where crops have been cultivated over the years. The electrodes (anode and cathode, 7cm diameter each), made of carbon felt material with conducting wires made of graphite, were housed in the same chamber and placed 4 cm apart. Voltage drop across seven external resistances 4670 Ω, 2190 Ω, 1000 Ω, 470 Ω, 220 Ω, 100 Ω and 47 Ω, were measured every 24 hours, with a digital multi-meter, for 40 days. The maximum open circuit voltage from this study was 731 mV, whereas the maximum power density was 65.40 mW/m^2 at a current density of 190.1 mAm^{-2}. The optimum performance of the MFC was achieved with the 470 Ω which is an indication that the internal resistance of the soil MFC of this present study is close to 470 Ω. This study revealed that MFCs constructed from agricultural topsoil are capable of producing electrical power continuously, across different external loads, without addition of any substrate.

Keywords: *Microorganisms, metabolism, performance, soil, external loads*

INTRODUCTION

The focus of global interest has been persistently directed towards alternative energy sources as, perhaps, one viable solution to the growing problem of fossil fuel depletion (Ieropoulos *et al*., 2012). Besides promising technologies such as photovoltaic, wind-turbines and hydropower, Microbial Fuel Cell (MFC) technology has been receiving increased attention as a potential part of this field of natural energy. The possibility of generating electricity from bacteria has been well established for almost one hundred years. But only in the past few years this capability had become more than a laboratory based experiment. It has been known that electricity can be generated using any biodegradable material, even wastewater, and that there is no need to add any special chemicals if bacteria is already present in the wastewater. While some iron-reducing bacteria, such as *Shewanella putrefaciens* and *Geobacter metallireducens* can be used to generate electricity, there are many other bacteria already present in wastewater that can do this (Logan and Regan, 2006).
Microbial Fuel Cell (MFC) technology is a new form of renewable energy technology that can generate electricity from what would otherwise be considered waste. It is a bio-electrochemical system that harnesses the natural metabolisms of microbes to produce electrical power. Within the MFC, microbes consume or degrade the nutrients in their surrounding environment and release a portion of the energy contained in the food in the form of electrons (Li, 2013). The electrons are then transferred to a terminal electron acceptor (TEA) which is reduced by the electrons. TEAs such as oxygen, nitrate and sulphate can diffuse into the cell and accept electrons to form new products that can then leave the cell. However, some bacteria can transfer their electrons outside the cell (exogenously) to the awaiting TEA. It is these bacteria that can produce power within an MFC system (Logan, 2008; Jenna, 2010).
Materials with abundance of microorganisms and high content of organic matter have been utilized in MFCs to generate electricity. These materials include, among others, industrial/domestic waste-water (Rabaey and Verstraete, 2005) marine sediment (Bond *et al*., 2002; Scott *et al*., 2008), sewage sludge (Zhang *et al*., 2012), garden compost (Parot *et al*., 2008) and animal waste (Yokoyama *et al*., 2006).
Results from several studies have demonstrated that the soil is suitable inoculums for MFCs designed for remediation and for electricity generation because of its high microbial load (Li, 2013; Samuel *et al.*, 2013; Deng *et al.*, 2014). It has been estimated that soil generally has a bacterial population of approximately 10^9

cells/g (Whitman *et al.*, 1998) and organic matter content of within 100 mg/g (Bot and Benites, 2005). Soils are naturally teeming with a diverse consortium of microbes, including the electrogenic microbes needed for MFCs, and are full of complex sugars and other nutrients that have accumulated over millions of years of plant and animal material decay. Soil-based MFCs (Fig. 1) adhere to the same basic principles of MFC operation. In this case, soil acts as the nutrient-rich anodic media, the inoculums, and the Proton Exchange Membrane (PEM). The anode is placed at a certain depth within the soil, while the cathode rests on top of the soil and is exposed to the oxygen in the air above it (Science Budies Staff, 2014).

Deng *et al*. (2014) noted that soil MFC without the carbon addition may generate power by using its own organic matter as fuel. The only natural components needed for a soil-based MFC to run are nutrient-rich soil and combining the soil with water to form mud. By implication, the soil MFCs can endlessly produce electricity if it does not run out of its nutrient-rich characteristics as long as conditions remain favorable for current production by the anode-associated microbes (Ashley and Kenny, 2010).This makes them very attractive for applications that only require low power but where replacing batteries may be time consuming and expensive. MFCs can possibly be used to power sensors particularly in the river and deep water environments where it is difficult to replace batteries. Powered by MFCs, the sensors can be left alone in remote areas for many years without maintenance (Li, 2013).

The influence of external resistance on the performance of MFCs has been studied by many researchers. Krishna *et al*. (2011) reported that the external resistance applied to MFCs during formation of the bacterial communities from sewage wastewater had no significant effect on power performance of the MFCs nor a significant influence on their anodic activity with both glucose and brewery wastewater as fuel. However, current generation, COD removal and the biomass yield were all directly influenced by the external load. Large differences in external resistance have been reported to affect both power production and microbial community structure.

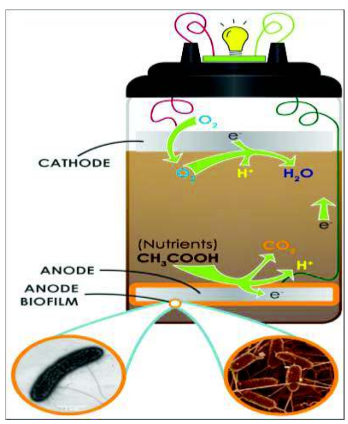

Fig. 1. A diagram of a Soil-based MFC. Source: (Wikimedia Commons, 2010)

Similarly, change in external resistance can change the anodic microbial community structure after the establishment of anodic microbial community. MFCs systems are flexible permitting different microbial community structures, established under different external resistances, to result in similar power production (Lyon *et al*., 2010). The flexibility of MFCs accounts for their ability to perform across a wide range of external loads. However, Maximum power point or optimum performance can only be achieved when external load is equal to the MFC's internal resistance (Logan *et al*., 2006). Output maximization is not possible if experiments with varying external loads are not performed.

Major researches in MFCs have been focused on waste water probably due to the dual advantage of wastewater treatment as well as electricity generation. No serious attention has, hitherto, been given to the soil-based MFCs for electricity generation, despite the large population of microbes present in the soil. Besides, the performance of the soil-based Membrane-less Single Chamber Microbial Fuel Cell (MSCMFC) across varied external loads has, hitherto, not been investigated. Therefore, this study is aimed at generating electricity from agricultural soil utilizing the microorganisms already present and the soil organic contents and nutrients as the sole substrates and to investigate the performance of the soil MSCMFC across varied external loads.

METHODOLOGY

Soil Sampling

Topsoil was collected from the vegetable garden at Appleton Junction adjacent U&I restaurant of the University of Ibadan (7°23′47″N 3°55′0″E), Nigeria. Soil sample was collected at a depth of 0-20 cm. The climate of this location is tropical wet and dry climate, with a lengthy wet season and relatively constant temperatures throughout the year. The mean total rainfall for Ibadan is 1420.06 mm. The mean maximum temperature is 26.46 °C, minimum 21.42 °C and the relative humidity is 74.55 %. This location was chosen because it is a rich farmland where crops have been cultivated over the years.

Preparation of Mud from Topsoil and MSCMFC Setup

After sampling, soil was thoroughly strained to remove any small hard particles (such as pebbles, rocks and twigs) the fine soil obtained after straining and mixed thoroughly until it was well prepared into mud. An MSCMFC kit designed by Keego Technologies LLC and assembled in the USA was used. It was set up according to the method described by Science Buddies Staff (2014). The electrodes (7 cm diameter) were assembled by carefully inserting the anode wire into the anode felt (carbon cloth), and the cathode wire into the cathode felt. Both wires were bent 90° at the points where the wires insulators end. A layer of mud was packed into the bottom of the fuel vessel up to the 1cm mark and it was pat down to obtain a smooth layer (Plate 1). The anode was placed in the mud by pressing it down firmly to squeeze out air bubbles after which the vessel was filled with more mud up to the 5 cm mark making the total volume of soil (mud) in the vessel 192 ml. Then, the cathode was gently placed on top of the mud but not covered with it. Finally, the lid of the MFC vessel was used to cover it, with the electrodes passed through the appropriate holes on the lid.

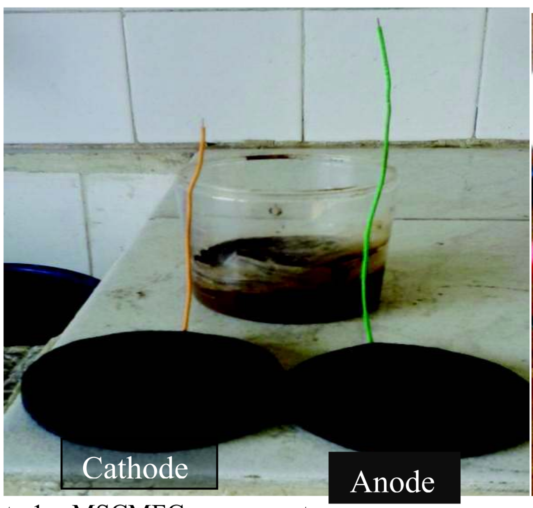

Plate 1. : MSCMFC components

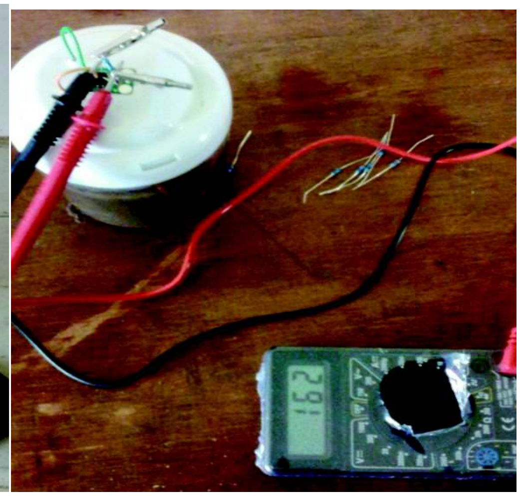

Plate 2: Multi-meter connected for voltage measurement

Data Acquisition and Calculations

The daily Open Circuit Voltage (OCV) was read with a digital multi-meter (Kelvin 50LE) after which crocodile clips were used to clip a multi-meter's probes and the resistor's lead to the cell's electrodes for voltage measurement (as shown on Plate 2). The voltage drops of the MFC across seven external resistances (4700 Ω, 2200 Ω, 1000 Ω, 470 Ω, 220 Ω, 100 Ω and 47 Ω) were noted after stabilization (5 to 10 minutes intervals). This measurement was repeated every 24hour, for the whole duration of the experiment. With the measured values of voltage, the current was determined from Equation 1, according to Ohm's law.

$$I = V/R \quad (1)$$

V = voltage across each resistor in Volts

R = resistance of each external load (Ω).

Current densities were obtained by normalizing the calculated currents to the anode surface area (0.00385 m^2). In order to assess maximum power, polarization and power density curves were obtained by varying external resistance between

4.7 kΩ and 47 Ω according to the method described by Deng *et al*. (2014). The power density (P) for each external load was calculated and normalized to the anode surface area (A_{an}) using equation (2) (Logan *et al.*, 2006).

$$P = \frac{V^2}{A_{an}R} \qquad 2$$

RESULTS AND DISCUSSION

Results

The soil MFC was successfully operated without any outside source of inoculation. Fig. 2 presents the OCVs of the MFC over the 40-days operational period. The performances of the MFC at the seven external resistances are presented in fig. 3. Polarization and power density curves obtained after 15 days of operation of the MFC are presented in fig. 4.

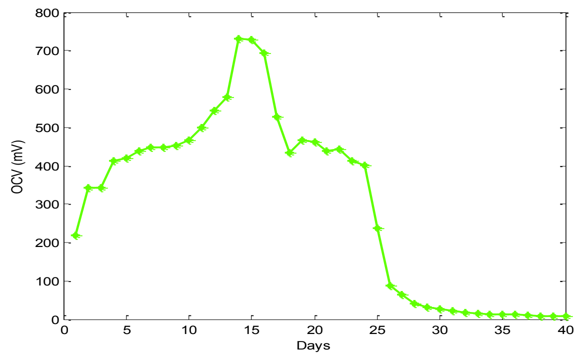

Fig 2: MFC Open Circuit Voltage

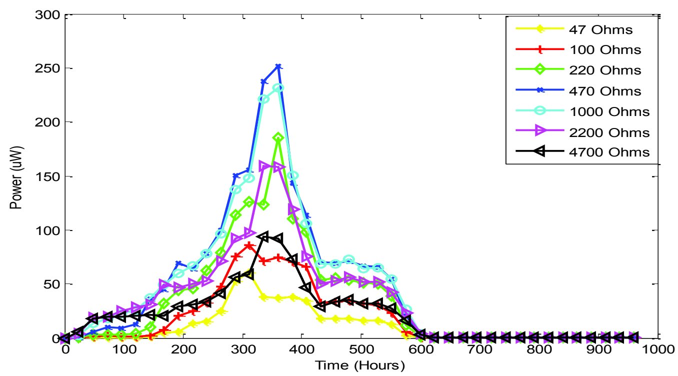

Fig 3: Power versus time plot of the soil MFC across set 3 external loads

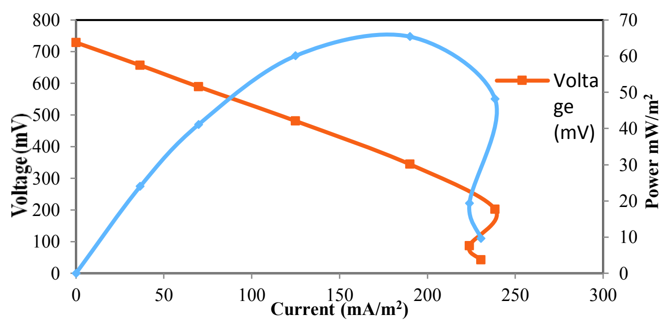

Fig. 4: Polarization and Power Density curves of the soil MFC

Internal Resistance

The daily internal resistance was calculated by linear regression of voltage against current according to Min *et al*. (2013). Figure 5 presents the MFC's internal resistance variation with days of operation.

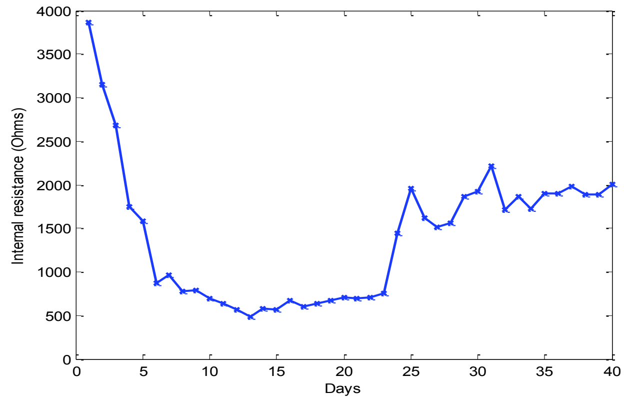

Fig 5: MSCMFC internal resistance variation with days

DISCUSSION

Opened circuit voltage (OCV) of a cell is the voltage measured across the terminals of the cell at infinite resistance where no current is flowing. It does not take into account internal losses (Logan *et al*., 2006). In MFCs, OCV reflects the ability of the biofilm to accumulate charge (Jenna, 2010). The maximum OCV achieved from this present study was 731 mV (Fig. 2). This size of voltage can be amplified for practical application if it is sustained. The present value is comparable to the value reported by Samuel *et al*. (2013) from a Membrane-less single chamber MFC inoculated with agricultural soil. Li (2013), however, studied the performance of a double chamber MFC, under similar conditions, with top soil as the anode inoculums and a cathode of conductive saltwater solution, and reported a maximum OCV which is 85.35 % lower than the maximum value from this present study. The performance of the MFC reported by Li (2013) also showed a negative gradient trend and could only generate electricity for 9 days. This is a clear demonstration that the absence of a membrane improves power densities. It is also an indication that the double chamber configurations may not be suitable for soil-based MFCs.

The maximum powers obtained from operating the MFC at the external resistances of 4700 Ω, 2200 Ω, 1000 Ω, 470 Ω, 220 Ω, 100 Ω and 47 Ω are 93.56 μW, 123.75 μW, 231.36 μW, 251.78 μW, 185.45 μW, 85.56 μW and 60 μW respectively (Fig. 3). For most MFC treating wastewater, it has been predicted that anodophilic microorganisms' proliferation is only possible when the MFCs are operated at external resistances close to their internal resistances (Lyon *et al*., 2010). A low external resistance promotes growth and metabolic activity of the anodophilic microorganisms since electron transport to the cathode is fascinated. However, when the external resistance is lower than the MFC's internal resistance, power output is reduced (Pinto *et al*., 2011). The results of the soil MFC of this present study concord with this prediction. As can be seen from Fig. 3, the soil MFC of this present study exhibited a better performance with the 470 Ω and 1000 Ω. The overall optimum performance of the MFC was achieved with the 470 Ω. This is an indication that the internal resistance of the MFC of this study lies between 470 Ω and 1000 Ω. This result conforms to the results of prior (UNH) research (Microcellutions, 2007). In a similar study, Jenna (2010) reported optimum performance at the same external load.

The maximum power density achieved from this MFC is 65.40 mW/m^2 at a current density of 190.1 mA/m2 (Fig. 4). The rapid voltage drop that is noticed from the polarization curve is a clear indication that Ohmic losses and concentration losses were dominant and thus the main limitation of the MFC's performance.

The power versus time plots (Fig. 3) mimic the phases that are typical in bacterial growth. The growth process begins with a lag phase as bacteria become accustomed to the environmental conditions and little growth is observed. This phase is followed by exponential growth of the microbial population and then the stationary phase where little growth is seen, but living cells are maintained. Lastly, a negative growth phase occurs if no new nutrients and carbon source are supplied to the bacteria (Jenna, 2010). These four phases are established in figure 3. These results proved that microorganisms present in the soil were actually responsible for the electricity generated.

The performance of the MFC improved with time for 360 Hours of continuous operation, as clearly indicated in the power versus time plots (Fig. 3) and the OCV plot (Fig. 4). A rapid drop was experienced between Day 15 and 18, then a constant phase. No improvement in performance was recorded after the first drop until the power output was reduced to near zero probably due to increased mass transfer, activation and Ohmic losses. The initial increase in performance with time of the soil MFC of this study can be attributed to enhancement of microbial metabolism due to availability of substrate in the form of soil organic contents. The exponential decrease in electricity generation may be attributed to a long period of starvation to which the microbes were subjected, which may have led to the death of some of the participating species, owing to the depletion of the soil organic contents with time. The biomass and activity of microorganisms is typically thought to be constrained by the availability and quality of carbon source (Wardle, 1992). Apart from the soil lacking the required moisture for the normal metabolism of the soil microbes, the carbon source and/or nutrients needed to activate them was also exhausted. This affected the activation energy needed for electrons generation and transfer from or to the compound reacting at the electrode surface and thus reduced the redox reaction at the cathode (Logan *et al*., 2006).

The soil MFC of this study is characterized by very high initial internal resistance (Fig. 5). There was an initial decrease in internal resistance from 3870.7 Ω to a minimum value of 484.14 Ω, the point at which the MFC exhibited optimum performance. The internal resistance remains fairly constant after which there was a non-linear increase. The initial reduction in internal resistance could be due to enhanced conductivity as a result of proliferation of the microorganisms with time. The increased values recorded after the optimum performance is obviously due to depletion of the soil biodegradable organic content needed for microbial metabolism. Thus, the MFC exhibited poor performance at this point probably due to higher anode over-potentials at the same working current (Watson and Logan, 2010).

CONCLUSION

This study revealed that agricultural topsoil is rich in active, highly electrogenic microbial community that can be used in membrane-less single chamber MFCs to generate electricity. MFCs utilizing agricultural topsoil need no outside source of inoculation due to the presence of the appropriate mixed bacterial community. Findings from this study also established that MFCs constructed from agricultural topsoil are capable of producing electric power continuously, across different external loads, for more than 960 hours without addition of any substrate. As it has been established for other types of MFCs, optimum performance of the soil MFC is achieved at external loads close to its internal resistance.

The major limitation of the soil MFC in this study was high internal resistance when the soil nutrient or carbon available for microbial metabolism was exhausted. This led to a rapid drop in power output after the optimum performance. Thus with a supply of appropriate substrate such as urine, septage or leachate from landfill, to enrich the soil; coupled with the right power management system (such as the use of micro-chips, converters or current boosters and capacitors), electricity may be cheaply harnessed from the soil for practical applications.

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