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Performance of a Single Chamber Soil Microbial Fuel Cell at Varied External Resistances for Electric Power Generation

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A B S T R A C T

Soil is beginning to attract research attention as suitable inoculums for Microbial Fuel Cells (MFCs) designed for remediation and for electricity generation probably due to its high microbial load. However, not much has been done in this aspect beyond laboratory based experiment. This study was aimed at generating electricity from agricultural soil, utilizing the microorganisms present in the soil, and investigating the performance of the soil MFC across varied external loads. The study used the mud watt MFC kit inoculated with mud prepared from topsoil collected from a garden. The electrodes, made from carbon felt material with conducting wires made from graphite, were housed in the same chamber and placed 4cm apart. Voltage drop across seven external resistances of 4670, 2190, 1000, 470, 220, 100, 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 m/Wm^2 at a current density of 190.1mA/m^2. The optimum performance of the MFC was achieved with the 470Ω at an internal resistance of 484.14 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. However, there is need for further studies to keep the MFC output constant at the maximum achievable power.

1. 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 [1]. 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. However, this capability did not exceed laboratory based experiment until the 20th century when research on this subject and the creation of MFCs received sporadic approach [2]. It is now established that electricity can be generated using any biodegradable material, even wastewater. While some iron-reducing bacteria, such as Shewanella putrefaciens and Geobacter metallireducens can be isolated and sub-cultured to generate electricity, there are many other bacteria already present in wastewater that can do this [3].

Microbial Fuel Cell (MFC) technology is a new form of renewable energy technology that can generate electricity from what would otherwise be considered as 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 [2] which are transferred to a Terminal Electron Acceptor (TEA). 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, there are some bacteria that can transfer their electrons exogenously to the awaiting TEA thereby producing power within an MFC system [4, 5]. 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 and domestic waste-water [6], marine sediment [7, 8], sewage sludge [9], garden compost [10], and animal waste [11]. MFCs are Versatile

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since microorganisms can be found in almost all environments and under almost all conditions [12].

The versatility of MFCs enables them to be used for a wide range of applications. The most common use of MFCs is wastewater treatment and simultaneous generation of electricity [12-14]. MFC systems have several advantages, like having a high efficiency due to the direct conversion of the fuel energy into electricity, working at room temperature, having lower cost because of the type of fuel it uses, the fact that it does not produce toxic by-products, as well as their ability to use a great diversity of organic compounds depending on the metabolic abilities of the organisms being used [15]. In spite of these advantages, the low power density level of MFCs still poses limitations to their real-world applications. Hence research efforts are being intensified in this field to improve the performance and reduce the construction and operating costs of the MFCs [16].

Results from several studies have demonstrated that soil is suitable inoculums for MFCs designed for remediation and for electricity generation probably due to its high microbial load [2, 17, 18]. It has been estimated that soil generally has a bacterial population of approximately 10^9cells/g [19] and its organic matter content is within 100mg/g [20]. It can be inferred, therefore, that 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 thereby making them suitable for MFC construction. 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 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 [21]. Deng et al. [18] noted that soil MFC without Carbon addition may generate power by using its own organic matter as fuel. The only natural component needed for a soil-based MFC to run is nutrient-rich soil and combination of the soil with water to form mud. By implication, the soil MFCs can endlessly produce electricity if they do not run out of their nutrient-rich characteristics as long as conditions remain favorable for current production by the anode-associated microbes [22].

Influence of external resistance on performance of the MFCs has been studied by many researchers. Krishna et al.[24] reported that the external resistance applied to MFCs during formation of the bacterial communities from sewage wastewater had no significant effect on power generating performance of the MFCs with no significant influence on their anodic activity with both glucose and brewery wastewater as fuel. However, current generation, Chemical Oxygen Demand (COD) removal and the biomass yield were all directly influenced by the external load.

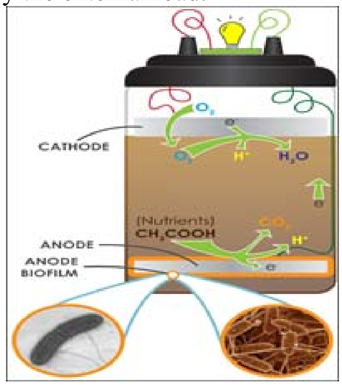

Figure 1. A diagram of a Soil-based MFC (Source: [23])

The study also reported that large differences in external resistance affect both power production and microbial community structure. Similarly, change in external resistance can change the anodic microbial community structure after its establishment. MFCs systems are flexible permitting different microbial community structures, established under different external resistances, to result in similar power production [25]. Flexibility of the 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 [26].

Although there is already a large body of literature covering different aspects of MFCs, in general no Particular interest has been given to soil MFCs for electricity generation, despite the large population of microbes present in the soil. Besides, performance of the soil-based Membrane-less Single Chamber Microbial Fuel Cell (MSCMFC) across varied external loads has, hitherto, not been investigated, to the best of the authors' knowledge. Therefore, this study is aimed at generating electricity from mud prepared from agricultural soil utilizing the microorganisms; and investigating performance of the soil MSCMFC across varied external loads.

2. METHODOLOGY

2.1. 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 is 21.42°C and the relative humidity is 74.55 %. This location was chosen because it is a farmland where crops have been cultivated over the years.

2.2. 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 was mixed thoroughly with distilled water until it was well prepared into mud. A MSCMFC kit designed by Keego Technologies LLC and assembled in the USA was used. It was set up according to the method described in [21]. The electrodes (7cm 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 over the bottom of the fuel vessel up to the 1cm mark of the vessel and was pat down to obtain a smooth layer (Fig. 2). 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 5cm mark making the total volume of soil (mud) in the vessel 192 cm^3. Then, the cathode was gently placed on top of the mud but not covered with it (as shown in Fig. 3). Finally, the MFC vessel was covered with its lid, with the electrodes passed through the appropriate holes on the lid.

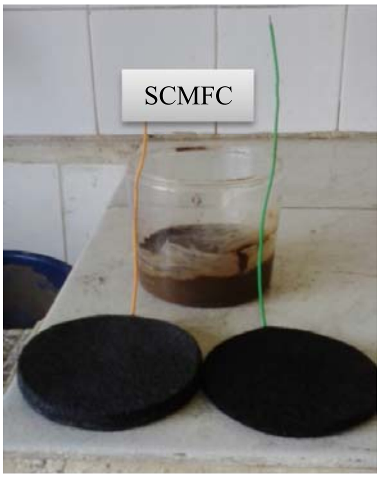

Figure 2. MSCMFC components

2.3. 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 the multi-meter's probes and the resistor's lead to the cell's electrodes for voltage measurement. The voltage drops of the MFC across seven external resistances (4700, 2200, 1000, 470, 220, 100, and 47 Ω) were noted after stabilization (5 to 10 minutes intervals). This measurement was repeated every 24 hour for 40 days. With the measured values of the voltage, the current was determined from Equation (1), according to Ohm's law.

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

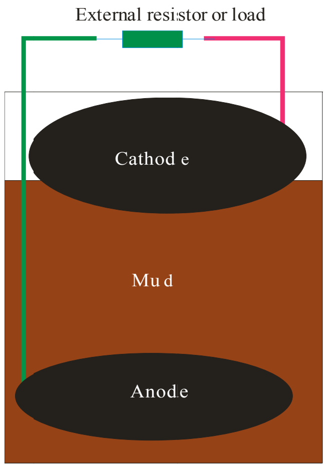

Figure 3. Schematic Diagram of MFC Setup

V = voltage across each resistor in Volts; R = resistance of each external load (Ω). The daily internal resistance was calculated by linear regression of voltage against current. Current densities were obtained by normalizing the calculated currents to the anode surface area ($0.00385m^2$). In order to assess maximum power, polarization and power density curves were obtained by varying the external resistance between 4.7 kΩ and 47 Ω according to the method described in [22]. The power density (P) for each external load was calculated and normalized to the anode surface area (A_{an}) using equation (2) [26].

$$P = \frac{V^2}{A_{an}R} \quad (2)$$

3. RESULTS AND DISCUSSION

3.1. Results

The soil MFC was successfully operated without any outside source of inoculation. Fig. 4 presents the OCVs of the MFC over the 40-days operational period. Performances of the MFC at seven external resistances are presented in Fig. 5. Polarization and power density curves obtained when the MFC produced maximum voltage and power (Day 15) are presented in Fig. 6.

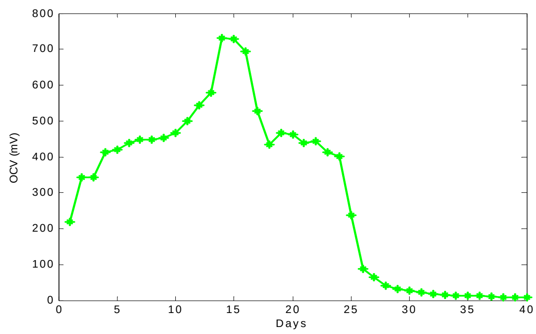

Figure 4. MFC Open Circuit Voltage

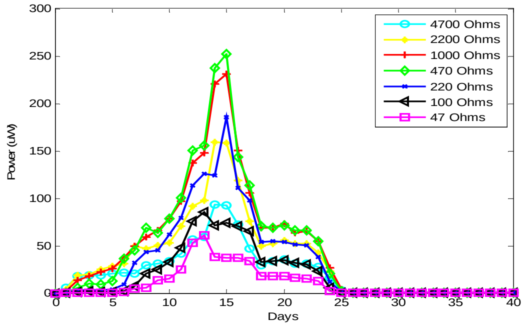

Figure 5. Power versus time plot of the soil MFC across the external loads

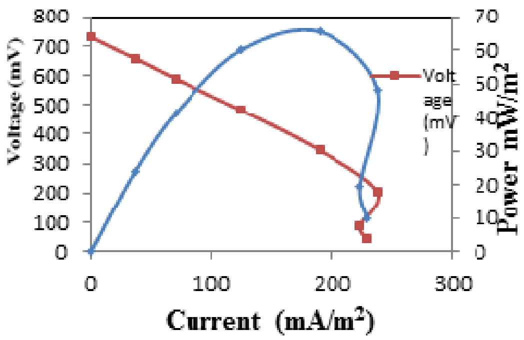

Figure 6. Polarization and Power Density curves of the soil MFC

3.1.1. Internal Resistance

The daily internal resistance was calculated by linear regression of voltage against current according to Min et al. [27]. Fig. 7 presents the MFC's internal resistance variation with operating days.

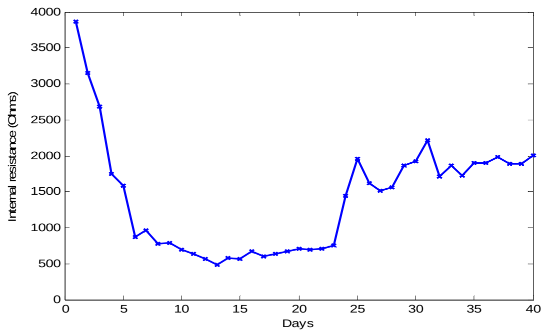

Figure 7. MSCMFC internal resistance variation with days

3.2. Discussion

3.2.1. MSCMFC Open Circuit Voltage

The 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 the internal losses [26]. In MFCs, OCV reflects the ability of the biofilm to accumulate charge [5]. The maximum OCV achieved from this study was 731mV (Fig. 4). This level 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. [19] from a Membrane-less single chamber MFC inoculated with agricultural soil. Li [2], 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 study. Performance of the MFC reported by Li [2] also showed a negative gradient trend and could only generate electricity for 9 days. This is a clear demonstration that absence of a membrane improves the power densities. It is also an indication that the double chamber configurations may not be suitable for soil-based MFCs.

3.2.2. MSCMFC Performance across External Loads

The maximum powers obtained from the operating MFC at the external resistances of 4700, 2200, 1000, 470, 220, 100, and 47 Ω are 93.56, 123.75, 231.36, 251.78, 185.45, 85.56, and 60 μW, respectively (Fig. 5). 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 [28]. 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 [29]. The results of the presented soil MFC is according to this prediction. As can be seen from Fig. 5 the soil MFC of the present study exhibited a better performance with the 470 Ω and 1000 Ω. The overall optimum performance of the MFC was achieved with the 470Ω. 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 [5] reported optimum performance at the same external load.

The maximum power density achieved from this MFC is 65.40mW/m^2 at a current density of 190.1mAm^{-2} (Fig. 6). This maximum power density is comparable with value of 66 mW/m^2 reported by Yazdi et al. [30] who determined the effect of external resistance on bacterial diversity and metabolism in MFCs, using four external resistances of 20, 249, 480, and 1000 Ω. The maximum power density obtained from this study is, however, higher than the values reported by Najafgholi et al. [31] from aerated Sediment MFCs treated with Sodium Chloride (NaCl) and Potassium Chloride (KCl), respectively. In the study, a maximum power density of 32.76mW/m^2 at a current density of 330.14mA/m^2 was reported for the soil MFC treated with NaCl, whereas the MFC treated with KCl produced maximum power density of 28.79mW/m^2 at a current density of 234.16mA/m^2. In a similar study, Muler [12] reported maximum power values from aerated soil MFCs which are relatively lower than the values obtained in the present study. This discrepancy may be attributed to the different sources of soil samples, differences in the used materials and MFC configurations, difference in operating conditions or in the species of active microbial community in the used soil samples. Besides, continuous aeration of soil MFCs has been reported to cause oxygen diffusion into the anode portion leading to growth of heterotrophic microorganisms, which contests with electrogenic bacteria for available substrate and thus results in decrease of cell performance as reported by Najafgholi et al. [31].

The power versus time plots (Fig. 5) 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 [5]. These four phases are clearly established in Fig. 5 These results proved that microorganisms present in the soil were actually responsible for the generated electricity.

As indicated in the power versus time plots (Fig. 5) and the OCV plot (Fig. 4) performance of the MFC improved with time for 360 hours of continuous operation. A rapid drop was experienced between Day 15 and 18 then a constant phase appeared. No improvement in performance was recorded after the first drop until the power output was reduced to near the zero which is probably due to increased mass transfer, activation and Ohmic losses. The initial increase in performance with time of the soil MFC of present study can be attributed to enhancement of microbial metabolism due to availability of substrate in the form of soil nutrients. 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 death of some of the participating species. The biomass and activity of microorganisms is typically thought to be constrained by availability and quality of carbon source [32]. 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 might have 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 [22].

The soil MFC of this study is characterized by very high initial internal resistance (Fig. 7) There was an initial decrease in internal resistance from 3870.7 Ω to a 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 non-linear increase in the internal resistance was probably due to higher anode over-potentials at the same working current [33].

4. CONCLUSION

This study supports previous studies in which it was reported 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 presence of the appropriate mixed bacterial community. The maximum power density achieved from this MFC is 65.40mWm^{-2} at a current density of 190.1mAm^{-2}. This maximum power density was achieved with the 470 Ω external load at an internal resistance of 484.14 Ω. A maximum OCV of 731mV was achieved on Day 15 of the experiment. These results showed that MFCs constructed from agricultural topsoil are capable of producing electric power continuously, across different external loads, for more than 40 days without addition of any substrate. As it has been established for other types of MFCs, optimum performance of the soil MFC was 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 replenish the soil nutrients; coupled with the right power management system (such as the use of micro-chips current boosters and capacitors), electricity may be cheaply harnessed from the soil for practical applications.

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