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PERFORMANCE ASSESSMENT OF A SINGLE CHAMBER AND SERIES CHAMBER MICROBIAL FUEL CELL (MFC)

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ABSTRACT
Microbial fuel cells are indeed renewable energy technology and potential alternative that has applications in the production of electricity. The purpose of this work is to construct and assess the performance of a single chamber microbial fuel cell using soil sample. Two MFCs were built: one was built and its performance was assessed in terms of variation of voltage and current with time and the other one in terms of the effect of cathode surface area on the performance of the MFC. The results are significant as we are able to record respective maximum current and voltage of 2.2mA and 0.6V and reason behind the non-linear relationship between current and voltage is clear. Another important relation was found is that the surface area of cathode which varies directly with current. Polarization curve was analyzed in which current density was illustrated as a function of voltage. Another significant result was that the Coulombic efficiency was found to be 92.6%. Furthermore, a voltage of 1.363V was achieved when the MFCs were connected in series. The results have indeed shown reasonable achievements.

Keyword: Columbic efficiency, Fuel cell, Microbes, Polarizability Curve, Single chamber.

1. INTRODUCTION
Microbial fuel cells (MFCs) have emerged in recent years as a promising yet challenging technology. In a MFC, microorganisms interact with electrodes using electrons, which are either removed or supplied through an electrical circuit. MFC is considered to be a promising sustainable technology to meet increasing energy needs, especially using wastewaters as substrates, which can generate electricity and accomplish wastewater treatment simultaneously, thus may offset the operational costs of wastewater treatment plant. Bacteria can be used in MFCs to generate electricity while accomplishing the biodegradation of organic matters or wastes. It is known that fossil fuels are non-renewable energy resources and contribute to various environmental issues [1].

MFCs (microbial fuel cells) are one of the potential alternatives for meeting the energy demand and they are environmentally friendly in nature [2].

The aim of this research is to construct and assess the performance of Microbial Fuel Cell (MFC) for the production of electricity.

2. THEORETICAL BACKGROUND

This outlines the various aspects of the technology and will explore its feasibility in industrial applications based on the latest research and experiments conducted by other researchers in this area.

Background

In 1910, M. C. Potter first observed the ability of E. coli to produce electricity [3]. Ever since, scientists have studied the ability of microbes to produce electric potentials in depth, and have incorporated this phenomenon into the design of microbial fuel cells (MFCs), which take advantage of natural biological processes in the microbes to catalyze the conversion of chemical energy in organic fuels into electrical energy. Recently, the search for alternative forms of energy has brought renewed interest to MFCs [4].

Microbes

Firstly, in order to understand the fundamental function of the MFC, it is important to have a grasp in some of the basic functions of the bacteria. In essence, bacteria breakdown organic matter and release energy in the process. Extra attention will be paid to certain bacteria which have the ability to generate electricity and to transfer electron effectively in the anode [5].

This type of bacteria is called Exoelectrogens, “exo “for exocellular and “electrogens” based on the ability to directly transfer electrons to a chemical or material that is not the immediate electron acceptor. There are many anaerobic bacteria that can only transfer electrons to soluble compounds such as nitrate or sulphate (not cell synthesized) that can diffuse across the cell membrane and into the cell. Exoelectrogenic bacteria are the most suited to function within an MFC due to their ability to transport electrons outside of the cell. This type of bacteria is useful in mediator-less MFC, a MFC system which do not require a ‘mediator’ to assist in electron transfer. Some mediators include, thionin, sulphate/sulphide methylene blue, pyocyanin etc., as well as others [6].

These exoelectrogens can be sourced in a number of places, according to [6] they are found in soil, marine sediment, waste water, fresh water sediment and activated sludge, which are rich with these microorganisms [7].

Principle of Fuel Cells

Microbial fuel cells (MFCs) are electrochemical devices that use the metabolic activity of microorganisms to oxidise fuels, generating current by direct or mediated electron transfer to electrodes [8], The device comprises of an anode chamber, a cathode chamber, electrodes, proton exchange membrane and an external circuit [9]. The MFC convert a biodegradable substrate directly into electricity. The anode holds the bacteria and the organic material in an anaerobic environment [10]. The cathode holds a conductive saltwater solution in a double chamber type MFC or air if it’s the single chamber. The bacteria generate protons and electrons as the organic substrate is being converted into energy. This energy is used and stored by the microbes for growth. The electrons are transferred directly to the anode electrode (in a mediator-less set-up) and to the cathode electrode via a copper wire or a conductive material. Protons pass through the ion exchange membrane to the cathode chamber to produce water as a result of the reduction process which is in terms of hydrogen transfer [11].

$$4H_2 + 4e^- + O_2 \rightarrow 2H_2O \qquad (1)$$

However, not all bacteria species are able to transfer electrons directly, therefore use of artificial chemicals such as “thionine, humicacid, neutral red, methyl blue and methyl viologen” is required. These are called redox mediators [11].

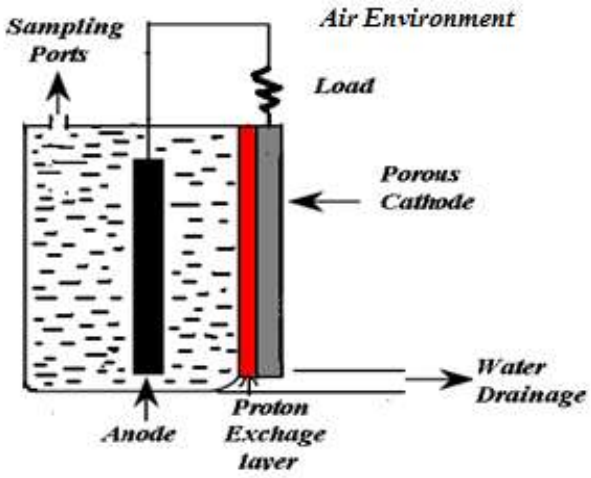

Figure 1: Schematic of Basic Components of MFC [12].

2.4 MFC Components

The microbial fuel cell consists of simple yet vital components to effectively harness the energy are as follows:

- Electrodes – both in the anode and cathode chambers
- Proton Exchange Membrane – (widely used Nafion as the least resistive membrane)
- Substrate – any organic matter used as source of energy for microorganisms i.e. wastewater
- Bacteria – exoelctrogens, most suited for MFC applications

2.4.1 Electrodes

The efficiency of MFC is dependent on many number of factors, and one is the material of the electrodes. There have been many MFC designs and configuration that have been tested and developed in recent years to improve the performance and efficiency of MFCs. However, the challenge to find the balance between performance and material cost remains difficult. This paper will explore the advantages and drawbacks of some of the electrodes that are widely used in today’s MFCs, in terms of their conductivity, surface properties, biocompatibility and cost [13]. The electrodes have a certain resistance hence the most effective ones are the least resistive. “The anodic resistance contributes to the overall cell resistance in MFC operation” [14].

However, for a large-scale application, the use of highly efficient electrode materials (such as Platinum) is not economically feasible. Thus, investment on more cost-effective alternatives is another priority in MFC research. The material characteristics which are critical for an effective electron transfer are high conductivity and mechanical strength. There is no requirement for bacteria adhesion. The scalability and cost-effectiveness are also taken into consideration. The most common material used for MFC anodes are carbonaceous materials due to their “good biocompatibility, good chemical stability, high conductivity and relatively low cost” [13].

2.5 Types of Microbial Fuel Cells

MFCs can be classified according to various parameters such as the design, architecture, and so on. In this section, microbial fuel cells will be classified into two main categories in terms of how they transport electrons to the electrode; mediator MFCs, and mediator less MFCs.

2.5.1 Mediator MFCs

Since the invention of microbial fuel cells, scientists have been using chemical mediators to enhance the electron transfer process. In mediator MFCs, microbes are not responsible of transporting electrons to the anodic surface because they do not synthesis a protein with active sites to help them do that. Instead, they use chemical mediators or agents that are also called “electroactive metabolites” [15]. The most used mediators are neutral red, Potassium Ferricyanide and methyl viologen under anaerobic conditions [16].

Anaerobic conditions are important because if oxygen is present, it will take the electrons and thus interrupting the mediator’s work, which is less electronegative than oxygen. During the process of electron transfer, the mediators inter the cell and accept the electrons before liberating them and donating them to the anode as the final electron acceptor. At this point, the mediator is oxidized back to its initial state after depositing its electrons. Years after the invention of mediator MFCs, scientists started looking for alternatives to enhance the electron transfer process and that is due to the fact that most of the efficient mediators are toxic for the microorganisms and the environment and expensive especially if the MFC is meant to treat wastewater [17].

2.5.2 Mediator-Less MFCs

As mentioned in the background section of the work, a group of professors from South Korea showed that MFCs don’t need mediators because most of the bacteria present in the wastewater have the tendency to transport electrons to the electrodes and produce electricity using long appendages called nanowires [16]. That makes the MFC non-toxic and less expensive. However, other parameters have to be taken into consideration mainly [18].

- The external resistance of the circuit
- The proton transfers to the cathode through a membrane, a week conductivity of protons results a variation in pH and hinders the microbial activity
- Oxygen reduction at the cathode

3. MATERIALS AND METHOD

This section provides the method and materials used for the work.

3.1 Single Chamber Microbial Fuel Cells

They are simple anode compartment where there is no definitive cathode compartment and may not contain proton exchange membranes. Porous cathodes form one side of the wall of the cathode chamber utilizing oxygen from atmosphere and letting protons diffuse through them. They are quite simple to scale up than the double chambered fuel cells and thus have found extensive utilization and research interests lately [19].

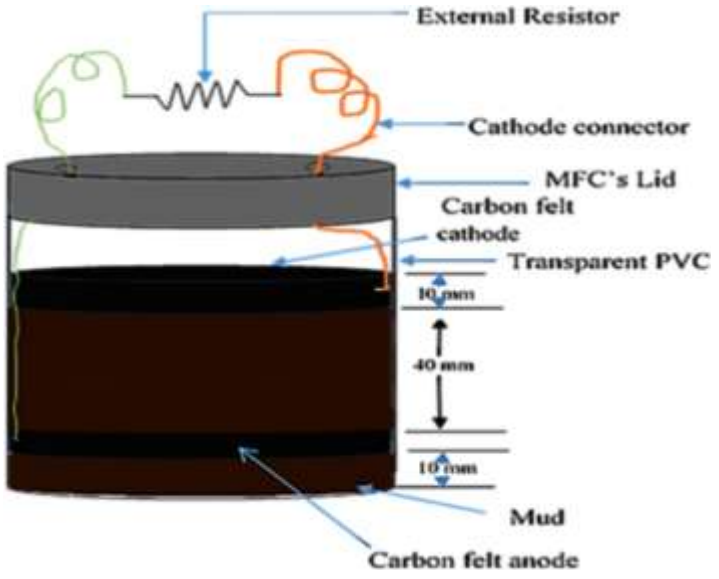

Figure 2: Single Chamber MFC [20].

3.2 Materials Selection

The materials selected for the experiment were selected according to the reviewed literatures.

3.2.1 Anode and Cathode Chamber

A single chamber MFC was chosen due to its high voltage output and low cost of construction. A food container made of a plastic capable of 3.5L was used, (Figure 2). Plastic is cheaper than most materials like ceramics besides the latter being subject to crack and consequent leakage.

3.2.2 Anode Electrode

In selecting the appropriate anode material, some important factors (or properties) needed to be considered, which are:

2. It should have high conductivity;
3. It should be non-corrosive;
4. It should be not expensive for large-scale application;
5. It should have high porosity.

However, different materials must have these properties. Usually, in most experiments, carbon paper or rod is used at the anode, it is highly conductive, non-corrosive and porous [10]. Thus, in this work, we are able to test the criteria and meet-up the three which are available before proceeding to the main work. Thus, for MFC anode electrodes, a carbon rod is chosen because of its non-corrosion, conductivity and non-porous properties. Three rods with approximate area of **6.92cm^2** each were tight to the anode (Plate 1).

Plate 1: carbon rod as electrode

$$A_{an} = \pi d(h + \frac{d}{2}) \quad (1)$$

where *d* is the diameter of a single carbon rod = 0.75cm, *h* is its height = 5.5cm and A_{an} is the area in cm^2.

Thus, the surface area of the anode electrode was calculated from Equation (1) to be $20.76cm^2$.

3.2.3 Cathode Electrode

Similar to the anode electrode, the cathode needs to be conductive and non-corrosive as its two main properties. Therefore, the same materials are used for the anode electrode.

3.2.4 Copper Wire and Multimeter

Copper wire is used as a material for the external circuit that connects the cathode and anode in this experiment. A digital Multimeter M832 was used for data collection.

3.2.5 Substrate

Garden soil was collected from biological garden and used as a substrate. Total mass of 2000g of the sample collected.

Plate 2: Substrate

3.3 Method

In this work, two MFCs were constructed. The following are step by step procedure for the construction: Firstly, two holes were indented at the cover of the plastic container, and make sure care is taken that, no tiny hole is left uncovered using a cello-tape. The garden soil was then moistened after applying an average amount of water to it. Then, the copper wires attached by the electrodes were connected to the respective anode and cathode.

Also, the anode was placed in a certain depth within the substrate with the cathode resting just above the substrate and exposed to air. The multimeter then closed the circuit, voltage and current were measured in different scenarios and corresponding current density and power density were calculated using equations 3.4 and 3.3 respectively. However, for the second part of the construction, the surface area of the cathode was altered appropriately, starting with 20.77cm^2, 41.54 cm^2, 62.31 cm^2, 83.08 cm^2 and 103.85 cm^2 respectively.

3.3.1 Analytical Calculations

The value of electric power, *P* is calculated from;

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

where *I* is the current, *R* is the external resistance and *V* is the voltage across the two electrodes.

Thus, using Equation (1) and (2), the power density P_d can be expressed as [8]:

$$P_d = \frac{P}{A_{an}} \quad (3)$$

where A_{an} is the total surface area of the anode (20.77cm^2 from Equation 1), also, current density was I_d can be expressed as [21]:

$$I_d = \frac{\mathrm{I}}{A_{an}} \quad (4)$$

While the Coulombic efficiency can be obtained from Equation (5) [14].

$$E_c = \frac{Cp}{Cn} \times 100\% \quad (5)$$

where C_p is the total Coulomb calculated by integrating current over time, and C_n is the theoretical amount of Coulombs that can be produced from the cell, which are given by:

$$C_p = \int_{t_0}^{t_n} Idt \quad (6)$$

and

$$C_n = \frac{FbS}{M} \quad (7)$$

where *F* is Faraday's constant (96485 Coulombs/mole-electron), *b* is moles of electrons/moles of substrate, *M* is molecular weight of the substrate and *S* is substrate concentration.

Coulombic efficiency E_c can also be obtained from the relation [10].

$$E_c = \frac{8\, x \int Idt}{F\, x\, V_{an}\, x\, COD} \quad (8)$$

where V_{an} is volume of the substrate at the anode, $\int \mathrm{Idt}$ is the total current integrated over time and *F* is Faraday's constant.

(a) Voltage (b) Current

Plate 3: Voltage and Current Measurement

4. RESULTS AND DISCUSSION

The performance of the MFCs constructed will be discussed in this chapter. Some important parameters are assessed in this section are: variation of voltage and current with time and the effect of cathode surface area on the performance of the MFC.

4.1 Variation of Voltage and Current with Time

Here, the variation of voltage with time interval wise was examined. The voltages were measured at every interval of five hours.

Table 1: Experimental Data Obtained from Single Chamber MFC1

Time (H)	Voltage (volts)	Current (mA)
0	0.360	0.000
5	0.300	0.300
10	0.480	0.780
15	0.560	0.021
20	0.580	0.200
25	0.160	2.200
30	0.330	0.100
35	0.370	0.100
40	0.390	0.200
45	0.440	0.200
50	0.470	0.050
55	0.480	0.100
60	0.550	0.100
65	0.600	0.100
70	0.440	0.090
75	0.460	0.150
80	0.450	0.250
85	0.470	0.170
90	0.470	0.050

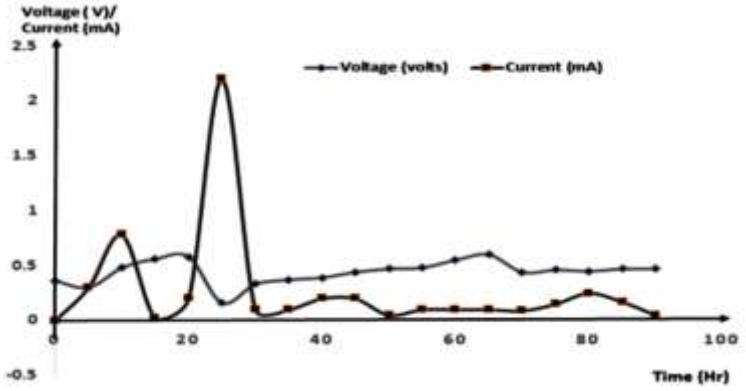

Figure 3: Voltage and Current variation with Time

Here, Figure 3 shows the mode of voltage and current generated in MFC1 over equal time interval. The values of the voltage showed a sudden decrease from 0.36V to 0.30V in the first 5 hours with increase current value from 0 to 0.3mA at the same time. This may be as a result of low proton conductivity due to the high absorption of water in the substrate. However, the current increases for the next 5 hours at a corresponding voltage of 0.48V, the voltage continue rising until at 0.58V before it experiences a significant voltage drop to 0.16 at the 25th hour.

Furthermore, we recorded a rise in voltage and falls of current, and later hours became steady varying with time. Also, the current rises at from this point before it eventually falls in the 30th hour to 0.1mA. This followed by a steady current, which decrease in voltage and increase current resulted from the low internal resistance in the cell. The low internal resistance results are due the use of oxygen as an electron acceptor [22]. A Potassium permanganate also produces similar effect [23]. This follows by the eventual increase in the voltage, which may be as a result of eventual growth of microbes. The corresponding maximum voltage and current were achieved at 65th and 25th hour (0.6V and 2.2mA).

Additionally, the non-linear relationship between voltage and the current could have been due to unsteady rate of microbial activity. This is one of the reasons why MFCs do not obey Ohm's law which signifies increase in voltage as the current increases.

[24] had the following result but using a double chamber MFC in a research conducted. This is shown in Figure 4.

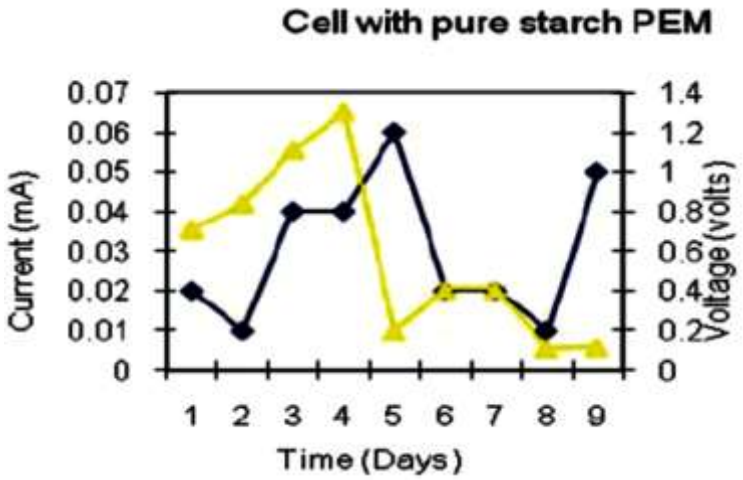

Figure 4: Results Time varying voltage and Current

4.2 Effect of Cathode Surface area to the Current on MFC2

Here, the effect of cathode surface area varying with current is reported.

Table 2: Effect of Cathode Surface Area on the Current

Cathode Surface Area (cm^2)	0.00	20.77	41.54	62.31	83.08	103.85
Current I (mA)	0.00	0.30	0.38	0.48	0.54	0.70

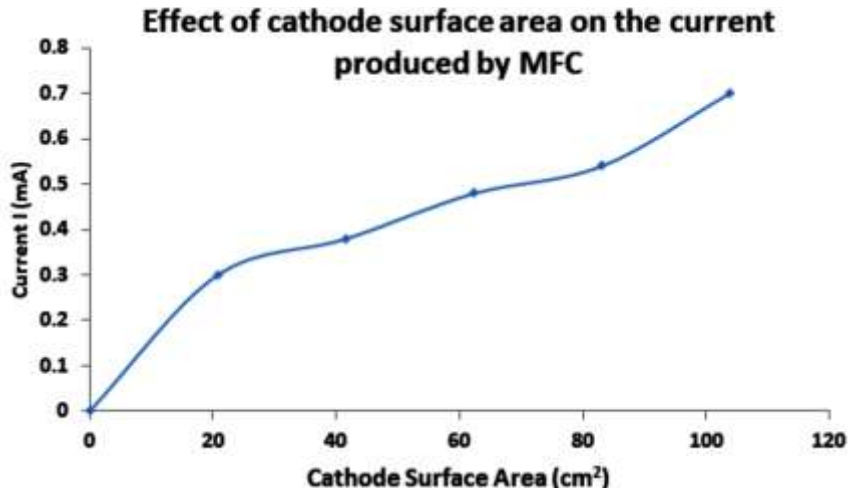

Figure 5: Effect of cathode surface area on the current produced by MFC

As it is reported in Figure 5, a significance increase in current as the surface area of the cathode increases was observed. Maximum current of 0.7mA was achieved with the surface area of 103.85cm^2. Thus, it implies that, as the surface area of the cathode increases, there will be a higher energy in the cathode to cause a significance reduction.

It is worth to note that, when attempting to increase the size of the anode surface area, we observed a nonlinear effect decrease in power density as reported in [25]. Since large MFCs need indeed large electrodes, increasing the surface area of the anode will result in a low efficiency, and thus a higher internal resistance of the cell. According to a research conducted by Bruce Logan and his team, they have doubled the cathode size and observed that the power has increased by 62% (Figure 6):

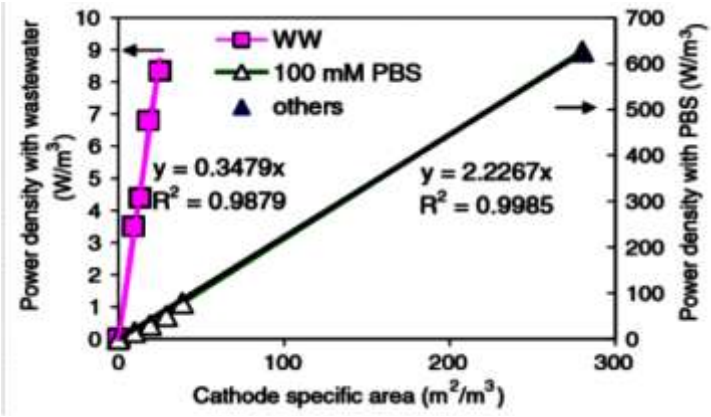

Figure 6: Power Density Variation with Cathode Specific Area

Moreover, another important parameter in assessing MFC evaluated was polarization curve and the Coulombic efficiency of the MFC.

4.3 Polarization Curve

The polarization curve is used here to illustrate the current density as a function of voltage (the electric potential of the electrodes) [10].

Table 3: Current Density Variation with Voltage

SN	Current density (mA/cm^2)	Voltage (volt)	SN	Current density (mA/cm^2)	Voltage (volt)
1	0.0000	0.36	11	0.0024	0.47
2	0.0140	0.30	12	0.0048	0.48
3	0.0380	0.48	13	0.0048	0.55
4	0.0010	0.56	14	0.0048	0.60
5	0.0096	0.58	15	0.0043	0.44
6	0.1060	0.16	16	0.0072	0.46
7	0.0048	0.33	17	0.0120	0.45
8	0.0048	0.37	18	0.0082	0.47
9	0.0096	0.39	19	0.0024	0.47
10	0.0096	0.44			

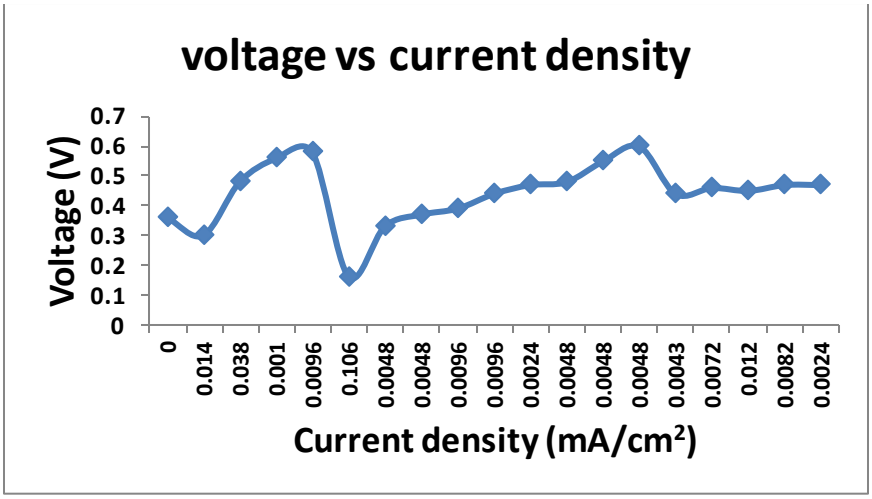

Figure 7: Current Density as a Function of Voltage

The plot demonstrates how well microbial fuel cells uphold the electric potential as a function of the current density. We observed that the voltage falls drastically to 0.3V corresponding to a current density of 0.014mA/cm². Three regions were identified from Figure 7, which show a drop in voltage (0.3V, 0.16V and 0.44V).

To better understand the abnormalities in the polarization curve, it is important to know the factors that affect the cell voltage. Some of the voltage losses are due to the electrodes over potentials and they change as the current changes.

There are three types of voltage losses that might cause the electrodes over-potentials; activation losses, bacterial metabolism and mass transport [10].

4.4 Coulombic Efficiency

The Coulombic efficiency of this work is calculated from Equation 8. Where we have found that; V_{an} = 2dm^3, F = 96485C/mole, I = 4.161mA, the time ranges from 0 to 90hrs or 324000s, the COD for garden soil = 580mg/L [26]. Thus, using the values, it is found that, the Coulombic efficiency is approximately to be around 92.6%. It demonstrates how well the constructed MFC does. This is a significance achievement.

Interestingly, another important result was obtained when the MFCs were connected in series (Plate 4). A combined voltage of 1.12V was achieved. This signifies how effective the MFCs can be to both domestic and commercial purposes when they get connected in series.

Plate 4: MFCs Series Connection

5. CONCLUSION

The results have shown how voltage and current vary with time. The effect of cathode surface area on the current generated by the MFC was analyzed. The result has shown that, the current increases with the increase in the cathode surface area. The results have also shown a reasonable Coulombic efficiency of about 92.6% when connected in series, the voltage raises to 1.363V.

RECOMMENDATIONS

Microbial Fuel Cell technology is still undergoing extensive research related to many aspects including its design, power optimization, reduction of internal resistance and potential scale-up. It is important to consider reducing the cost of the electrodes by avoiding precious metals at the cathode. In addition, it is essential to try different types of proton exchange membranes that is both cheap and efficient in terms of separating the chambers and allowing the passage of protons while hindering the migration of other substrates. Additional work can be focused on trying different temperature and pressure conditions to assess their effects on power density. Throughout this work, we used single-chamber MFCs. Finally, more effort should be focused on evaluating the microorganisms present in different substrate by growing cultures of microbes in various environments.

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