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

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ABSTRACT

Microbial fuel cells (MFCs) represent renewable energy technology with potential applications in electricity generation. This study aimed to construct and evaluate the performance of a single-chamber MFC using soil samples. Two MFCs were built for this purpose: one to assess performance by monitoring the variation of voltage and current over time, and the other to examine the effect of cathode surface area on MFC performance. Microbial fuel cells are important due to their potential to generate renewable energy, treat wastewater, remediate contaminated environments, serve as biosensors, and be scalable and integrated with other technologies, making them a promising solution for addressing various environmental and energy challenges. Notable results included recording maximum currents and voltages of 2.2 mA and 0.6 V, respectively, which elucidated the non-linear relationship between current and voltage. Additionally, it was found that the cathode surface area has a direct impact on the current produced. The polarization curve, illustrating current density as a function of voltage, was also analyzed. Another significant finding was a coulombic efficiency of 92.6%. Furthermore, connecting the MFCs in series achieved a voltage of 1.363 V. These results indicate substantial progress in the field. This study contributed to the advancement of MFC technology and its potential for practical applications in renewable energy generation, wastewater treatment, and environmental sustainability.

Keywords: Microbial fuel cells, Renewable energy, Environmental sustainability

INTRODUCTION

Microbial fuel cells (MFCs) have recently gained attention as an innovative yet challenging technology. In an MFC, microorganisms interact with electrodes, either donating or accepting electrons through an electrical circuit. This technology is considered a promising sustainable solution to meet growing energy demands, particularly when utilizing wastewater as a substrate. MFCs can generate electricity while simultaneously treating wastewater, potentially offsetting the operational costs of wastewater treatment plants. Given the nonrenewable nature of fossil fuels and their environmental impact, MFCs are viewed as a potential ecofriendly alternative for energy production (Wikipedia, 2021; Rittmann et al., 2013. MFCs can convert the chemical energy stored in organic matter, such as waste biomass or wastewater, into electrical energy through the metabolic activities of microorganisms (Gude, 2016). This process allows for the generation of renewable and sustainable energy from organic waste, which would otherwise be left untreated or disposed of in an environmentally harmful manner (Logan, 2018).

The application of MFCs can provide valuable real-time data for environmental monitoring and decision-making (Donovan *et al*., 2013). MFCs can be designed and scaled to suit various applications, from small-scale portable devices to large-scale systems for community-level energy generation and wastewater treatment (Logan, 2018). The modular nature of MFCs allows for their integration with other technologies, such as solar panels or wind turbines, to create hybrid renewable energy systems (Gude, 2016).

Microbial fuel cells are important due to their potential to generate renewable energy, treat wastewater, remediate contaminated environments, serve as biosensors, and be scalable and integrated with other technologies, making them a promising solution for addressing various environmental and energy challenges.

Optimization of MFC design and operating parameters: The performance of MFCs can be influenced by various factors, such as electrode materials, reactor configuration, and operating conditions. This study may investigate the optimization of these parameters to enhance the power output and efficiency of MFCs.

The performance of MFCs is heavily dependent on the composition and activity of the microbial communities involved. This study may explore the relationship between the microbial community structure and the MFC's performance, which can inform strategies for improving the efficiency of the system. Scalability and commercialization challenges: One of the major barriers to the widespread adoption of MFCs is the challenge of scaling up the technology from lab-scale to real-world applications. This study may address the challenges and potential solutions for scaling up MFC systems and making them more commercially viable.

This research aims to design and evaluate the performance of a Microbial Fuel Cell (MFC) for electricity generation. This study may contribute to the advancement of MFC technology and its potential for practical applications in renewable energy generation, wastewater treatment, and environmental sustainability.

In 1910, M. C. Potter first observed the ability of E. coli to produce electricity (Bullen *et al.*, 2016). 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 (Potter, 2011).

In 1910, M. C. Potter was the first to notice that E. coli bacteria could generate electricity (Bullen *et al*., 2016). Since then, extensive research has been conducted on the ability of microbes to produce electrical potentials, leading to the development of microbial fuel cells (MFCs). These cells leverage the natural biological processes of microbes to convert the chemical energy in organic materials into electrical energy. The recent quest for alternative energy sources has sparked a revived interest in MFCs (Potter, 2011).

To comprehend the fundamental function of a Microbial Fuel Cell (MFC), it is essential to understand some basic bacterial functions. Essentially, bacteria decompose organic matter and release energy in the process. Special focus is given to certain bacteria that can generate electricity and effectively transfer electrons to the anode (Atanassoc, 2020).

These bacteria, known as exoelectrogenic, derive their name from "exo-" meaning outside and "electrogens" referring to their ability to directly transfer electrons to a chemical or material that is not the immediate electron acceptor. Many anaerobic bacteria can only transfer electrons to soluble compounds like nitrate or sulfate, which can diffuse across the cell membrane. In contrast, exoelectrogenic bacteria can transport electrons outside the cell, making them ideal for functioning within an MFC. These bacteria are particularly useful in mediator-less MFCs, systems that do not require a mediator to facilitate electron transfer. Common mediators include thionin, sulfate/sulfide, methylene blue, and pyocyanin, among others (Du *et al*., 2021).

According to Du *et al*., exoelectrogenic can be sourced from various environments rich in these microorganisms, such as soil, marine sediment, wastewater, freshwater sediment, and activated sludge (Song, 2017).

MATERIALS AND METHODS

Single chamber microbial fuel cells

These are basic anode compartments without a distinct cathode compartment or proton exchange membranes. Porous cathodes, which are positioned on one side of the cathode chamber wall, use atmospheric oxygen and allow protons to diffuse through them. Their simpler design makes them easier to scale up compared to double-chambered fuel cells, leading to increased research and application (Park and Zeikus, 2020).

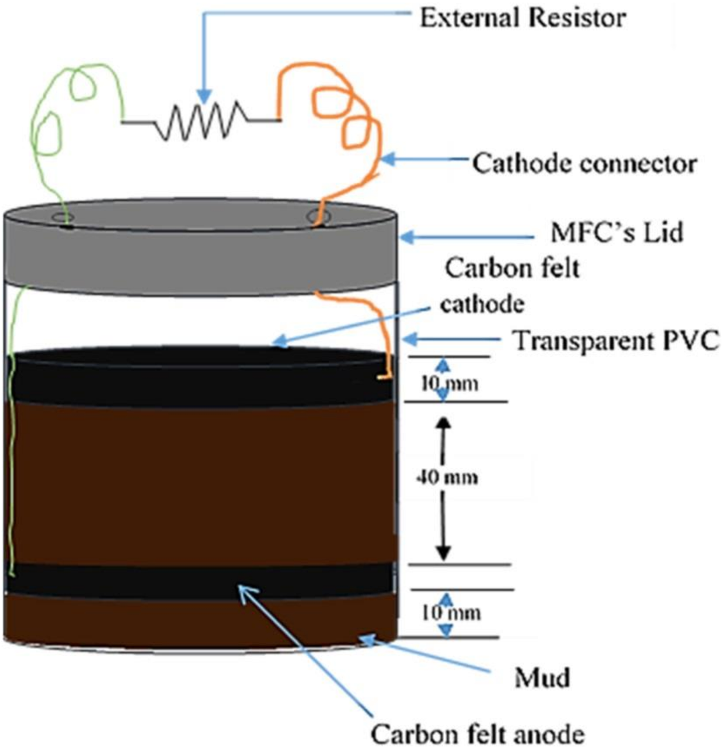

Figure 1: Single chamber MFC (Simeon and Raji, 2016)

Materials' selection

Anode and Cathode Chamber

A single-chamber microbial fuel cell (MFC) was selected for its high voltage output and cost-effectiveness. A plastic food container with a capacity of 3.5 liters was used for construction (see Figure 1). Plastic is more affordable compared to materials like ceramics, which are prone to cracking and leakage.

Anode Electrode

When choosing an anode material, several key factors must be considered:

i. High electrical conductivity
ii. Resistance to corrosion
iii. Cost-effectiveness for large-scale use
iv. High porosity

Various materials can meet these criteria. For this MFC, carbon rod is an attractive anode material choice for single-chamber MFCs due to its high conductivity, biocompatibility, large surface area, mechanical stability, cost-effectiveness, and easy availability, making it a suitable option for various MFC applications. Three carbon rods, each with an approximate area of 6.92 cm², were secured to the anode. (Figure 2).

Figure 2: Carbon Rod as Electrode

The total surface area of the anode was then **20.76cm²**. The surface area was calculated from equation (1) below:

$$A_{an} = \pi d \, (h + d/2) \qquad (1)$$

Where d is the diameter of a single carbon rod = 0.75cm, h is its height = 5.5cm and A is the area in cm^2.

Usually, in most experiments, carbon paper or rod is used at the anode, it is highly conductive, non-corrosive and porous (Logan, 2008).

Cathode Electrode

Like the anode, the cathode must be both conductive and resistant to corrosion. Hence, we utilized the same materials as those used for the anode.

Copper Wire

Copper serves as the material for the external circuit that links the cathode and anode in this experiment.

Multimeter

Data collection was carried out using a digital Multimeter model M832 shown in Figure 3.

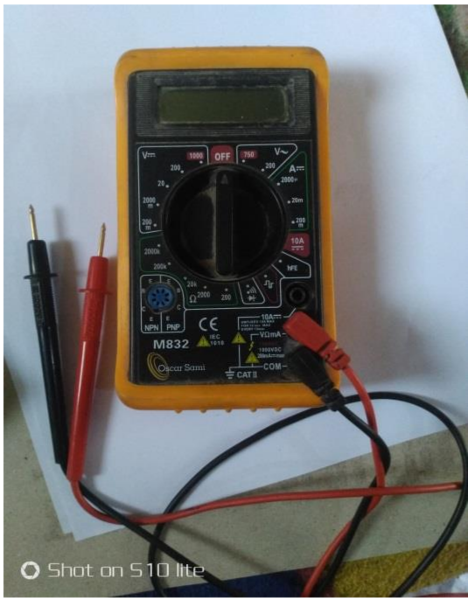

Figure 3: Multimeter

Substrate

The substrate used was garden soil gathered from a biological garden, with a total sample mass of 2000 grams as shown in Figure 4.

Soil preparation is an important aspect of setting up a single-chamber microbial fuel cell (MFC). Here's a step-by-step guide on soil preparation for a single-chamber MFC:

1. Collect soil samples from a suitable location, such as a garden, field, or wetland. The soil should be rich in organic matter and have a diverse microbial community.
2. Pass the soil through a fine mesh sieve (2-4 mm) to remove any large particles, roots, or debris. This will help create a more homogeneous soil mixture.
3. Adjust the soil moisture content to around 50-60% of the soil's water holding capacity. This can be done by adding water or drying the soil as needed.
4. Incorporate a source of organic matter, such as compost, manure, or cellulose-rich materials (e.g., shredded newspaper, sawdust), into the soil. This will provide the necessary carbon and nutrients for the microbial community to thrive.
5. If necessary, adjust the soil pH to be slightly acidic (pH 6-7) using a pH-modifying agent like sulfuric acid or

hydrochloric acid. This can help create a more favorable environment for the electrochemically active microorganisms.

6. To create an anaerobic environment, you can purge the soil with an inert gas like nitrogen or argon. This can be done by flushing the soil with the gas for several minutes.

7. Mix the soil thoroughly to ensure a uniform distribution of organic matter, nutrients, and microorganisms.

8. Incubate the prepared soil for a few days to allow the microbial community to stabilize and acclimate to the new conditions.

Figure 4: Substrate

Method

Two microbial fuel cells (MFCs) were assembled following these steps:

1. Preparation of the Container: Two holes were carefully made in the cover of a plastic container. To ensure no leaks, all tiny openings were sealed with cellotape.

2. Soil Preparation: Garden soil was moistened with a sufficient amount of water.

3. Electrode Setup: Copper wires were connected to the electrodes, with one wire attached to the anode and the other to the cathode.

4. Electrode Placement: The anode was positioned at a specific depth within the soil, while the cathode was placed above the soil and exposed to air.

5. Measurement and Analysis: The circuit was closed using a multimeter, and voltage and current were measured under various conditions. The current density and power density were then calculated using equations (3) and (4), respectively. For the second part of the construction, the surface area of the cathode were 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.

Analytic calculations

The value of electric power, P, was calculated from

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

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

e

The power density P_d is the given by equation (3) (Rabaey and Verstraete, 2017):

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

Where $\mathbf{A}_{an}$ is the total surface area of the anode **(20.77cm^2)**

Current density was I_d was also obtained from equation (4) (Wang *et al.,* 2018):

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

The coulombic efficiency can be obtained from equations (5) to (7) (Liu *et al.,* 2015):

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

Where C_p = total coulomb calculated by integrating current over time, C_n = theoretical amount of coulombs that can be produced from the cell.

$$C_n = \frac{FbS}{M} \quad (6)$$

And,

$$C_p = \int_{t_0}^{t_n} Idt \quad (7)$$

Where F = Faraday's constant (96485 Coulombs/mole-electron), b = moles of electrons/moles of substrate, Molecular weight of the substrate and S = substrate concentration.

Coulombic efficiency E_c can also be obtained by equation (8) (Logan, 2018):

$$E_c = \frac{8 \text{ X } \int \text{Idt}}{\text{F X Van X COD}} \quad (8)$$

Where Van = volume of the substrate at the anode, $\int$ Idt is the total current integrated over tim

(a) voltage readings

(b) current readings

Figure 5 (a) and (b): voltage and current measurement

RESULTS AND DISCUSSION

In this chapter, we will discuss the performance of the constructed MFCs. Key parameters examined include the changes in voltage and current over time and the impact of cathode surface area on the MFCs' performance.

Variation of voltage and current with time

The voltage changes over time were analyzed, with measurements taken at five-hour intervals.

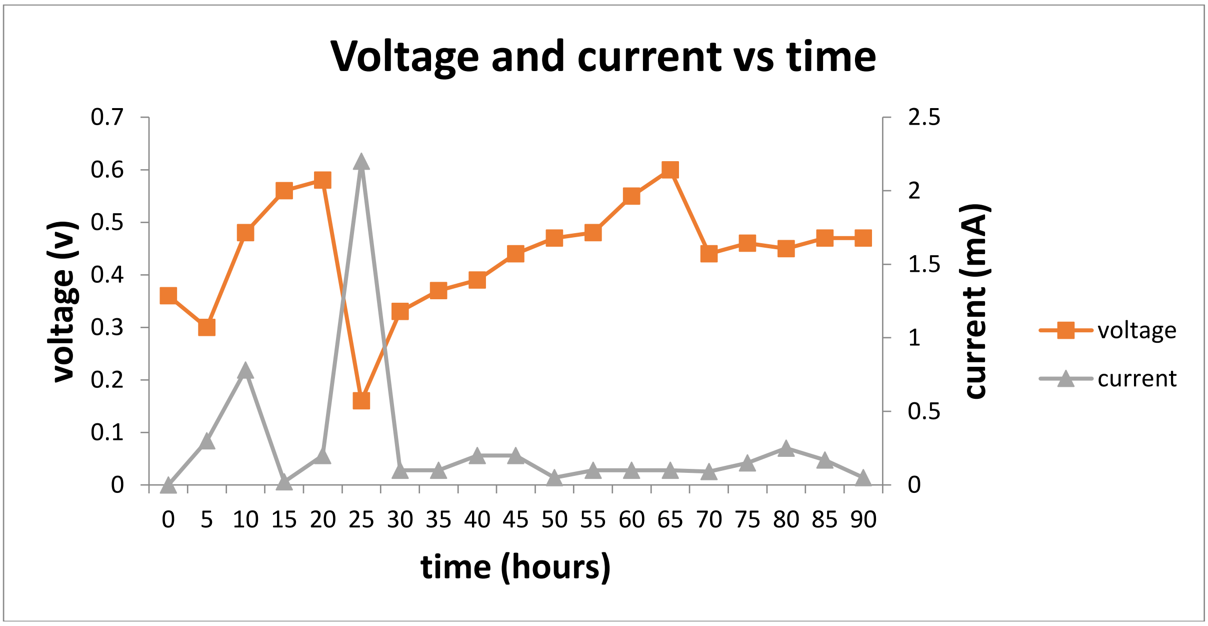

Figure 6: Variation of voltage and current with time

Figure 6 illustrates the voltage and current behavior of MFC1 over equal time intervals. Initially, the voltage drops sharply from 0.36V to 0.30V within the first 5 hours, while the current increases from 0 to 0.3mA. This decrease in voltage could be attributed to low proton conductivity caused by high water absorption in the substrate. Over the next 5 hours, the current increases further, reaching 0.48V, and the voltage continues to rise until it peaks at 0.58V. However, at the 25th hour, there is a significant voltage drop to 0.16V, though the current continues to increase until it reaches 0.1mA at the 30th hour. After this point, the current stabilizes, and the decrease in voltage coupled with the increase in current is likely due to the low internal resistance of the cell. This low resistance is attributed to the use of oxygen as an electron acceptor (Rabaey *et al.*, 2017), with potassium permanganate having a similar effect (Momoh and Neayor, 2010). Eventually, the voltage increases again, which may be due to the growth of microbes. The maximum voltage and current were recorded at the 65th and 25th hours, respectively, with values of 0.6V and 2.2mA. The non-linear relationship between voltage and current is likely due to the fluctuating microbial activity, which is why MFCs do not follow Ohm's law, where voltage typically increases with current. Livinus et al. (2012) obtained similar results using a double-chamber MFC in their research.

Effect of cathode surface area to the current on MFC2

From Figure 7, it is evident that increasing the surface area of the cathode leads to a significant rise in current, with a peak current of 0.7 mA achieved at a surface area of 103.85 cm². This suggests that a larger cathode surface area enhances the energy available, resulting in a notable reduction in resistance.

However, it is crucial to note that attempts to increase the anode surface area have shown a non-linear decline in power density (Aelterman et al., 2018). In large microbial fuel cells (MFCs), while larger electrodes are necessary, increasing the anode surface area can lead to lower efficiency and higher internal resistance.

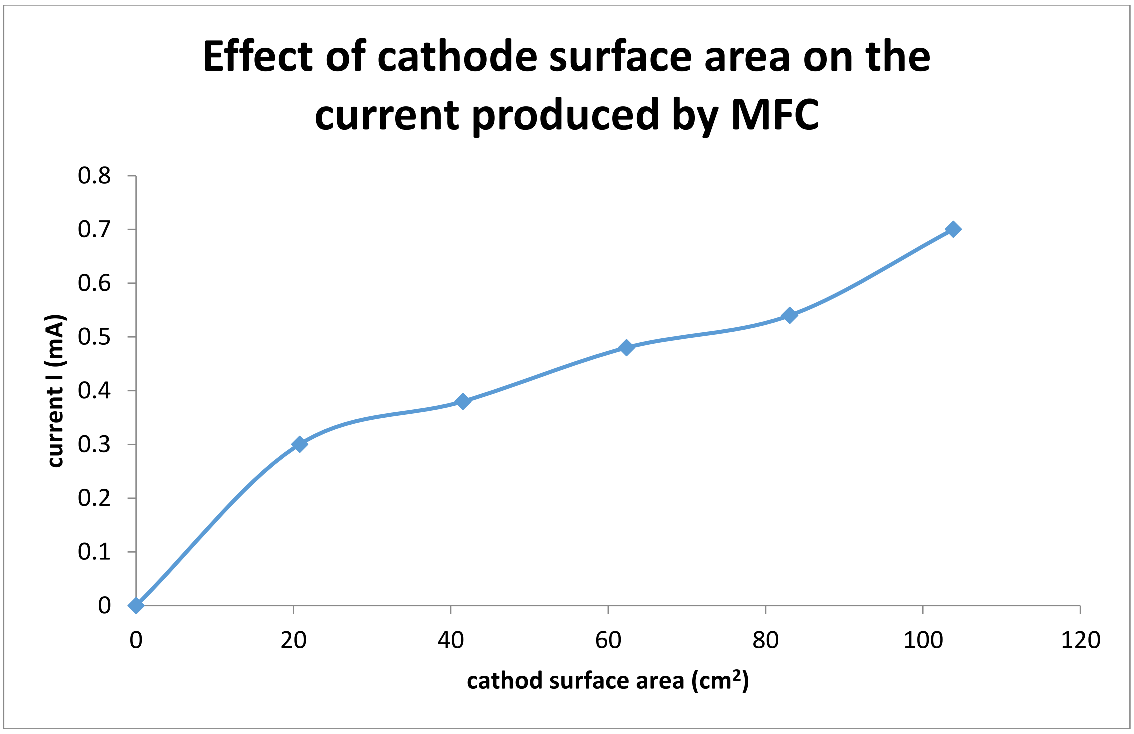

Figure 7: Effect of cathode surface area on the current produced by MFC

Additionally, important metrics for evaluating MFC performance include the polarization curve and the Coulombic efficiency of the cell.

Polarization curve

We use a polarization curve to show how current density varies with voltage (the electric potential of the electrodes) (Logan, 2018).

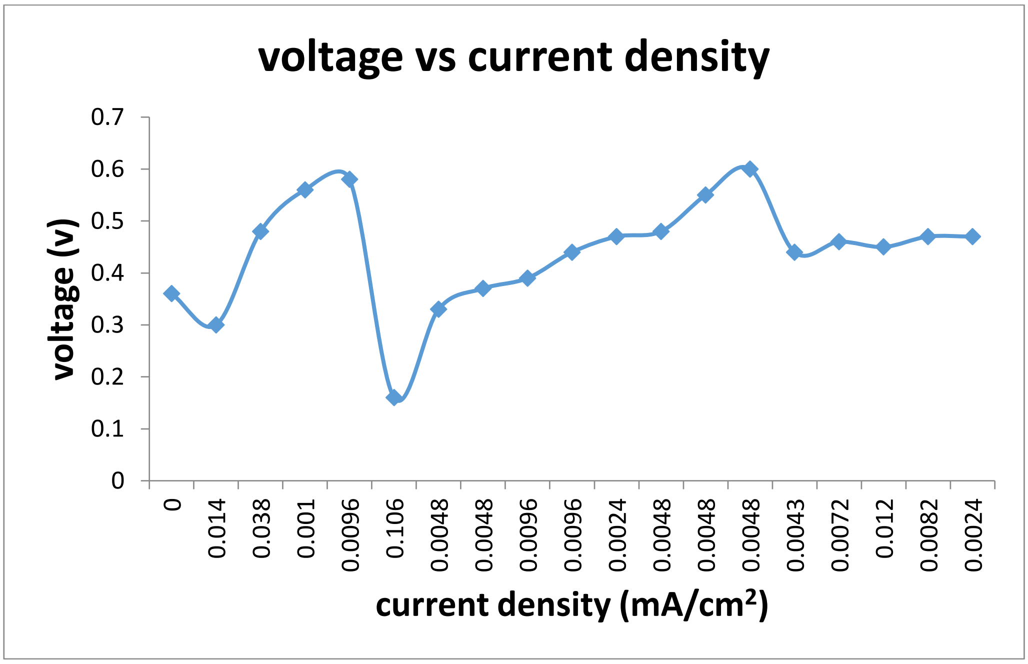

Figure 8: current density as a function of voltage

The plot in Figure (8) illustrates how microbial fuel cells maintain their electric potential in relation to current density. It shows a significant drop in voltage to 0.3V at a current density of 0.014mA/cm². There are three distinct regions where the voltage decreases (0.3V, 0.16V, and 0.44V).

To better understand these irregularities in the polarization curve, it's crucial to consider the factors influencing cell voltage. Some voltage losses are attributed to the over-potentials of the electrodes, which vary with current. These losses can be categorized into three types: activation losses, bacterial metabolism, and mass transport (Logan, 2018).

Activation Losses

To facilitate oxidation-reduction reactions, a certain energy threshold must be surpassed, often resulting in energy loss as heat. Additionally, energy is lost due to the movement of electrons from the bacteria to the anode surface, whether directly or indirectly.

Bacterial Metabolism

Energy losses arise from the bacteria's energy requirements to sustain metabolic processes, especially in generating the proton gradient within their electron transport chain.

Mass Transfer Losses

Two main factors contribute to energy losses here. First, the movement (or flux) of substrate reactants to the anode is often inadequate. Second, the migration of protons from the anode to the cathode may be restricted, leading to a buildup of H+ ions at the anode and a rise in pH at the cathode.

Columbic efficiency

The coulombic efficiency was approximately 92.6%, as calculated from equation (8), demonstrating the strong performance of the constructed MFC. This achievement is significant.

Another key finding was observed when the MFCs were connected in series, resulting in a combined voltage of 1.12V. This indicates the potential effectiveness of MFCs for both domestic and commercial applications when linked in series.

CONCLUSION

The results indicate how voltage and current change over time. An analysis of the impact of cathode surface area on the current produced by the Microbial Fuel Cell (MFC) revealed that the current increases as the cathode surface area enlarges. Additionally, the data showed a notable coulombic efficiency of approximately 92.6%. When connected in series, the voltage increased to 1.363V.

RECOMMENDATIONS

Microbial Fuel Cell (MFC) technology is still being extensively researched, with ongoing work addressing various aspects such as design, power optimization, and reduction of internal resistance, as well as scaling up the technology. One key area is reducing the cost of electrodes by avoiding the use of precious metals at the cathode. Another important focus is experimenting with different types of proton exchange membranes that are both affordable and efficient, ensuring they effectively separate the chambers and allow protons to pass while blocking other substrates. Research could also explore how varying temperature and pressure conditions impact power density. Although this study used single-chamber MFCs, future work could investigate alternative designs and architectures of fuel cells. Additionally, greater effort should be directed towards analyzing the microorganisms in various substrates by cultivating microbial cultures in different environments.

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