

OPTIMIZATION OF MICROBIAL FUEL CELL PERFORMANCE: EFFECTS OF EXTERNAL RESISTORS AND PH USING ABATTOIR WASTEWATER

Haruna, S.I.*, Igboro, S.B., Ibrahim, F.B. and Abubakar, U.A.

Department of Water Resources and Environmental Engineering Ahmadu Bello University Zaria

*Corresponding email: harunshittu@gmail.com

ABSTRACT

Microbial Fuel Cells (MFCs) offer a sustainable method for generating electricity from waste materials while treating wastewater. However, their efficiency is influenced by various operational parameters. This study addresses the problem of optimizing MFC performance by investigating the effects of external resistance and substrate pH on voltage, current, power, power density, and current density in dual-chamber MFCs using abattoir wastewater. The aim is to identify optimal conditions for maximizing power output and stabilizing microbial growth. The methodology involves operating MFCs under batch anaerobic conditions for 15 days, with experiments conducted at varying external resistances (10Ω, 100Ω, 200Ω, 470Ω, 1000Ω) and initial pH values (6, 7, 8, and 9). Results demonstrate that a high-power output of 21.1 mW·m⁻² was achieved at pH 9 with the highest bacterial count of 7.9×10⁷ CFU/ml, indicating significant microbial activity and a voltage of 350 mV over a 1000 Ω resistor. The study recommends adjusting initial substrate pH to stabilize MFC performance by controlling microbial activity and reducing methanogenesis. These findings highlight the importance of optimizing external resistance and pH to enhance the efficiency of MFCs for practical applications in renewable energy generation and environmental remediation.

Keywords: Microbial fuel cells; Abattoir wastewater, External resistors; Power.

1 INTRODUCTION

Microbial Fuel Cells (MFCs) are innovative bioreactors that harness the metabolic activities of microorganisms to convert chemical energy stored in organic substrates into electrical energy [1]. The foundation of this technology lies in the electrochemical reactions catalyzed by electrogenic bacteria, which oxidize organic compounds at the anode, releasing electrons that flow through an external circuit to the cathode, where they reduce oxygen. This process not only generates electricity but also facilitates the degradation of organic pollutants, making MFCs a promising technology for sustainable energy production and wastewater treatment [2]. According to recent research, "MFCs offer a dual benefit of waste treatment and renewable energy production, positioning them as a key technology for future sustainability" [3]. The efficiency of MFCs is influenced by various factors, including the type of substrate used, the microbial community, the configuration of the cell, and the operating conditions such as pH and external resistance. Previous studies have demonstrated that substrates ranging from simple compounds like glucose to complex organic wastes can be used in MFCs, with varying degrees of power output [4, 5]. However, achieving optimal performance requires careful management of these factors to balance microbial activity and electrochemical efficiency. A recent study emphasized that "optimizing substrate composition and operational conditions is crucial for maximizing MFC performance" [6]. One critical aspect of MFC operation is the selection of an appropriate external resistance. The external resistance influences the voltage and current generated by the MFC, impacting the overall power output. According

to Ohm's law, the power output of an MFC is maximized when the external resistance equals the internal resistance of the cell. However, finding this balance can be challenging, as internal resistance varies with changes in operational parameters and microbial activity [5]. Recent studies have reiterated the importance of this balance, indicating that "the correct match between external and internal resistance is crucial for optimizing power output in MFCs" [4, 6]. In this study, we investigate the combined effects of external resistance and initial substrate pH on the performance of dual-chamber MFCs inoculated with anaerobic digester sludge. By systematically varying external resistances and initial pH values, we aim to identify the optimal conditions for maximizing power output and stabilizing microbial growth. This research builds on previous findings that highlight the importance of these factors in enhancing MFC efficiency and explores new strategies for optimizing MFC performance through precise control of operating conditions [4]. Our findings suggest that careful adjustment of external resistance and substrate pH can significantly improve the efficiency of MFCs. By optimizing these parameters, we can enhance the electrochemical performance and stability of MFCs, making them more viable for practical applications in renewable energy generation and environmental remediation. As stated in a recent review, "The integration of optimized resistance and pH control strategies holds great potential for advancing MFC technology toward commercial applications"[6]. Another significant factor affecting MFC performance is the initial substrate pH. The pH of the substrate can influence microbial growth and activity, as different microbial species thrive at different pH levels. Electrogenic bacteria, which are crucial for electricity generation, have specific pH requirements for optimal performance. Additionally, the pH affects the solubility and availability of substrates and nutrients, further influencing microbial activity. Adjusting the initial substrate pH can help create a favorable environment for electrogenic bacteria while inhibiting methanogens, which compete for substrates and reduce overall efficiency [7]. Recent research has shown that "maintaining an optimal pH is essential for maximizing the activity of electrogenic bacteria and suppressing competing microbial processes" [8, 9].

2 MATERIALS AND METHODS

2.1 MFC Construction

A double-chamber microbial fuel cell (MFC) was constructed using readily available and inexpensive materials. The chambers were made from fifteen plastic containers with dimensions of 18.3 cm in height and to 15.3 cm in diameter. These containers served as the anode, cathode and gas collector chambers.

2.2 Proton Exchange Membrane (PEM) Preparation

Proton exchange membrane was essential for ion exchange between the anode and cathode chambers. It was prepared using 100g of Agar and 1.5 liters of 1M potassium chloride (KCl) solution. The Agar was boiled in the KCl solution for 10 minutes to ensure thorough saturation, then casted in 2inch PVC pipe of 17cm long and stored in a freezer at -4°C to solidify. Once solidified, PVC gum was used to create a leak-proof connection.

2.3 Electrode Setup

Five holes were drilled into each of the graphite rods. Five 8inch nut and bolts were screwed into the holes to firmly pin the steel mesh. Graphite rods rapped in steel mesh were used as electrodes due to their high conductivity and chemical stability. The anode electrode was a 10 cm long, 10cm wide and 0.8 cm thick graphite rod rapped in a 5cm-by-5cm steel mesh, immersed in the anode chamber filled with a mixture of 1.5 liter of abattoir wastewater and slug used as inoculum. The cathode electrode was similarly prepared and placed in the cathode chamber containing 1.5 liter of plain water.

2.4 Circuit Assembly

The assembly of the H-shaped MFC was done as shown in Figure 2. Copper wires were attached to the bolts on the graphite electrodes and extended through small holes in the container caps. These wires

connected to a digital multimeter for measuring open-circuit voltages and currents. Various resistors, ranging from 10 Ω to 1000 Ω , were connected in series with the circuit to study their effects on the MFC performance.

2.5 Experimental Procedure

The MFC was operated under batch mode anaerobic conditions for 15 days circle. Each day, the voltage and current across the resistors were measured using a digital multimeter. The measurements were recorded every 12 hours. The power (P), current density (I_d), and power density (P_d) were calculated using the following formulas:

$$P = VI \quad (1)$$

Where P represents the MFC Power output; V and I represent the voltage and current respectively.

$$PD = \frac{P}{A} \quad (2)$$

Where PD represents the power density; P and A represent the power output of the MFC and area of the anode respectively.

$$CD = \frac{I}{A} \quad (3)$$

Where CD represents the current density; I and A represent the current of the MFC and area of the anode respectively.

2.6 Data Collection and Analysis

The generated voltage and current were recorded daily across each resistor. These values were used to calculate the power output, current density, and power density. Graphs were plotted to analyze the variation of these parameters over the fifteen-day period.

2.7 Experimental Variations

To observe the influence of different resistances, resistors of values 10 Ω , 100 Ω , 200 Ω , 470 Ω , and 1000 Ω were employed. The anode chamber contained 1.5L of abattoir wastewater, while 1.6kg of sucrose was used as a nutrient source for the bacteria.

2.8 Experimental Setup

To investigate the efficiency and performance of the microbial fuel cells (MFCs) under varying conditions, a well-defined experimental setup was constructed. The setup consists of dual-chamber MFCs, which are instrumental in evaluating the impact of different external resistances and substrate pH values on power output and microbial activity. As illustrated in Figures 1 and 2, the dual-chamber MFCs are designed with separate compartments for the anode and cathode. Figure 1 shows the schematic diagram of the MFC setup, detailing the arrangement and connection of the components, while Figure 2 provides a photographic view of the actual experimental setup. The anode chamber, filled with abattoir wastewater, facilitates microbial growth and electron production. The cathode chamber contains a proton exchange membrane prepared with Agar and KCl solution, essential for ion exchange between the chambers.

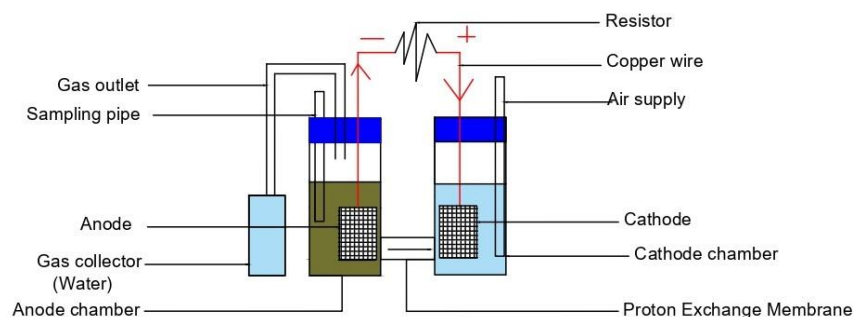


Figure 1. Microbial Fuel Cell configuration with Cathode and Anode



Figure 2a. Set up of H-shaped microbial fuel cell



Figure 2b. Open circuit current reading

2.9 Observations and Measurements

The digital multimeter readings provided daily voltage and current data, which were then used to calculate power and power density. The impact of each resistor on these parameters was evaluated to determine the optimal resistance for maximum power generation. Bar chart was used to show the bacterial count for the various MFCs at varied pH.

2.10 Graphical Representation

The results were presented in graphs showing voltage, current, and power against time for each resistor. Additionally, power density and current density were plotted to illustrate their dependence on the external resistance. This detailed method allows for replication of the experiment and provides a comprehensive understanding of how external resistance and pH influences the performance of microbial fuel cells.

3 RESULTS AND DISCUSSION

The presentation of results centers on interpreting Ohm's law, which states that current (or power) is directly proportional to voltage and inversely proportional to external resistance.

3.1 The Influence of external resistance on voltage output in Microbial Fuel Cells (MFCs)

Figure 4 illustrates the voltage readings at a pH value of 7 throughout the experimental period using various resistances. As shown in Figure 4, an increase in resistance results in a higher potential difference across the external circuit. Unlike most commercial galvanic cells, where the potential difference across an external resistance remains nearly constant over a wide range of resistance values due to negligible internal resistances, the MFC system studied displays a noticeable variance in voltage readings with different external resistances. This suggests that the internal resistance of the MFC system is considerably high, making the output voltage sensitive to changes in the external circuit. According to [1], this characteristic is common in dual-chambered MFCs, as the proton transfer rate is typically low.

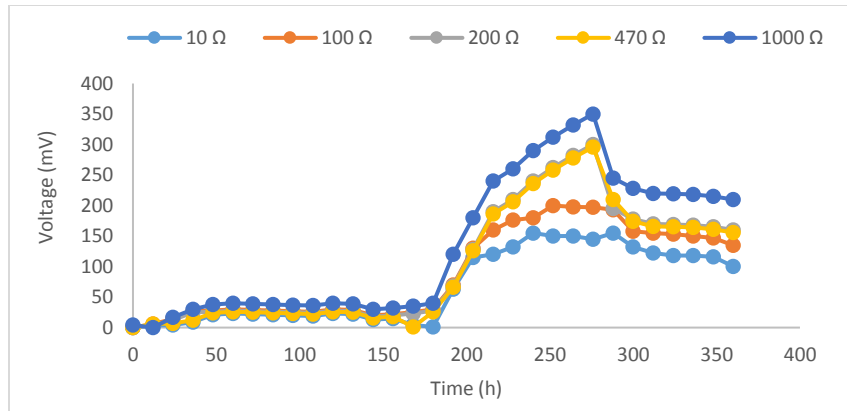


Figure 3a. Voltage Output at pH 7 Across Various External Resistances

3.2 The Influence of external resistance on current output in Microbial Fuel Cells (MFCs)

Figure 3b shows that higher current densities were achieved with lower external resistances at a pH of 7, consistent with Ohm's law. The high current values observed at low resistances result in a significant voltage drop across the internal resistance of the cell, leading to a lower measured voltage across the external resistance, as seen in Figure 3. According to research by [1] the internal resistance in most dual-chambered MFCs typically ranges around 1,000Ω. This indicates that solely relying on voltage readings to assess MFC performance is insufficient, as a high voltage reading recorded at a resistance value of 1,000 Ω, as shown in Figure 3a, corresponds to the lowest current density. Therefore, the most effective way to evaluate MFC performance is to also consider the power output.

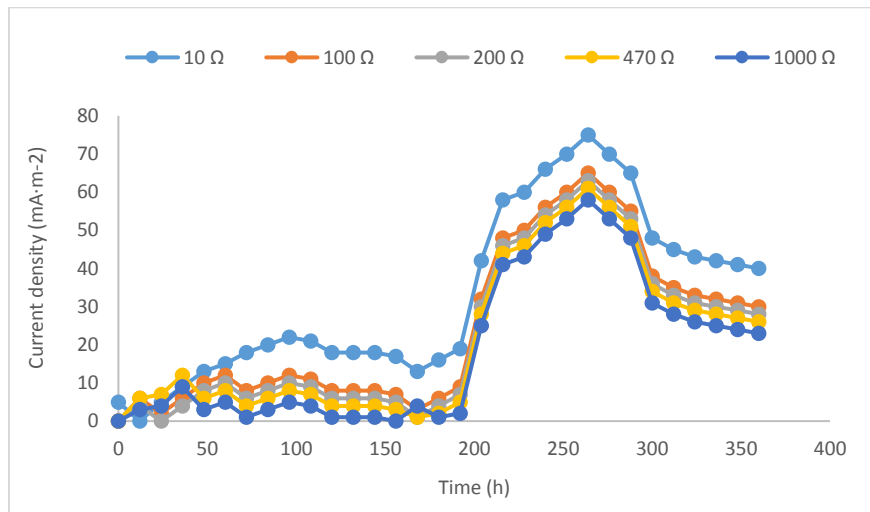


Figure 3b. Current Output at pH 7 Across Various External Resistances

3.3 The influence of external resistance on MFC power output

Figure 4 shows that higher external resistance values result in greater power density in the MFC due to lower voltage drops across internal resistance, thus more energy is utilized by the external circuit. Despite both 470Ω and 1,000Ω having similar power densities, a 1,000 Ω resistor performed better at pH 7, producing higher voltage output. Studies indicate that optimal power outputs depend on specific resistance values, influenced by the MFC's internal characteristics and microbial community [9, 10].

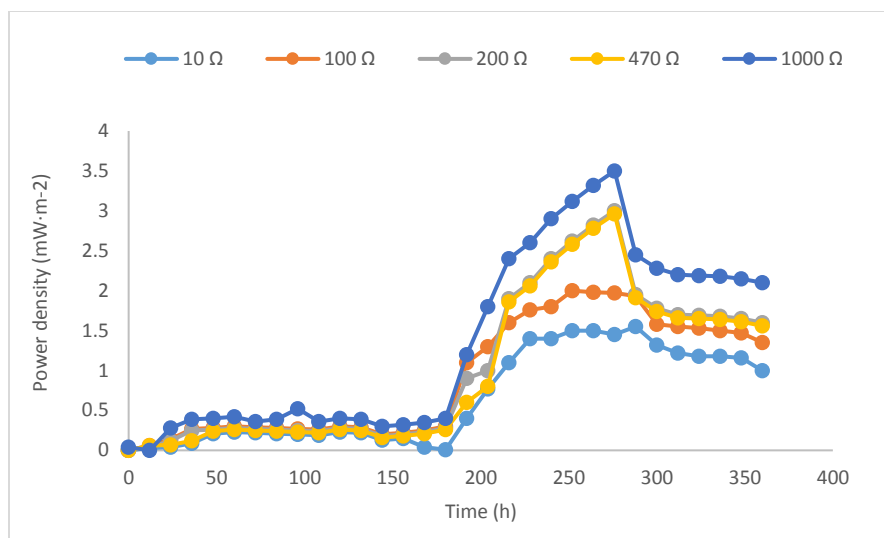


Figure 4. Power Output at pH 7 Across Various External Resistances

3.4 The Effect of pH on Microbial count and Impact on Voltage and Power Output

In figure 5 MFC-E, with a pH value of 9, showed the highest bacterial count of 7.9×10^7 CFU/ml. This indicates that a highly alkaline environment promotes substantial microbial growth. Robust microbial activity at pH 9 suggests that this condition is particularly favorable for maintaining high and stable voltage output in MFCs, which is essential for their practical application. A study by [11] supports these findings, indicating that alkaline conditions enhance the performance of MFCs by fostering a more active microbial community. MFC-A, with a pH value of 7, recorded a bacterial count of 4.7×10^7 Cfu/ml. The neutral pH condition supports rapid microbial growth, as evidenced by the significant bacterial count. This environment is conducive to high microbial activity, which translates to efficient electron transfer and stable voltage output in the MFC. However, the subsequent decline in microbial activity could be attributed to nutrient depletion, leading to a stationary or death phase in the bacterial population. A similar conclusion was reached by [11], who noted that neutral pH conditions optimize the growth of electrogenic bacteria, enhancing MFC efficiency. MFC-B as shown in figure 5, with a pH value of 8, had a bacterial count of 3.8×10^7 Cfu/ml. Although the microbial growth is lower compared to pH 9 and 7, it still indicates moderate activity. This pH level provides a less optimal but acceptable environment for microbial growth and MFC performance. A study by [11] found that slightly alkaline conditions could still support adequate microbial activity for satisfactory MFC performance, though not as effectively as higher pH levels. Both MFC-C and MFC-D, with a pH value of 6, had the lowest bacterial count of 3.2×10^7 Cfu/ml. The acidic environment appears to be the least favorable for microbial growth among the tested conditions. This reduced microbial activity likely results in lower voltage and power output in the MFC, as fewer electrogenic bacteria are available to facilitate the electron transfer processes. According to recent research by [6], acidic conditions tend to inhibit microbial growth, thus adversely affecting MFC efficiency.

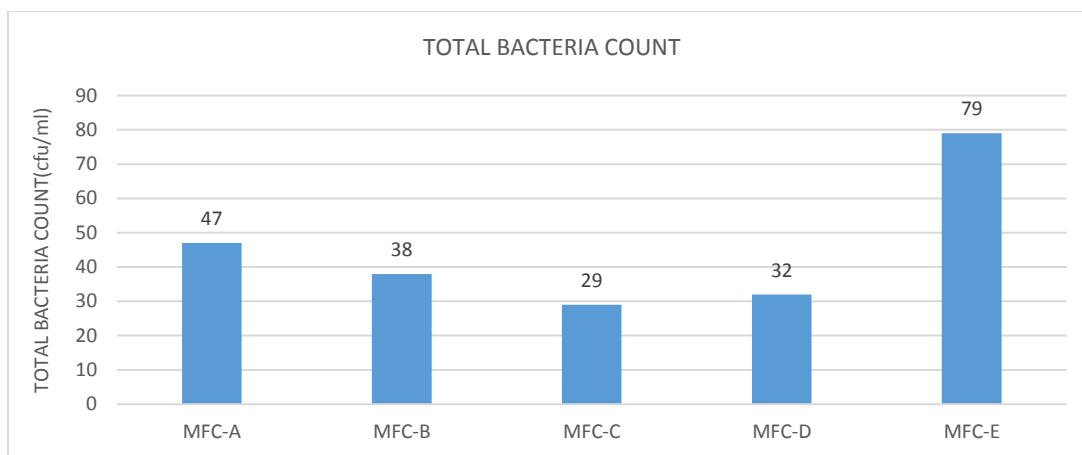


Figure 5. Total Bacterial Count Across Different MFCs with Varied pH Levels

3.5 The Influence of pH on Proton Release

Table 1 shows that the final pH in the anode chamber is consistently lower than the initial pH due to proton release during substrate consumption. Limited proton flux to the cathode chamber leads to proton accumulation, increasing internal resistance and affecting voltage output. Studies confirm that microbial oxidation in the anode chamber releases protons, lowering pH [12, 13]. Despite starting with a high initial pH, a low final pH can occur, as seen with pH 9, indicating significant proton formation. pH 9 showed a greater pH change than other values, indicating more proton release. Although pH 7 had the highest microbial count (Figure 5), it experienced the least pH change and released fewer protons [14].

Table 1. Changes in pH in the anode chamber for MFC with 1,000Ω external resistor.

Initial pH	Final pH	Change in pH
6.2	3.6	2.6
7.4	6.8	0.6
8.0	7.3	0.7
9.1	6.3	2.8

3.6 The influence of pH on voltage and power output

Figures 6a and 6b show that the pH 9 substrate solution generated the highest and most stable voltage output over time, indicating prolonged microbial activity. The pH 7 substrate produced the second-highest power output but was less stable, likely due to high microbial growth rates followed by bacterial death and settling. This suggests that microbial growth significantly impacts power output, with pH 9 suppressing methanogenesis more effectively than pH 7, resulting in higher power output. Although pH 6 showed significant proton liberation, its low microbial count led to the lowest power output, demonstrating that microbial count has a more significant influence on power output than proton liberation. Studies indicate that the voltage output in microbial fuel cells (MFCs) is influenced by the pH of the substrate solution, with higher pH levels generally leading to higher power outputs due to better microbial activity and less methanogenesis [13, 15]. The stability of power production at pH 9, as shown in the figures, aligns with findings that higher pH values can enhance the metabolic activity of electrogenic bacteria, leading to sustained power generation [7]. The instability observed at pH 7 can be attributed to fluctuations in microbial growth and death rates, which affect the overall power output [8]. Furthermore, the lower power

output at pH 6, despite significant proton liberation, underscores the critical role of microbial count in power production in MFCs [14, 16, 17].

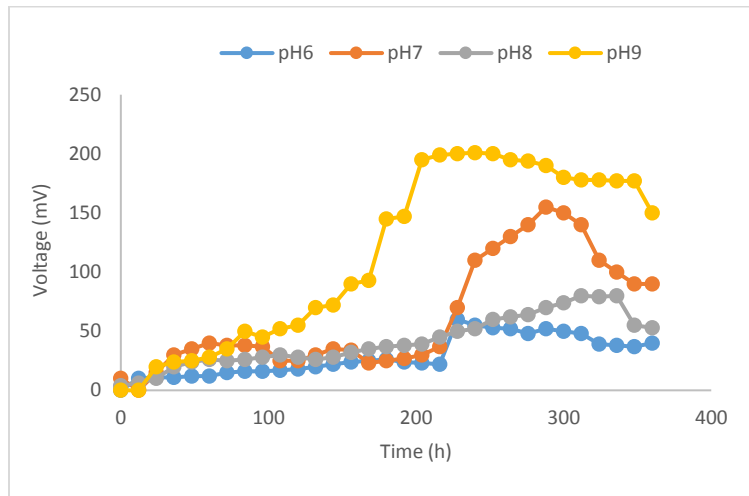


Figure 6a. Voltage output for different pH values using a 1,000Ω external resistor

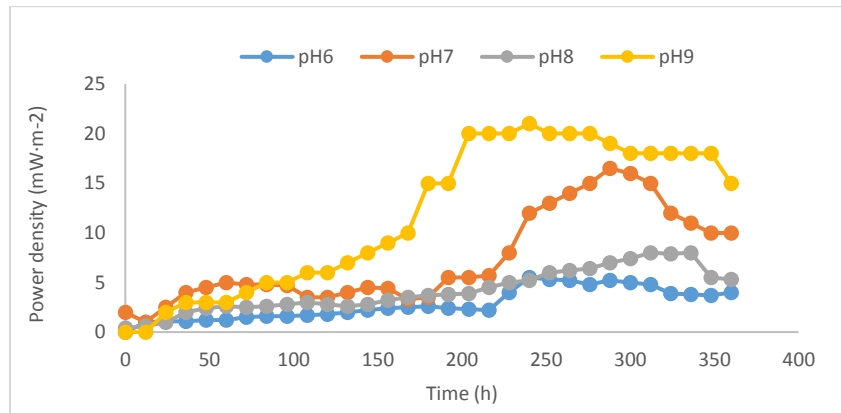


Figure 6b. Power output for different pH values using a 1,000Ω external resistor.

3.7 The Degeneration of the Proton Exchange Membrane

Upon disassembling the MFC chamber, fouling was found on the anode side of the proton exchange membrane (PEM) and anode for all pH values. Figure 7 clearly shows this fouling, which was partially removable but caused permanent damage, hindering proton transfer and reducing power output. This aligns with findings that biofouling and deposition of organic/inorganic matter block ion exchange pathways, reducing PEM conductivity and efficiency [6, 9]. Prolonged operation leads to microbial activity-related [14, 18, 19, 20, 21], with biofouling causing permanent damage.



Figure 7a. Degenerated Membrane



Figure 7b. Degenerated anode on the Anode Chamber Side

4 CONCLUSIONS

This study highlights the significant impact of external resistance and initial substrate pH on the performance of dual-chamber microbial fuel cells (MFCs). Higher external resistances, particularly 1000 Ω , optimally balance voltage output and power density, with a maximum potential difference of 350 mV and power density of 21.1 mW·m⁻² achieved at pH 9. An alkaline environment (pH 9) also promoted the fastest bacterial growth rate and stabilized maximum voltage output compared to other pH values. The findings underscore the importance of microbial activity in enhancing MFC efficiency, with alkaline conditions suppressing methanogenesis. Despite membrane fouling reducing proton transfer and power output, MFCs continued to generate substantial voltage. Overall, optimizing external resistance and substrate pH is essential for improving MFC performance, with implications for renewable energy generation and wastewater treatment. Further research is needed to address membrane deterioration and ensure long-term stability.

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