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ELECTRICITY GENERATION FROM FOOD WASTE LEACHATE (RICE) USING MICROBIAL FUEL CELL

Sim Sy Yi[a*], Pravin Raj Kannan[a], Kah Haw Law[b], Mohd Abdul Talib Mat Yusoh[c], Alvin John Lim Meng Siang[d], Ammar Alamshah[e]

[a]Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, 86400, Johor, Malaysia
[b]Electrical and Electronic Engineering Programme Area, Universiti Teknologi Brunei, Bandar Seri Begawan BE1410, Brunei
[c]School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam Selangor, Malaysia
[d]Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, Parit Raja, 86400, Johor, Malaysia
[e]ARES Energy Sdn Bhd,42300, Puncak Alam, Selangor, Malaysia

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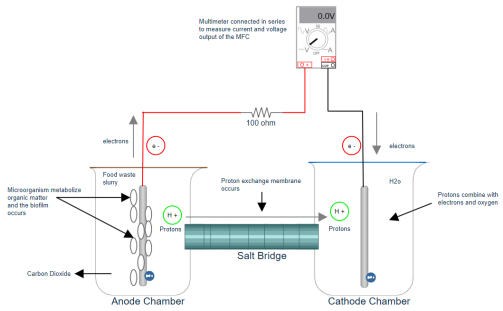
*Corresponding author
sysim@uthm.edu.my

Graphical abstract



Abstract

The growing need for renewable energy and effective waste management has encouraged the development of microbial fuel cells (MFCs), which convert organic waste into electricity. This study investigates electricity generation from food waste leachate, specifically rice slurry, using a dual-chamber MFC. The anode chamber was filled with rice slurry as the substrate, while the cathode chamber contained water with potassium permanganate as the oxidizing agent. Experimental trials were conducted under three conditions: (i) electrode comparison between copper and carbon graphite plates, (ii) temperature variations at room temperature and direct sunlight, and (iii) addition of potassium ferricyanide in the anode and potassium permanganate in the cathode chambers. Performance was evaluated by monitoring voltage, current, and power output across 10 days. Results showed a peak voltage of 137 mV, current of 1.37 mA, and maximum power of 0.1877 mW using graphite electrodes on Day 5. Elevated temperatures enhanced microbial activity and energy generation, while chemical additives improved electron transfer and redox efficiency. These findings demonstrate the potential of MFCs to provide dual benefits of renewable energy generation and sustainable waste reduction, supporting scalable eco-friendly energy solutions.

Keywords: Renewable energy, microbial fuel cells (MFCs), food waste leachate, rice slurry, electrode materials, dual-chamber MFC.

1.0 INTRODUCTION

Food waste in municipal solid waste may be composted, used as fertiliser, or harnessed for energy production. Fruit waste is generated across the whole fruit supply chain, from cultivation to household consumption. Inadequately managed organic waste has consistently posed a threat to environmental integrity and human health [1], [2], [3]. This trash has the potential to generate power in modern society. The predominant technique for power generation is the use of biomass. Biomass has substantial power production however lacks efficiency. Microbial fuel cells provide an additional method for transforming organic resources into energy. Moreover, its value is undervalued. Preliminary study indicates that microbial fuel cells has significant potential for energy generation owing to their eco-friendly, efficient, and reliable

processes, as well as their absence of hazardous byproducts. [4]Food waste is a significant portion of municipal solid waste worldwide. The Food and Agriculture Organisation (FAO) reports that about one-third of global food production, roughly 1.3 billion tonnes per year, is squandered. This not only intensifies environmental problems but also signifies a considerable depletion of resources, including water, energy, and labour [5]. Recent initiatives to reduce food waste have included its conversion into a renewable energy resource. Notable technologies include anaerobic digestion, composting, and microbial fuel cells. Although anaerobic digestion and composting mostly concentrate on waste management and soil enhancement, microbial fuel cells (MFCs) distinctly provide the twin advantages of waste minimisation and power production[5]. Microbial Fuel Cells (MFC) produce power via bacterial metabolic processes. MFC components consist of an anode, cathode, separator, and substrate. MFCs consist of two electrodes, a separator, and electrolytes, similar to batteries. In microbial fuel cells, the substrate resides in the anode chamber, while the cathode chamber contains water in the presence of oxygen. The membrane barrier between compartments must permit proton passage. A peripheral circuit linked to both electrodes facilitates the transfer of electrons between compartments. Studies indicate that various substrates may significantly influence the efficacy of microbial fuel cells (MFCs), with organic-rich substrates such as food waste proving more successful owing to their elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD) [6].Recent improvements in MFC technology have concentrated on enhancing electrode materials and designs to augment power output. The use of carbon-based materials, including graphite and carbon nanotubes, has shown potential in improving electron transfer rates. Furthermore, the advancement of biocompatible and economical membrane materials has been essential in overcoming the constraints related to proton exchange efficiency.This research will use surplus food as substrates for microbial fuel cells (MFC). This research will further examine alternative power output criteria to enhance power production under resource limitations. Improper treatment of organic waste adversely affects both human health and the environment. Organic waste, such as food waste, is difficult to eliminate. Daily household chores need energy. Renewable energy facilities may generate electricity from organic waste for residential, commercial, and industrial use. Biomass may provide substantial energy; nevertheless, burning results in heat loss and diminishes efficiency. The installation costs are substantial, and the system is designed to provide energy to several residences. MFCs are sustainable energy sources that mitigate heat loss more effectively than biomass. Although biomass may provide more power output, MFCs are more cost-effective to install and may be implemented in any home. Materials for MFCs are either inaccessible or prohibitively costly [7]. These problems may be surmounted using various methods and resources. MFC may produce electricity by harnessing organic waste, including spoilt food.The effectiveness of MFCs is affected by several parameters, such as the microbial population, electrode materials, temperature, and pH levels. Research demonstrates that sustaining a neutral pH and an ideal temperature range (20–45°C) may markedly improve microbial activity and, therefore, energy production [8].MFCs have obstacles like limited power output and scaling issues, despite their promise. Contemporary research investigates hybrid systems that integrate microbial fuel cells with other renewable energy sources to mitigate these constraints. Research indicates that microbial fuel cells (MFCs) may serve as a viable renewable energy source. In remote areas with restricted electrical access, MFCs can provide sustainable energy. This approach transforms food waste into power to reduce waste and foster a circular economy. Moreover, the incorporation of MFCs into waste management systems corresponds with international initiatives to fulfil sustainable development goals (SDGs), especially those concerning inexpensive and clean energy, responsible consumption and production, and climate action [9].

2.0 LITERATURE REVIEW

This section outlines the capacity of microbial fuel cells (MFCs) to transform chemical energy from organic substrates into electrical energy via microbial metabolism. The optimisation of critical factors such as pH, temperature, and substrate concentration is highlighted, with the use of food waste as a substrate for sustainable energy production.

2.1 Principle of Microbial Fuel Cell

The Microbial Fuel Cell operates by harnessing the ability of microorganisms to convert organic substrates into electrical energy via metabolic processes. Microorganisms in the anode compartment oxidise organic molecules, resulting in the liberation of electrons and protons. Electrons are sent from the anode to the cathode, via an external circuit, resulting in the generation of an electric current. Concurrently, protons traverse a proton exchange membrane towards the cathode, where they participate in a reduction process with oxygen, resulting in the formation of water. This method efficiently transforms chemical energy into electrical energy. The effectiveness of the MFC is affected by several factors, including the individual microbial species, the substrate used, and the existing environmental conditions. [10].

Microbial Fuel Cells (MFCs) function by using the metabolic processes of microbes to transform the chemical energy contained in organic substrates into electrical energy. The process starts in the anode chamber, where microorganisms oxidise organic substrates such as glucose. The oxidation process liberates electrons (e^-) and protons (H^+), as shown in chemical equation 2.1.

$$C6H12O6 + 6H2O \rightarrow 6CO2 + 24H+ + 24e- \text{(Eq 2.1)}$$

This metabolic process, facilitated by electrogenic bacteria like Geobacter and Shewanella, decomposes glucose into carbon dioxide (CO2), protons (H+), and electrons (e−) [11]. Electrons traverse an external circuit to the cathode, producing an electric current, while protons move to the cathode chamber via a proton exchange membrane (PEM) or salt bridge to preserve electrical neutrality.

At the cathode, protons and electrons combine with oxygen to form water. The cathode reaction is described as:

$$O2 + 4H+ + 4e- \rightarrow 2H2O \quad \text{(Eq 2.2)}$$

This reaction completes the electrochemical process, producing water as a harmless byproduct. The flow of electrons through

the external circuit generates electricity that can be harnessed for practical applications [12].

2.2 Optimization Parameters of Microbial Fuel Cell

This research highlights the need of optimising factors including pH, temperature, and substrate concentration to enhance microbial fuel cell (MFC) performance. Studies indicate that sustaining a neutral pH and an ideal temperature range of 20-30°C substantially enhances power output [13]. Nonetheless, the extensive temperature range lacks clarity on its durability under variable circumstances, which may influence microbial activity and power generation in practical applications. Substrate concentration is crucial, with Cheng et al. [14] determining 5 g/L as ideal for maximising power density in food waste-fed MFCs. This research primarily examines food waste and does not address other forms of organic waste or the long-term effects of byproducts such as ammonia and volatile fatty acids, which may impede microbial function [15].

This study investigates chemical improvements using Potassium Ferricyanide in the anode chamber and Potassium Permanganate in the cathode chamber to rectify these deficiencies. Potassium Ferricyanide augments electron transfer efficiency, whilst Potassium Permanganate promotes cathodic processes and total power output [16]. This methodology seeks to assess performance enhancements independent of pH measurements, constrained by equipment limitations. The literature underscores the constraints of research performed in controlled laboratory settings, which may not accurately represent real-world situations characterised by variable temperatures, substrates, and chemical concentrations [17]. Long-term performance data is often lacking, despite its significance, since microbial populations may evolve over time, influencing stability and efficiency. Moreover, the majority of research examine factors such as temperature, substrate concentration, and chemical presence in isolation, neglecting their potential synergistic effects, which may be significant. Finally, scaling concerns, including prices, reactor dimensions, and maintenance, are hardly considered in real applications [18].

This project seeks to investigate the effects of chemical additives and variations in combined parameters under controlled and semi-variable conditions, thereby offering enhanced understanding of the interactions among chemical factors, environmental conditions, and microbial activity in microbial fuel cell performance.

In addition to pH, temperature, and substrate concentration, several other factors significantly influence the performance of microbial fuel cells. The microbial community composition plays a central role, as electrogenic bacteria such as Geobacter and Shewanella determine the rate of electron transfer to the anode [19]. The electrode material and surface area also directly affect microbial attachment, biofilm growth, and electrical conductivity, making carbon-based electrodes more efficient compared to metals such as copper [20], [21]. Another important factor is the internal resistance of the system, which depends on the separator type and electrolyte conductivity; reducing internal resistance enhances power output [20]. Furthermore, operational conditions such as substrate loading rate, hydraulic retention time, and oxygen diffusion into the anode chamber can either support or inhibit microbial activity and electrochemical reactions [25], [26]. Addressing these factors collectively is essential to optimize power generation, stability, and scalability of MFC systems."

2.3 Microbial Communities

Microbial populations in MFCs are crucial for substrate breakdown and electron transport, directly affecting power production efficiency. Bacterial species such as Geobacter and Shewanella are often emphasised for their electrogenic properties, attributed to their capacity to transmit electrons to the anode. Fernando et al. (2012) highlighted the significance of Shewanella oneidensis in bio-decolorization and power generation in microbial fuel cells (MFCs) [19]. In food waste applications, mixed microbial consortia are beneficial since they improve substrate degradation by more efficiently decomposing complex organic molecules compared to single strains [13]. Nonetheless, these consortia encounter obstacles like interspecies conflict, community instability, and the need for appropriate environmental conditions to sustain balanced activity [18].

This initiative employs mixed microbial consortia to enhance the decomposition of domestic food waste and fruit peels. The system utilises varied microbial populations to attain elevated degradation rates and enhance power production efficiency, hence improving waste management and energy recovery.

2.4 Microbial Communities

The materials and configurations of MFCs are essential for enhancing performance and efficiency. Essential components include the anode and cathode, often constructed from conductive substances like as carbon cloth or graphite, which enable electron transport. The proton exchange membrane (PEM) is crucial for facilitating proton migration while inhibiting oxygen crossing. The configurations of MFCs may vary, with prevalent designs including single-chamber and dual-chamber systems, each influencing substrate flow and the overall electrochemical milieu. The judicious selection and organisation of these materials and combinations augment microbial activity and power production [20].

2.5 Reactor Design

The design of MFC reactors plays a crucial role in determining their efficiency and long-term stability. Single-chamber systems often face limitations due to oxygen diffusion into the anode, which disrupts anaerobic microbial activity and reduces electron transfer efficiency. They also suffer from biofouling, pH imbalances, and lower power densities [25], [26].

In contrast, dual-chamber reactors are widely adopted for research purposes because they enable effective separation of the anaerobic anode chamber and aerobic cathode chamber. This separation improves microbial growth, minimizes oxygen crossover, and enhances redox reactions. Furthermore, dual-chamber systems help maintain more stable pH gradients, which are essential for sustaining microbial metabolism and ensuring higher energy yields [25], [21].

When designing an MFC reactor, several criteria must be considered. The electrode surface area and positioning

influence microbial colonization and the efficiency of electron transfer [20]. The choice of separator, such as a proton exchange membrane or salt bridge, must balance ion transfer efficiency against cost-effectiveness [20], [21]. Additional factors include the control of hydraulic retention time (HRT), which affects substrate utilization, and the substrate loading rate, which determines microbial activity and prevents inhibitory byproduct accumulation. Practical issues such as construction cost, material availability, biofouling prevention, and long-term operational stability also need to be evaluated to ensure reactor scalability and sustainability [25], [26].

2.6 Electrodes

Electric current in a circuit circulates when the loop is intact, enabling electrons to travel uninterrupted from the power source, through the load, and back. Electrodes, essential elements in fuel cells and microbial fuel cells (MFCs), enable electron transfer. Electrode materials are generally metallic or carbonaceous, selected according to conductivity, corrosion resistance, surface area, and sustainability "as shown in Figure 1. Widely used carbon-based products such as graphite fibre brushes, carbon cloth, graphite rods, carbon paper, reticulated vitreous carbon (RVC), and carbon felt are esteemed for their conductivity and extensive surface areas, which augment microbiological activity. Metallic elements like zinc and copper are used for their conductivity and economic efficiency, however they may emit ions that impede microbiological activity. The choice of electrode materials seeks to reconcile performance and sustainability, with carbon-based materials being favoured for their exceptional characteristics in MFC operations. [21][22][23]

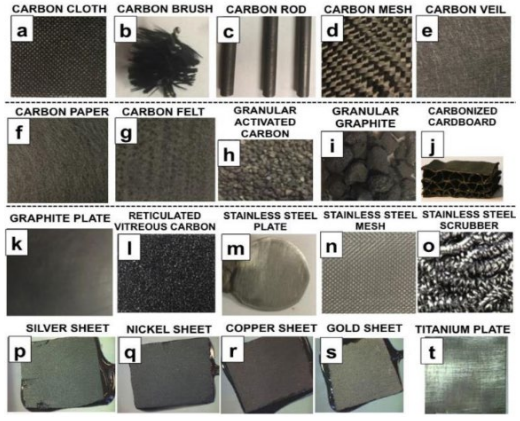


Figure 1 Materials suitable to be used as MFC's electrodes

2.7 Electrodes

Separators like proton exchange membranes (PEMs) and salt bridges facilitate proton transfer between the anode and cathode. While PEMs are more efficient, salt bridges provide a cost-effective alternative.

2.8 Data Collection Method

Evaluating the efficacy and practicality of MFCs in power generation from food waste necessitates the observation of their electrical output by current and voltage sensor. These sensors provide real-time data on MFC performance, which is crucial for system enhancement and scalability in practical applications. A similar methodology was employed in [24], where a resistor was connected to measure voltage and determine the corresponding electric current generated by MFCs. This research seeks to improve current approaches by using contemporary current and voltage sensors, therefore establishing a solid framework for assessing MFC efficiency in energy production from food waste.

2.9 Experimental Setup

Experimental setups of microbial fuel cells (MFCs) generally consist of a dual-chamber system, where the anode chamber contains organic substrates such as food waste, and the cathode chamber holds an oxidizing agent, often potassium permanganate dissolved in water, to facilitate reduction reactions. The two chambers are connected by a salt bridge or proton exchange membrane to allow proton transfer while maintaining separation of anaerobic and aerobic zones. Electrodes, commonly made of carbon-based materials such as graphite or alternative metals like copper, are inserted into each chamber and connected externally through a resistor to complete the circuit. Variations in the setup are frequently introduced to study the influence of different parameters, including electrode type, temperature conditions (e.g., room temperature versus direct sunlight), and chemical additives such as potassium ferricyanide or potassium permanganate that enhance electron transfer and redox efficiency. Voltage, current, and power output are typically measured using multimeters or current sensors, providing data for evaluating the overall performance of MFCs under different operating conditions [29]–[33].

2.10 Environmental Considerations of Chemical Additives

Although potassium ferricyanide and potassium permanganate are frequently used as chemical additives to enhance microbial fuel cell (MFC) performance by improving electron transfer and redox efficiency, their widespread long-term use poses environmental safety concerns. Potassium ferricyanide, despite its efficiency, may release free cyanide under extreme conditions, making it potentially hazardous [27]. Potassium permanganate is a strong oxidizer, and its spillage or residual discharge may cause oxidative stress to aquatic ecosystems and sediment contamination [28]. To mitigate these risks, researchers have proposed environmentally benign alternatives. Natural or synthetic redox mediators such as neutral red, methylene blue, and anthraquinone derivatives have demonstrated efficacy with lower toxicity [29]. Mediator-less systems using electrogenic bacteria like *Shewanella oneidensis*, capable of secreting flavins or phenazines, have emerged as sustainable approaches, eliminating the need for external mediators [30]. Additionally, enzyme-based cathodes employing laccase and ABTS have shown effective oxygen reduction and offer biodegradable, low-toxicity alternatives to ferricyanide [31].

3.0 METHODOLOGY

This study evaluates electricity generation from a dual-chamber microbial fuel cell (MFC) using rice slurry as the substrate. The methodology is structured around three objectives: (i) compare electrode materials, (ii) examine temperature effects, and (iii) assess chemical additives. The section details the materials, reactor construction, experimental protocols, data acquisition, and analysis used to ensure repeatability and controlled comparisons.

3.1 Materials and Reagent

Electrodes. Copper and graphite plates (10 cm × 10 cm × 0.25 cm; exposed area 210 cm^2) were used to allow fair, like-for-like comparisons across configurations. Graphite was selected for its corrosion resistance and good conductivity; copper for its high conductivity but known corrosion tendency. Both anode and cathode used identical material per setup.

Anode substrate. Rice slurry was prepared by mixing one bowl of cooked rice with water to form a homogeneous slurry; ~50 g rice was used in the anode. To ensure an active microbial community, ~4 L of pool water was added to the anode chamber.

Cathode medium. The cathode chamber was filled with ~4 L of water. For the chemical-additive study, 20 g potassium permanganate ($KMnO_4$) was introduced as an oxidizing agent.

Chemical mediator (anode, additive study). 50 g potassium ferricyanide ($K_3Fe(CN)_6$) was added to the anode chamber when evaluating mediator effects.

Separator (salt bridge). A salt bridge was fabricated in-house due to the cost/availability constraints of ion-exchange membranes. The recipe used 200 mL water, 8 g agar, and 30 g salt, heated and mixed, then cast into a cylindrical PVC tube and frozen to set.

3.2 Block Diagram of the Proposed Dual Chamber MFC

The process involves collecting food waste (e.g., rice slurry), pretreating it, and utilizing it in the anode chamber. Microbial activity in the anode chamber releases electrons and protons, with electrons traveling through an external circuit and protons migrating through a salt bridge to the cathode chamber, generating electricity, as shown in Figure 2.

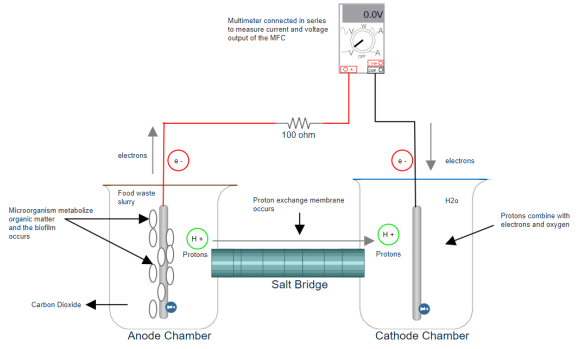


Figure 2 Block diagram of the Generation of electricity from food waste using a Microbial Fuel Cell

3.3 Flowchart of MFC Process and Setup

Electrode Selection: Copper and graphite plates (210 cm^2) are tested to identify the optimal electrode material as shown in the Figure 3.

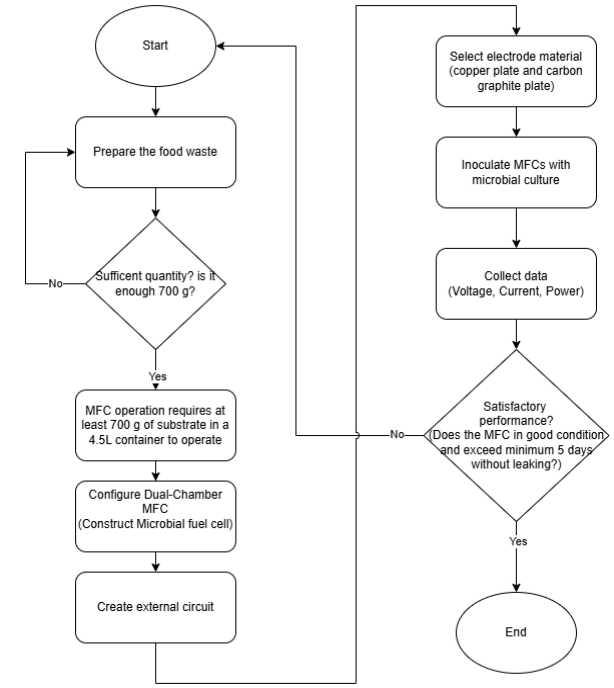


Figure 3 Electrode Material Selection and Performance Evaluation

Temperature Testing: Room temperature and direct sunlight setups evaluate the influence of temperature on microbial activity and power generation , as shown in Figure 4.

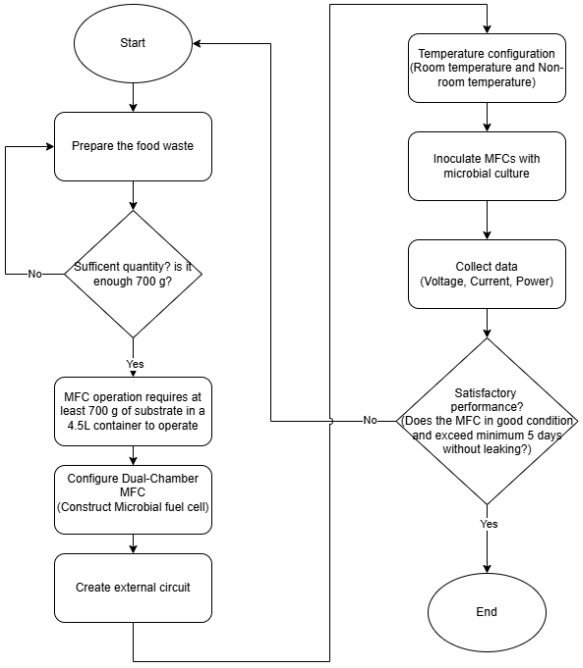


Figure 4 Temperature Variation and Its Effect on MFC Efficiency

Chemical Additives: Potassium ferricyanide (anode) and potassium permanganate (cathode) are tested to enhance electron transfer and reduction efficiency.

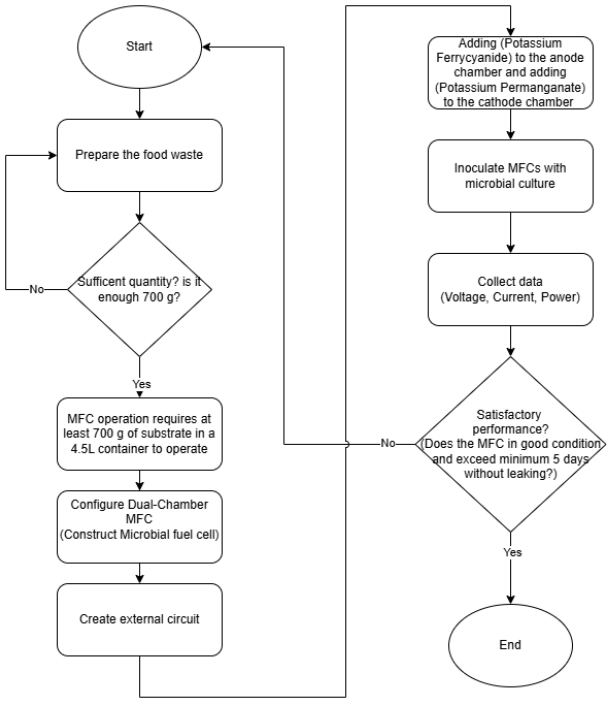


Figure 5 Illustrates Chemical Additives and Their Impact on MFC

3.4 Experimental Setup

3.4.1 Objective 1: Electrode Materials

Two setups (copper and graphite plates) with rice slurry in the anode chamber and water in the cathode chamber are tested at room temperature as shown in Figure 6 and 7..

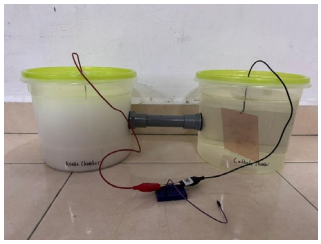


Figure 6 MCF with copper plate electrode

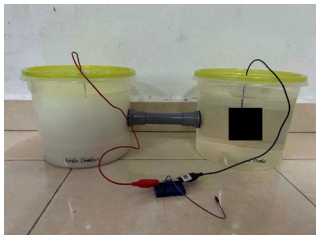


Figure 7 MFC with carbon-based graphite plate

3.4.2 Objective 2: Temperature Variations

Identical setups with graphite electrodes are tested under room temperature and direct sunlight conditions to evaluate the effect of temperature variation on MFC performance. The experimental setups are shown in Figures 8 and 9.

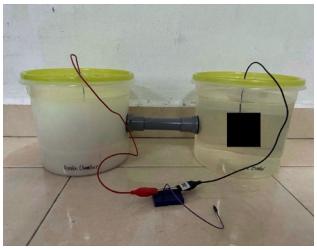


Figure 8 MFC with room-temperature setup

Figure 9 MFC with non-room temperature

3.4.3 Objective 3: Chemical Additives

Graphite electrodes are used with chemical additives in the anode (50g potassium ferricyanide) and cathode (20g potassium permanganate), "as shown in Figure 10.

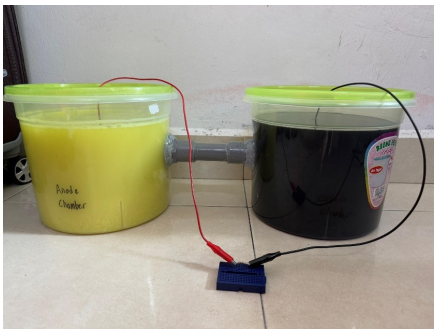


Figure 10 Evaluating chemical additives.

3.5 External Circuit

The fundamental layout of the external circuit proposed the utilization of a boost converter as its external load. Due to the unavailability of a function generator that can generate a 10V signal at a frequency of 50kHz, and the unexpectedly high results of the MFC, the external circuit is replaced with a resistor with a resistance of 100Ω.

The selection of the optimal resistance for the external circuit in the MFC was carried out by testing three different resistor values: 100 Ω, 220 Ω, and 300 Ω. The power output, which is a key performance indicator, was calculated using equation 3.1:

$$P = \frac{V^2}{R} \quad \text{(Eq 3.1)}$$

where P represents power (in mW), V denotes voltage (in V), and R signifies resistance (in Ω). The voltage values obtained from experiments over a span of 10 days, along with the corresponding resistance values, were utilised to calculate the power output. The analysis revealed that the 100 Ω resistor consistently yielded the highest power output across all testing days in comparison to the 220 Ω and 300 Ω resistors. On 30 May, the recorded voltage was 0.458 V, yielding the subsequent power outputs for each resistor:

For R = 100Ω

$$P = \frac{(0.458)^2}{100} \approx 2.10mW \quad \text{(Eq 3.2)}$$

For R = 220Ω

$$P = \frac{(0.458)^2}{220} \approx 0.95mW \quad \text{(Eq 3.3)}$$

For R = 300Ω

$$P = \frac{(0.458)^2}{300} \approx 0.70mW \quad \text{(Eq 3.4)}$$

The calculations indicate that the 100 Ω resistor generated markedly greater power than the other resistors. This trend persisted throughout the 10-day testing duration, with power outputs progressively diminishing over time. This behaviour is prevalent in microbial fuel cells due to factors such as substrate depletion (the rice slurry) and fluctuations in microbial activity.

A graph entitled "Power Output vs. Days for Different Resistor Values" was created to enhance the analysis. Figure 11 illustrates that the 100 Ω resistor attained the maximum power output on each day. The power curves for the 220 Ω and 300 Ω resistors consistently exhibited lower values during the testing period, thereby confirming that the 100 Ω resistor is the most efficient choice

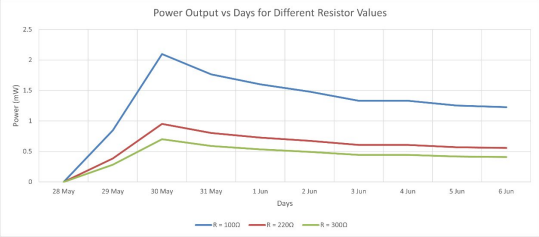


Figure 11 Illustrates the Power Output vs. Days for Different Resistor Values

The results correspond with the theoretical principle of maximum power transfer, which is achieved when the external resistance equals the internal resistance of the MFC. The measured maximum power output with the 100 Ω resistor suggests that this value closely approximates the internal resistance of the MFC. The system attains optimal performance in energy generation by maximising power transfer

In summary, through the calculations of power output, graphical analysis, and theoretical reasoning, it has been established that the ideal resistance for the MFC external circuit is 100 Ω. This resistance value guarantees efficient system operation and optimal power output, as demonstrated by the reliable results throughout the testing phase

4.0 DATA ANALYSIS AND RESULTS

4.1 Electrode Materials

4.1.1 Copper Plate Raw Data Revise

The experimental setup produced daily measurements of voltage, current, and calculated power output, as detailed in Table 1. Measurements were recorded daily at 11:50 PM from November 18, 2024, to November 25, 2024, to ensure consistent timing and conditions for assessment. The variations in open-circuit voltage (VOC), voltage, current, and power over the experimental period are shown in Figures 12, 13, 14, and 15, respectively

Table 1 Voltage, Current, and Power Output Over Time

Day	Date	Voltage (Voc)	Voltage (mV)	Current (mA)	Power (mW)	Time
1	18/11/2024	78.3mV	2.29mV	0.78mA	0.0610mW	11.50pm
2	19/11/2024	97.2mV	2.81mV	0.97mA	0.0943mW	11.50pm
3	20/11/2024	121.6mV	3.75mV	1.22mA	0.1484mW	11.50pm4
4	21/11/2024	126.2mV	4.20mV	1.26mA	0.1590mW	11.50pm
5	22/11/2024	137mV	5.25mV	1.37mA	0.1877mW	11.50pm
6	23/11/2024	43.02mV	3.91mV	0.43mA	0.0185mW	11.50pm
7	24/11/2024	7.98mV	1.36mV	0.08mA	0.0006mW	11.50pm
8	25/11/2024	0mV	0mV	0mA	0mW	11.50pm

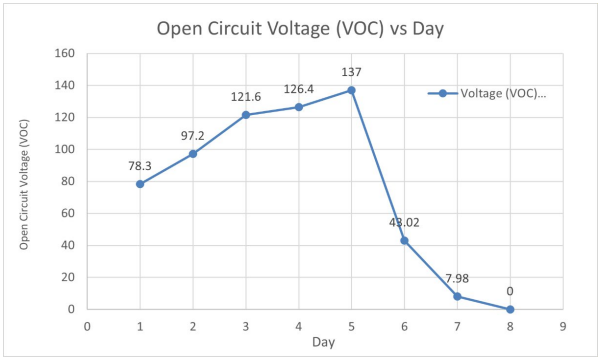


Figure 12 Open Circuit Voltage (VOC) vs Day

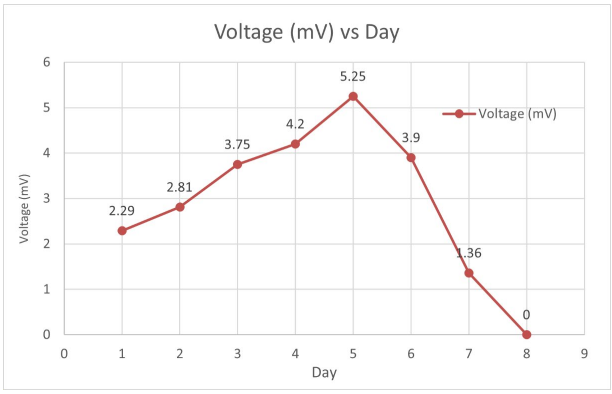


Figure 13 Voltage (mV) vs Day

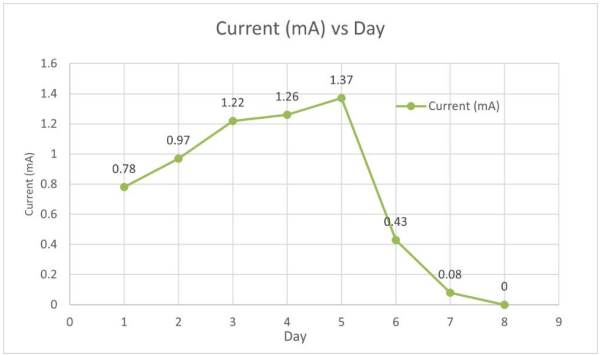


Figure 14 Current (mA) vs Day

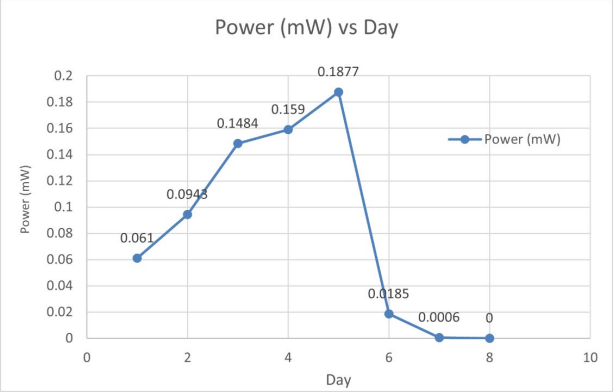


Figure 15 Power (mW) vs Day

4.1.2 Data Analysis (Copperplate)

The information has been carefully examined. The goal is to assess the effectiveness of the microbial fuel cell. It uses rice slurry as the substrate and copper electrodes. Assessed essential performance indicators. These include power density and total coulombs transferred. Also conducted statistical analyses for average power output and standard deviation. This helped us gain insights into the system's efficiency and performance patterns over time.

Power density is calculated using Equation 4.1. It involves dividing the power output by the electrode surface area. The area used in this study is 210 cm². This metric shows the energy generation potential. It relates to the size of the electrode. The total coulombs transferred show the electron movement over time. This is calculated using Equation 4.2. It considers the current (I) and the time duration (t). Data is analysed. Statistical evaluations are used. Mean power output and standard deviation help uncover trends. They reveal variability in performance. See Equations 4.3 and 4.4. The calculated parameters for the copper plate are summarized in Table 2

$$Power\ Density = \left(\frac{Power}{Area}\right) \quad \text{(Eq4.1)}$$

$$Total\ coloumb\ tranfered = (I \times t) \quad \text{(Eq4.2)}$$

$$Mean\ power\ output = \left(\frac{P1 + P2 + P3 + P4 + P5 + P6 + P7 + P8 + P9}{9}\right) \quad \text{(Eq4.3)}$$

$$Standard\ deviation = \left(\sqrt{\frac{(P1 - u)^2 + (P2 - u)^2 + (P3 - u)^2 + (P4 - u)^2 + \ldots}{9}}\right) \quad \text{(Eq4.4)}$$

Table 2 Calculated values of the parameters (copper plate)

Date	Power Density (x 10^{-6} W/cm^2)	Total Coulombs Transferred (C)	Mean Power Output	Standard Deviation
18.11.2024	0.29	67.39		
19.11.2024	0.45	83.81		
20.11.2024	0.71	105.41		
21.11.2024	0.77	108.86	0.084mW	0.07
22.11.2024	0.89	118.37		
23.11.2024	0.09	37.15		
24.11.2024	0	6.91		
25.11.2024	0	0		

4.1.3 Carbon Graphite Plate Raw Data Revise

Table 2 below provides a summary of the raw data for voltage, current, and calculated power output. The table presents a straightforward account of daily measurements collected from November 23, 2024, to December 12, 2024. The values illustrate the MFC's performance at room temperature, highlighting the trends observed over time.

Table 3 Voltage, Current, and Power Output Over Time (Carbon Graphite Plate)

Day	Date	Voltage (Voc)	Voltage (mV)	Current (mA)	Power (mW)	Time
1	23/11/2024	30.02mV	1.15mV	0.3mA	0.009mW	6.30pm
2	24/11/2024	41.66mV	1.67mV	0.42mA	0.0175mW	6.30pm
3	25/11/2024	58.32mV	1.96mV	0.58mA	0.0338mW	6.30pm
4	26/11/2024	61.8mV	2.20mV	0.62mA	0.0383mW	6.30pm
5	27/11/2024	63.5mV	2.39mV	0.64mA	0.041mW	6.30pm
6	28/11/2024	68.5mV	2.58mV	0.69mA	0.0473mW	6.30pm
7	29/11/2024	76.7mV	2.79mV	0.78mA	0.0598mW	6.30pm
8	30/11/2024	79.9mV	3.90mV	0.80mA	0.0639mW	6.30pm
9	1/12/2024	75.8mV	2.63mV	0.76mA	0.0576mW	6.30pm
10	2/12/2024	64.1mV	2.45mV	0.64mA	0.0410mW	6.30pm
11	3/12/2024	79.4mV	3.95mV	0.79mA	0.0627mW	6.30pm
12	4/12/2024	87mV	2.85mV	0.87mA	0.0757mW	6.30pm
13	5/12/2024	83.2mV	2.79mV	0.83mA	0.0691mW	6.30pm
14	6/12/2024	92.3mV	3.17mV	0.93mA	0.0858mW	6.30pm
15	7/12/2024	86.1mV	3.07mV	0.86mA	0.0740mW	6.30pm
16	8/12/2024	83.2mV	2.75mV	0.83mA	0.0691mW	6.30pm
17	9/12/2024	64.1mV	2.3mV	0.64mA	0.0410mW	6.30pm
18	10/12/2024	42.61mV	1.75mV	0.43mA	0.0183mW	6.30pm
19	11/112/2024	22.55mV	0.9mV	0.23mA	0.0052mW	6.30pm
20	12/12/2024	0mV	0mV	0mA	0mW	6.30pm

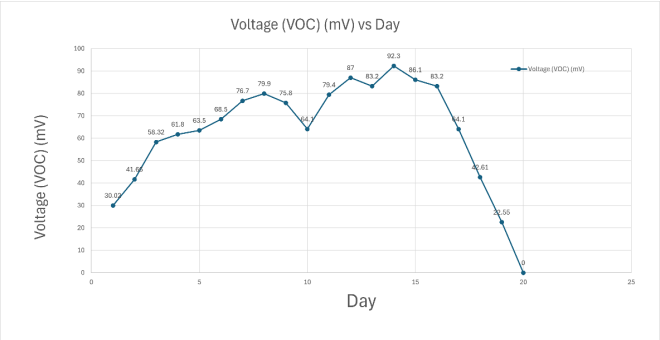


Figure 16 Open Circuit Voltage (VOC) vs Day

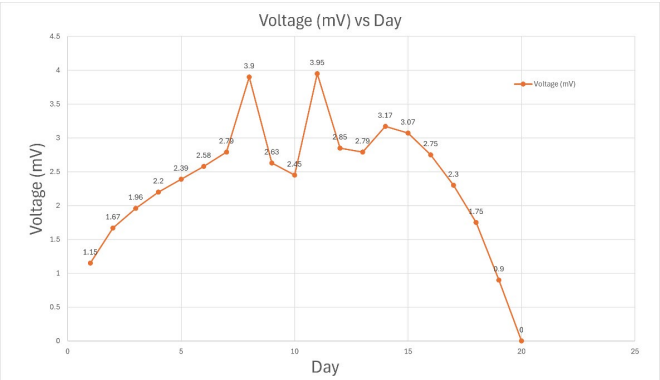


Figure 17 Voltage (mV) vs Day

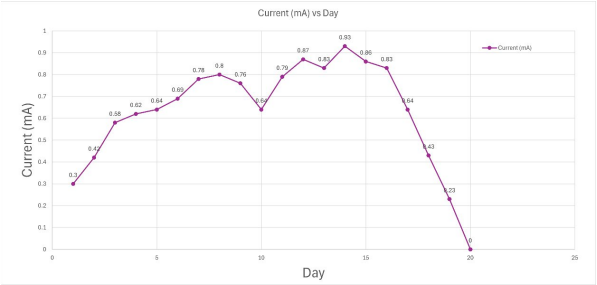


Figure 18 Current (mA) vs Day

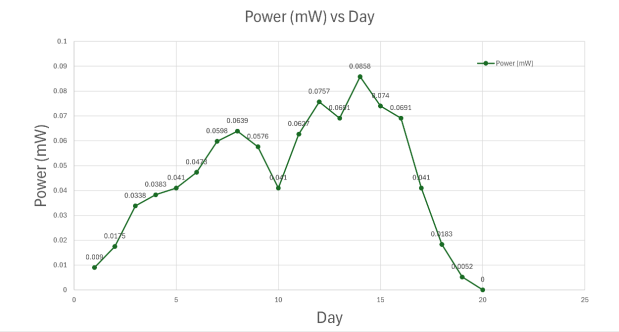


Figure 19 Power (mW) vs Day

4.1.4 Data Analysis (Carbon Graphite Plate)

The gathered data has been meticulously examined to assess the efficacy of the MFC using rice slurry as the substrate and copper electrodes. Essential performance measures, including power density, total coulombs transmitted, and statistical analyses for mean power output and standard deviation, were computed to assess the system's efficiency and performance trends over time.

The power density is calculated using Equation 4.1, which entails dividing the power output by the electrode surface area of 210 cm^2 used in this investigation. This statistic provides insight into the energy generating capacity relative to the electrode's dimensions. The total coulombs transmitted, reflecting the overall electron movement over time, is calculated using Equation 4.2, which incorporates the current (I) and the time length (t). Statistical analyses, including mean power output and standard deviation, are derived from the data to reveal patterns and variability in performance (Equations 4.3 and 4.4). The calculated parameters for the copper plate are summarized in Table 4.

Table 4 Calculated values of the parameters (carbon graphite plate)

Date	Power Density (x 10^{-6} W/cm^2)	Total Coulombs Transferred (C)	Mean Power Output	Standard Deviation
23/11/2024	0.04	25.92		
24/11/2024	0.08	36.39		
25/11/2024	0.16	50.11		
26/11/2024	0.18	53.57		
27/11/2024	0.2	55.3		
28/11/2024	0.23	59.62		
29/11/2024	0.28	67.4		
30/11/2024	0.30	69.12		
1/12/2024	0.27	65.66		
2/12/2024	0.2	55.3	0.05mW	0.05
3/12/2024	0.3	68.3		
4/12/2024	0.36	75.2		
5/12/2024	0.33	71.7		
6/12/2024	0.41	80.4		
7/12/2024	0.35	74.3		
8/12/2024	0.33	71.7		
9/12/2024	0.2	55.3		
10/12/2024	0.09	37.2		
11/112/2024	0.02	19.9		
12/12/2024	0	0		

4.1.5 Observation and Discussion

The comparison between copper and graphite electrodes demonstrated that graphite consistently produced higher voltage and power output throughout the experiment. This result can be attributed to the superior biocompatibility, stability, and electrical conductivity of carbon-based materials compared to metals. Graphite provides a larger effective surface area for microbial attachment and is resistant to corrosion, allowing stable biofilm growth and efficient electron transfer. In contrast, copper electrodes are prone to corrosion and ion leaching, which inhibit microbial activity and reduce long-term performance. Similar findings were reported by Logan et al. [20], who emphasized the advantages of carbon-based electrodes over metal electrodes, and by Zhang et al. [21], who observed that electrode corrosion limits efficiency and stability in MFC systems.

4.2. Temperature Variations

4.2.1 Room temperature Raw Data Revise

The raw data for voltage, current, and calculated power output is summarized in Table 5 below. The table provides a clear record of daily measurements taken from November 23, 2024, to December 12, 2024. These values represent the performance of the MFC under room temperature conditions, showcasing the trends over time. The variations in open-circuit voltage (VOC), voltage, current, and power over the experimental period are shown in Figures 20, 21, 22, and 23, respectively.

Table 5 Voltage, Current, and Power Output Over Time (Room temperature)

Day	Date	Voltage (Voc)	Voltage (mV)	Current (mA)	Power (mW)	Time
1	23/11/2024	30.02mV	1.15mV	0.3mA	0.009mW	6.30pm
2	24/11/2024	41.66mV	1.67mV	0.42mA	0.0175mW	6.30pm
3	25/11/2024	58.32mV	1.96mV	0.58mA	0.0338mW	6.30pm
4	26/11/2024	61.8mV	2.20mV	0.62mA	0.0383mW	6.30pm
5	27/11/2024	63.5mV	2.39mV	0.64mA	0.041mW	6.30pm
6	28/11/2024	68.5mV	2.58mV	0.69mA	0.0473mW	6.30pm
7	29/11/2024	76.7mV	2.79mV	0.78mA	0.0598mW	6.30pm
8	30/11/2024	79.9mV	3.90mV	0.80mA	0.0639mW	6.30pm
9	1/12/2024	75.8mV	2.63mV	0.76mA	0.0576mW	6.30pm
10	2/12/2024	64.1mV	2.45mV	0.64mA	0.0410mW	6.30pm
11	3/12/2024	79.4mV	3.95mV	0.79mA	0.0627mW	6.30pm
12	4/12/2024	87mV	2.85mV	0.87mA	0.0757mW	6.30pm
13	5/12/2024	83.2mV	2.79mV	0.83mA	0.0691mW	6.30pm
14	6/12/2024	92.3mV	3.17mV	0.93mA	0.0858mW	6.30pm
15	7/12/2024	86.1mV	3.07mV	0.86mA	0.0740mW	6.30pm
16	8/12/2024	83.2mV	2.75mV	0.83mA	0.0691mW	6.30pm
17	9/12/2024	64.1mV	2.3mV	0.64mA	0.0410mW	6.30pm
18	10/12/2024	42.61mV	1.75mV	0.43mA	0.0183mW	6.30pm
19	11/112/2024	22.55mV	0.9mV	0.23mA	0.0052mW	6.30pm
20	12/12/2024	0mV	0mV	0mA	0mW	6.30pm

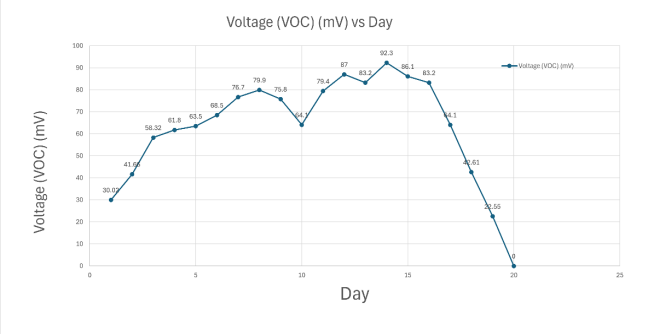


Figure 20 Open Circuit Voltage (VOC) vs Day

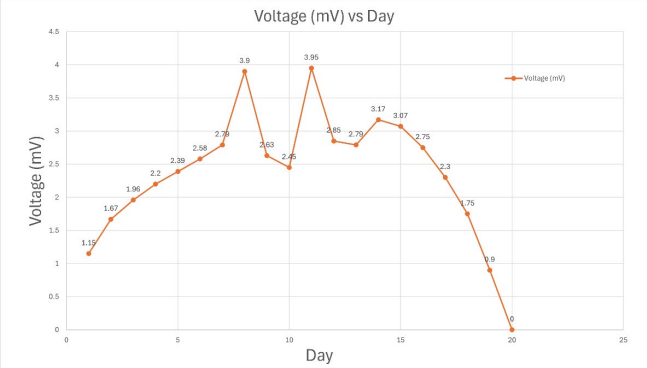


Figure 21 Voltage (mV) vs Day

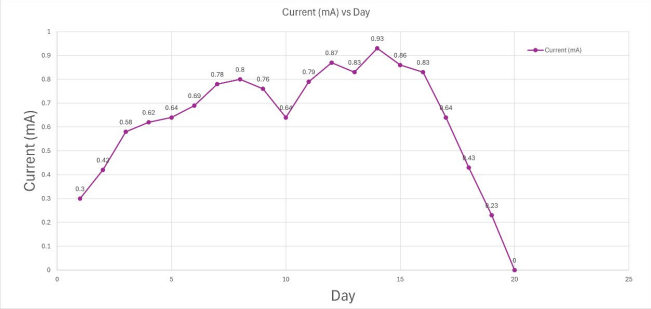


Figure 22 Current (mA) vs Day

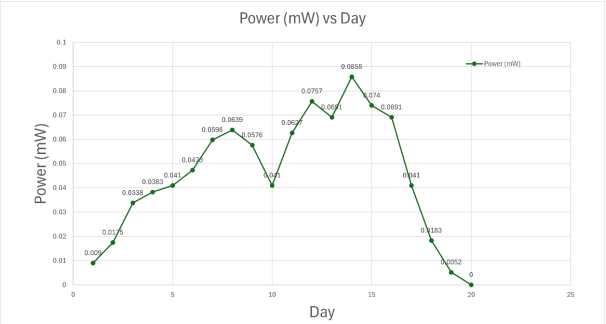


Figure 23 Power (mW) vs Day

4.2.2 Data Analysis (Room Temperature)

The gathered data has been meticulously examined to assess the efficacy of the MFC using rice slurry as the substrate and copper electrodes. Essential performance measures, including power density, total coulombs transmitted, and statistical analyses for mean power output and standard deviation, were computed to assess the system's efficiency and performance trends over time.

The power density is calculated using Equation 4.1, which entails dividing the power output by the electrode surface area of 210 cm^2 used in this investigation. This statistic provides insight into the energy generating capacity relative to the electrode's dimensions. The total coulombs transmitted, reflecting the overall electron movement over time, is calculated using Equation 4.2, which incorporates the current (I) and the time length (t). Statistical analyses, including mean power output and standard deviation, are derived from the data to reveal patterns and variability in performance (Equations 4.3 and 4.4). The calculated parameters for the copper plate are summarized in Table 6.

Table 6 Calculated values of the parameters (carbon graphite plate)

Date	Power Density (x 10^{-6} W/cm^2)	Total Coulombs Transferred (C)	Mean Power Output	Standard Deviation
23/11/2024	0.04	25.92		
24/11/2024	0.08	36.39		
25/11/2024	0.16	50.11		
26/11/2024	0.18	53.57		
27/11/2024	0.2	55.3		
28/11/2024	0.23	59.62		
29/11/2024	0.28	67.4		
30/11/2024	0.30	69.12		
1/12/2024	0.27	65.66		
2/12/2024	0.2	55.3	0.05mW	0.05
3/12/2024	0.3	68.3		
4/12/2024	0.36	75.2		
5/12/2024	0.33	71.7		
6/12/2024	0.41	80.4		
7/12/2024	0.35	74.3		
8/12/2024	0.33	71.7		
9/12/2024	0.2	55.3		
10/12/2024	0.09	37.2		
11/112/2024	0.02	19.9		
12/12/2024	0	0		

4.2.3 Non-Room Temperature Raw Data Revise

The raw data for voltage, current, and calculated power output is summarized in Table 7 below. The table provides a clear record of daily measurements taken from November 28, 2024, to December 6, 2024. These values represent the performance of the MFC under room temperature conditions, showcasing the trends over time. The raw data for voltage, current, and calculated power output is summarized in Table 7 below. The table provides a clear record of daily measurements taken from November 28, 2024, to December 6, 2024. These values represent the performance of the MFC under room temperature conditions, showcasing the trends over time. The variations in open-circuit voltage (VOC), voltage, current, and power over the experimental period are shown in Figures 24, 25, 26, and 27, respectively.

Table 7 Voltage, Current, and Power Output Over Time (Non-Room temperature)

Day	Date	Voltage (Voc)	Voltage (mV)	Current (mA)	Power (mW)	Time
1	28/11/2024	31.17mV	0.86mV	0.31mA	0.009mW	6.45pm
2	29/11/2024	65.7mV	1.24mV	0.66mA	0.0434mW	6.45pm
3	30/11/2024	78.8mV	2.9mV	0.8mA	0.0630mW	6.45pm
4	1/12/2024	187.7mV	7.13mV	1.9mA	0.3566mW	6.45pm
5	2/12/2024	78.8mV	2.90mV	0.8mA	0.063mW	6.45pm
6	3/12/2024	297.9mV	6.9mV	3mA	0.8937mW	6.45pm
7	4/12/2024	206mV	3.2mV	2.1mA	0.4326mW	6.45pm
8	5/12/2024	79.9mV	2.45mV	0.8mA	0.0639mW	6.45pm
9	6/12/2024	0mV	0mV	0mA	0mW	6.45pm

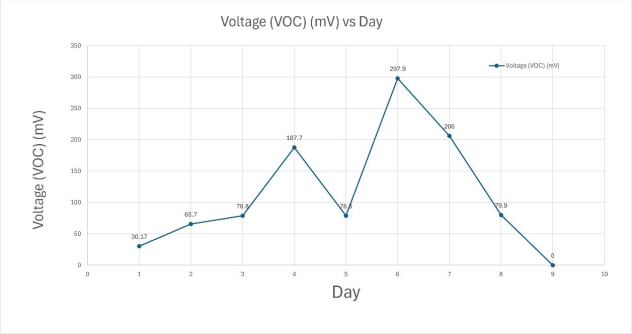


Figure 24 Voltage (V)C) vs Day

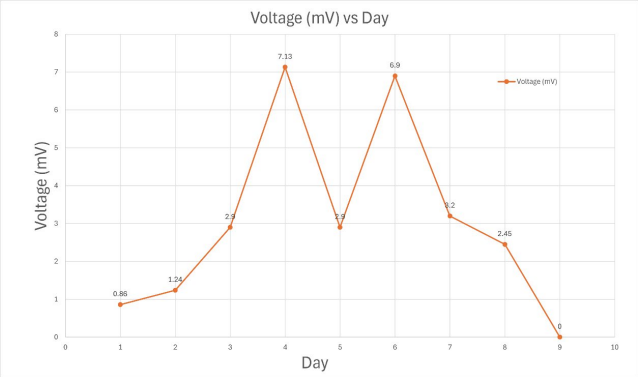


Figure 25 Voltage (mV) vs Day

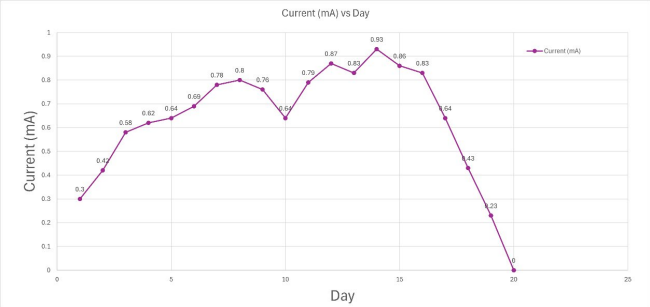


Figure 26 Current vs Day

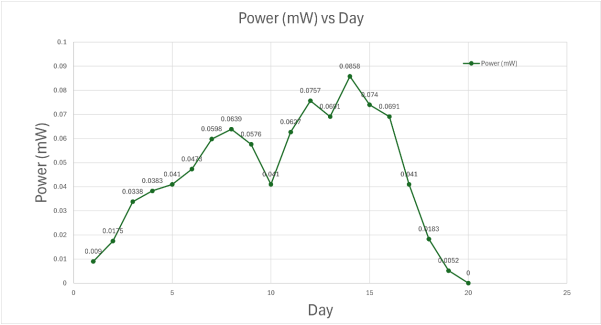


Figure 27 Power (mW) vs Day

4.2.4 Data Analysis (Non-Room Temperature)

The data has been analysed. The performance of the MFC was evaluated. Rice slurry was used as the substrate. Copper electrodes were employed. Analysed critical performance indicators. These include power density, total coulombs transmitted, and statistical evaluations. Then focused on average power output and standard deviation. This helped us gain insights into the system's efficiency and performance trends over time.

Calculate the power density with Equation 4.1. It divides the power output by the electrode surface area. The area is 210 cm^2 for this investigation. This statistic shows the energy generating capacity. It relates to the electrode's dimensions. The total charge transferred shows the cumulative electron movement over time. It is calculated using Equation 4.2. This equation includes the current (I) and the time interval (t). Then derive statistical analyses from the data. This includes mean power output and standard deviation. These analyses reveal patterns and variability in performance. See Equations 4.3 and 4.4 for details.) The calculated parameters for the copper plate are summarized in Table 8."

Table 8 Calculated values of the parameters (Non-room temperature)

Date	Power Density (x 10^{-6} W/cm^2)	Total Coulombs Transferred (C)	Mean Power Output	Standard Deviation
28/11/2024	0.04	26.8		
29/11/2024	0.21	57		
30/11/2024	0.3	69		
1/12/2024	1.7	165		
2/12/2024	0.3	69	0.21mW	0.282
3/12/2024	4.3	259		
4/12/2024	2.1	181.5		
5/12/2024	0.3	69		
6/12/2024	0	0		

4.2.5 Observation and Discussion

The MFC maintained under direct sunlight generated higher voltage and power density compared to the one operated at room temperature. This improvement can be explained by the increased metabolic activity of electrogenic bacteria at elevated temperatures, which accelerates substrate degradation and electron release. The enhanced microbial growth rate under warmer conditions improves electron transfer rates to the anode and increases current production. This finding is consistent with Pant et al. [25], who reported that MFCs achieve higher performance when operated within the 20–45 °C range, and with Zhang et al. [21], who also confirmed that elevated temperatures promote microbial metabolism and consequently improve bioelectrochemical performance.

4.3 Chemical Additives

4.3.1 Raw Data Revise (Influence Of Chemicals)

The raw data for voltage, current, and calculated power output is summarized in Table 9 below. The table provides a clear record of daily measurements taken from December 10, 2024, to December 24, 2024. These values represent the performance of the MFC under room temperature conditions, showcasing the trends over time. The variations in open-circuit voltage (VOC), voltage, current, and power over the experimental period are shown in Figures 28, 29, 30, and 31, respectively.

Table 9 Voltage, Current, and Power Output Over Time (Influence of chemical)

Day	Date	Voltage (Voc)	Voltage (mV)	Current (mA)	Power (mW)	Time
1	10/12/2024	101.4mV	40.81mV	1mA	0.1014mW	6.30pm
2	11/12/2024	161.1mV	18.4mV	1.6mA	0.2578mW	6.30pm
3	12/12/2024	193.2mV	22.7mV	1.9mA	0.3671mW	6.30pm
4	13/12/2024	209.7mV	24.37mV	2.1mA	0.4404mW	6.30pm
5	14/12/2024	203.2mV	26.08mV	2mA	0.4064mW	6.30pm
6	15/12/2024	234.2mV	35.2mV	2.3mA	0.5387mW	6.30pm
7	16/12/2024	232.3mV	30.13mV	2.3mA	0.5343mW	6.30pm
8	17/12/2024	262.3mV	38.2mV	2.6mA	0.6820mW	6.30pm
9	18/12/2024	289.2mV	39mV	2.9mA	0.8388mW	6.30pm
10	19/12/2024	283.5mV	38.9mV	2.8mA	0.7938mW	6.30pm
11	20/12/2024	189.4mV	23.97mV	1.9mA	0.3599mW	6.30pm
12	21/12/2024	207.1mV	27.50mV	2.1mA	0.4349mW	6.30pm
13	22/12/2024	186.9mV	21.2mV	1.9mA	0.3551mW	6.30pm
14	23/12/2024	180.1mV	18.9mV	1.8mA	0.3242mW	6.30pm
15	24/12/2024	168.4mV	15.3mV	1.7mA	0.2863mW	6.30pm

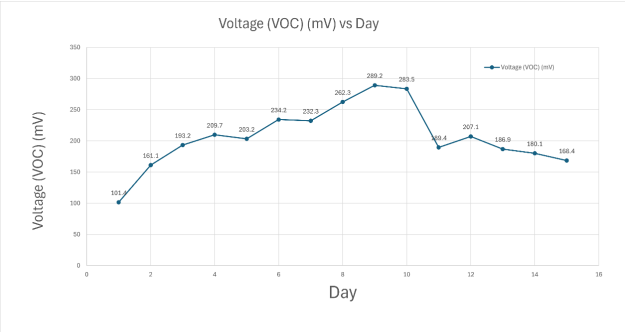


Figure 28 7 Voltage (VOC) (mV) vs Day

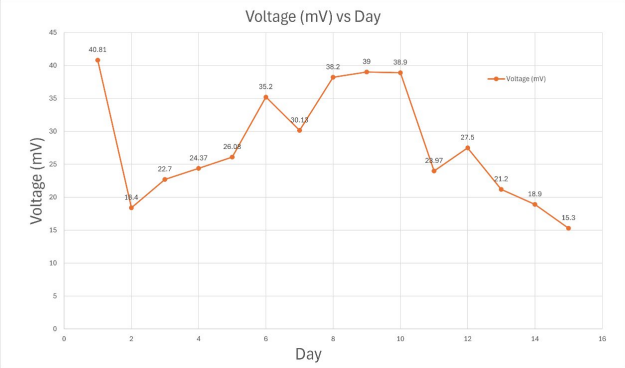


Figure 29 Voltage (mV) vs Day

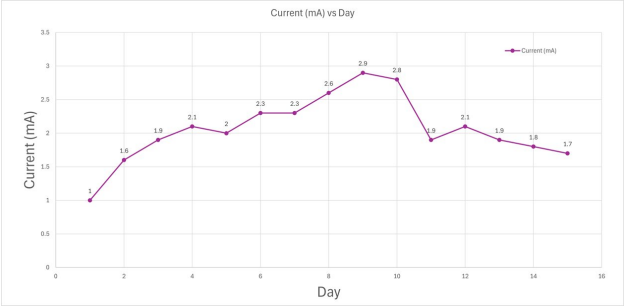


Figure 30 Current vs Day

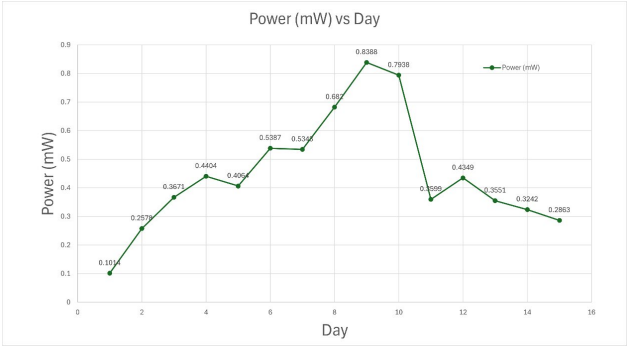


Figure 31 Power (mV) vs Day

4.3.2 Data Analysis (Influence of Chemicals)

The data has been analysed. The goal was to evaluate the efficacy of the microbial fuel cell. Rice slurry was used as the substrate. Copper electrodes were employed. The study analysed critical performance indicators. These include power density, total coulombs transmitted, and statistical evaluations. Looked at average power output and standard deviation. This helped us gain insights into the system's efficiency and performance trends over time.

Then calculate the power density. By using Equation 4.1. It divides the power output. The electrode surface area is 210 cm^2. This area is used in this investigation. This statistic shows the energy generating capacity. It relates to the electrode's dimensions. The total coulombs transmitted show the cumulative electron transfer over time. This is calculated using Equation 4.2. It considers the current (I) and the time length (t). Statistical analyses show mean power output and standard deviation. These are derived from the data. They reveal patterns and variability in performance. See Equations 4.3 and 4.4.) The calculated parameters for the influence of chemicals are summarized in Table 10

Table 10 Calculated values of the parameters (Influence of chemicals)

Date	Power Density (x 10^{-6} W/cm^2)	Total Coulombs Transferred (C)	Mean Power Output	Standard Deviation
10/12/2024	0.48	86.4		
11/12/2024	1.23	138.24		
12/12/2024	1.75	164.16		
13/12/2024	2.1	181.44		
14/12/2024	1.94	172.8		
15/12/2024	2.57	198.72		
16/12/2024	2.54	198.72		
17/12/2024	3.25	224.64	0.45mW	0.33
18/12/2024	3.99	250.56		
19/12/2024	3.78	241.92		
20/12/2024	1.71	164.16		
21/12/2024	2.07	181.44		
22/12/2024	1.69	164.16		
23/12/2024	1.54	155.52		
24/12/2024	1.36	146.88		

4.3.3 Observation and Discussion

The addition of potassium ferricyanide to the anode and potassium permanganate to the cathode significantly improved MFC performance compared to the control setup. Ferricyanide acts as an electron mediator, facilitating rapid electron transfer from the microbial community to the anode, while permanganate serves as a strong electron acceptor, enhancing the redox potential of the cathode. These combined effects reduced internal resistance and increased voltage and power

output. This outcome agrees with Rabaey and Verstraete [20], who highlighted the effectiveness of electron mediators in enhancing MFC efficiency, and with Liu et al. [26], who demonstrated that permanganate addition in the cathode improves electron acceptor capacity and overall MFC performance.

5.0 DISCUSSION

This research investigated MFC power production using rice slurry as a substrate and assessed temperature, chemical additives, and electrode materials. A multimeter was used for voltage measurements because of the INA219 sensor's limitations with low voltages. The research advocates for the future use of devices such as boost converters to enhance measurements.

Elevated temperatures enhanced microbial activity and electricity generation, while gas leaks presented safety hazards. Chemical additions such as Potassium Ferricyanide and Potassium Permanganate enhanced electron transport and voltage stability, making them advantageous in laboratory configurations. Nonetheless, scalability and environmental effects need more evaluation.

Graphite electrodes exhibited superior performance compared to copper, demonstrating enhanced durability and stability for microbial adhesion and electron transfer. The research found that chemical mediators and carbon-based electrodes in a regulated environment are effective for continuous energy generation; nonetheless, enhancements in reactor design are crucial for enduring efficiency and safety.

6.0 CONCLUSION

The research investigated dual-chamber microbial fuel cells using rice slurry as a substrate to produce sustainable energy via the conversion of organic waste into power. Critical determinants affecting performance were electrode materials, thermal conditions, and chemical additives. Carbon graphite electrodes, with a surface area of 210 cm^2, surpassed copper in terms of stability and power production. On Day 5, the peak voltage was 137 mV, the current was 1.37 mA, and the power measured 0.1877 mW; further performance deterioration occurred owing to substrate depletion, underscoring the need for substrate replacement.

Temperature regulation substantially influenced MFC performance. Configurations in direct sunlight produced more energy owing to heightened microbial activity. Nevertheless, elevated temperatures may disrupt microbial populations, requiring careful temperature regulation.

Chemical additions, such Potassium Ferricyanide at the anode and Potassium Permanganate at the cathode, enhanced voltage, current, and power generation by facilitating electron transport and cathodic reactions. These additions improved system efficiency relative to configurations devoid of chemicals.

The research underscores the need of enhancing electrode materials, regulating temperature, and using chemical additives to augment MFC performance. It recommends further investigations into new materials such as carbon nanotubes and graphene-coated electrodes to augment conductivity, decrease expenses, and boost durability. Stabilising temperature and investigating different chemical additions may enhance performance.

Prolonged investigations into substrate replenishment, microbial adaptability, and scalability are essential for enhancing MFC systems for practical applications in renewable energy and waste management. Microbial Fuel Cells (MFCs) has the capacity to serve as a cost-efficient, sustainable method for diminishing organic waste and producing renewable energy.

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Conflicts Of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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