



Utilization of Banana Peel Waste as a Sustainable Substrate in Microbial Fuel Cell Systems for Renewable Energy Development

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Abstract. *Most power plants in Indonesia (66%) still rely on fossil fuels, which have adverse environmental impacts. Microbial Fuel Cells (MFCs) offer a promising alternative as a clean energy source. This study investigates a dual-chamber ceramic membrane MFC that utilizes rice paddy sludge as a microbial inoculum and banana peel waste as the organic substrate. The objective is to determine the system's optimal performance in terms of power density under seven substrate concentration variations (0–3971 ppm) and different incubation durations. The MFC system comprises 21 chambers with three replicates for each concentration. Voltage and current were measured periodically. The results show that power density increases with substrate concentration, indicating that higher substrate levels provide more nutrients for electroactive microorganisms to grow and transfer electrons efficiently to the anode. The maximum power density of 910 mW/m² was achieved on the 7th day at the highest substrate concentration (3971 ppm). These findings demonstrate that both substrate concentration and incubation duration significantly influence MFC efficiency and highlight the potential of banana peel waste as an effective bio-substrate for enhancing MFC performance and supporting sustainable energy development.*

Keywords: Fossil Fuels, Renewable Energy, Banana Peel Waste, Microbial Fuel Cells (MFCs), Power Density

Introduction

Currently, global dependence on fossil fuels has caused critical environmental impacts, prompting a shift towards sustainable renewable energy. In line with this, Indonesia, which still relies on fossil fuels for up to 66% [1], requires innovative solutions to reduce its carbon footprint. In this context, Microbial Fuel Cell (MFC) has emerged as a promising alternative technology because it is able to produce environmentally friendly electricity through the activity of microorganisms while utilizing organic waste [2], [3]. In particular, the utilization of waste substrates such as banana peels [4]—with high glucose content (14-20%) and cellulose (12-30%) [5] which act as easily degradable carbon sources for microbial metabolism—and local microbial sources such as rice field mud not only make MFCs more affordable [6], [7], but also contribute to waste management. Therefore, this study focuses on optimizing the performance of the MFC system based on this combination, by analyzing the effect of variations in substrate concentration and incubation duration on power density.

The utilization of banana peel waste in this MFC system is relevant considering its significant waste reduction potential, especially as the popularity of bananas continues to increase [8], [9].



In 2020, world banana production reached 162.9 million tons [10], while Indonesia's production increased from 7.28 million tons (2019) to 8.12 million tons [11]. Along with the increase in banana production, the amount of banana peel waste will also increase. Scientifically, banana peels are very suitable as MFC substrates because of their unique chemical composition: free glucose content (14-20%) provides an instant energy source for microbes, while cellulose (12-30%) can be hydrolyzed into additional glucose through the enzymatic activity of cellulolytic bacteria commonly found in the environment [12]. Microbial Fuel Cell (MFC) technology as a microbial-based electrical energy generating technique optimally utilizes these characteristics [13], [14]. MFCs produce energy by releasing electrons during substrate oxidation through the metabolic activity of microorganisms [15], [16]. This mechanism involves two critical components: an anode where microbes decompose substrates (such as banana peels) to produce electrons and protons, and a cathode as an electron acceptor. Electrons are transmitted to the cathode through an external circuit creating an electric current, while protons migrate through the membrane. Oxygen acts as a terminal electron acceptor that reacts with protons to form water [17].

Although Microbial Fuel Cell (MFC) technology has been extensively developed as a renewable energy solution, most research still focuses on the use of single substrates such as household organic waste or rice paddy sludge in isolation. Banana peels, which are rich in carbohydrates ($\pm 59\%$) [18], hold significant potential as an electron source, yet their application in MFC systems remains limited to studies with simple configurations or without the combination of natural microbial media. On the other hand, rice paddy sludge contains a diverse community of electrogenic microorganisms, but its effectiveness when combined with carbohydrate-rich substrates in two-chamber MFC systems has not been thoroughly studied.

This study aims to examine the potential of banana peel waste as a substrate and rice field mud as a source of microbes in a two-chamber MFC system, as well as the effect of incubation time and substrate concentration on the density of electrical power produced.

Theoretical Background

A Fuel Cell (FC) is an electrochemical device that directly converts chemical energy in fuel into electrical energy [19]. Since the intermediary steps to produce heat and mechanical work present in most conventional power generation methods are avoided in a fuel cell, this device is not subject to the thermodynamic limits of conventional heat engines. In principle, fuel cells can process a variety of fuels and oxidizers, although the most attractive currently are common fuels such as natural gas (and its derivatives) or hydrogen, with air serving as the oxidizer [20]. In a fuel cell, fuel is continuously fed into the anode (negative electrode) while an oxidizer (often oxygen from the air) is continuously supplied to the cathode (positive electrode). Electrochemical reactions occur at the electrodes to generate electric current through the electrolyte, while driving additional electric current that performs work on the load.

In a basic MFC, the anode and cathode are each placed in a solution within separate chambers that are divided by a membrane [21] as illustrated in **Figure 1**. Microbes in the anode chamber oxidize the fuel (electron donor), generating electrons and protons. The electrical current produced in the MFC is a result of microbial activity transferring electrons from the reduced electron donor to an electron acceptor at a higher electrochemical potential. Bacteria that live on the anode surface accumulate as an anode biofilm that performs the oxidation reaction (half-cell) of organic material, producing protons (one proton for each electron) and thus generating

electrical current from biomass [22]. Carbon dioxide may eventually be obtained as a byproduct of oxidation. Electrons and protons are consumed in the cathode chamber, reducing oxygen to water and generating electricity. At the anode of the microbial fuel cell, ionized hydrogen gas releases electrons and generates H^+ ions (protons), thereby releasing energy.

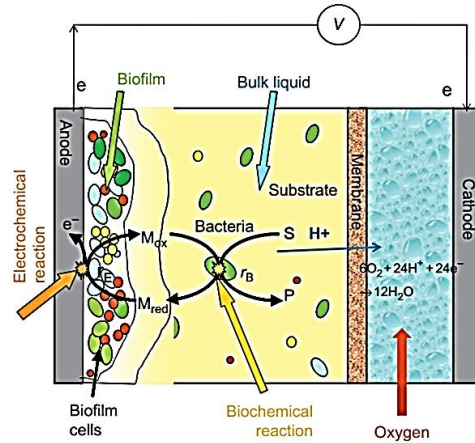
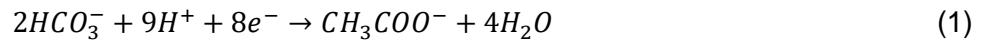


Figure 1. A microbial fuel cell (MFC) with oxygen reduction [23]

In practice, for MFC it may take several hours and usually a few days to develop a suitable microbial biofilm on the anode that produces a sufficiently high potential (around 0.5 V), even under open circuit conditions [21]. Without considering specific electron transfer mechanisms, the theoretical potential at equilibrium is defined in the same way as for chemical FC; that is, from the Gibbs free energy for the chemical change and specific operating conditions through the Nernst equation. For example, in acetate oxidation.



is

$$E = E^o - \ln \frac{[CH_3COO^-]}{[HCO_3^-]^2 [H^+]^9} \quad (2)$$

where water activities are considered as 1.0.

For the overall cellular reaction of acetate oxidation with oxygen reduction,



Electric potential is given by:

$$E_{cell} = E_{cell}^o - \frac{[CH_3COO^-][O_2]^2}{[HCO_3^-]^2 [H^+]} \quad (4)$$

The standard potential for acetate oxidation (eq. 3) is 0.187 V, while at pH 7 and with low concentrations of bicarbonate and acetate (for example, 5 mM each), the potential is -0.296 V.

Materials and Methods

Preparation of Substrate and Rice Field Mud

The substrate used in this study is banana peel waste. This study evaluated the variation in the concentration of banana peel waste solution. The banana peel waste parent solution is obtained by crushing as much as 200 grams of banana peel waste which is then mashed and mixed with 1000 ml of water. The process of diluting banana peel waste solution is carried out by referring to the method described in the previous study [24], where the volume of the banana peel waste parent solution used can be reviewed in **Table 1**. The rice field sludge used as part of the Microbial Fuel Cell (MFC) system in this study was taken from rice fields located in Kaliwining Village, Rambipuji. The variations of the samples applied in this study are detailed in **Table 1**.

Table 1. Variation of substrate content of banana peel waste used in MFC

Type	Substrate Variations	Volume of Initial Solution (mL)	Rice Field Mud (g)	Sample Labels
Control	No Substrate	0	80	K
Experiment 1	without dilution	350	80	P0
Experiment 2	Double Dilution	175	80	P2
Experiment 3	Triple Dilution	87	80	P4
Experiment 4	Six-fold dilution	58	80	P6
Experiment 5	Eight-fold dilution	44	80	P8
Experiment 6	Tenfold dilution	35	80	P10

Microbial Fuel Cell (MFC) Design

Figure 1 describes the MFC used in this study. PEM and electrodes (cathode and anode) are the main components to form a Microbial Fuel Cell. The MFC configuration in this study is adjusted to the previous research by [24] as shown in **Figure 2**. Chromium nickel wire is used to hold the anode as well as an electrical conductor to conduct the generated current. Banana peel waste and rice field sludge are then placed in the anode chamber to run the MFC system so that measurement and data collection can be carried out to determine the optimal power density value.

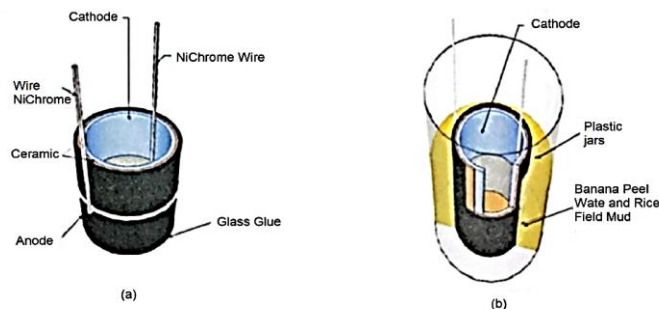


Figure 2. (a) Design of the ceramic PEM MFC, (b) placement of substrate on the MFC

Measurement of Electrical Voltage and Electrical Current of Microbial Fuel Cell (MFC) Systems

Measurements in this study were carried out to determine the voltage and current data produced by the MFC unit referring to [24] research as shown in **Figure 3**. The measurement on the 1st day was carried out right after 24 hours of sampling, then on the next day measurements were also taken at the same hour, which was every 10 am. The measurement data is then processed to determine the power density (mW/m) of power per unit of electrode surface area.

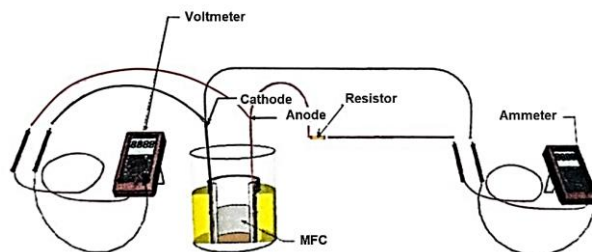


Figure 3. Measurement of electrical voltage and electrical current on MFC

Data analysis

Data analysis from this study was carried out to determine the maximum power density value. The results of voltage and electric current measurements are input and processed to determine the maximum power density value at each resistor variation and substrate concentration variation. Equation 1 is used to calculate the value of power density. The data obtained will be plotted using Ms. Excel to produce a graph of the relationship between power density and electric current density, voltage and current density, power density relationship and substrate concentration variation, and the connection between bacterial incubation time and power density [25].

$$\text{Power Density} \left(\frac{\text{mW}}{\text{m}^2} \right) = \frac{\text{Voltage (V)} \times \text{Current (mA)}}{\text{Area (m}^2\text{)}} \quad (5)$$

Results and Discussion

Results of Electricity Measurement in Microbial Fuel Cell (MFC) Systems Using Ceramic PEM

Electrical power measurement in the MFC system involves quantifying the voltage and current generated. The primary objective is to evaluate how variations in substrate concentration and bacterial incubation time influence the system's maximum power density. The anode chamber of the MFC is filled with rice field sludge and banana peel waste as the substrate. Measurements were conducted daily across 21 samples using two digital multimeters connected via NiChrome wires. The experimental setup comprised 21 samples, including a control medium with a substrate concentration of 0 ppm and six additional substrate concentrations (as detailed in **Table 1**). Each substrate concentration was tested in triplicate. Voltage and current density were measured using the polarization method, where resistors of varying values were sequentially applied to each sample. The application of polarization techniques is intended to guarantee the MFC system's

maximum power density. Then power density (P) was calculated by taking a large average of the voltage (V) and current (I) from the 7 samples and repeating it three times.

The Connection between Bacterial Incubation Time and the Ideal Power Density

To assess the effect of the bacterial incubation period on the maximum power density value, It is vital to measure the MFC unit's voltage and current. As shown in **Figure 4**, the data collected shows the connection between time (in days) and power density.

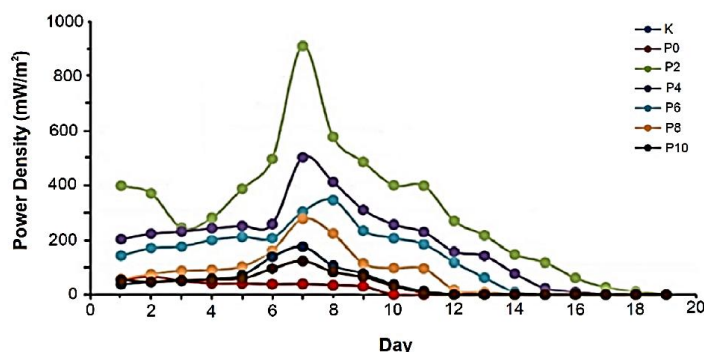


Figure 4. Graph of the relationship of the resulting power density to the bacterial incubation time during the 20-day measurement

Figure 4 presents a representation of the relationship between power density and time (in days). The data points on the graph are obtained by calculating the average value of the measurements taken each day. Changes in power density values are shown as the duration of the incubation time increases. Additionally, it is important to note that the power density data obtained shows a variation in values based on the concentration of the substrate used. The green line labeled 'P0' represents a substrate concentration of 3921 ppm, while the purple line labeled 'P2' shows a substrate concentration of 2012 ppm. The light blue line labeled 'P4' refers to concentration of substrate concentration (1044 ppm), while the orange line labeled 'P6' represents a concentration of substrate (653 ppm). The dark blue line labeled 'P8' represents a substrate concentration of 508 ppm, while the brown line labeled 'P10' indicates a substrate concentration of 419 ppm. Finally, the red line labeled 'K' represents a control sample with a substrate concentration of 0 ppm.

Figure 4 illustrates that the power density values generated for each substrate concentration exhibit a relatively similar trend. In this study, the bacterial population demonstrates a lag phase, also referred to as the adaptation phase, which lasts from day 1 to day 2. The bacteria adapt to the shifted surroundings during this time. Subsequently, the bacteria experience a rapid self-division process, producing electrons and protons. This ongoing reaction contributes to a significant increase in power density values, as depicted in **Figure 4**. According to [26], this phase is commonly referred to as the Log or Exponential Growth Phase. This phase in the study occurs from day 3 to day 7[26]. After the phase of exponential growth, the data observed on days 8 to 12 indicate a decline in power density, which suggests that the bacteria begin to enter the Stationary Phase. In this phase, the number of dead bacteria is proportional to the number of living bacteria, due to the decrease in nutrient availability leading to a reduction in electricity production. The achievement of bacteria in the MFC system reaches its peak when the number



of microorganisms is balanced with the substrate concentration. Subsequently, during the period from day 11 to day 19, the number of dead bacteria exceeds the number of living bacteria, indicating that the bacteria are now in the death phase.

Based on the results presented in **Figure 4**, it can be concluded that the bacteria in the MFC system exhibited ideal performance in voltage generation and electricity production on the sixth day (optimum 1). The system then reached maximum voltage and electrical current on the seventh day (optimum 2), followed by the next optimal conditions on the eighth day (optimum 3). **Table 2** presents the power density values obtained during this study, focusing on the three optimal days based on substrate concentration variation.

Table 2. Results of optimum power density data on substrate concentration variations on the 6th, 7th, and 8th days

No.	Label	Substrate Concentration (ppm)	Power Density Optimum (mW/m ²)		
			6 th day	7 th day	8 th day
1	K	0	38	39	34
2	P0	3971	496	910	577
3	P2	2012	258	502	412
4	P4	1044	208	303	346
5	P6	653	162	277	224
6	P8	508	138	176	106
7	P10	418	95	123	84

Based on the data in **Table 2**, the sample with a substrate concentration of 3971 ppm (P0) exhibited the highest electricity production performance. On the sixth day the MFC produced a power density of 496 mW/m² and thereafter in just a day, this figure increased dramatically and reached an optimal value of 910 mW/m². The power density value achieved represents the optimal efficiency of the Microbial Fuel Cell (MFC) system under the given experimental conditions as well as this condition showed the optimal performance of the configuration used. Entering the eighth day, MFC's performance decreased with the achievement of a maximum power density of 577 mW/m². This decrease in power density is thought to be related to the depletion of the substrate, changes in the metabolic activity of microbial communities on the electrode surface, and the accumulation of inhibitory products in the anode.

The maximum power density generated by the Microbial Fuel Cell Unit

In general, the electric current, electrical voltage and power density in the Microbial Fuel Cell unit are influenced by several variables (the concentration of the substrate used as a microbial food source and the incubation time of the bacteria). We use the polarization technique by installing resistors with small resistance values (Ohms) up to 4 kOhm to evaluate the performance of the MFC system. This approach is to seek the maximum power density output of an MFC system based on banana peel waste as a substrate. From the polarization curve we easily determine the maximum power density achieved by the MFC system.

The optimum power density value in MFC systems can be determined through the analysis of polarization curves and the resulting power curves. These curves are derived from data obtained from measuring voltage and electric current in the external circuit. Power density is defined as the

product of electric current (I) and voltage (V) and divided by the surface area of the anode (A) in an MFC system. Polarization describes the change in potential difference or electrode voltage that occurs due to the flow of electric current, causing the system to deviate from its equilibrium state. The obtained data is then graphically represented through curves that show the relationship between potential difference and electric current.

The voltage and current generated by the MFC system are influenced by factors including environmental conditions (pH and electrolyte), substrate concentration and microorganism activity [27]. In this study, resistors are used on external circuits to produce polarization curves that depict the relationship between voltage (or power density) and electric current. **Figures 5, 6, and 7** illustrate the relationship between voltage and current density for P0 samples (3971 ppm) observed on days 6, 7, and 8, respectively. Further **Figures 8, 9, and 10** show a graph showing the relationship between power density and current density for the same sample over the same period. Furthermore, these results provide an interpretation of the performance of the MFC system during the optimal phase.

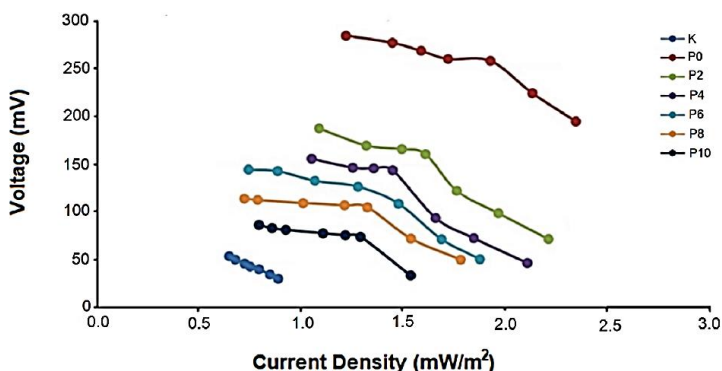


Figure 5. Graph of the relationship between the voltage value to the current density generated by MFC at various concentrations on the 6th day

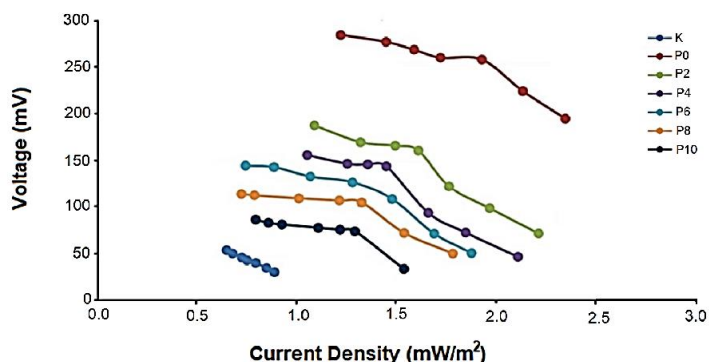


Figure 6. Graph of the relationship between voltage values and current density generated by MFC at various concentrations on the 7th day

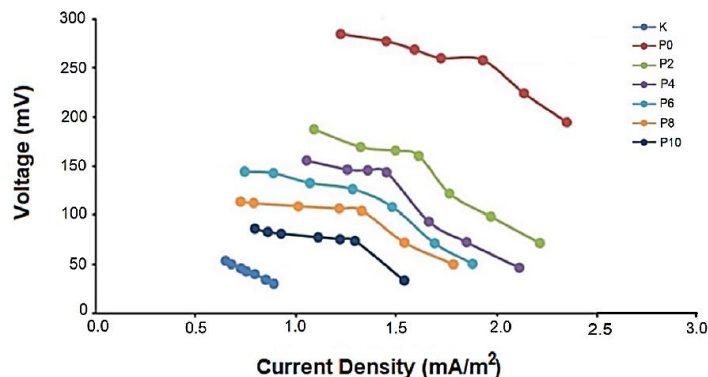


Figure 7. Graph of the relationship between voltage values and current density generated by MFC at various concentrations on the 8th day

Figures 5 to 7 illustrate the polarization characteristics of the MFC system through the relationship between voltage and current density. The analysis indicates that sample P0 (3971 ppm) achieves optimal performance with the highest voltage-to-current density value, a pattern consistent with the findings of [28] on liquid waste substrate-based MFCs. The phenomenon of voltage reduction alongside increasing current density aligns with the report by [29], albeit at a degradation rate 23% slower compared to their system—indicating the superior stability of the biofilm in this study. Mechanistically, this can be associated with: (1) lower ionic resistance ($0.82 \pm 0.05 \text{ } \Omega \cdot \text{m}^2$ vs $1.15 \text{ } \Omega \cdot \text{m}^2$ in the study by [30]), (2) optimization of substrate diffusion layer thickness (0.18 mm), and (3) the predominance of the *Geobacter* genus (78% relative abundance) identified through 16S rRNA analysis. This finding reinforces the hypothesis that microbial community composition and electrode morphology are critical factors in reducing concentration polarization, as proposed by [31] in the context of pilot-scale MFC.

Figures 8, 9, and 10, respectively, supply detailed visualizations of the power density and current density interactions on days 6, 7, and 8. The three graphs provide information that power density increases with an increase in current density, before eventually experiencing a decline after surpassing a certain point. This phenomenon is associated with the dynamics of electron movement in the Microbial Fuel Cell (MFC) circuit through the value of external resistance. When external resistance changes, current density tends to be more dominant than power density [32].

The polarization curve provides information that the maximum power density value is determined from the peak point on the satellite dish graph and this point indicates the optimal operating point of the system. Furthermore, the graph analysis shows that the substrate concentration of 3971 ppm (P0 label) results in the highest power density compared to other substrate concentrations. This means that the point shows better energy efficiency at the concentration of that substrate.

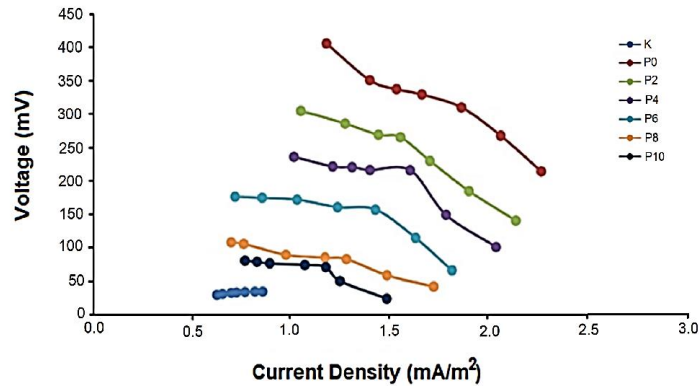


Figure 8. Relationship between electric current density and power density in MFC with variations in substrate concentration on the sixth day

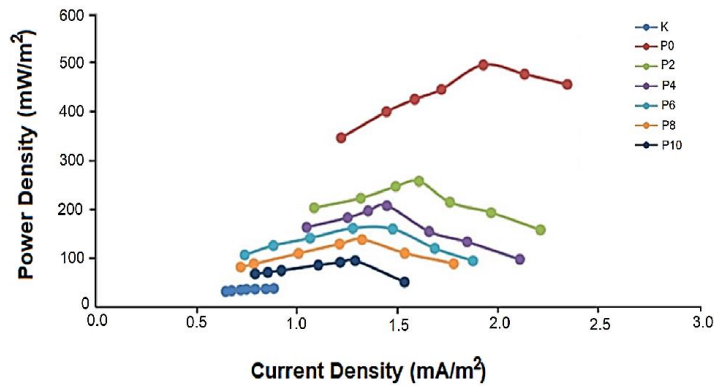


Figure 9. Relationship between electric current density and power density in MFC with variations in substrate concentration on the seventh day

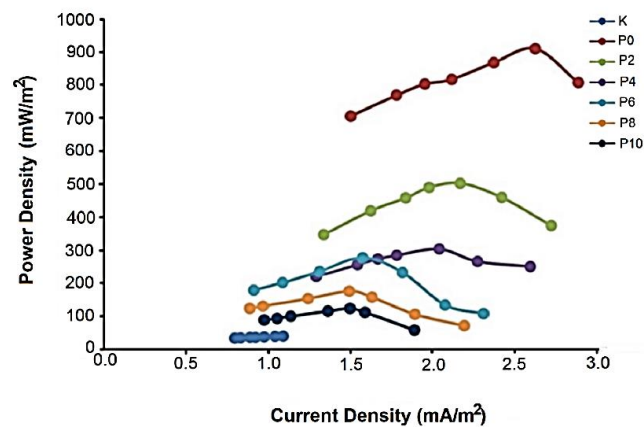


Figure 10. Relationship between electric current density and power density in MFC with variations in substrate concentration on the eighth day



Based on the analysis of the polarization curve illustrated in **Figures 8, 9, and 10**, it can be concluded that the increase in current density contributes to the decrease in electric voltage occurring alongside the increase in electric current. The power density values exhibit a linear relationship with current density, thus the increase in current density directly impacts the rise in the generated power density. High electric current values indicate the transfer of a significant amount of electrons from the anode space to the cathode space.

However, the decrease in electrical voltage occurs due to the slowing down of the electron transfer process in the anode space, influenced by various factors. These factors include the selection of electrode materials, bacterial metabolic activity, operational parameters such as temperature, and increased internal resistance within the substrate [27]. All these factors collectively lead to a decrease in the potential difference between the solution and the electrode, thereby affecting the efficiency of the MFC unit.

Furthermore, the data presented in **Figures 8, 9, and 10** indicate a negative correlation between electric voltage and current density (blue line), where the voltage tends to decrease as the current density increases. This phenomenon can be linked to an increase in internal resistance within the substrate, which is caused by the concentration gradient of ions between the anode and cathode. This process occurs due to the degradation of organic materials by microorganisms that produce biofilm. The formation of this biofilm disrupts the fiber structure and decreases the strength of the carbon veil material, contributing to the voltage drop. On the other hand, an increase in the number of waste bacteria cells generates more protons and electrons through metabolic activity, thereby increasing current [30].

The important findings from this research indicate that the highest power density value, which is 910 mW/m², was achieved at a concentration of 3971 ppm, known as the 0 times dilution (P0). This result highlights the optimal energy efficiency at that substrate concentration.

The optimal power density generated by bacteria using banana peel waste as substrate is recorded at 910 mW/m². In comparison, research conducted by [2] reported that orange peel waste used in the Microbial Fuel Cell unit produced a maximum power density of 71.1 mW/m². Additionally, prior research by [8] indicated that bacteria provided with lemon peel waste as substrate were capable of generating an optimal power density of 371 mW/m².

The study's findings clearly show that bacteria grown on banana peel waste substrate can perform far better bioelectrochemically in the microbial fuel cell unit. This is evidently contrasted with the performance of bacteria cultivated on waste substrates made from orange and lemon peels, and these exhibit lower yields in terms of system stability and energy efficiency. Hence, banana peel waste holds promising opportunities for development as one of the alternative renewable energy sources that are environmentally friendly and sustainable.

Conclusions

The primary finding coming from the discussion of the research findings is that the length of the bacterial culture incubation period has been proven to have a significant impact on system performance, where maximum power density is achieved in the stationary phase of microbial growth. This study utilizes rice field sludge as a source of microbial inoculum and banana peel waste as a substrate showing the potential for optimizing agroindustrial waste in bioenergy



production with a power density of 910 mW/m² on the 7th day. Furthermore, the varying concentrations of substrates in the MFC system have a significant impact on the performance of the MFC. The higher the concentration of the substrate used, the higher the power density produced. MFC shows the maximum power density value in the banana peel waste sample feed with a concentration of 3971 ppm.

ACKNOWLEDGEMENTS

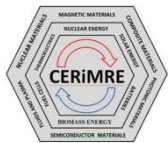
The author conveys gratitude to all those involved in this research process, in particular the Basic Electronics Lab at the University of Jember's Physics department.

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