SINTEK JURNAL: Jurnal Ilmiah Teknik Mesin
ISSN: 2088-9038, e-ISSN: 2549-9645
Homepage: http://jurnal.umj.ac.id/index.php/sintek

THE EFFECT OF VARIATION IN ELECTRODE TYPE AND AREA ON ELECTRICAL PRODUCTIVITY OF MFC WITH SAGO STEM SUBSTRATE

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Accepted: 20-10-2024 Revised: 29-11-2024 Approved: 01-12-2024

ABSTRACT

Microbial Fuel Cells (MFC) offer a promising solution for developing efficient and environmentally friendly alternative energy sources. MFCs convert chemical energy into electrical energy through anaerobic reactors equipped with anode and cathode electrodes containing substrates and microbes. This study investigates the effect of electrode type and area on the production of current, voltage, and power density using sago stem substrates in an MFC system enhanced with *Lactobacillus plantarum*. These bacteria play a critical role in facilitating electrolysis, thereby increasing electrical energy output. A dual-chamber MFC design was employed, testing electrode materials (copper, aluminum, nickel, and graphite carbon) and areas (30 cm², 40 cm², and 60 cm²). Measurements of current, voltage, and power density were taken over 36 hours. Results indicate that electrode area significantly influences voltage and current, while electrode type determines power density. The highest average power density, 432.953 mW/m², was achieved using nickel electrodes with a 30 cm² surface area. These findings underscore the importance of optimizing electrode properties to enhance the performance of MFCs.

Keywords: MFC; sago stem substrate; electrode type; power density

ABSTRAK

Microbial fuel cells (MFC) menawarkan solusi yang menjanjikan untuk mengembangkan sumber energi alternatif yang efisien dan ramah lingkungan. MFC mengubah energi kimia menjadi energi listrik melalui reaktor anaerobik yang dilengkapi dengan elektroda anoda dan katoda yang berisi substrat dan mikroba. Penelitian ini menyelidiki pengaruh jenis dan luas elektroda terhadap produksi arus, tegangan, dan densitas daya dengan menggunakan substrat batang sagu pada sistem MFC yang diperkuat dengan Lactobacillus plantarum. Bakteri ini memainkan peran penting dalam memfasilitasi elektrolisis, sehingga meningkatkan output energi listrik. Desain MFC dua ruang digunakan, dengan menguji bahan elektroda (tembaga, aluminium, nikel, dan karbon grafit) dan luas area (30 cm^2, 40 cm^2, dan 60 cm^2). Pengukuran arus, tegangan, dan kepadatan daya dilakukan selama 36 jam. Hasilnya menunjukkan bahwa area elektroda secara signifikan memengaruhi tegangan dan arus, sedangkan jenis elektroda menentukan kepadatan daya. Kepadatan daya rata-rata tertinggi, 432,953 mW/m², dicapai dengan menggunakan elektroda nikel dengan luas permukaan 30 cm². Temuan ini menggarisbawahi pentingnya mengoptimalkan sifat elektroda untuk meningkatkan kinerja MFC.

***Kata Kunci**: MFC; substrat batang sagu; jenis elektroda; densitas daya*

1. Introduction

One of the solutions for developing efficient and environmentally friendly alternative energy is the Microbial Fuel Cell, or MFC for short. MFC is an innovative form of an energy source that is friendly to the environment and is considered a potential option to meet future energy needs [1]. MFC involves reduction and oxidation reactions, requiring an oxidizer in the process where electrons produced by bacteria from the substrate are transferred to the anode and cathode connected by conductive materials as resistors. The energy produced can be obtained from various substrates such as glucose, acetate, butyrate, lactate, ethanol, and cellulose [2]. In the context of alternative energy development, MFC has several advantages when compared to fuel cell systems in general. Microorganisms in MFC act as biocatalysts, where a fuel cell generally uses platinum metal (Pt) as a catalyst. In addition, the fuel used in the MFC system is organic material so that organic waste is included in the fuel that can be degraded into electrical energy. Microorganisms that act as biocatalysts have the ability to adapt to various types of organic materials.

MFC can convert chemical energy into electrical energy using a system that runs in an anaerobic reactor equipped with anode and cathode electrodes containing substrates and bacteria. MFC technology is an energy transducer that converts chemical energy contained in reduced organic matter into electrical energy [3]. In general, MFC consists of components such as anodes, cathodes, ion or proton exchange membranes, and electrical circuits. The functionality of the MFC system depends on the bacterial metabolism process that degrades glucose into hydrogen (H_2) and oxygen (O_2). Hydrogen serves as a substrate in the reduction reaction with oxygen, resulting in the release of electrons at the anode as a source of electrical energy [4]. The electrons formed are then transmitted through the external circuit from the anode to the cathode, where the electrolyte solution acts as an electron acceptor, generating the formation of electrical voltage.

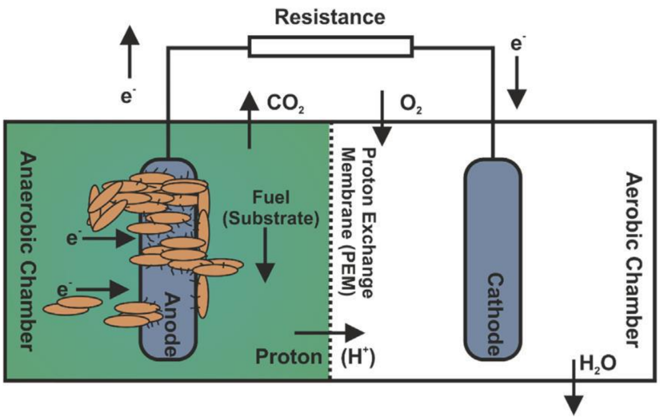


Figure 1. Schematic of the Microbial Fuel Cell [5]

Using glucose as a substrate and oxygen as an electron acceptor, the electrode reaction can be formulated as follows:

Anode:

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^- \quad (1)$$

Cathode:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (2)$$

The overall reaction of the MFC is as follows:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \quad (3)$$

In MFC, there are two types of materials required, namely anode and cathode. The characteristics of the electrodes, including type, shape, and distance, are one of the factors that can affect the overall performance of the MFC. The anode is an important component of the MFC because it acts as an electron mediator to the external power generator. The most important characteristics that should be considered in the selection of anode materials are the available surface area, roughness, conductivity, biocompatibility, microorganisms, and substrate [6].

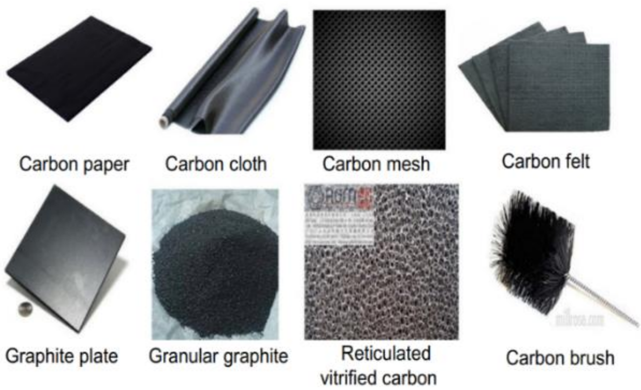


Figure 2. Carbon Electrode [7]

The cathode is another important component that acts as an electron acceptor from an external source and transfers it to the electrolyte or aerobic bacteria in the MFC. In the case of ion transfer, the hydrogen produced in the anaerobic chamber will be transferred to the cathode [8]. The cathode material is the electrode pole in an electrochemical cell that is polarized and positively charged. Materials that can be used as cathodes can be ordinary carbon materials such as graphite plates but can also be used with catalysts such as platinum [9]. In the cathode there is an electrochemical reduction reaction in which the oxide is reduced. The most relevant properties sought in cathodes are catalytic qualities, high surface area and high conductivity [4].

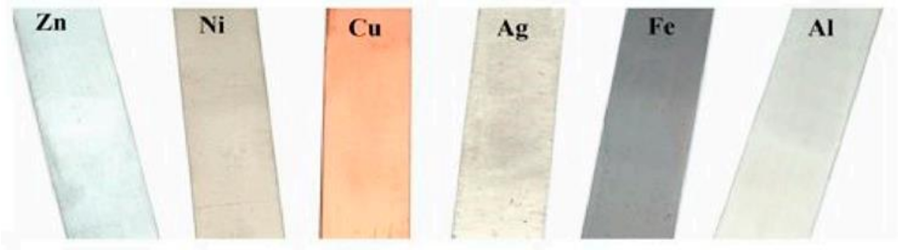


Figure 3. Different Types of Metal Electrodes [6]

The microbes used in the MFC system have certain characteristics, namely the ability to withstand high temperatures, the ability to utilize light as an energy source, and the ability to transfer electrons directly to the electrode. Microorganisms present in waste will undergo oxidation of biodegradable molecules such as acetate, producing electrons, protons, and CO_2. In MFC, the role of microbes is very significant in the electrolysis process to generate electrical energy, as seen in Figure 4 with examples of bacteria such as *Lactobacillus plantarum*. MFC research with the addition of *Lactobacillus plantarum* has been conducted by [10] with the results of maximum electrical power measurements on lactose substrate of 63 mW. The maximum electrical power generated in the series circuit 3 with lactose substrate is 290.51 mW.

Figure 4. *Lactobacillus plantarum* [11]

Most microorganisms have difficulty surviving at pH levels > 9.5 or < 4. The optimal pH range for growth generally falls between 6.5 – 7.5. When cultured on agar media, *Lactobacillus plantarum* forms colonies with a diameter of about 2 to 3 mm, grayish-white in color, and has a convex shape, specifically known as lactic acid bacteria. *Lactobacillus plantarum* is capable of breaking down complex compounds into simpler ones, producing lactic acid as the final product. Lactic acid can lower the pH of the substrate, creating an acidic environmental condition. The presence of *Lactobacillus plantarum* can increase the acidity level of the substrate by about 1.5 to 2.0% [2].

The salt bridge is a tool that plays an important role in the MFC system because it is responsible for maintaining the neutrality of the electric charge in the solution. This is because the concentration of the electrolyte solution on the salt bridge is higher than the electrolyte concentration on both electrodes, so that negative ions from the salt bridge reach the positively overcharged side of the cell, and positive ions from the salt bridge diffuse to the other part that is negatively overcharged. The salt bridge facilitates the continuous flow of electrons through the outer circuit, resulting in spontaneous redox processes at the electrodes. Ionic mobility in the salt bridge affects the R of the solution, where the smaller the R value of the solution, the maximum current strength will be produced, in accordance with Ohm's Law which says that resistance is inversely proportional to current strength [12].

The use of biomass as a substrate becomes an important factor, as the substrate functions as nutrition and an energy source in microbial biological processes. Most of the microbial nutrient sources from plants consist of macromolecular compounds, including complex carbohydrates such as starch and cellulose [13]. Sago plants are wetland plants, relatively easy to care for, and have various benefits from their stems to their leaves. The potential sago land in Indonesia reaches 5.5 million hectares [14]. The sago plant has several chemical compositions, such as the sago trunk bark containing 56.86% cellulose, sago waste 19.55% cellulose, wood 39% cellulose, pentose sugar 20.6%, starch 24%, lignin residue 20.6%, and extractives 10% [15]. Sago cultivation is widespread in various regions of Indonesia such as Riau, Papua, Maluku, Aceh, the Riau Islands, South Kalimantan, and Southeast Sulawesi. Especially in South Kalimantan, data from the Indonesian Ministry of Agriculture (2022) recorded the area of sago plantations reaching 5895 hectares. The high starch content in sago palms makes them an important staple food for the community. In addition, the relatively high cellulose content also provides benefits as nutrition for microorganisms.

Research using MFC with plant stems has been widely conducted, but research on MFC utilizing sago stem substrates is still very limited. The research conducted [2] used sago palm stem substrate and utilized the content of *Lactobacillus plantarum* bacteria within it by adding potassium permanganate electrolyte solution and pH 7 potassium phosphate buffer. The research results show that the maximum current and voltage produced are 1.3 mA and 102.3 mV, with a power density of 91.089 mW/m². The cellulose content in sago stems allows them to be used as a substrate and as nutrition for microorganisms. Therefore, this research aims to determine the electricity production from sago pith substrate using MFC technology by varying the type of electrodes. The independent variables applied in this study and make it different from previous studies are variations in electrode area and electrode type. The size of the electrode area is varied in this study because it will affect the value of voltage and electric current produced by the MFC, while variations in the type of electrode will affect the value of power density. In this study, a two-chamber MFC was used, with the sago pith substrate placed in the anode chamber and $KMnO_4$ solution placed in the cathode chamber. Measurements of voltage, current, and power density generated from the sago pith substrate circuit were then conducted over a period of 36 hours. Electric current and electrical voltage data will be processed into power density (mW/m^2), which is the power per unit electrode surface area. Power density can be calculated using the following equation [16]:

$$Power\ Density = \frac{I \times V}{A} \quad (4)$$

where, I is the electric current (mA), V is the electrical voltage (volts), and A is the electrode surface area (m^2).

2. Methods

The research was conducted on an experimental basis with variations in type (copper, aluminum, nickel and carbon graphite electrodes) and electrode area (30 cm^2, 40 cm^2, dan 60 cm^2). The control variables in this study were temperature and substrate incubation period. The temperature applied in this study was assumed to be the ideal room temperature (25^{o}C), while the pH was periodically monitored using a pH meter to be in the range of 6.5 - 7.5. Control of the substrate incubation period was conducted for 24 hours with an anaerobic or closed system after the addition of *Lactobacillus plantarum* bacteria as much as 14 mL for each substrate mixture. The research procedure carried out in this experiment consists of initial preparation, namely: electrolysis equipment preparation, substrate preparation, and electrolyte preparation, MFC experiments, and data collection in the form of current strength, voltage, and power density.

Preparation of Electrolysis Equipment

The electrolysis device used in the MFC system is pre-prepared before use.

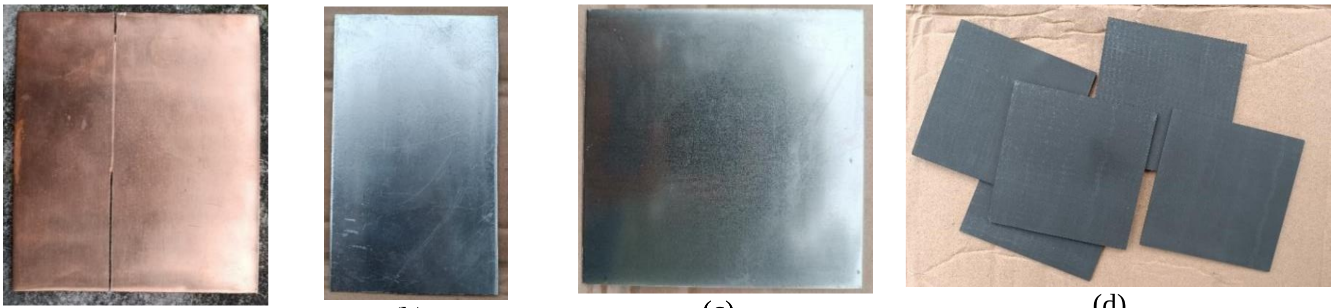
Preparation of Salt Bridge

The salt bridge is made from agar and NaCl salt. The preparation is done by dissolving 14 grams of agar and 1 M NaCl into 1000 mL of distilled water and then heating it. After the solution is ready, it is placed into the prepared PVC pipe and then cooled.

Figure 5. Preparation of a Salt Bridge from Agar

Electrode Preparation

The electrodes used are copper, nickel, aluminum, and graphite carbon with areas of 30 cm^2, 40 cm^2, and 60 cm^2. They are then connected with cables as a link for measuring the electric current.



(a) (b) (c) (d)

Figure 6. Electrodes: (a) Copper, (b) Aluminum, (c) Nickel, (d) Carbon Graphite

Substrate Preparation

The substrate used in this research is sago stem. Sago stems were chopped and blended to be mashed and then distilled water was added. The ratio of sago stem substrate to distilled water is 260 grams of sago stem and 600 mL of distilled water. Adding *Lactobacillus plantarum* bacteria as much as 14 mL for each substrate mixture, then incubated for 24 hours with an anaerobic system. The substrates used in the anode compartment were all the same for each research variation.

Figure 7. Addition of *Lactobacillus plantarum* Bacteria to the Substrate

Electrolyte Preparation

The electrolyte used is aquadest with a volume of 800 mL and the addition of Potassium Permanganate ($KMnO_4$) 0.15 M. The electrolyte solution in each cathode compartment in this study is the same.

Figure 8. Addition of $KMnO_4$ 0.15 M

MFC Construction

MFC is constructed by placing two chambers side by side connected by a salt bridge. On the anode side, the container is isolated from the air, while on the cathode side, the container is left open. The carbon graphite electrode is placed in the anode compartment with an area of 50 cm², while the electrode variations (copper, aluminum, nickel, and carbon graphite) are placed in the cathode compartment with area variations of 30 cm², 40 cm², and 60 cm². The equipment is prepared in such a way and given adhesive to prevent any leaks.

Figure 9. MFC Arrangement

MFC Experiment

In this study, the MFC experiment was conducted with variations in electrode type and size. The MFC was created by placing two chambers connected by a salt bridge. The container at the anode is filled with substrate and isolated from the air, while the container at the cathode is filled with electrolyte and not isolated. The conditions in this research step are assumed to be at a fixed room temperature, which is 25°C.

Figure 10. MFC Reactor at the Initial Stage of Fermentation for 24 Hours

Measurement of Power Density

The current and voltage of the MFC system are measured using a digital multimeter VISERO DT-9205A. Before the measurements are taken, the digital multimeter is calibrated first. Data collection was conducted every 2 hours for 36 hours, followed by the calculation of power density from the measurements of current strength and electrical voltage.

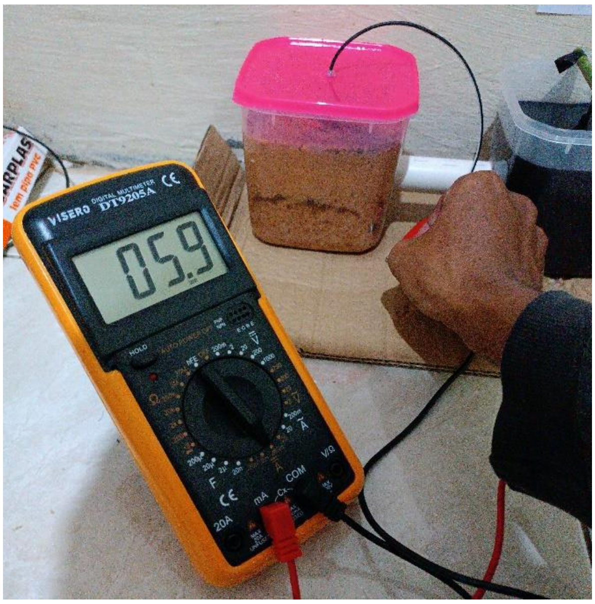


Figure 10. Data Collection Stage

3. Results and Discussion

Result of Electric Current Measurement Against Variations in Electrode Type and Area

The process of substrate degradation in bacterial metabolism will produce electrons (e^-), protons (H^+), and carbon dioxide (CO_2). The electrons (e^-) that adhere to the electrode will flow through a copper wire, which will then be read by the measuring instrument, and continue to flow to the cathode compartment. Meanwhile, protons (H^+) will diffuse to the cathode compartment through a salt bridge and then bind with oxygen. (O_2). From that bond, water will be formed. (H_2O). The number of electrons flowing through a copper wire constitutes the magnitude of the electric current, while the speed of the electrons in the flow represents the magnitude of the voltage.

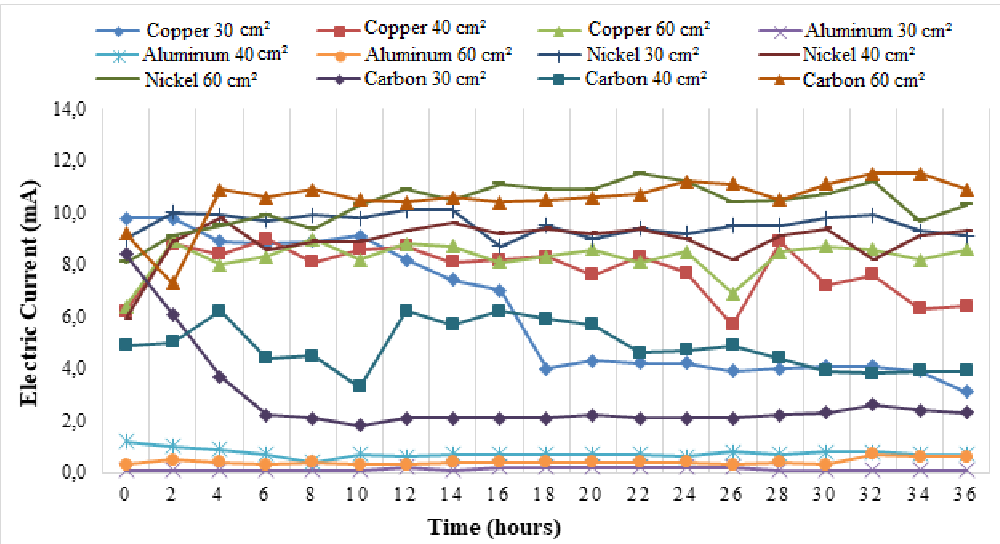


Figure 12. Graph of MFC Electric Current with Variations in Electrode Type and Area

In Figure 12, the results of the measurement during the MFC process are shown, where the figure displays the measurement results of the electric current over 36 hours with variations in the type and area of the electrodes used. The increase in electrical value measured by the multimeter occurs when microbes break down simple substrates present in the medium. The decrease in electricity is also caused by microbes adapting to break down more complex substrates into simpler ones. The increase and decrease in electrical current values indicate the dynamism of the system because it is driven by living organisms. The factors that influence are the electrode, the electrolyte solution content, and protons. The internal resistance of the electrode depends on the quantity and conductivity of the material as well as its shape and composition [17].

Figure 12 shows that the electrode with an area of 60 cm² is better compared to the areas of 40 cm² and 30 cm² because the larger the area of the electrode, the faster the process of current formation in the MFC can occur. This is in line with the research [18] where the study varied the electrode area used in the MFC system. The research results state that the larger the electrode area, the faster the conversion to electrical energy occurs, and the generated current is higher.

Based on the average current values produced, the highest value was obtained from the graphite carbon electrode 60 cm², followed by nickel 60 cm², nickel 30 cm², nickel 40 cm², copper 60 cm², copper 40 cm², copper 30 cm², graphite carbon 40 cm², graphite carbon 30 cm², aluminum 40 cm², aluminum 60 cm², and aluminum 30 cm². Based on the measurement results, it shows that the type of material and the area of the electrode have an influence on the MFC system results. At an area of 30 cm² and 40 cm², the best current value was obtained with a nickel electrode, while at an area of 60 cm², the highest current value was obtained with a graphite carbon electrode, with the current produced being slightly higher than that of the nickel electrode.

Results of Electrical Voltage Measurements with Variations in Electrode Type and Area

Figure 13 shows that the electrode with an area of 60 cm^2 tends to be better compared to the 40 cm^2 area, and similarly, the electrode with an area of 40 cm^2 tends to be better than the 30 cm^2 area. Because the larger the area of the electrode, the faster the process of voltage formation in the MFC. This is in line with the research [19] where the study varied the electrode area used in the MFC system. The research results stated that the larger the electrode surface area, the greater the electrical energy produced. Based on the average voltage values produced, the highest value was obtained from the 60 cm² graphite carbon electrode, followed by the 40 cm² nickel, 60 cm² copper, 30 cm² nickel, 60 cm² nickel, 40 cm² copper, 40 cm² graphite carbon, 30 cm² copper, 30 cm² graphite carbon, 40 cm² aluminum, 60 cm² aluminum, and 30 cm² aluminum. Factors that influence internal resistance include the electrode, the electrolyte solution content, and protons. The internal resistance of the electrode depends on the quantity and conductivity of the material as well as its shape and composition.

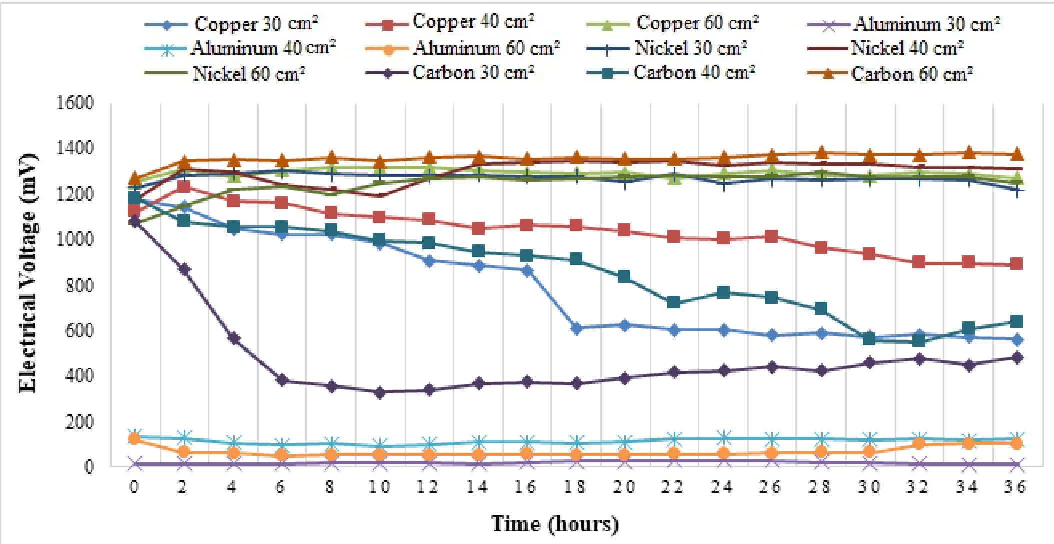


Figure 13. Electrical Voltage Measurements of the MFC with Variations in Electrode Type and Area

Electrical conductivity is a measure of a material's ability to conduct electric current. Although, as seen in Table 1, the best electrical conductivity value is in copper, in this study, the highest voltage result was obtained from graphite carbon. However, in the stability of the voltage produced on areas of 30 cm² and 40 cm², nickel is better compared to other materials.

Table 1. Material Properties [20]

Material	Electric conductivity (10.E6 Siemens/m)	Electric resivity (10. E-8 Ohms.m)	Thermal conductivity (W/m.K)
Copper	58.7	1.7	386
Aluminium	36.9	2.7	237
Nickel	14.3	7.0	91
Carbone	5.9	16.9	54
Carbon (graphite)	2 to 3 × 10^5	2.5 × 10^{-6} to 5.0 × 10^{-6}	-

Results of Electrical Voltage Measurements Against Variations in Electrode Type and Area

Based on the measurement results to obtain the maximum current and voltage values in each reactor with variations in electrode type and size, it can be seen that power density is an indicator of the electrical power generated per unit area of the electrode surface. Power density reflects the electrical power generated per unit area of the electrode surface.

From Figure 14, calculations using various types and sizes of electrodes, the highest power density was obtained with a 30 cm² electrode, reaching 432.953 mW/m² with a nickel electrode, while the lowest value of 0.037 mW/m² was recorded with an aluminum electrode. For a 40 cm² electrode, the highest power density was 317.275 mW/m² with a nickel electrode, while the lowest value was 1.020 mW/m² with an aluminum electrode. Meanwhile, the 60 cm² electrode showed the highest power density of 265.075 mW/m² with a graphite carbon electrode, with the lowest value reaching 0.255 mW/m² with an aluminum electrode. The value of power density produced is fundamentally influenced by the magnitude of the current and voltage generated by each electrode. The relationship between power density, current strength, and electrical voltage is directly proportional. In other words, the higher the current strength and electrical voltage generated, the greater the power density achieved.

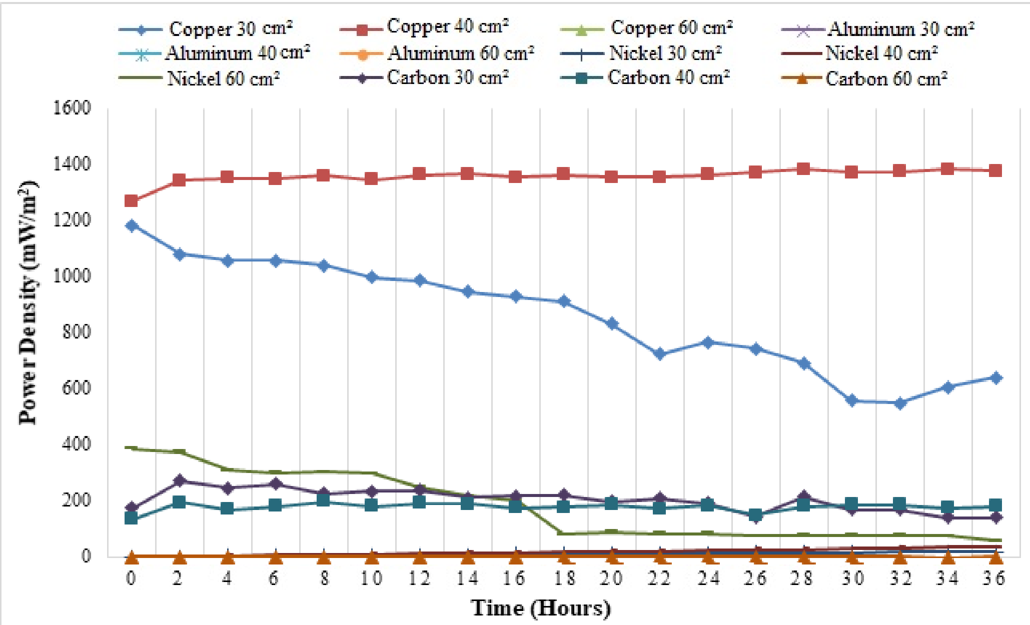


Figure 14. Graph of the Power Density Measurement Results of the Microbial Fuel Cell

The recorded power density shows that the electrode with an area of 30 cm² is the most optimal choice for its use. The current and voltage values produced by the MFC system have an inverse relationship with the electrode area used, so the 60 cm² electrode, although larger, does not achieve optimal results. On the contrary, the most optimal power density value is observed on the electrode with an area of 30 cm². These findings are in line with the research [18] where the study varied the electrode area between 20 cm² and 40 cm² to produce power density values. Where the research results concluded that a smaller surface area (20 cm^2) would yield a higher power density value and be more efficient in the use of electrode material.

The selection of electrode materials plays a crucial role in determining the resulting power density. The findings of this study indicate that the highest average value was found in the 30 cm^2 nickel electrode, followed by the 40 cm^2 nickel, 60 cm^2 graphite carbon, 60 cm^2 nickel, 30 cm^2 copper, 60 cm^2 copper, 40 cm^2 graphite carbon, 30 cm^2 graphite carbon, 40 cm^2 copper, 40 cm^2 aluminum, 60 cm^2 aluminum, and 30 cm^2 aluminum. These measurement results show that the nickel electrode has the highest power density value, followed by the copper electrode, graphite carbon electrode, and aluminum electrode.

4. Conclusion

The study demonstrates that variations in electrode type significantly influence the electric current and voltage produced by MFCs utilizing sago palm stem substrate. Among the electrode materials tested, graphite carbon with a surface area of 60 cm² generated the highest current (10.5 mA) and voltage (1383 mV). However, the electrode area itself showed no substantial impact on current formation, although larger areas expedited the process. Interestingly, the power density was found to be inversely proportional to the electrode area, with the nickel electrode of 30 cm² achieving the highest power density value of 432.953 mW/m², outperforming larger electrodes.

Furthermore, environmental factors such as temperature, pH, and humidity were observed to influence the performance of the MFC system. To enhance consistency and reliability in future research, it is recommended to maintain steady environmental conditions using controlled chambers. Additionally, exploring alternative bacteria with higher electrochemical activity could provide insights into maximizing power density. These findings highlight the importance of optimizing electrode properties and environmental parameters to improve the efficiency and scalability of MFC technology.

Acknowledgments

The authors express their sincere gratitude to the Department of Mechanical Engineering, Faculty of Engineering, Universitas Lambung Mangkurat, for the facilities and resources provided to support this research. Special thanks are also extended to the technical staff and laboratory team for their assistance during the experiments. Lastly, we acknowledge the SINTEK JURNAL editorial team and reviewers for their invaluable contributions, which have significantly enhanced the quality of this work.

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