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Fabrication of Single Chamber Microbial Fuel Cell (SMFC) Using Soil as a Substrate

Siti Kudnie Sahari[1]*, Mohd. Zulhilmi Firdaus Rosli[1], Amir Maina Butit[1], Kuryati Kipli[1], Martin Anyi[1], Asmahani Awang[2], Marini Sawawi[1], Mohamad Rusop Mahmood[3], Lilik Hasanah[4], Abdul Rahman Kram[1], Zaidi Embong[5] and Hafsah Nahrawi[6]

[1]*Faculty of Engineering, Universiti Malaysia Sarawak, 94300 UNMAS, Kota Samarahan, Sarawak, Malaysia*
[2]*Faculty of Science and Natural Resources, Universiti Malaysia Sabah, 88400 UMS, Kota Kinabalu, Sabah, Malaysia*
[3]*Faculty of Electrical Engineering, Universiti Teknologi Mara, 40450 UiTM, Shah Alam, Selangor, Malaysia*
[4]*Faculty of Mathematics and Sciences Education, Indonesia University of Education, Bandung, Jawa Barat 40154 Indonesia*
[5]*Faculty of Applied Science and Technology, Universiti Tun Hussein Onn Malaysia, 84600 UTHM, Muar, Johor, Malaysia*
[6]*Faculty of Resources Science and Technology, Universiti Malaysia Sarawak, 94300 UNMAS, Kota Samarahan, Sarawak, Malaysia*

ABSTRACT

This paper presents a Single-chamber Microbial Fuel Cell (SMFC) design by utilizing soil as a substrate with two sets of electrode combinations, which are graphite-activated carbon and copper-zinc of different sizes. It was found that graphite and activated carbon produced greater power density compared to copper and zinc. Moreover, it was observed that the graphite-activated carbon cloth electrode with a bigger surface area of 51cm^2 resulted in a higher power density of 904mW/m^2. To further improve the voltage production of this model, four SMFCs were stacked in series and connected to a DC-DC boost converter to increase the voltage to 1.482 V for the copper-zinc electrode and 1.722 V for the graphite-activated carbon electrode, respectively, which was sufficient to light up an LED light.

Keywords: Activated carbon, copper, DC-DC boost converter, graphite, soil microbial fuel cell (SMFC), zinc

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E-mail addresses:
sskudnie@unimas.my (Siti Kudnie Sahari)
emifirdausi@gmail.com (Mohd. Zulhilmi Firdaus Bin Rosli)
butitamirmaina45@gmail.com (Amir Maina Butit)
kkuryati@unimas.my (Kuryati Kipli)
amartin@unimas.my (Martin Anyi)
asmahani_awang@yahoo.com (Asmahani Awang)
smarini@unimas.my (Marini Sawawi)
rusop@salam.uitm.edu.my (Mohamad Rusop Mahmood)
lilikhasanah@upi.edu (Lilik Hasanah)
karahman@unimas.my (Abdul Rahman Kram)
zembong@gmail.com (Zaidi Embong)
nhafsah@unimas.my (Hafsah Nahrawi)
* Corresponding author

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INTRODUCTION

Most countries worldwide rely on fossil fuels as their main source of energy, including the United States, Australia, China, Russia, India, and Southeast countries (IEA, 2019). However, the consumption of fossil fuels can result in the depletion of natural resources and the carbon dioxide emission that leads to global warming. Hence, an alternative energy source is needed to ensure human survival on Earth without relying on fossil fuels.

In order to meet the growing energy demand, various renewable energy sources have been developed. One renewable energy technology that is still in development is the Microbial Fuel Cell (MFC). The implementation of MFC may reduce foreign matter emitted by heavy industry, such as carbon dioxide and wastewater, that harm human life and the ecosystem. MFC is a bio-electrochemical system that converts chemical reactions in an organic compound to electrical energy through the catalytic activities of bacteria prepared in biofilm. Electrical energy in this system is achieved by producing an electron from the end-product of the bacteria. The electron will then flow from an anode chamber (where oxidation occurs) to a cathode chamber (where reduction takes place) (Rabaey et al., 2005).

MFC is believed to have operational and functional advantages over the current energy generation technologies, which does not cause any environmental problems. This technology has been studied in recent years on different parameters such as substrates concentration (Marashi & Kariminia, 2015), pH of substrates (Luo et al., 2017), and microorganism culture (Cao et al., 2019). In addition, the most important component in the fabrication of MFC is the electrode cost and efficiency. Therefore, numerous electrode materials and configurations have been investigated to improve the performance of MFC (Tremouli et al. 2018; Kook et al., 2021; Liu et al., 2014; Yu et el., 2012). In principle, the material composition of the electrode affects the internal resistance that can contribute to lower power output. Several characteristics of an electrode, such as surface area, electrical conductivity, stability, and durability, should be considered to increase the power density of the system (Eom et al., 2020). Recently, Khan and co-researchers reported that maximum power densities ranging from 469 to 651 mW/m^{-2} are obtained by CNT/PPy-modified carbon paper electrodes dual-chambered MFCs (Khan et al., 2020). Birjandi et al. (2016) also achieved a maximum power density of 49.8 mW/m^2 using dual-chamber MFCs with an aerobic cathode composed of $Fe@Fe^2O^3$/graphite composite electrodes. However, in the last decade, You et al. (2007) claimed that the Pt is the best electrode material for MFC compared to graphite and carbon cloth. According to the literature, there are obvious contradictions in experimental results regarding the effects of electrode materials on the power output generation of MFC, indicating that the subject still requires further investigation and discussion. Therefore, in this study, we investigated the characteristics of electrodes such as materials compositions and electrode size on the performance of MFC.

METHODOLOGY

Design Stage Construction of Single-Chamber Microbial Fuel Cell (SMFC)

In this study, a single chamber was used to extract an electron from bacteria to generate electricity during the process. A single chamber has the potential to channel electron flow throughout the SMFC in a low-cost method since it does not require PEM to transfer an electron from the anode to the cathode chamber (Saravanan & Karthikeyan, 2018). Considering that the lack of PEM might reduce the rate of electron transfer, the power generated might not be as high as that generated by a double-chamber MFC (Uddin et al., 2019). Figure 1 illustrates the experimental setup for soil-based SMFC. A rectangular plastic container (12 × 11cm) was used as MFC. The mixture of 80% mixed soil for plant pots, 10% water and 10% chicken were blended until completely mixed. The mixture was then placed in the cell. Two sets of combination electrodes were used in this experiment. In the first combination, copper and zinc plates were used as an anode and cathode. The second combination consisted of graphite felt as the anode while activated carbon as the cathode. Both electrodes were connected via a single core connecting wire. In this experiment, the activated carbon was plated with stainless steel because it can perform as a platinum plate, thereby increasing the performance of MFC (Watson et al., 2013).

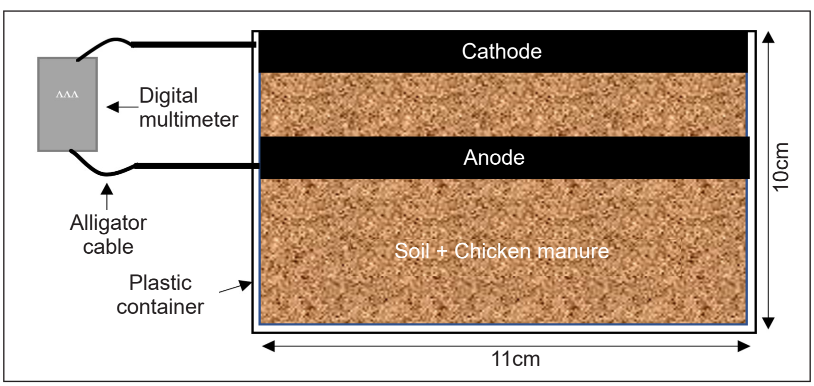


Figure 1. Schematic diagram of soil-based SMFC

The soil-based SMFC in this design is operated by the process of redox (reduction and oxidation) reaction initiated by bacteria under aerobic and anaerobic conditions. Oxidation is the process of losing an electron, while reduction is gaining an electron. In this SMFC, the bacteria oxidize organic or inorganic compounds in the soil to generate an electron. The flow of electrons from anode to cathode produces electricity. The oxidation and reduction equations are referenced in Equations 1 and 2.

At the anode chamber:

$$CH_3COO^- + 2H_2O \rightarrow 2CO_2 + 8e^- + 7H^+ \qquad [1]$$

At the cathode chamber:

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \qquad [2]$$

Since a single soil-based SMFC produces limited voltage, four SMFCs were connected in series, as shown in Figure 2. The block diagram of a series of four SMFCs is shown in Figure 3. The anode chamber was connected to the positive pole of the multimeter, and the cathode chamber was connected to the negative pole. According to Zhao et al. (2017), the series combination of SMFC results in a higher voltage due to the summation of the voltages from every individual source. The two stripes of single-core copper wire were then connected to the anode and cathode plates to complete the external circuit.

Figure 2. Stacking of four soil-based SMFCs

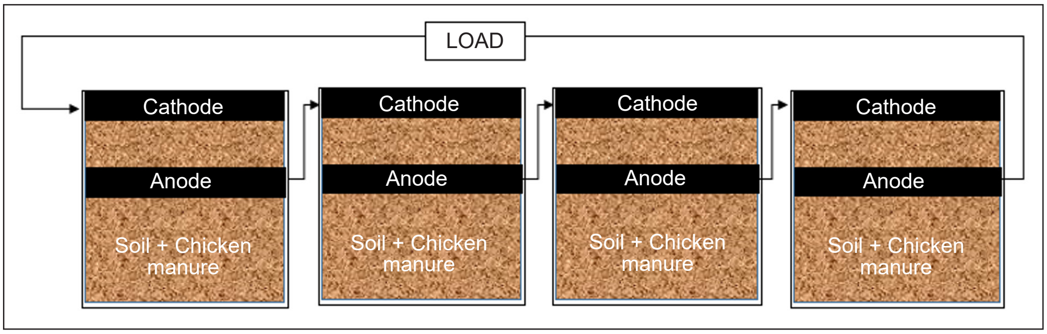


Figure 3. Block diagram of four stacks of soil-based SMFC in series

Electrode Sizes

Two different electrode sizes were used in this study to investigate the performance of the soil-based SMFC power generation. Small electrodes: copper, zinc, graphite and activated carbon, with the dimensions of 6 cm in height, 8.5 cm in width and 0.1 cm in thickness, were used. These dimensions were equivalent to 51 cm^2 surface area or 51 cm^3 of volume. Meanwhile, there was a gap of approximately 2 cm separating the anode from a copper electrode, which was necessary to establish the potential difference of this system. From this scaling, a sum of 204 cm^3 volumes of soil was required as a substrate for bacterial growth. On the other hand, copper, zinc, graphite and activated electrodes with the dimensions of 8 cm height, 11 cm width and 0.1 cm thickness were used to represent the large surface area of an electrode. Thus, the overall surface area and volume of these electrodes were 88cm^2 and 8.8cm^3, respectively, which was 27% larger than the surface area and volume of smaller electrodes. Meanwhile, a gap of 3 cm separated the anode from the copper electrode. Based on the dimensions of these electrodes, approximately 484 cm^3 volume of soil was required as a substrate.

Electricity Generating Parameter

The rate of electricity generation was measured to determine the performance of soil-based SMFC. The parameter quantified the effectiveness of SMFC by calculating current and power densities to identify their power generation and self-sustaining power generation device capabilities.

The magnitude of the current density, power, and power density was calculated based on the surface area of the electrodes and the chamber volume. The current was directly measured at the anode and cathode terminals using a digital multimeter. Equations 3 and 4 illustrate the equations used to formulate electricity parameters (Ullah & Zeshan, 2020).

$$P = IV \quad [3]$$

$$PD = \frac{P}{A} \quad [4]$$

Where, I is current (mA), A is surface area, P is power (mW), V is voltage (V), and PD is power density (mW/m^2).

RESULTS AND DISCUSSION

Comparison of Different Electrodes Material

In this section, the performances of SMFC made from different electrode materials were compared. As in Figure 4, graphite-activated carbon has a higher average power density than copper-zinc after 20 days of observation. Graphite-activated carbon has a higher power density compared to other electrode materials due to its high electrical conductivity and chemical stability (Liu et al., 2004). Furthermore, the lower power density of copper-zinc electrodes might cause the toxic effect of copper on bacteria, which decreases the bacteria activity (Yu et al., 2012). However, both curves showed fluctuation over the observation days. The fluctuation in value could be caused by the uncoated electrode in this study exposed to catalysts, such as hydrochloric acid and

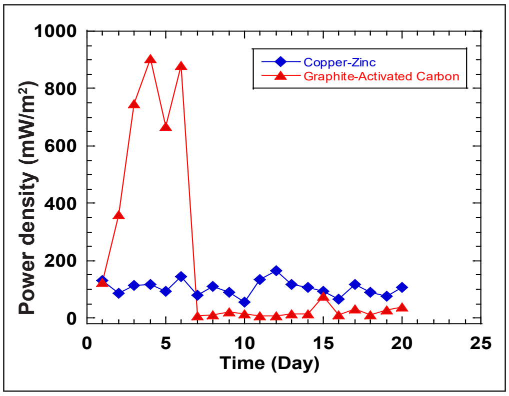
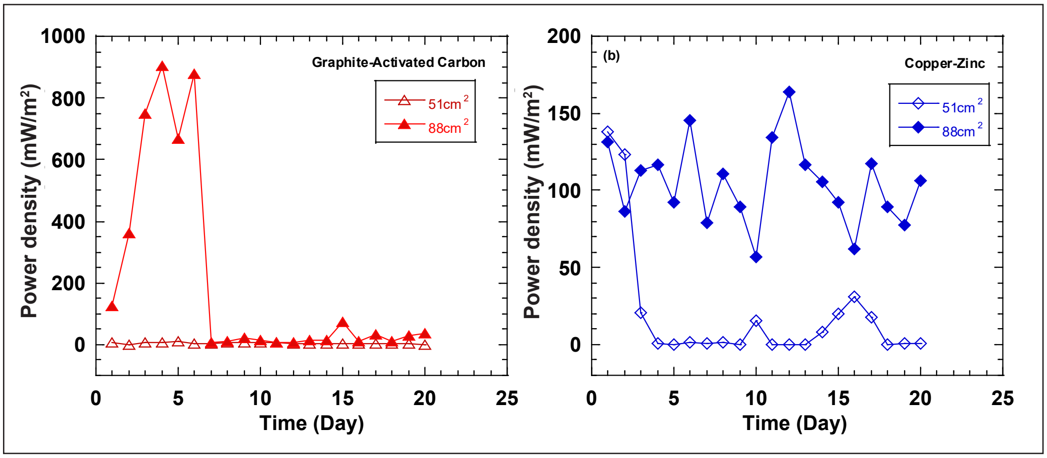


Figure 4. Generated power density of different electrode's material

sodium hydroxide (Prabowo et al., 2016). Furthermore, another factor that can cause fluctuation in electricity generation is the external environment, such as temperature, as discussed in the previous studies (Ghaneam et al., 2016).

Comparison of Different Electrode Size

Figure 5 shows the graph of power density for copper-zinc and graphite-activated carbon electrodes with different electrode scaling. As a result, we can see that during the observation days, the fluctuation values of the power densities for both sets of electrodes were observed. The inconsistency of power densities may be attributed to the metabolic activity rate of the electrogenic bacteria at the fluctuation of temperature during the experiment (Liu et al., 2016; Tremouli et al., 2017). For copper-zinc electrodes, the maximum power generated by 51cm^2 surface area was 137.85 mW/m^2. Meanwhile, the maximum power generated by a surface area of 88cm^2 electrodes was 146.0 mW/m^2. A similar trend was observed for graphite-activated carbon electrodes, where the 88cm^2 of electrode resulted in a higher power density of 904mW/m^2 compared to that of 51cm^2 electrode size, which produced only 9.28 mW/m^2. These results may be attributed to the fact that more electrons were transferred from the anode to the cathode when the surface area of the electrode was increased, as suggested in previous studies (Sadeqzadeh et al., 2012; Qian & Morse, 2011).



(a) (b)

Figure 5. Power density graph of the different electrode's size of MFC: (a) Using graphite and activated carbon; and (b) using copper and zinc as the electrodes

DC-DC Boost Converter Application

To further enhance the effectiveness and efficiency of the SMFC, a DC-DC boost converter was installed in series with SMFC that was expected to increase the output voltage from the power source. Generally, a DC-DC boost converter is a power converter that levels up the output voltage from the input voltage to a specified level using a switch-mode power supply. Besides its simplicity of design and convenience, the boost converter also provides a cost-effective method to improve power generation, which can then be implemented on SMFC.

The proposed circuit topology is shown in Figure 6. The DC-DC boost converter topology consisted of an RLC circuit, diode, Arduino Nano, and MOSFET. The internal parameters for this circuit are listed in Table 1. The LED has been used as an indicator of the functioning of the DC-DC booster. Table 2 shows the comparison of the maximum voltage output of a single soil-based SMFC, a four-series soil-based SMFC and a four-series soil-based SMFC with a DC-DC booster. It is shown that a series connection

Table 1
DC-DC boost converter parameters

Device and Model	Parameter or Model
C	33 µF
R	10 Ω
L	100 µH
MOSFET	IRFZ44N MOSFET
Arduino Nano	ATmega328
Diode	1N4007 Diode

Table 2
Summary of output voltage with different circuit configurations

Types of electrodes	Configuration of MFC	Maximum voltage (V)
Graphite -Activated Carbon	Single soil-based SMFC	0.721
	4 series of soil-based SMFC	1.22
	4 series of soil-based SMFC with a DC-DC boost converter	1.722
Copper -zinc	Single soil-based SMFC	0.464
	4 series of soil-based SMFC	0.790
	4 series of soil-based SMFC with a DC-DC boost converter	1.592

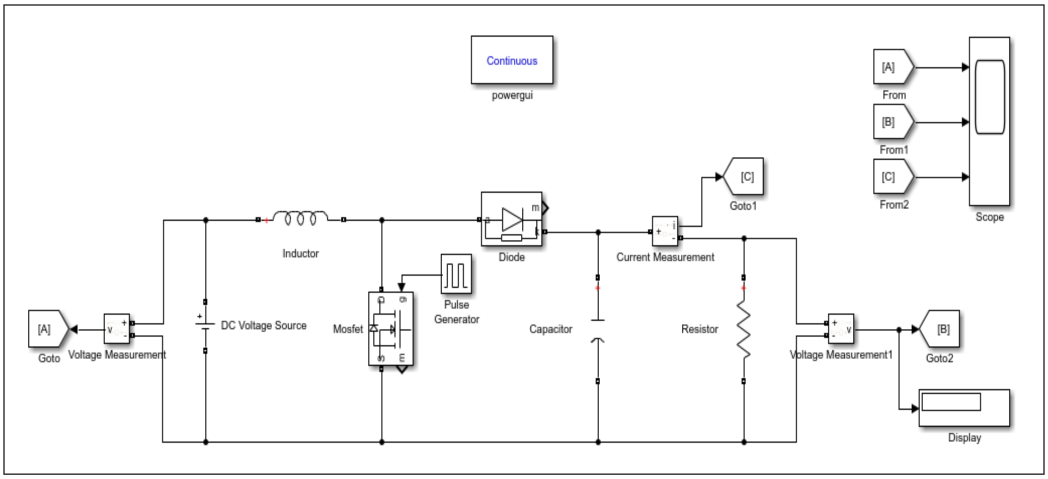


Figure 6. Topology proposed DC-DC converter

can increase the voltage level of SMFC. The level voltage was observed to elevate by more than 40% when the DC-DC boost converter was used, as shown in Figures 7 and 8. The increased level of voltage was sufficient to light the LED.

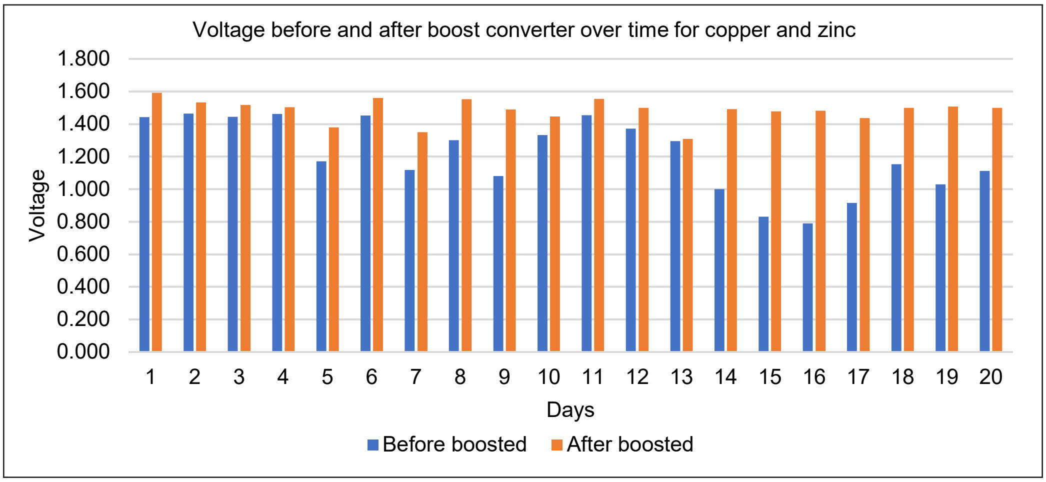


Figure 7. Voltage before and after boost converter for copper and zinc

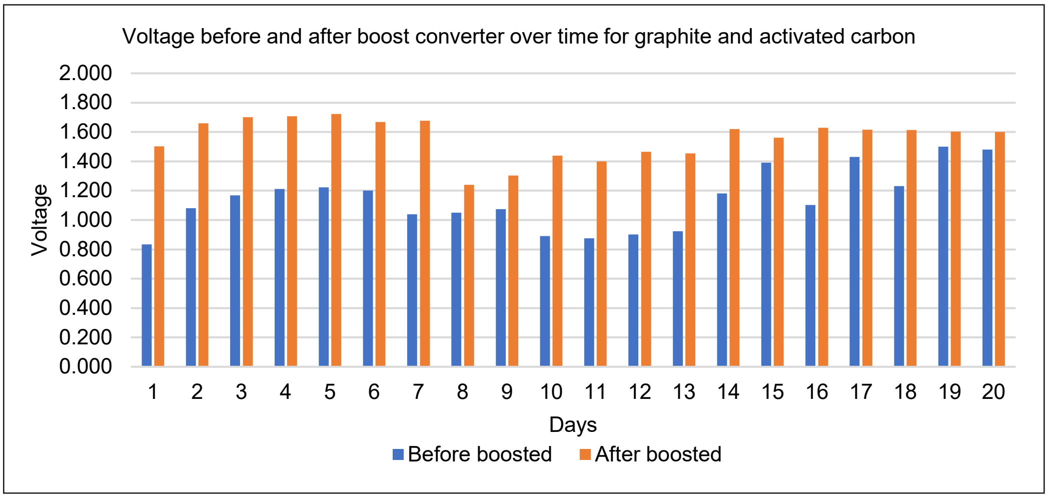


Figure 8. Voltage before and after boost converter for graphite and activated carbon

COMPARISON OF PREVIOUS STUDIES

Table 3 shows the performance of different electrode materials and surface areas. It is shown that the power density generated from this study is comparable to that obtained in previous literature. To the best of our knowledge, our study is the first to report a power density of 904mW/m^2 generated by soil-based SMFC, the highest value power density generated to date.

Table 3
Recent literature of MFC with respect to electrode materials and sizes

Electrodes Cathode material		Size of anode	Surface area of anode	Power density	Reference
Anode	Cathode				
Carbon based	Carbon cloth	2 cm × 2 cm	4 cm^2	679.7mW/m^2	Qiao et al., 2015
Carbon based	Graphene oxide	2cm × 1cm	-	102 mW/m^2	Zhao et al., 2013
Carbon based	Carbon brush	2.5cm × 2.5cm	16 cm^2	4.25 mW/m^2	Choi & Cui, 2012
Carbon based	Carbon felt	2.5cm × 2.5 cm	2.5 cm^2	784 mW/m^2	Yang et al., 2017
Carbon based	Activated Carbon	-	1.5 cm^2 projected area	0.51 mW/m^2	Sokol & Bradford, 2019
Carbon brush	Carbon cloth	2.5 cm (length) 2.5 cm (diameter)	-	844 mW/m^2	Li et al., 2019
Graphite rod	Graphite rod	3 cm × 4 cm	-	0.31±0.03 W/m^2	Liu et al., 2019
Carbon felt	Carbon felt	10 cm (height) 1cm (diameter)	-	8.67mW/m^2	Khan et al., 2015
Graphite	Stainless steel	2 cm × 10 cm × 15 cm	-	2.6 W/m^3	Ghanem et al., 2016
Carbon paper	Stainless steel	2 cm × 10 cm × 15 cm	-	0.8 W/m^3	Ghanem et al., 2016
Graphite	Copper	-	31.4 cm^2	700 mW/m^2	Prabowo et al., 2016
Graphite	Activated Carbon	8cm × 11 cm × 0.1 cm	88 cm^2	904 mW/m^2	*This study
Copper	Zinc	8cm × 11 cm × 0.1 cm	88 cm^2	146.0 mW/m^2	*This study

CONCLUSION

The effect of parameters dependence, such as electrodes sizes and materials, on the performance of single-chamber MFC (SMFC) were studied using soil as a substrate. The combination of graphite-activated carbon as both anode and cathode shows a significantly higher power density than copper or zinc. Moreover, this research proves that a larger electrode surface area could generate a better power density than a small electrode surface area. The utilization of a DC-DC boost converter at the output of SMFC further improves the voltage generation in this system. However, the SMFC is unable to supply a constant voltage due to inconsistency in the rate of flow of electrons at the electrode terminals. In summary, this study proves that soil can be used as an energy source, but further improvement is needed to attain the highest potential.

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