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Research Article

Enhancing microbial fuel cell performance with carbon powder electrode modifications for low-power sensors modules

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Abstract. Microbial Fuel Cell (MFC) is a promising technology for harnessing energy from organic compounds. However, the low power generation of MFCs remains a significant challenge that hinders their commercial viability. In this study, we reported three distinct modifications to the stainless-steel mesh (SSM), carbon cloth, and carbon felt electrodes using carbon powder (CP), a mixture of CP and ferrum, and a blend of CP with sodium citrate and ethanol. The MFC equipped with an SSM and CP anode showed a notable power density of 1046.89 mW.m^{-2}. In comparison, the bare SSM anode achieved a maximum power density of 145.8 mW m^{-2}. Remarkably, the 3D-modified SSM with a CP anode (3D-SSM-CP) MFC exhibited a substantial breakthrough, attaining a maximum power density of 1417.07 mW m^{-2}. This achievement signifies a significant advancement over the performance of the unaltered SSM anode, underscoring the effectiveness of our modification approach. Subsequently, the 3D-SSM-CP electrode was integrated into single-chamber MFCs, which were used to power a LoRaWAN IoT device through a power management system. The modification methods improved the MFC performance while involving low-cost and easy fabricating techniques. The results of this study are expected to contribute to improving MFC's performance, bringing them closer to becoming a practical source of renewable energy.

Keywords: Anode Modification, Carbon Powder, Internet of Things (IoT), Microbial Fuel Cell, Power Management Systems, Renewable Energy, Stainless Steel Mesh

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1. Introduction

As a result of the rising population, energy demand is increasing rapidly, aggravating climate change, and threatening the world with an energy shortage. The world has limited available fossil fuels, including coal, gasoline, and diesel. Additionally, these resources are limited to regenerating, often taking thousands of years (Bose *et al.* 2018). These concerns highlight the critical importance of discovering sustainable alternative energy sources to enhance global energy security. Renewable energy contributes to energy sustainability and protects the nation's natural resources, making renewable energy's production, storage, and consumption critical areas of modern research.

Microbial fuel cells (MFCs) are considered a viable renewable energy source for low-power devices. MFCs effectively produce electricity from various sources, including natural organic matter, complex organic waste, and sustainable biomass. In addition, it can be integrated with wastewater treatment applications (Oliveira *et al.* 2013) and with plant microbial fuel cells (Palmero and Pamintuan 2023; Malinis *et al.* 2023). Electrons resulting from microbial-catalyzed biochemical reactions flow to the anode. Through an external circuit, electrons flow to the cathode electrode, generating electricity as a result of the potential difference between the electrodes. MFCs can mitigate environmental pollutants, including wastewater, and contribute to the overall reduction of demand for fossil fuels. Besides, MFCs produce minimal operational noise compared to other renewable energy generators such as wind turbines and certain types of hydroelectric plants.

MFCs' performance has been significantly improved through the implementation of some innovative strategies and materials, and a wide variety of small devices can be powered by MFCs, including environmental sensors, low-power electronic components, and wastewater treatment systems (Ewing *et al.* 2014; Gajda *et al.* 2015; Ieropoulos *et al.* 2016; Khaled, Ondel, and Allard 2016; Prasad and Tripathi 2018). In addition, MFC is considered a sustainable energy source, capable of generating power for an extended duration compared to alternative energy sources directly harvested from living plants (Chong *et al.* 2019a; Chong *et al.* 2019b; Chong *et al.* 2022). The health and longevity of the plants influence the sustainability of the energy supply from living plants. However, low power output continues to be one of the most significant obstacles for its practical and industrial applications. A significant limiting factor is the inefficient electron transport from the cell membrane to the anode. The ability of MFCs to

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transfer electrons relies on the formation of a microbial biofilm on the anode surface, requiring adhesion and survival on the anode surface (Li *et al.* 2018a). Challenges in commercializing MFCs include limited power output and incomplete understanding and control of the biofilm (Duarte and Kwon 2020).

The anode materials affect the electron transfer and the bacterial adhesion to the anode surface, thus affecting the MFC performance (Qiao *et al.* 2007). The anode electrode surface of various electrodes is commonly modified to improve electron transfer from bacteria to the electrode surface and enhance bacterial adhesion, as such modification changes the physical and chemical properties of the electrode. Numerous studies have been carried out to enhance MFC performance through anode modification. The nanowires of ∝-FeOOH and TiO_2 loaded on a carbon paper anode were investigated by (Jia *et al.* 2016), and the results showed a significant improvement in power density. Moreover, modifying the carbon paper anode with cobalt nanoparticles, graphene, and nitrogen-doped carbon dots improved the performance of the MFC (Guan *et al.* 2019; Mohamed *et al.* 2018; Zhou *et al.* 2019).

A high-power density was achieved in (Zhong *et al.* 2018) by $MnFe_2O_4$ coating on carbon felt (CF). Using MnO_2 with polyaniline (PANI) or $MnCo_2O_4$ resulted in a higher power density than untreated CF (Wang *et al.* 2017; Yang *et al.* 2021). Another effective technique involves CF surface modification with poly(bisphenol A-co-epichlorohydrin) and carbon nanotubes (Li *et al.* 2018b). Carbon cloth (CC) modification was implemented to enhance MFC performance using coal-tar pitch and He gas, significantly increasing power density (Liu *et al.* 2021). Other materials such as MoO_2/PANI, $NiWO_4$ as well as the impregnation of $NiWO_4$ onto reduced graphene oxide (rGO) and the use of poly(diallyldimethylammonium chloride)-rGO are excellent modifiers for improving the performance of the CC anode (Chen *et al.* 2020; Geetanjali, Rani, and Kumar 2019b, 2019a).

Other modification methods have been implemented for non-carbon materials. For example, investigations to enhance stainless steel's performance using different anode modifiers (carbon, PANI, and heat treatment) have shown positive results compared to anodes made of plain stainless steel (Liang *et al.* 2017). Moreover, Zheng *et al.* (2015) improved the performance of an SSM through modification with a carbon black composite using a dip-and-dry method.

Various approaches have been implemented to improve the bio-electrocatalysis of the stainless-steel electrode. For example, a stainless-steel electrode was flame-oxidized and surface coated with carbon nanoparticles to improve electrochemical performance and provide a more biocompatible surface for the electrode (Guo *et al.* 2014). Moreover, an SSM was coated with carbon nanotubes and implemented as a biocathode, achieving a 49-fold higher power density than the uncoated SSM biocathode (Zhang *et al.* 2013).

The previous studies underscore the potential for enhancing MFC performance through innovative electrode modifications. They also highlight the significant promise of utilizing the SSM as an anode electrode and the critical need for low-cost modification techniques. The selected approach in this study is based on its demonstrated efficiency in enhancing MFC performance while maintaining cost-effectiveness. This hypothesis is substantiated by prior research findings, which consistently affirm the method's efficacy and economic viability.

This study aimed to modify the electrodes of MFCs using three distinct experimental techniques. The first modification technique involved coating an SSM with CP, while the second and third techniques involved the alteration of CC and CF, respectively, by incorporating a mixture of CP and either ferrum or sodium citrate, along with ethanol. The most effective modified electrodes were integrated into a single-chamber MFC, and their ability to power Internet of Things (IoT) sensors or devices through a power management system was evaluated.

Although MFCs have long been the research subject, our study is distinguished by the innovative application of cost-effective modification techniques. Through the utilization of these economic approaches, substantial improvements in MFC performance have been achieved. Specifically, the proposed 3D-SSM-CP anode achieves a maximum power density nearly 10 times higher than the bare SSM anode. It is noteworthy to emphasize that MFCs powered the LoRa module entirely throughout the entire data transmission process. This focus on cost-effective modifications signifies a significant stride toward making MFC technology more accessible and applicable in practical applications.

2. Materials and Methods

2.1. MFC Configuration

All MFC experiments were conducted using a single MFC chamber with a height of 17 cm and a diameter of 14 cm, as illustrated in Figure 1(a). The cathode and anode electrodes had the same diameter of 14 cm and were placed with a specific optimal distance between them, as depicted in Figures 1(b) and 1(c). A commercial composite soil comprising soybean and oil palm waste, decanter cake, and a concentration of 20 million microbes per gram was employed as the substrate and inoculum for the MFCs. It is noteworthy that the size of the MFC chamber, electrode dimensions, electrode spacing, and type of substrate remained consistent across all experiments.

2.2. Electrode Preparation

To modify the stainless-steel mesh anode with carbon powder (SSM-CP), a 0.3 mm SSM layer was initially treated with sulfuric acid (one mole) for 24 h. Afterwards, three stable solutions of CP and ethanol were prepared by dissolving 0.5 g, 10 g, and 30 g of CP in 100 mL of ethanol. Next, three distinct SSM electrodes were immersed in the previously prepared solution using the dipping and drying method to achieve a uniform coating of CP and ethanol on the SSM electrode. The process was repeated three times to obtain SSM-CP. For obtaining 3D-SSM-CP, a 5° difference was created by folding the SSM electrode, as depicted in Figure 1(d), and it was subjected to the same procedure as SSM-CP. Finally, the prepared electrodes were tested in three separate MFCs.,

The modified CC and CF electrodes were prepared using a two-step process involving the application of CP, poly(tetrafluoroethylene) (PTFE), and ferrum. In the first step, a solution of CP and PTFE (4 mL per 0.5 g) was coated onto one side of both CC and CF electrodes. The coated electrodes were dried at room temperature for 2 h and then heated at 370 °C for 0.5 h. Next, additional layers of PTFE solution (2.5 mg per coating) were brushed onto the coated side of the electrodes. After each coating, the electrodes were dried at room temperature and heated for 10 min at 370 °C. In the second step, a mixture of ferrum and Nafion binder (2 ml of binder per g of ferrum catalyst) was applied to the non-coated side of the electrodes. The electrodes were left to dry at room temperature for 24 h. The modified electrodes were then used as cathodes in the MFC.

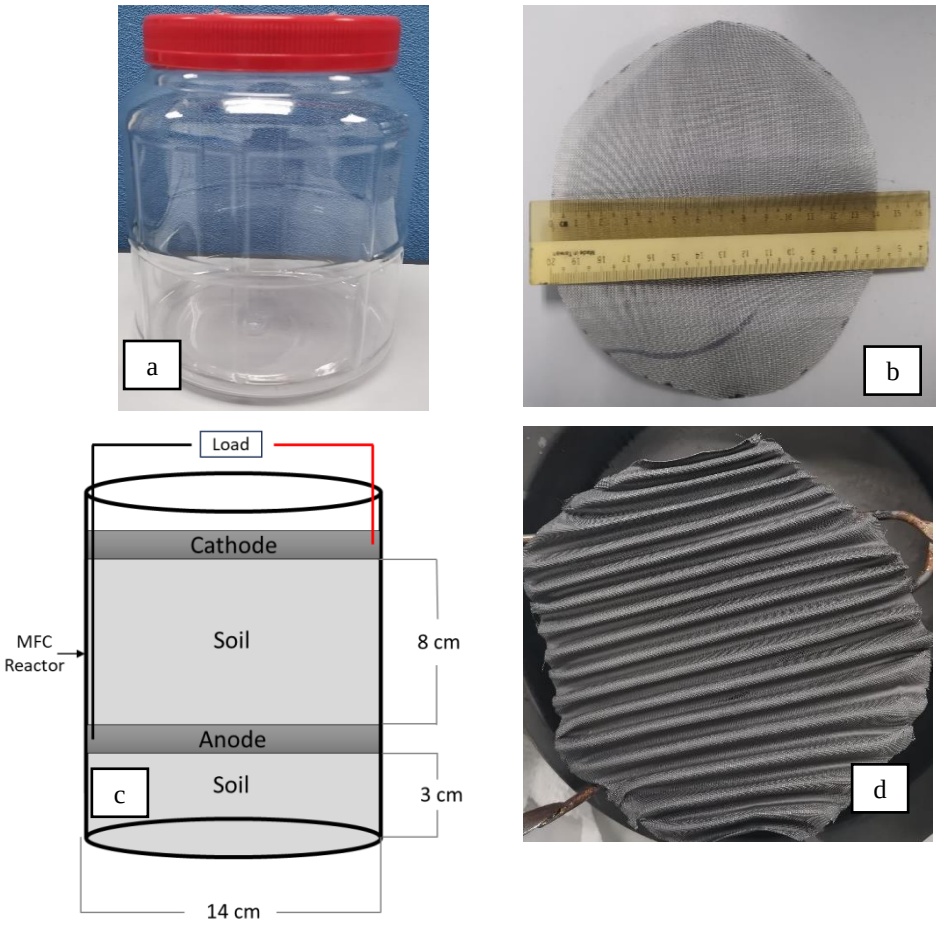

Fig. 2 (a) Single MFC chamber, (b) SSM electrode, (c) Schematic diagram of MFC Reactor, and (d) 3D-SSM electrode

The CC and CF anode electrodes were modified with sodium citrate and ethanol. The modification involved heating the mixture in a gas cooker at a ratio of 1:2. The electrodes were then immersed in the mixture and subsequently dried at 80 °C for 30 min. This process was repeated three times for each electrode. In a separate modification procedure, the electrodes were treated similarly but without the heating and drying steps to evaluate the significance of these steps.

2.3. Power Management System

A power management system is critical for sensor devices that rely on MFCs as a power source, as the power generated by MFCs is often insufficient to sustain the entire system. The proposed power management system was designed to harvest energy from the MFC and provide power to an IoT device. The power management system comprises a harvester (BQ25570) manufactured by Texas Instruments, which extracts microwatts to milliwatts of power from high-impedance DC sources and a rechargeable battery (3.7 V) to store the harvested energy. In addition, the BQ25570 chip is attached to a supercapacitor (0.22 F, 5.5 V) to enhance the energy harvesting capability of the power management system. The electrical energy generated by the MFC is simultaneously stored in the supercapacitor and rechargeable battery. The battery management functions prevent overcharging of the rechargeable battery by the extracted power. The BQ25570 chip incorporates an efficient boosting charger with a highly efficient, low-power buck converter capable of providing sufficient power to small electronic devices.

Fig. 1 Six MFCs equipped with the 3D-SSM-CP anode and connected in series.

The power management system was connected to six MFCs in a series configuration equipped with a 3D-SSM-CP electrode and a CF electrode as the anode and cathode, respectively (see Fig. ***2***). The RAK4200 LoRa Module was used as the load in the experiment. This module is highly suitable for long-range data collection applications and has low energy

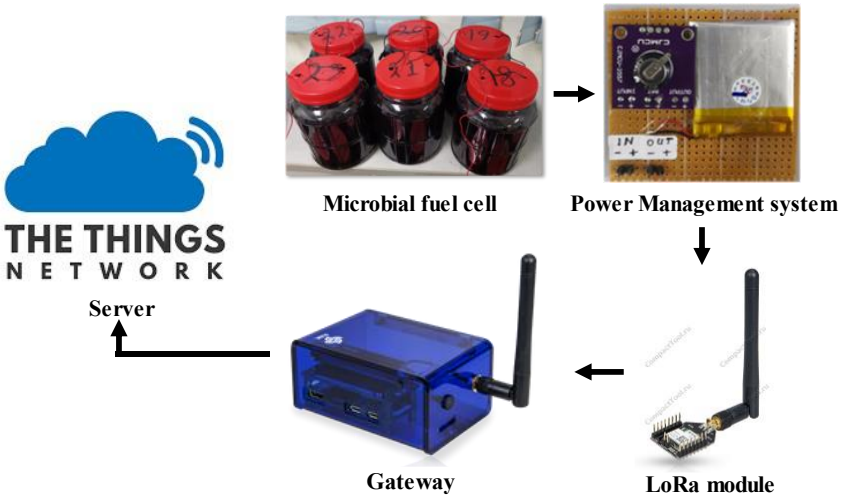

Fig. 3 System configuration to power an IoT device using MFCs as a power source.

consumption. The LoRa Module was connected to a local gateway and subsequently to the internet, enabling the uploading and visualization of the measured data on the Things Network server. Fig. ***3*** depicts the system configuration.

3. Results and Discussion

3.1. Anode Electrode Modification Results.

Fig. **4** demonstrates that the SSM-CP anode electrode outperformed plain SSM significantly. This improvement can be attributed to the carbon coating on the SSM surface, which enhances bacterial adhesion and electron transfer between the bacteria and the electrode, leading to increased colonization on the SSM-CP surface. The modification with 10 g of CP resulted in a 7.1-fold increase in power density compared to plain SSM. According to (Li, Cheng, and Thomas 2017), carbon materials can facilitate the colonization of surfaces by microbes and the formation of biofilms by creating a conductive microenvironment for extracellular electron transfer. Referring to Fig. **4**(a), we can observe the power density and voltage variation between the four MFCs due to the different ratios of CP used in the anode modification. Although the power density and the voltage were unstable in the MFC equipped with a 10 g modified anode, it exhibited the highest power density and voltage during the fourteen days. When using an anode modified with 30 g of CP, the MFC was less stable and had a higher voltage than the MFC with the uncoated electrode. The lowest performance was recorded when using the MFC with an unmodified anode, achieving a maximum power density of 145.8 mW m^{-2} at 0.116 V.

Modifying the SSM electrode with CP resulted in a 3.6-fold increase in the current. The best performance was obtained using a 10 g modified anode, with the highest value recorded at 20.758 mA on the twelfth day. Therefore, using the MFC equipped with SSM coated with a mixture of CP and ethanol (10 g/100 ml) demonstrated the highest performance. These results highlight the excellent microbial bioelectrocatalytic activity of the SSM-CP anode, with the optimal ratio of CP to ethanol being 10 g/100 ml. Fig. 5 illustrates the power density and voltage generation of the MFC equipped with 3D-SSM-CP, which exhibited the highest power density of 1417.07 mW m^{-2}, 1.3 times higher than that achieved with the MFC equipped with

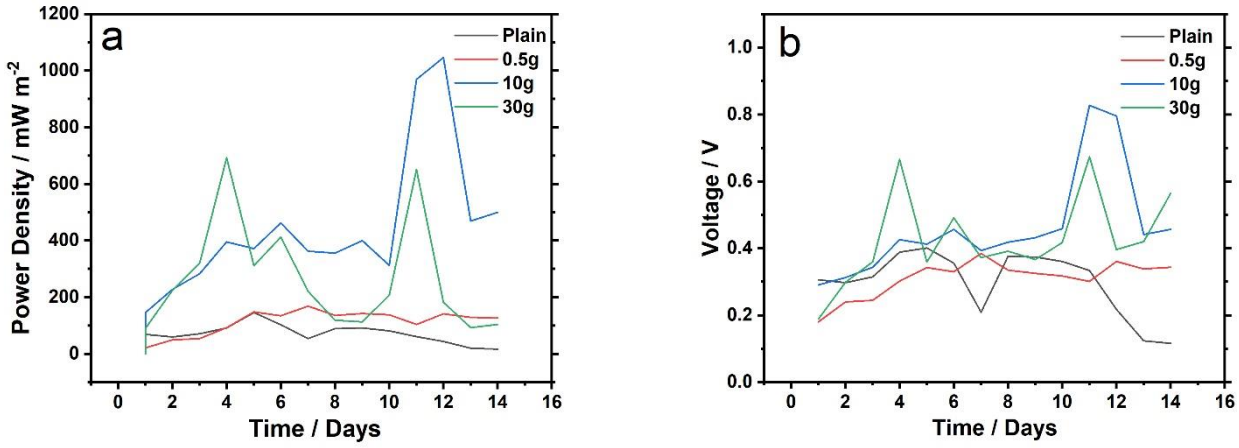

Fig. 4 (a) Power density versus time and (b) voltage versus time of four champers using different modified SSM-CP anodes.

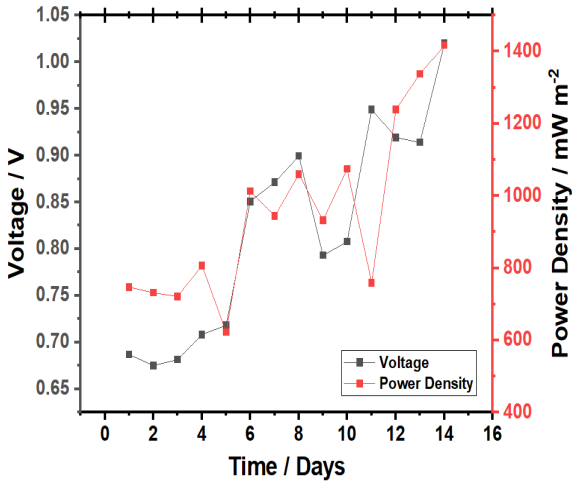

Fig. 5 Power density and voltage versus time of the MFC using 3D-SSM-CP anode.

SSM-CP (1046.89 mW m^{-2}). The 3D-SSM-CP electrode enhanced the power density by increasing electrode surface area, enabling greater biofilm growth.

Based on this experiment, it is evident that CP can enhance MFC performance. This improvement can be attributed to increased conductivity, which facilitates electron transfer between the bacteria and the electrode, and increased surface area, enhancing microbial attachment and interaction with the electrode. However, the 10 g ratio of carbon powder to ethanol was identified as optimal due to its balanced effect on electron transfer and microbial attachment, resulting in better performance than other ratios. However, it should be noted that excessive use of carbon powder can lead to decreased performance and inhibit biofilm formation, as an excessive amount may clog the porous structure of the electrode. This underscores the importance of carefully calibrating the ratio for optimal MFC performance.

The second experimental finding illustrates the impact of CP, PTFE, and ferrum on the CC and CF electrodes when used as cathodes. The voltage of the MFCs with modified electrodes was higher for the first nine days than those MFCs with non-modified electrodes. Eventually, it decreased to become lower than the MFCs with unmodified electrodes. Conversely, the maximum power density was achieved using non-modified electrodes. However, the power density declined on day seven, reaching 97.3 mW m^{-2} on day fourteen, as depicted in Fig. **6**. The MFCs equipped with modified electrodes consistently demonstrated a power density of less than 100 mW m^{-2}, indicating stable performance.

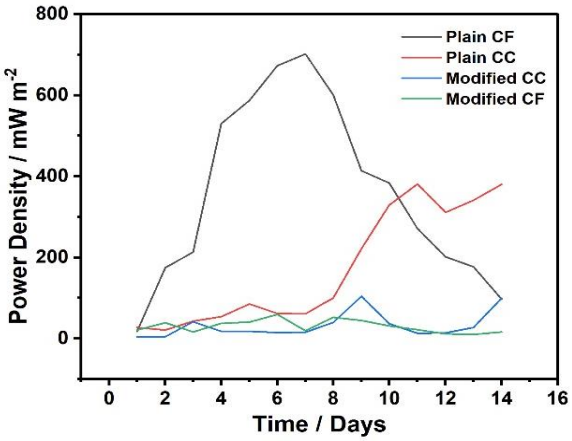

Fig. 6 Power density versus time of the MFC using modified CF and CC cathodes

In contrast, the MFCs using plain CF and CC exhibited a maximum power density of 701.7 mW m^{-2} and 380.4 mW m^{-2}, respectively. While the voltage of the MFCs with modified electrodes initially showed higher values, their power density ultimately remained lower than those of the MFCs with non-modified electrodes. These results suggest that electrode modification may lead to higher voltage but not necessarily an increase in power density. Further research is needed to explore the optimal utilization of CP, PTFE, and ferrum for enhancing the performance of MFC electrodes.

The latest experiment's results demonstrate sodium citrate's potential to enhance the efficiency of electrodes in an MFC. However, the extent of improvement varied based on the electrode type and the method of depositing sodium citrate onto the electrode. Fig. **7**(a) illustrates the power density of three different MFCs equipped with a plain CC anode, a modified CC anode, and a modified CC anode with heating involved. The maximum power density obtained from the unmodified CC anode was 95.7 mW m^{-2}. However, after modification with sodium citrate and ethanol, the maximum power density reached 407.9 mW m^{-2} on day 14, 4.2 times higher than that of the MFC with an unmodified CC anode.

Further improvement was observed when heating was involved in modifying the CC anode, resulting in a maximum power density of 468.8 mW m^{-2}. This result represents a 13% increase over the modified CC anode and a 79.5% increase over the unmodified CC anode. Furthermore, the results of CF modified with sodium citrate and ethanol demonstrated improved performance after modification. Referring to Fig. **7** (b), it can be observed that the power density was as low as 200 mW m^{-2} for the MFC with modified CF without the heating procedure. However, when heating was involved, the power density increased to 828.1 mW m^{-2}. Applying heat during modification leads to a more uniform and adhesive coating of the electrode surface with sodium citrate, facilitating a more effective electron transfer process. The heat treatment also induces physical and chemical changes in the CF structure, potentially enhancing its electrical conductivity and active site availability, thus improving electrochemical performance.

Based on the data presented in Fig. **7**, it is evident that the modification with sodium citrate significantly influences the performance of MFCs. This enhancement can be attributed to several interconnected factors. Firstly, sodium citrate has been observed to stimulate microbial proliferation, leading to an augmented microbial population within the MFC system. This heightened microbial abundance facilitates improved bacterial adhesion to the electrode surface, enhancing electron transfer processes. The modification process involving sodium citrate and ethanol also increases the electrode's surface area. This expansion provides more active sites for electrochemical reactions, further contributing to the overall improvement in power density. The reference to (Yang and Wang 2019) supports these findings by underscoring that sodium citrate promotes a more robust microbial community and enhances the utilization efficiency of essential nutrients, such as proteins and carbohydrates. This suggests a more productive and efficient microbial ecosystem within the MFC.

Furthermore, the modification of the anode electrode with sodium citrate resulted in an enhancement in biocompatibility,

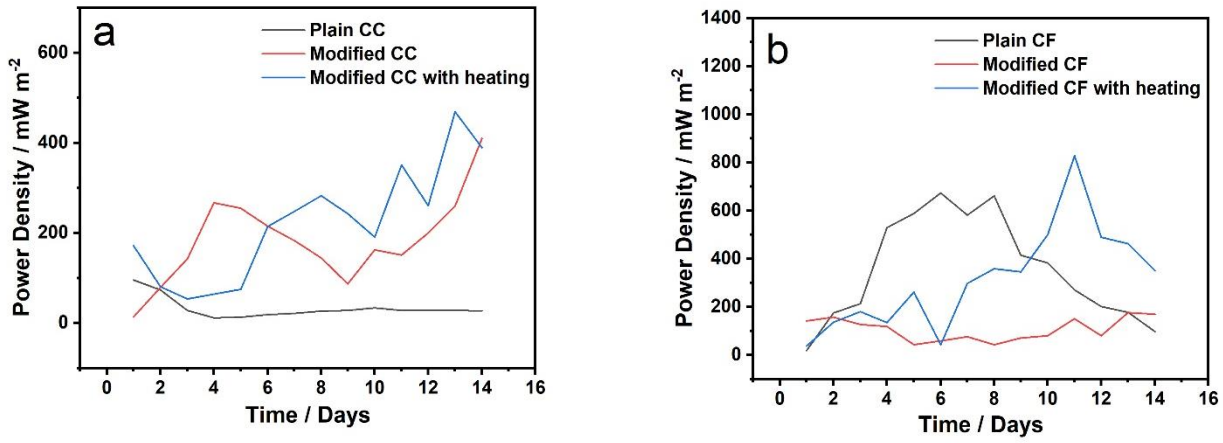

Fig. 7 Power density versus time of the MFC (a) using CC and (b) CF cathodes modified with sodium citrate.

indicating a more favourable environment for microbial colonization and activity. This directly correlates with the observed increase in current output, a critical metric in evaluating MFC performance. The findings demonstrate that heating the sodium citrate-ethanol mixture and drying the electrode can further enhance the electrode's performance compared to modification without heating. This suggests that the heating procedure is pivotal in optimizing the modification process, further validating its impact on MFC electrode performance. These detailed clarifications provide a more comprehensive understanding of the observed improvements and underscore the potential of sodium citrate modification, especially when combined with the heating step, as a promising technique for advancing microbial fuel cell applications.

The power density achieved in this study surpasses the values reported in previous studies. For instance, Zhang *et al.* (2013), You *et al.* (2011), and Pu *et al.* (2018) achieved power densities of 147 mW m², 951.6 mW m², and 1190.94 mW m², respectively, following treatment of the SSM electrode. While previous studies have modified the SSM to achieve high power densities (Ying *et al.*, 2018; Zheng *et al.*, 2015), it is noteworthy that our investigation employed a cost-effective modification technique alongside a single MFC, resulting in an impressive power density of 1417.07 mW m².

3.2. Power Management System Results.

The voltage and current were recorded using an EX542 digital multimeter and transmitted wirelessly to a computer via a communication module to ensure data accessibility and real-time monitoring. Fig. **8**(a) shows the charge curve of the voltage and current of the rechargeable battery and supercapacitor when being charged by the MFCs. The MFCs could charge the supercapacitor and rechargeable battery from 2.8 V to 3.4 V in approximately 11 min. Over 1.8 h, the MFCs could charge the rechargeable battery and supercapacitor to 3.5 V. Fig. **8**(b) also demonstrates the discharge process of the rechargeable battery during the transmission of 10 data sets. The voltage and current levels declined to nearly zero during the LoRa device's sleep mode and then rose again when data was transmitted again. The MFCs entirely powered the LoRa device throughout the data transmission process, including the gateway connection, the sleep/active mode regulation, and multiple data set transmissions. The results of this experiment demonstrate the potential of MFCs as a renewable energy source for periodically and effectively charging batteries and supercapacitors to power IoT sensors or small electronic devices.

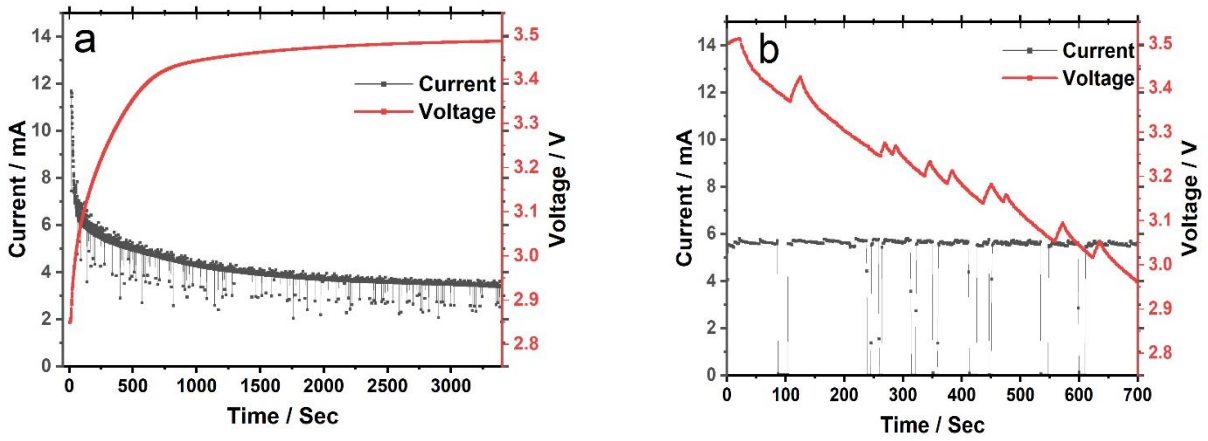

Fig. 8 (a) Voltage and current levels versus time of the rechargeable battery while being charged by MFCs, and (b) voltage and current levels versus time of the rechargeable battery while transmitting different sets of data.

3.3. Limitations and Recommendations for Future Work

While our study advances MFC technology, it is essential to acknowledge its limitations. Experiments were conducted in controlled conditions, which may differ from real-world applications. Constraints in tools and instruments and our focus on cost-effectiveness in material selection may have influenced our approach. Further research is needed to optimize the MFC electrode for low-cost, high-performance composites. CP shows promise, but its full potential, including the use of alternative binders, requires exploration. Enhancing sodium citrate deposition and assessing long-term stability are recommended. Optimizing MFC design and configuration can increase output and efficiency. For example, adjusting the electrode spacing and using other type of substrate can lead to higher electricity generation and improved performance. Exploring practical applications of the optimized MFC for low-power IoT use cases, especially in resource-limited settings, is another crucial step in expanding the reach of this technology to underserved communities. This work aligns with United Nations Sustainable Development Goal 7 (Affordable and Clean Energy), as it provides a sustainable pathway for harnessing energy from organic compounds.

4. Conclusions

This study evaluated the impact of electrode modifications on MFC performance using different materials, including CP, PTFE, ferrum, and sodium citrate. The results showed that CP improved the MFC anode performance, with optimal results obtained when using 10 g/100 ml of CP mixed with ethanol. However, the cathode results were inconclusive, showing an initial voltage increase but a lower power density. Sodium citrate improved performance when added to CC and CF electrodes, with further enhancement observed with heating. These findings suggest a potential for sodium citrate to enhance the MFC electrode's efficiency. The 3D-SSM-CP anode electrode exhibited exceptional performance and was effectively used with a power management system to power an IoT device. The MFC electrodes were modified using a simple and cost-effective method, resulting in improved performance, which calls for further exploration of the combination of modifications.

Abbreviation	Definition
MFC	Microbial Fuel Cell
SSM	Stainless Steel Mesh
CP	Carbon Powder
3D-SSM-CP	3D-modified Stainless Steel Mesh with a Carbon Powder
IoT	Internet of Things
CF	Carbon Felt
CC	Carbon Cloth
PANI	polyaniline
SSM-CP	Stainless steel mesh anode modified with carbon powder
PTFE	Poly(tetrafluoroethylene)

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