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Performance Evaluation of Carbon Felt-Based Plant Microbial Fuel Cells Using Different Soil Types for Low-Power Energy Harvesting

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Abstract

Plant Microbial Fuel Cells (PMFCs) have emerged as a promising renewable energy technology capable of generating electricity through the interaction between plant roots and soil microorganisms. However, their relatively low electrical output limits their practical application in powering low-power electronic devices. This study investigated the influence of different soil types on the electrical performance of soil-based PMFCs using carbon felt as both the anode and cathode. Two PMFC configurations were constructed using paddy soil and organic soil, and their performance was evaluated based on open-circuit voltage and power output over a six-day observation period. The results showed that both configurations successfully generated electrical energy through plant–microbial interactions. The paddy soil configuration achieved a higher maximum power output of 0.0372 μW, while the organic soil configuration produced a maximum of 0.0212 μW. These findings demonstrate that soil type influences the electrical performance of PMFC systems when the electrode material is kept constant. Although the generated power remains relatively low, the study confirms the potential of PMFC technology as a sustainable, environmentally friendly, and low-cost energy source for future low- power Internet of Things monitoring applications.

1. Introduction

The increasing demand for electrical energy and the continuous depletion of fossil fuel resources have accelerated the search for sustainable and environmentally friendly energy sources [1,2]. Renewable energy technologies have become increasingly important in reducing greenhouse gas emissions while supporting future low-power electronic applications [1]. Among these technologies, Plant Microbial Fuel Cells (PMFCs) have attracted significant attention due to their ability to generate electricity naturally through the interaction between plant roots and electrogenic microorganisms in the soil [2,3]. During the decomposition of organic matter released by plant roots, microorganisms transfer electrons to the anode, producing electrical energy that can be harvested through an external circuit [3,6,8]. Compared with conventional Microbial Fuel Cells (MFCs), PMFCs offer continuous substrate availability from living plants, allowing long-term electricity generation without damaging the plant itself [3,4,5].

Despite these advantages, the electrical output produced by PMFCs remains relatively low, limiting their capability to directly power electronic devices [4,5,7]. The performance of PMFC systems is strongly influenced by factors such as soil properties, microbial activity, and electrode materials [6,9,12]. Therefore, identifying

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suitable combinations of soil type and electrode material is essential for improving electrical generation efficiency [9,11,15]. In addition, integrating simple energy storage devices can help accumulate the harvested energy for intermittent operation of low-power electronic systems [4,10].

This study investigates the performance of two PMFC configurations constructed using different soil types and electrode materials. The electrical performance was evaluated based on open-circuit voltage, power output, and capacitor charging capability to determine the most effective configuration for future low-power IoT monitoring applications.

2. Methodology

The system block diagram in Fig. 1 illustrates the overall operation of the proposed PMFC energy harvesting system. Electrical energy is generated through the interaction between plant roots and soil microorganisms, where electrons released during microbial metabolism are collected by the anode and transferred to the cathode. The harvested energy is then regulated by a power management circuit before being stored in an energy storage device, such as a rechargeable battery or capacitor. The stored energy can subsequently be supplied to low-power IoT devices, including a microcontroller and environmental sensors. The system performance is influenced by factors such as soil type, soil moisture, plant type, and organic matter content.

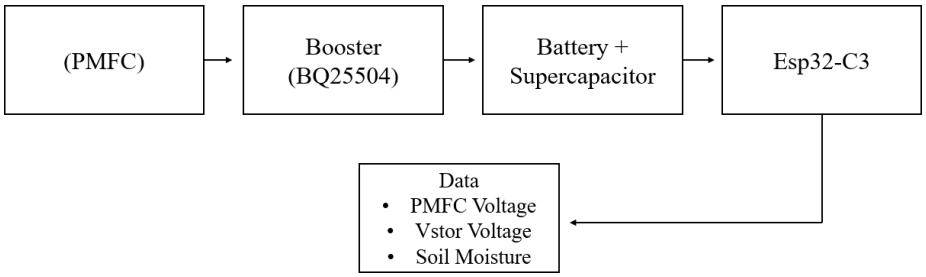


Fig. 1 *System Block Diagram*

The flowchart in Fig. 2 shows, in a clear and step-by-step way, how the PMFC that generated power for monitoring system is developed and tested, while directly reflecting the three main objectives of the project. The process starts with preparing the soil by adding water and fertilizer to encourage microbial activity. Electrodes are then placed into the soil to collect electrons released when microorganisms break down organic matter.

The electrical energy produced is passed through a power management circuit to regulate the voltage and is stored in a 5.5V supercapacitor. This stored energy provides a stable power supply for charging low-power microcontroller. At the same time, environmental factors such as moisture level are monitored to understand how they affect system performance.

If the output power is found to be insufficient, system parameters are adjusted and the process is repeated to improve efficiency. This iterative approach ensures both effective experimentation and practical system operation. Overall, the flowchart highlights a structured and systematic method for developing a sustainable, renewable, and off-grid energy solution.

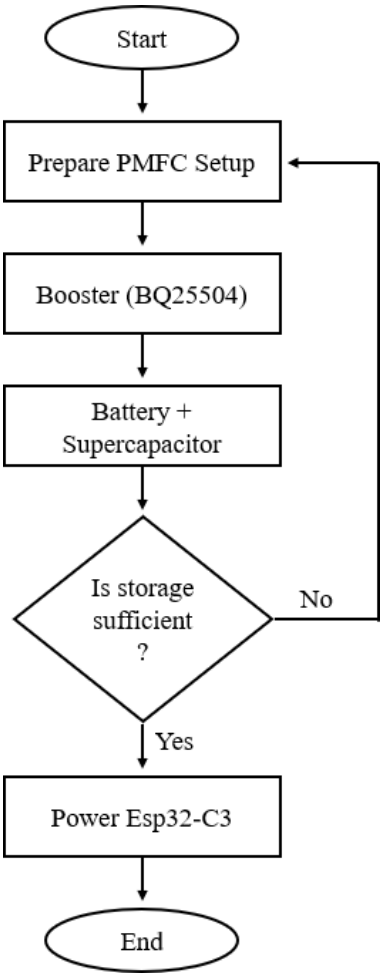


Fig. 2 *System Flowchart*

Fig. 3 shows the proposed PMFC system consisting of four individual pots planted with Javanese Ginseng. Each pot provides sufficient space for root growth, microbial activity, and electrode placement to support bioelectricity generation. The separate PMFC units allow performance comparison while maintaining a compact and manageable experimental setup.

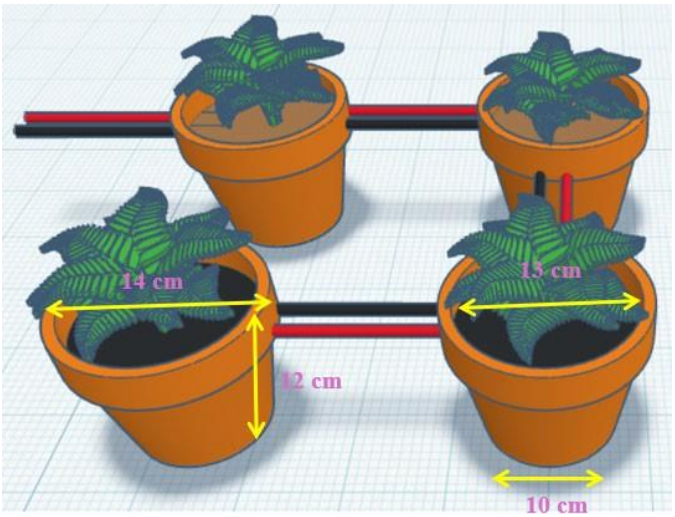


Fig. 3 *Design of PMFC setup*

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Fig. 4 illustrates the structure of the proposed PMFC unit. The cathode, made of carbon felt, is positioned near the soil surface to facilitate the oxygen reduction reaction, while the anode (carbon felt or graphite plate) is placed at the bottom of the pot in the oxygen-limited zone where microbial activity is highest. Both electrodes are connected to an external circuit for electrical measurements. This configuration promotes efficient electron transfer while maintaining a simple and compact PMFC design.

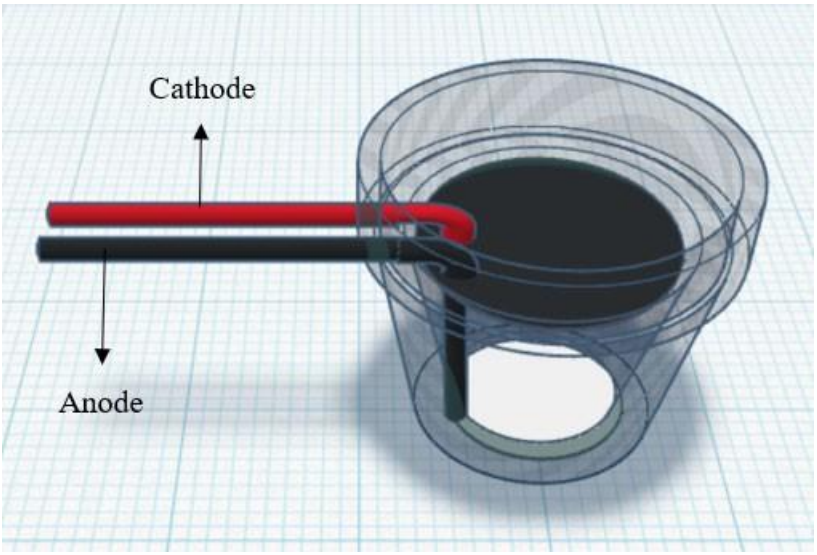


Fig. 4 *View of the PMFC Setup*

Two PMFC units were prepared using two different soil types, namely paddy soil and organic soil, while carbon felt was used as both the anode and cathode in each configuration. Javanese Ginseng (*Talinum triangulare*) was selected as the host plant to provide a continuous source of organic compounds for microbial activity. The anode was positioned at the bottom of the pot, whereas the cathode was placed near the soil surface. Electrical connections were established using copper wires, and a root booster was added to promote root development and microbial activity, thereby enhancing the bioelectricity generation performance of the PMFC.

The BQ25504 ultra-low-power energy harvesting IC was used as the power management circuit to boost and regulate the low voltage generated by the PMFC. As shown in Fig. 5, the PMFC output is supplied to BQ25504, which incorporates a DC-DC boost converter, maximum power point tracking (MPPT), and energy storage management. The harvested energy is boosted and stored in an energy storage device, providing a more stable power source for low-power electronic applications. The integrated design of the BQ25504 improves energy harvesting efficiency while simplifying the overall circuit configuration, making it suitable for PMFC- based energy harvesting systems.

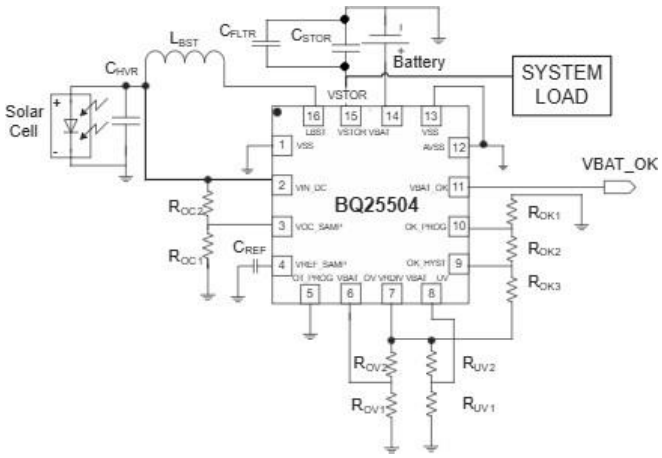


Fig. 5 *BQ25504 Booster Circuit.*

3. Result and Discussion

The electrical performance of the PMFC system was evaluated by monitoring the open-circuit voltage, *Voc*, current, power output, and soil moisture under controlled indoor conditions. Measurements were recorded daily at 11:30 p.m. to ensure consistency throughout the experiment. Before data collection, all PMFC components and measuring instruments were properly connected and calibrated to obtain accurate and reliable readings. Fig. 7 presents the total *Voc* recorded for all PMFC configurations during the experimental period.

Two PMFC configurations were constructed using different types of soil, namely paddy soil and organic soil, with carbon felt used as both the anode and cathode. This configuration enabled a comparative evaluation of the effect of soil type on the electrical performance of the PMFC system.

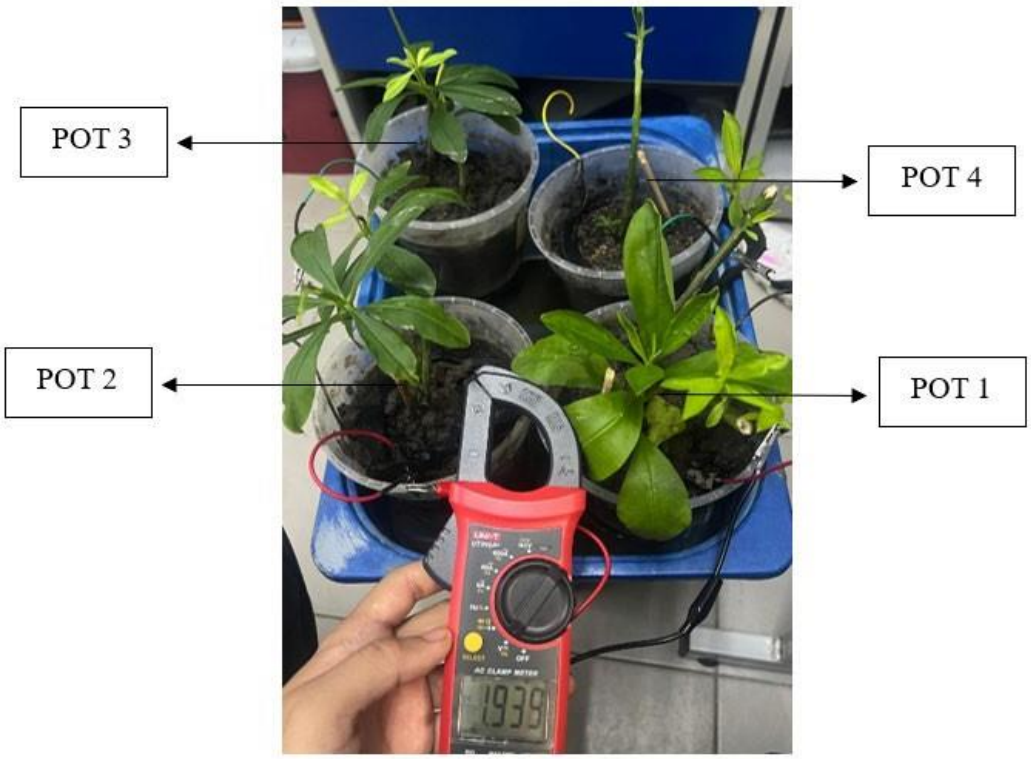


Fig. 7 *Total PMFC Voc readings.*

Table 1 presents the open-circuit voltage, *Voc* generated by the two PMFC configurations over six days. Among the two configurations using carbon felt as the anode, Pot 4 (organic soil) consistently produced higher *Voc* values than Pot 2 (paddy soil). Pot 4 reached a maximum *Voc* of 269.70 mV, while Pot 2 recorded a maximum of 262.80 mV. The higher voltage generated by Pot 4 suggests that organic soil provided a more favourable environment for microbial activity, resulting in improved electrical performance compared to paddy soil when the same anode material was used.

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Table 1: Open Circuit Voltage for Two Pots

DAY	POT 2 (*Voc*,mV)	POT 4 (*Voc*,mV)
1	147.40	80.60
2	167.10	105.40
3	155.50	203.30
4	216.10	164.60
5	213.10	187.60
6	262.80	269.70

Fig. 8 presents the *Voc* of the two PMFC configurations over the 7-day observation period, providing a clearer visualization of the data presented in Table 1. The graph highlights the voltage trends, fluctuations, and stability of each configuration, allowing a direct comparison between the PMFCs using paddy soil and organic soil. The observed trends help evaluate the influence of soil type on the electrical performance of the PMFC system throughout the experimental period [9,11].



Fig. 8 *Open circuit voltage of PMFC setups over 6 days.*

While the *Voc* indicates the maximum voltage generated by the PMFC, it does not represent the actual usable power delivered to a load. Therefore, the power output was calculated using the measured load voltage and load current based on P=V×I. Table 2 presents the power output of the two PMFC configurations, allowing the effect of soil type on energy generation performance to be compared.

Table 2: Power Output for Two Pots

DAY	POT 2 (µW)	POT 4 (µW)
1	0.0101	0.0000
2	0.0042	0.0000
3	0.0281	0.0000
4	0.0281	0.0000
5	0.0372	0.0001
6	0.0212	0.0212

Table 2 presents the power output of the two PMFC configurations over the six-day observation period. Both configurations generated relatively low power output throughout the experiment. Pot 2 (paddy soil) consistently produced higher power than Pot 4 (organic soil) from Day 1 to Day 5, reaching a maximum of 0.0372 µW on Day 5. In contrast, Pot 4 produced negligible power during the same period and only reached 0.0212 µW on Day 6, which was equal to the output of Pot 2. These results indicate that the paddy soil configuration exhibited better electrical performance than the organic soil configuration under the tested conditions.

This study investigated the performance of two PMFC configurations using paddy soil and organic soil with carbon felt as both the anode and cathode. The experimental results confirmed that both configurations could generate electrical energy through plant–microbial interactions [12,13,14]. The paddy soil configuration demonstrated better electrical performance, producing a higher maximum power output of 0.0372 µW, while the organic soil configuration generated a maximum of 0.0212 µW. The findings indicate that soil type significantly influences the electrical performance of PMFC systems when the electrode material is kept constant. Although the generated power remains relatively low, the study demonstrates the feasibility of PMFC technology as a sustainable and environmentally friendly energy harvesting method for future low-power IoT applications [4,5,7,10]. Further improvements in electrode design, energy management circuits, and experimental conditions are recommended to enhance the overall performance of the PMFC system.

4. Conclusion

This study investigated the performance of two PMFC configurations using paddy soil and organic soil with carbon felt as both the anode and cathode. The results confirmed that both PMFCs could generate electrical energy through plant–microbial interactions. Among the two configurations, the PMFC using paddy soil produced a higher maximum power output of 0.0372 µW, while the organic soil configuration reached 0.0212 µW. These findings indicate that soil type influences the electrical performance of PMFC systems when the electrode material is kept constant. Although the power generated was relatively low, the study demonstrates the feasibility of PMFC technology as a renewable and environmentally friendly energy harvesting source for future low-power IoT applications. Future work should focus on improving power output and integrating efficient energy management circuits to enhance system performance.

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