

Research article

Electricity Generation from Bio-treatment of Sewage Sludge Plant Microbial Fuel Cells with *Oryza sativa*

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Abstract

Plant microbial fuel cells (PMFCs) are emerging biotechnological devices that support renewable energy sources. PMFCs can be integrated with various substrates, such as sewage sludge, municipal compost, or even fertilizer, to enhance bioelectricity production. In this study, the performance of paddy (*Oryza sativa*) PMFCs was evaluated using municipal wastewater treatment sewage sludge and the PMFC performance was compared with natural paddy soil. Graphite fiber electrodes containing 3 kg of paddy soil and sewage sludge were installed in each PMFC system. All PMFCs were conducted on a balcony equipped with a rain shelter, where sunlight, temperature, and humidity varied for 90 days. The voltage outputs for the PMFC and sewage-PMFC reached maximum power outputs of 680 ± 28.31 mV (27.78 mW/m²) and 562.50 ± 69.22 mV (19.01 mW/m²), respectively. Notable decreases in pH and electrical conductivity (EC) were observed throughout the experiment and were attributed to bioelectrochemical processes within the PMFCs. The dominant microbial phyla identified in both PMFCs were *Proteobacteria*, *Bacteroidetes*, and *Chloroflexi*. This study demonstrated that the power generation of PMFCs can be enhanced by bio-treatment of sludge and various plants can be used for future sludge treatment. Overall, this research demonstrated the potential of plant microbial fuel cells for further improving energy recovery from sewage sludge generated by the biological treatment process.

Keywords: bioelectricity; sewage sludge; plant microbial fuel cells; waste valorization; renewable energy

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1. Introduction

Currently, energy demand is increasing as the need for clean, renewable energy sources. Interest in bioenergy production and energy recovery from biological treatment has been a concern, as a sustainable source of energy. Alternative technologies for bioenergy production and resource recovery are required for the future. Plant microbial fuel cells (PMFCs) are eco-friendly biotechnological devices that integrate sediment microbial fuel cells (SMFCs) and plant rhizodeposition to convert chemical energy into electrical energy. SMFCs are set up in the same manner as microbial fuel cells (MFCs). Organic compounds are oxidized by electrochemically active bacteria (EAB) under anaerobic conditions at the anode, releasing electrons that are transported to the cathode. Bio-electricity is generated by electron transport through redox reactions and can be harvested by electrodes. The difference between them is that SMFCs use a naturally oxygen-containing ingredient as a proton exchange membrane (PEM) to separate the electrodes (Xu et al., 2015). Nevertheless, MFCs and SMFCs experience electrode clogging due to incomplete degradation of organic compounds, thereby reducing their efficiency (Liu et al., 2016). Plant microbial fuel cells can not only solve this problem but also increase bioenergy production through bio-electrochemical systems. According to PMFCs systems, plants produce organic substances through photosynthesis, and plant roots excrete a portion of these substances including glucose, amino acids, lysates, etc. Besides, root exudation provides a supplement to electrochemically active bacteria capable of converting organic substances into electrical energy in the rhizosphere (Logan et al., 2006; Strik et al., 2008; Kacmaz et al., 2024; Lepikash et al., 2024).

The performance of PMFCs depends on various factors, including plant species, microbial community at the rhizosphere (Wang et al., 2015), PMFC configuration (Nitorisavut et al., 2017; Regmi et al., 2017), electrode materials and electrode sizes (Ueoka et al., 2016; Sudirjo et al., 2018), soil types and substrates (Moqsud et al., 2015), and the environment. In PMFCs, conductive plants increase microbial activity and support organic degradation. Many plants have been selected for PMFCs, such as *Glyceria maxima*, *Spartina anglica*, *Typha latifolia* (Timmers et al., 2012; Oon et al., 2015), *Wachendorfia thyrsiflora* and *Cyperus papyrus nanus* (Gulamhussein et al., 2020), mostly due to their suitability for anaerobic environments. Typically, wetland or waterlogged plants play a key role in PMFC systems because their environments maintain anaerobic conditions and support anaerobic microorganisms. Marshy plants have been used in PMFCs due to their ability to survive in anaerobic and high salinity conditions. In addition, their root biomass increases microbial activity (Gulamhussein et al., 2020). Agricultural plants, such as rice, can also be used in PMFCs where they can simultaneously reduce greenhouse gas emissions and recover nutrients (Chong et al., 2025). A previous study reported that PMFC with *Oryza sativa* had a power density of 11.1 mW/m² and produced a 39% reduction in methane emissions (Khudzari et al., 2019). It showed that PMFC systems are associated with lower methane emissions by inhibiting methanogenic processes (Arends et al., 2014).

Furthermore, the soil or substrate characteristics influence the roots and soil interface, which relates to the healthy relationship between microbes and plants. In addition, agricultural soil can generate more power than forest soil because it contains polyphenols, acetate from organic fertilizers, and a diversity of microbes, whereas forest soil contains non-electrogenic microbes (Chong et al., 2025). Among the needs for clean energy, waste valorization, and resource recovery, PMFCs are an alternative biotechnology due to their low cost and longevity, and they can be applied to other

technologies such as biosensors, bioremediation, and wastewater treatment. According to previous studies, PMFCs are capable of degrading organic contents. Villasenor et al. (2013) demonstrated the potential of wetland PMFC configuration for wastewater treatment and energy recovery. Sludge and wastewater are rich in organic matter, which can be served as supplemental food sources for microbes in PMFCs to generate energy while simultaneously treating wastewater (Ismail & Jaeel, 2013). For instance, thickened waste-activated sludge was applied as a substrate in *W. thyrsoflora* PMFCs, yielding the highest power output of 1036 mW/m³ (Gulamhussein et al., 2020). In another study, a *Dracaena* plant-based microbial fuel cell with 30% municipal solid waste compost showed the highest density of 204 mW/m² and current density of 255 mA/m² (Sonu et al., 2025). Although PMFCs are still emerging and face limitations in their bioelectricity generation performance, it is essential to explore their application in waste management and improve their performance. Thus, this study aimed to investigate the performance of paddy (*Oryza sativa*) PMFCs using sewage sludge to enhance bioelectricity production and support waste valorization.

2. Materials and Methods

2.1 Substrate preparation

Two substrates were selected in this study: 1) natural paddy field soil samples, and 2) sewage sludge. A composite soil sampling method was designed to collect 5 soil subsamples and mix them into a single representative sample (approximately 20 kg of each substrate). Topsoil of approximately 0-20 cm depth was collected from the demonstration paddy fields of Valaya Alongkorn Rajabhat University, Pathum Thani (14°08'06.6"N 100°36'36.1"E). Sewage sludge was obtained from the sludge-drying site of the central municipal wastewater treatment facility in Nava Nakorn Industrial Zone, which was prepared for composting. Sewage sludge was treated at the treatment plant through processes including conditioning and dewatering, and some sludge was open-dried for 2-4 months for composting, while others were then transferred to a landfill.

Physicochemical properties, including pH, electrical conductivity (EC), organic carbon, and organic matter, were evaluated. The electrode method was used to measure pH and EC values. For pH measurement, a dried sample was mixed with DI water, stirred for 15-30 minutes, and the suspension was then measured with a pH meter (multiHQ40d, HACH USA) (ISO, 2021). Additionally, an EC meter (multiHQ40d, HACH USA) was used to measure the EC of the sample by adding DI water at a 1:5 ratio, shaking for 1 h, and filtering the supernatant (FAO, 2021; ISO, 2025). Soil moisture content was determined by the gravimetric method, using the difference in the weights of the wet and dry samples, which were dried at 110°C for 16-24 h in an oven (ASTM, 2019). The organic carbon content was determined by acid wet oxidation, and the organic matter content was indirectly estimated by multiplying the organic carbon concentration by 1.724 (Walkley, 1947; Nelson & Sommers, 1996). All parameters were evaluated in triplicate (n=3), and the properties are shown in Table 1. Before setting up PMFCs, all substrates were air-dried for 5-7 days, ground, and screened through a 2 mm sieve. All substrates in this study were maintained under equilibrium and saturation conditions (Wetser et al., 2015) by keeping the water level constant and were left for 1 month before conducting PMFC experiments.

Table 1. Physiochemical properties of soil and sewage sludge

Parameter Sample*	pH	Electrical Conductivity ($\mu\text{S}/\text{cm}$)	Moisture (%)	Organic Carbon (%)	Organic Matter (%)
Soil	5.73 $\pm$ 0.11	63.7 $\pm$ 9.3	60 $\pm$ 0.81	2.7 $\pm$ 0.2	4.6 $\pm$ 0.6
Sewage sludge	5.05 $\pm$ 0.25	256.0 $\pm$ 12.0	44 $\pm$ 0.82	4.7 $\pm$ 0.5	8.1 $\pm$ 0.8

2.2 Plant cultivation

In this study, rice seeds (*Oryza sativa*) were obtained from Pathum Thani Rice Research Center. Rice seeds were soaked in water and incubated at 25-27 °C without light. After rice shooting, the rice plants were grown in the soil until 1 month old, and then 5 similar-length plants were planted in PMFC systems.

2.3 PMFC design and operation

In this study, *Oryza sativa* was selected for the experiment. PMFCs were constructed in polypropylene pots (15 cm diameter and 20 cm height). Each pot contained 3 kg of homogenized substrates and 2 L of deionized water. Graphite fiber (100 mm diameter and 3 mm thickness) was selected as the electrode material. The distance between the anode and cathode was approximately 5-7 cm. The anode was immersed in the soil while the cathode was placed on the top of the soil. Both the anode and the cathode were woven with copper wire and connected to a 1000- Ω external resistor to complete a closed circuit for both the anode and the cathode, and around each electrode. In this experiment, the performance of *Oryza sativa* PMFC with sewage sludge (sewage-PMFC) was compared with that of *Oryza sativa* PMFC with natural paddy soil (PMFC). All experiments were done in triplicate and conducted on the balcony of the environmental science laboratory (Valaya Alongkorn Rajabhat University, Thailand) for 90 days, with a rain shelter provided and sunlight, temperature, and humidity varying with the weather. To keep all experiments waterlogged, all treatments were irrigated daily. In addition, pH and electrical conductivity (EC) were monitored weekly. All soil samples at the cathode were collected and measured for pH and EC using a portable electrode meter (multiHQ40d, HACH USA) (ISO 10390, 2021; ISO11265, 2025; FAO, 2021).

2.4 Performance of PMFCs and sewage-PMFCs

The bioelectricity of the PMFCs was evaluated in terms of voltage and current. The electrodes were connected across the resistor and measured daily using a data logger acquisition device (2700 Keithley, USA). The electrical and power outputs were evaluated using Ohm's law, and current density was calculated based on the anode area using equations (1) and (2) (Moqsud et al., 2015).

$$I = V/\alpha R \quad (1)$$

$$P = V_x I \quad (2)$$

Where I represents current (mA), V represents voltage (mV), R represents the external load resistance (Ohms), a represents electrode surface area (m²), and P represents power (mW).

After 30 days, the polarization was investigated across the different resistors (ranging from 10 Ω to 15 K Ω). The Internal resistances and power densities were calculated based on previous literature, which states that the maximum power density is obtained when the internal resistance equals the external resistance (R_{ext}), as shown in equations (3) (Logan et al., 2006; Tongphanpharn et al., 2023).

$$R_{int} = R_{ext} = P_{max}/I^2 \quad (3)$$

Where I represents the current corresponding to the maximum power density.

2.5 High-throughput sequencing of the 16S rRNA gene amplicon and statistics analysis

At the end of the experiment, the soil samples of both PMFCs were collected for analysis of microbial community structure using 16S rRNA gene amplicon high-through sequencing. The DNA was extracted from 0.25 g of the anode soil of each PMFC using a commercial DNA extraction kit (DNeasy PowerSoil Kit, QIAGEN, Germany) and transferred for sequencing (Gibthai, Thailand). The V3 and V4 regions of microbial 16S rRNA genes were amplified using the following universal primers: 341F (5'- CCTACGGGNGGCWGCAG -3') and 805R (5'-GACTACHVGGGTATC TAATCC-3'). The libraries were prepared using a Truseq Nano DNA library kit (Illumina, USA) and were sequenced on an Illumina Miseq platform with 300 bp paired-end reads of the gene sequences were obtained (Caporaso et al., 2010). The sequences were clustered into operational taxonomic units (OTUs) with 97% sequenced identity. The diversity indices of microbial communities were processed using QIIME (Caporaso et al., 2010) and the taxonomic classification was represented using SILVA database (Quast et al., 2013).

For the statistical analysis, descriptive statistics and analysis of variance (one-way ANOVA (IBM SPSS Statistics version 19.0) were used to compare the electrical voltage, pH, and EC values of all treatments. A significance level at P -value less than 0.05 was provided to compare PMFCs and sewage-PMFCs.

3. Results and Discussion

3.1 Performance of PMFCs

The voltage outputs of both PMFCs were shown in Figure 1. After running the bio-electrochemical systems for 15 days, the closed circuits showed varying voltage outputs. The highest voltage for the PMFC was 680 $\pm$ 28.31 mV, while sewage-PMFC showed the highest voltage of 562.50 $\pm$ 69.22 mV. Comparing the PMFC and sewage-PMFC, the PMFC showed significantly higher voltage output ($P<0.05$). The results suggested that the variation in both PMFCs voltage outputs reflected microbial activity based on the organic content in the substrates. Typically, root exudates contain organic substances, including low-molecular-weight compounds such as amino acids, and sugars, which serve as supplements for electrochemically active bacteria (EBA) (Pinton & Varanini, 2007; Hamelers et al., 2009). After 30 days of the experiment, PMFC polarization was tested to assess the bioelectrochemical system's characteristics. The internal resistance was

estimated to be 239Ω at the maximum power density of 4.53 mW/m^2 . The polarization curve showed patterns similar to those observed in previous PMFC studies (Moqsud et al. 2015). It has been suggested that bioelectricity generation in PMFCs is due to the biochemical process of EBA at the anode (Tongphanpharn et al., 2023).

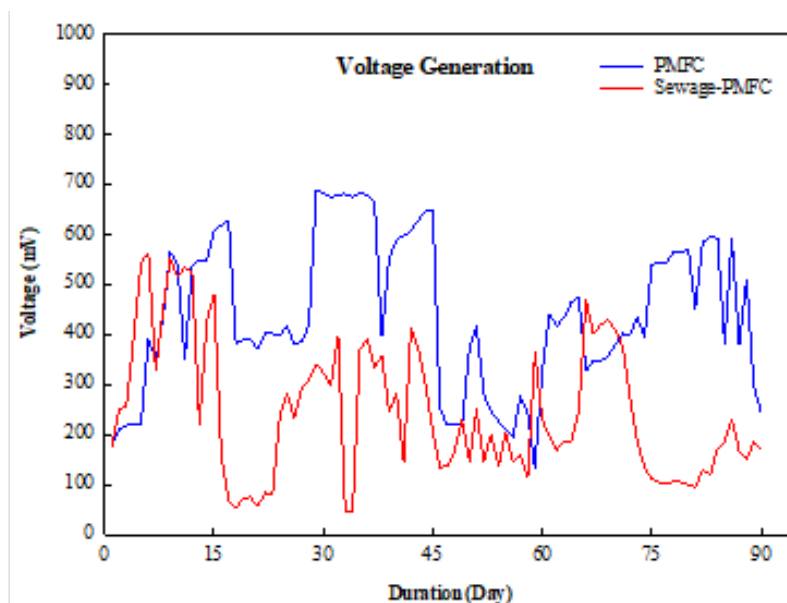


Figure 1. Voltage generation of PMFC and Sewage-PMFC versus time

The sewage-PMFCs voltage output increased sharply at the initial stage and then gradually decreased at the end of the experiment. This suggested that the excessive organic content in municipal sewage sludge (4.7% organic carbon and 8.1% organic matter) adversely affected the relationship between root plants and microbial activity. According to a previous study, excessive compost can inhibit root and plant growth. In addition, the high organic matter content could increase decomposition rates and phytotoxicity, inhibiting the plant's ability to absorb other nutrients (Sonu et al., 2025). Although the abundance of organic content in soil or other substrates can enhance bioelectricity production in PMFC systems, appropriate values should be considered alongside soil-root and microbial interactions. A similar decrease in voltage output was observed in both PMFCs in this study (days 40th- 60th), caused by the drying out of PMFC cells, which affected microbial activity and redox potential, as reported in a previous study; the bioelectricity of PMFCs dropped during the dry phase (Chen et al., 2024).

3.2 The changes of pH and EC in PMFCs

The pH and EC values of the soil-water interface at the cathode of all PMFCs were monitored weekly, as shown in Figure 2(a). The pH values for PMFC ranged from 6.00 ± 0.07 to 7.76 ± 0.45 , while the sewage-PMFC showed values from 7.70 ± 0.15 to 8.27 ± 0.16 , as shown in Figure 2. Generally, pH values of both PMFCs showed a slightly increasing trend from the initial acidic (5.03 and 5.73 pH of sewage sludge and soil, respectively) to neutral pH values. As shown in a previous study, rapid consumption of H^+

during the oxygen reduction reaction at the cathode can increase pH in the cathode chamber of MFCs (Wu et al., 2019). According to the PMFC systems, the cathode was placed at the interface between the soil surface and water. The increase in pH during the experiment was influenced by redox reactions among microorganisms, plants, soil, substrates, and the PMFC electrode system (Guan et al., 2019; Tongphanpharn et al., 2023). In addition, the pH range of 6 to 9 was generally suitable for bioelectrochemical systems (BES) (Behera et al., 2009). In contrast, a decrease in pH from 8 to 6 in MFCs inhibited exoelectrogenic microorganism metabolism, resulting in a decrease in power density from 600 mW/m² to 158 mW/m² in a previous study (Oliveira et al., 2013; Kuleshova et al., 2022).

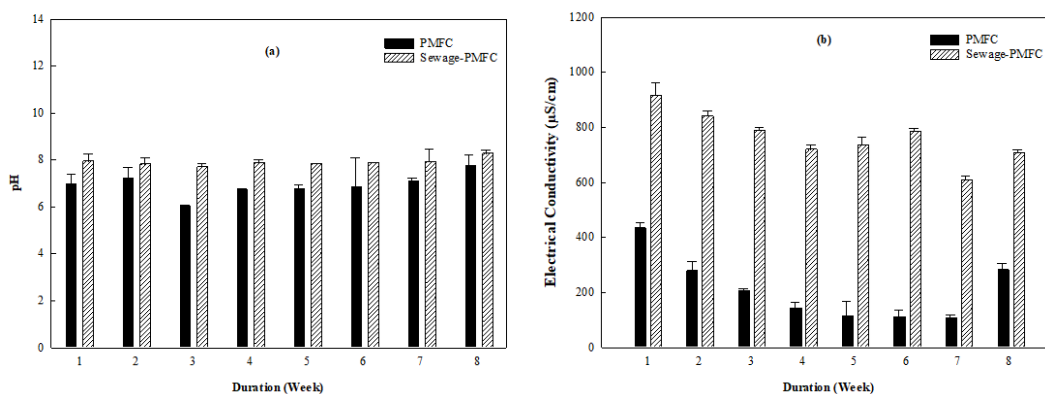


Figure 2. Variation of pH and EC (a) Changes of pH of PMFC and sewage-PMFC; (b) changes of EC of PMFC and sewage-PMFC

Generally, EC concentration in soil reflects soil fertility and barrenness, and it is influenced by soil solution (Guan et al., 2019). For electrical conductivity (EC), the PMFC had an EC range of 105.27 ± 11.80 to 432.33 ± 22.76 $\mu\text{S/cm}$, while the sewage-PMFC ranged from 608.33 ± 14.70 to 916.33 ± 45.41 $\mu\text{S/cm}$, respectively, as shown in Figure 2(b). EC values for all treatments decreased over the duration of the experiment. This indicated that bioelectrochemical process played a role in the migration of soluble ions in PMFCs. As reported in a previous study, the redox reaction in PMFCs could influence EC in the soil, where the anode facilitates the oxidation of organic compounds and reducing ions, while the cathode facilitates reducing ions at a higher state (Rabaey et al., 2006; He et al., 2009; Zhao et al., 2009). Typically, ionic strength positively affected ion transport. Several studies reported that high concentrations of EC increase power density in MFC systems (Timmers et al., 2010; Kiran et al., 2023; Vijay et al., 2023). On the other hand, PMFC systems could drive a strong bioelectrochemical process because plants can likely take up the associated EC in soil. Nonetheless, different soil properties could affect the composition of soil ions. Since sewage sludge was used as the PMFC substrate in this study, the initial EC concentration was high, resulting in slightly lower voltage output. Excessive EC values may inhibit plant growth, microbial metabolism, and rhizodeposition. Consequently, this leads to decreased photosynthetic activity and physiological disorders (Hakim et al., 2014). Thus, this needs to be further studied to develop the power production of PMFC coupled with bio-sludge.

3.3 Microbial communities

At the end of the experiment, anode soil samples from all treatments were analyzed for their microbial community. High-throughput sequencing of 16S rRNA genes, amplified using 16S V3–V4 341F and 805R primers, was performed for microbial analysis. Figure 3 presents the relative abundance of microbial communities at the phyla and family level. The taxonomy classification showed that the most predominant phylum across all samples was *Proteobacteria*, with a relative abundance of 19.98–20.79%, followed by *Patescibacteria*, *Bacteroidetes*, *Chloroflexi*, and *Planctomycetes*, with relative abundances of 14.51%–18.11%, 6.60–8.35%, 4.24–12.50%, and 4.04–4.83%, respectively. The most abundant family was *Geobacteraceae*, which ranged from 1.25% to 4.24%, followed by *Rhodocyclaceae* (0.32% to 1.31%) and *Desulfobulbaceae* (0.43% to 1.01%). As reported in previous studies, *Geobacteraceae* play a key role in the electrochemical system for electricity generation in PMFCs (Kan et al., 2011; Yates et al., 2012) since the root exudates of PMFCs provide acetate, organic compounds, and other substrates act as electron donors for EBA. In addition, microbial species such as *Desulfobulbus*, *Natronocella acetinitrilica*, *Beijerinckiacae*, *Rhizobiales*, *Bacteroidetes*, and *Chloroflexi*, which were found at the anode of paddy PMFCs, were considered as producing bioelectricity (Kaku et al., 2008; De Schampelaire et al., 2010). In the PMFC system, the electroactive bacteria (EBA) form biofilms at the anode, affecting microbial diversity, population dynamics, and competition (Berendsen et al., 2018). The presence of an electrical circuit may enhance the growth of specific electroactive bacteria while inhibiting others, thereby shifting community composition (Blanco-Romero et al., 2022). Similarly, there is a difference in bioelectricity production in this study. Microbial diversity is influenced by plant types, substrates, and environments. Therefore, soil properties and bio-sludge used in PMFCs influenced the relationship between microbial groups and plant roots, thereby affecting the variation in electricity production. Nonetheless, further research is needed to reveal the unclear aspects of microbial population changes, carbon, nitrogen, sulfur, and iron cycling, competition among microbial groups, and the reduction of greenhouse gas emissions in bio-sludge PMFCs.

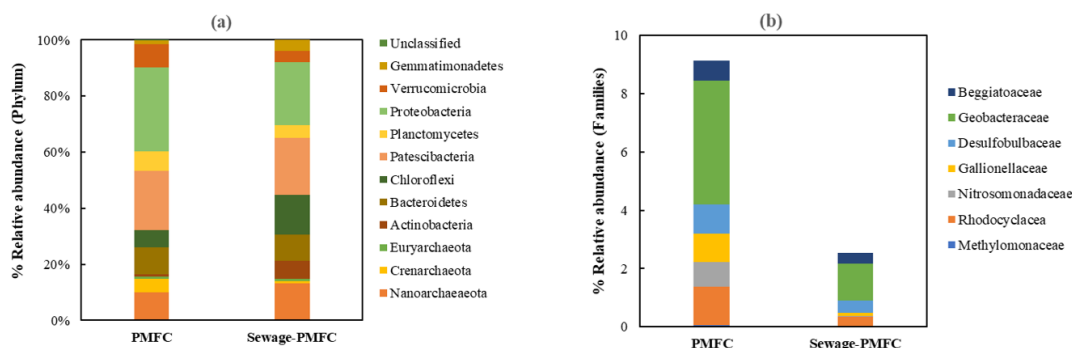


Figure 3. Microbial communities of all PMFC (a) Relative abundance of phyla of all PMFCs; (b) Relative abundance of families of all PMFCs

4. Conclusions

PMFC and sewage-PMFC with *Oryza sativa* were conducted for 90 days. The voltage output of PMFC achieved the maximum voltage of 680 ± 28.31 mV (27.78 mW/m²) while sewage-PMFC reached the maximum voltage of 562.50 ± 69.22 mV (19.01 mW/m²), respectively. Sewage-PMFC showed a lower voltage output than PMFC, likely due to excessive EC values and organic matter content. The gradual reduction in EC concentrations and pH values, which were slightly increased to a neutral level during the experiment, was associated with the bioelectrochemical systems in PMFCs. High-throughput sequencing of the 16S rRNA gene revealed that *Proteobacteria*, *Patescibacteria*, *Bacteroidetes*, *Chloroflexi*, and *Planctomycetes* were the most abundant phyla in the anode microbial community. *Geobacteraceae*, the exoelectrogen microbial group, was the dominant group in both PMFCs and showed the highest abundance in PMFC. On the other hand, excessive sewage sludge could adversely affect plants, root exudates, and microorganisms in PMFCs, leading to lower electricity production. Therefore, this study showed that bio-treatment waste can be used in PMFCs as additional substrates or soil amendments; however, the suitability of the content should be further investigated. Furthermore, the relationship between plants' root-soil and microbial community, along with the application of waste valorization should be addressed.

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6. Authors' Contributions

Natagarn designed conceptualization, performed the research, data analysis and writing original draft; Natsima contributed to formal analysis and analytic tools; Montip involved in investigation and data analysis; Weerawat coordinated the research, review and editing the paper.

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7. Conflicts of Interest

The authors declare no conflict of interest.

References

- Arends, J. B., Speeckaert, J., Blondeel, E., De Vrieze, J., Boeckx, P., Verstraete, W., Rabaey, K., & Boon, N. (2014). Greenhouse gas emissions from rice microcosms

- amended with a plant microbial fuel cell. *Applied Microbiology and Biotechnology*, 98(7), 3205-3217.
- ASTM. (2019). *ASTM D2216-19; Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass*. ASTM International.
- Behera, M., & Ghangrekar, M. A. (2009). Performance of microbial fuel cell in response to change in sludge loading rate at different anodic feed pH. *Bioresource Technology*, 100(21), 5114-5121.
- Berendsen, R. L., Vismans, G., Yu, K., Song, Y., de Jonge, R., Burgman, W. P., Burmølle, M., Herschend, J., Bakker, P. A. H., & Pieterse, C. M. (2018). Disease-induced assemblage of a plant-beneficial bacterial consortium. *The ISME journal*, 12(6), 1496-1507.
- Blanco-Romero, E., Garrido-Sanz, D., Durán, D., Rivilla, R., Redondo-Nieto, M., & Martín, M. (2022). Regulation of extracellular matrix components by AmrZ is mediated by c-di-GMP in *Pseudomonas ogarae* F113. *Scientific Reports*, 12(1), Article 11914. <https://doi.org/10.1038/s41598-022-16162-x>
- Caporaso, J. G., Kuczynski, J., Stombaugh, J., Bittinger, K., Bushman, F. D., Costello, E. K., Fierer, N., Peña, A. G., Goodrich, J. K., Gordon, J. I., Huttley, G. A., Kelly, S. T., Knights, D., Koenig, J. E., Ley, R. E., Lozupone, C. A., McDonald, D., Muegg, B. D., Pirrung, M., Reeder, J., ... & Knight, R. (2010). QIIME allows analysis of high-throughput community sequencing data. *Nature methods*, 7(5), 335-336.
- Chen, B., Li, L., Cai, W., & Garg, A. (2024). Bioelectricity generation in plant microbial fuel cells: Influence of vegetation density and unsaturated soil properties. *Biomass and Bioenergy*, 181, Article 107053. <https://doi.org/10.1016/j.biombioe.2024.107053>
- Chong, P. L., Chuah, J. H., Chow, C. O., & Ng, P. K. (2025). Plant microbial fuel cells: A comprehensive review of influential factors, innovative configurations, diverse applications, persistent challenges, and promising prospects. *International Journal of Green Energy*, 22(3), 599-648.
- De Schamphelaire, L., Cabezas, A., Marzorati, M., Friedrich, M. W., Boon, N., & Verstraete, W. (2010). Microbial community analysis of anodes from sediment microbial fuel cells powered by rhizodeposits of living rice plants. *Applied and Environmental Microbiology*, 76(6), 2002-2008.
- FAO. (2021). *Standard operating procedure for soil electrical conductivity soil/water, 1:5*. Food and Agriculture Organization.
- Guan, C. Y., Tseng, Y. H., Tsang, D. C., Hu, A., & Yu, C. P. (2019). Wetland plant microbial fuel cells for remediation of hexavalent chromium contaminated soils and electricity production. *Journal of Hazardous Materials*, 365, 137-145.
- Gulamhussein, M., & Randall, D. G. (2020). Design and operation of plant microbial fuel cells using municipal sludge. *Journal of Water Process Engineering*, 38, Article 101653. <https://doi.org/10.1016/j.jwpe.2020.101653>
- Hakim, M. A., Juraimi, A. S., Hanafi, M. M., Ismail, M. R., Rafii, M. Y., Islam, M. M., & Selamat, A. (2014). The effect of salinity on growth, ion accumulation and yield of rice varieties. *The Journal of Animal and Plant Sciences*, 24(3), 874-885.
- Hamelers, H. V., Ter Heijne, A., Sleutels, T. H., Jeremiasse, A. W., Strik, D. P., & Buisman, C. J. (2010). New applications and performance of bioelectrochemical systems. *Applied Microbiology and Biotechnology*, 85(6), 1673-1685.
- He, Z., Kan, J., Wang, Y., Huang, Y., Mansfeld, F., & Nealson, K. H. (2009). Electricity production coupled to ammonium in a microbial fuel cell. *Environmental Science and Technology*, 43(9), 3391-3397.
- Ismail, Z. Z., & Jaeel, A. J. (2013). Sustainable power generation in continuous flow microbial fuel cell treating actual wastewater: influence of biocatalyst type on

- electricity production. *The Scientific World Journal*, 2013(1), 713515. <https://doi.org/10.1155/2013/713515>
- ISO. (2021). *ISO 10390: Soil, treated biowaste and sludge—Determination of pH* (3rd ed.). International Organization for Standardization.
- ISO. (2025). *ISO 11265: Environmental solid matrices — Determination of the specific electrical conductivity* (2nd ed.). International Organization for Standardization.
- Kacmaz, G. K., & Eczacioglu, N. (2024). The mechanism of bioelectricity generation from organic wastes: Soil/plant microbial fuel cells. *Environmental Technology Reviews*, 13(1), 75-94.
- Kaku, N., Yonezawa, N., Kodama, Y., & Watanabe, K. (2008). Plant/microbe cooperation for electricity generation in a rice paddy field. *Applied Microbiology and Biotechnology*, 79(1), 43-49.
- Kan, J., Hsu, L., Cheung, A. C., Pirbazari, M., & Nealson, K. H. (2011). Current production by bacterial communities in microbial fuel cells enriched from wastewater sludge with different electron donors. *Environmental Science and Technology*, 45(3), 1139-1146.
- Khudzari, J. M., Gariépy, Y., Kurian, J., Tartakovsky, B., & Raghavan, G. V. (2019). Effects of biochar anodes in rice plant microbial fuel cells on the production of bioelectricity, biomass, and methane. *Biochemical Engineering Journal*, 141, 190-199.
- Kiran, R., Yadav, R., Sathe, D., & Patil, S. A. (2023). Halophilic CO₂-fixing microbial community as biocatalyst improves the energy efficiency of the microbial electrosynthesis process. *Bioresource Technology*, 371, Article 128637. <https://doi.org/10.1016/j.biortech.2023.128637>
- Kuleshova, T. E., Galushko, A. S., Panova, G. G., Volkova, E. N., Apollon, W., Shuang, C., & Sevda, S. (2022). Bioelectrochemical systems based on the electroactivity of plants and microorganisms in the root environment. *Sel'skokhozyaistvennaya Biologiya [Agricultural Biology]*, 57(3), 425-440. <https://doi.org/10.15389/agrobiology.2022.3.425eng>
- Lepikash, R., Lavrova, D., Stom, D., Meshalkin, V., Ponamoreva, O., & Alferov, S. (2024). State of the art and environmental aspects of plant microbial fuel cells' application. *Energies*, 17(3), Article 752. <https://doi.org/10.3390/en17030752>
- Liu, B., Williams, I., Li, Y., Wang, L., Bagtzoglou, A., McCutcheon, J., & Li, B. (2016). Towards high power output of scaled-up benthic microbial fuel cells (BMFCs) using multiple electron collectors. *Biosensors and Bioelectronics*, 79, 435-441.
- Logan, B. E., & Regan, J. M. (2006). Microbial fuel cells—challenges and applications. *Environmental Science and Technology*, 40(17), 5172-5180.
- Moqsud, M. A., Yoshitake, J., Bushra, Q. S., Hyodo, M., Omine, K., & Strik, D. (2015). Compost in plant microbial fuel cell for bioelectricity generation. *Waste Management*, 36, 63-69.
- Nelson, D. W., & Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. In D.L. Sparks, A.L. Page, P.A. Helmke, R.H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston & M. E. Sumner (Eds.) *Methods of Soil Analysis: Part 3 Chemical Methods* (pp. 961-1010) . Soil Science Society of America (SSSA). <https://doi.org/10.2136/sssabookser5.3.c34>
- Nitisoravut, R., & Regmi, R. (2017). Plant microbial fuel cells: A promising biosystems engineering. *Renewable and Sustainable Energy Reviews*, 76, 81-89.
- Oliveira, V. B., Simões, M., Melo, L. F., & Pinto, A. M. F. R. (2013). Overview on the developments of microbial fuel cells. *Biochemical Engineering Journal*, 73, 53-64
- Oon, Y. L., Ong, S. A., Ho, L. N., Wong, Y. S., Oon, Y. S., Lehl, H. K., & Thung, W. E. (2015). Hybrid system up-flow constructed wetland integrated with microbial fuel cell for simultaneous wastewater treatment and electricity generation. *Bioresource Technology*, 186, 270-275.

- Pinton, R., Varanini, Z., & Nannipieri, P. (2007). *The rhizosphere: biochemistry and organic substances at the soil-plant interface*. CRC press.
- Quast, C., Pruesse, E., Yilmaz, P., Gerken, J., Schweer, T., Yarza, P., Peplies, J., & Glöckner, F. O. (2012). The SILVA ribosomal RNA gene database project: improved data processing and web-based tools. *Nucleic Acids Research*, 41(Database Issue), D590-D596. <https://doi.org/10.1093/nar/gks1219>
- Rabaey, K., Van de Sompel, K., Maignien, L., Boon, N., Aelterman, P., Clauwaert, P., De Schampheleire, L., Pham, H. T., Vermeulen, J., Verhaege, M., Lens, P., & Verstraete, W. (2006). Microbial fuel cells for sulfide removal. *Environmental Science and Technology*, 40(17), 5218-5224.
- Regmi, R., & Nitisoravut, R. (2017). Effect of configuration and growth stages on bioenergy harvest in the paddy type microbial fuel cell under greenhouse condition. In *2017 International conference on green energy and applications (ICGEA)* (pp. 109-112). IEEE. <https://doi.org/10.1109/ICGEA.2017.7925465>
- Strik, D. P., Hamelers, H. V. M., Snel, J. F., & Buisman, C. J. (2008). Green electricity production with living plants and bacteria in a fuel cell. *International Journal of Energy Research*, 32(9), 870-876.
- Sonu, K., Syed, Z., Singh, G., Tiwari, M. K., & Sogani, M. (2025). Performance evaluation of a *Dracaena* plant-based microbial fuel cell utilizing municipal solid waste compost as substrate and stainless steel mesh-supported 3D *Cassia fistula* as bioanode. *Waste Disposal and Sustainable Energy*, 7(3), 453-467. <https://doi.org/10.1007/s42768-025-00244-3>
- Sudirjo, E., Buisman, C. J. N., & Strik, D. P. B. T. B. (2018). Electricity generation from wetlands with activated carbon bioanode. *IOP Conference Series: Earth and Environmental Science*, 131(1), Article 012046. <https://doi.org/10.1088/1755-1315/131/1/012046>
- Timmers, R. A., Strik, D. P., Hamelers, H. V., & Buisman, C. J. (2010). Long-term performance of a plant microbial fuel cell with *Spartina anglica*. *Applied Microbiology and Biotechnology*, 86(3), 973-981.
- Timmers, R. A., Rothballer, M., Strik, D. P. B. T. B., Engel, M., Schulz, S., Schlöter, M., Schlöter, M., Hartmann, A., Hamelers, B., & Buisman, C. (2012). Microbial community structure elucidates performance of *Glyceria maxima* plant microbial fuel cell. *Applied Microbiology and Biotechnology*, 94(2), 537-548. <https://doi.org/10.1007/s00253-012-3894-6>
- Tongphanpharn, N., Guan, C. Y., Chen, W. S., Chang, C. C., & Yu, C. P. (2023). Evaluation of long-term performance of plant microbial fuel cells using agricultural plants under the controlled environment. *Clean Technologies and Environmental Policy*, 25(2), 633-644.
- Ueoka, N., Sese, N., Sue, M., Kouzuma, A., & Watanabe, K. (2016). Sizes of anode and cathode affect electricity generation in rice paddy-field microbial fuel cells. *Journal of Sustainable Bioenergy Systems*, 6(1), 10-15.
- Vijay, A., Ghosh, P. C., & Mukherji, S. (2023). Power generation by halophilic bacteria and assessment of the effect of salinity on performance of a denitrifying microbial fuel cell. *Energies*, 16(2), Article 877. <https://doi.org/10.3390/en16020877>
- Villasenor, J., Capilla, P., Rodrigo, M. A., Cañizares, P., & Fernández, F. J. (2013). Operation of a horizontal subsurface flow constructed wetland–microbial fuel cell treating wastewater under different organic loading rates. *Water Research*, 47(17), 6731-6738.
- Walkley, A. (1947). A critical examination of a rapid method for determining organic carbon in soils—effect of variations in digestion conditions and of inorganic soil constituents. *Soil Science*, 63(4), 251-264.

- Wang, N., Chen, Z., Li, H. B., Su, J. Q., Zhao, F., & Zhu, Y. G. (2015). Bacterial community composition at anodes of microbial fuel cells for paddy soils: the effects of soil properties. *Journal of Soils and Sediments*, 15(4), 926-936.
- Wetser, K., Liu, J., Buisman, C., & Strik, D. (2015). Plant microbial fuel cell applied in wetlands: Spatial, temporal and potential electricity generation of *Spartina anglica* salt marshes and *Phragmites australis* peat soils. *Biomass and Bioenergy*, 83, 543-550.
- Wu, P. H., Wang, Y., Wu, P. H., Lu, S. Y., & Yu, C. P. (2019). Effects of cathode materials on H₂O₂ production in microbial fuel cells. *Desalination and Water Treatment*, 153, 105-111.
- Xu, B., Ge, Z., & He, Z. (2015). Sediment microbial fuel cells for wastewater treatment: challenges and opportunities. *Environmental Science: Water Research and Technology*, 1(3), 279-284.
- Yates, M. D., Kiely, P. D., Call, D. F., Rismani-Yazdi, H., Bibby, K., Peccia, J., Regan, J. M., & Logan, B. E. (2012). Convergent development of anodic bacterial communities in microbial fuel cells. *The ISME journal*, 6(11), 2002-2013.
- Zhao, F., Rahunen, N., Varcoe, J. R., Roberts, A. J., Avignone-Rossa, C., Thumser, A. E., & Slade, R. C. (2009). Factors affecting the performance of microbial fuel cells for sulfur pollutants removal. *Biosensors and Bioelectronics*, 24(7), 1931-1936.