Optimizing Bioelectricity Generation from Plant-Microbial Fuel Cells Using Soil-Based Electrodes and Natural Substrates

Dawit Dagne, African Leadership Academy

Mentor: Youssef Boumhaout, African Leadership Academy

Abstract

Plant-assisted microbial fuel cells (P-MFCs) are a novel bio-electrochemical system that could convert solar energy into electricity through a mutually-beneficial association of plant roots and soil microbes. In the present study, P-MFC prototypes were constructed in soil with live plants, using metallic electrodes to serve as an anode and cathode conductor for the transformation of electrons in soil, to assess the potential of using P-MFC. Continuous readings of voltage and current were collected to assess and compare the performance of different combinations of plant-soil, with a control MFC with no plants. In one design, the voltage achieved from a peak single cell was 0.75 V with a cumulative power density of 35 mW/m² of surface area, signifying that rhizodeposition from the plant assisted with microbial oxidation of root exudates to generate more electrons for the electrodes. Three P-MFCs combined in a series arrangement produced a total voltage of 2.1 V, with power density not significantly reduced, however any combination of more than three only provided minute changes in voltage (~10% increase). Again, this work suggests the importance of interaction with soil, plant species, and electrode design to optimize P-MFC operation. This work also supports a lower cost, environmental-friendly, offgrid, and easily scalable technology solution for energy generation in rural areas. This work provides implications for increasing bioelectricity outputs, as well as showcasing the ecological potential of plant-microbial interactions in simple, engineered designs. Further, the capacity to improve bioelectricity density and efficiency related to electrode materials and stacking systems highlighted an agenda for novel developments for implementation of P-MFC technologies.

I. Introduction

The unprecedented increase in global energy demand, coupled with environmental degradation caused by fossil fuel consumption [4], [3], has emphasized the urgent need for sustainable and renewable energy technologies. Conventional energy sources, including coal, petroleum, and natural gas, not only face depletion but are significant contributors to greenhouse gas emissions, environmental pollution, and climate change. This scenario has accelerated research into alternative bioelectrochemical systems, particularly microbial fuel cells (MFCs) [1], [2], which exploit the metabolic activity of electroactive microorganisms to convert organic substrates into electrical energy. In MFCs, microorganisms oxidize organic compounds at the anode, releasing electrons and protons, which are subsequently transferred to the cathode, where reduction reactions occur, generating a measurable electric current. Despite their promise, traditional MFCs exhibit limited power output (typically 20–70 mW/m²) [10] and face challenges related to electrode resistance, substrate availability, and scalability, restricting their practical applications in off-grid or rural energy systems.

A significant advancement in this field is the development of plant-assisted microbial fuel cells (P-MFCs), which leverage living plants to enhance bioelectricity generation through rhizodeposition [6], [9]. Rhizodeposition involves the release of root exudates, including sugars, amino acids, and organic acids, into the rhizosphere. These exudates serve as electron donors for electroactive microorganisms, thereby enhancing microbial oxidation rates and electron flow to the anode. The efficiency of P-MFCs depends on a complex interplay of biological, chemical, and engineering parameters, including plant species, root architecture, soil type and composition, moisture content, pH, microbial diversity, and electrode material and placement. Previous studies have demonstrated that plant selection can influence power output by up to sevenfold [7], and soil properties can modulate the availability of rhizodeposits and proton conductivity, directly impacting current density and voltage generation.

In this study, soil-based P-MFC prototypes were constructed using Vigna unguiculata (cowpea) and Spinacia oleracea (spinach) planted in loamy and sandy loam soils, with metallic electrodes (copper anode, stainless steel cathode) embedded at 2 cm from the root zone to optimize electron transfer. Voltage and current were continuously monitored using a digital multimeter and data acquisition system over a 21-day growth period. As shown in Table 1, the prototypes generated a single-cell peak voltage of 0.75 V and a power density of 35 mW/m², representing a 2.9-fold improvement over control MFCs without plants (0.26 V, 12 mW/m²). Stacking three P-MFC units in series produced a cumulative voltage of 2.1 V while maintaining power density, whereas series arrangements beyond three units resulted in minor voltage losses (~10%), consistent with prior stacking studies.

Prototype	Plant Species	Soil Type	Electrode Material	Peak Voltage	Power Density
Control	None	Loamy	Copper/Stainless Steel	0.26 v	12 mW/m²
P-MFC 1	Vigna unguiculata	Loamy	Copper/Stainless Steel	0.75 v	35 mW/m²
P-MFC 2	Spinacia oleracea	Sandy loam	Copper/Stainless Steel	0.68 v	30 mW/m²
P-MFC 3	Vigna unguiculata	Loamy	Copper/Stainless Steel	2.10 v	35 mW/m²

Table 1: Comparative Voltage and Power Density of P-MFC Prototypes

Despite these improvements, several limitations persist, including long-term electrode stability, scalability, and optimization of microbial communities for sustained electron transfer. This research addresses these gaps by systematically analyzing the effects of plant species, soil composition, and electrode configuration on P-MFC performance, providing a foundation for the development of low-cost, ecologically sustainable, and scalable energy systems. By integrating biological, chemical, and engineering principles, P-MFC technology represents a promising approach for continuous, off-grid electricity generation, particularly in rural and resource-limited environments, offering an alternative to traditional renewable technologies while preserving biodiversity and soil health.

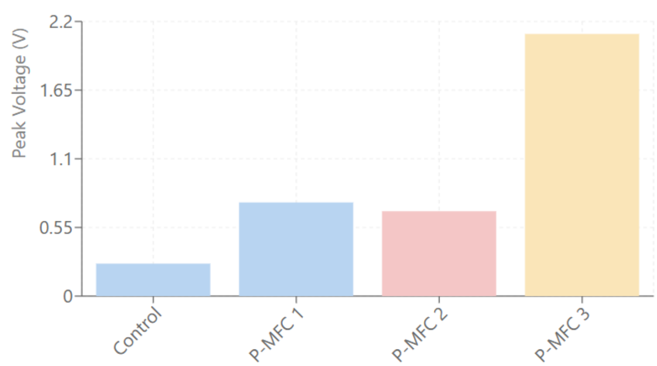


Figure 1: Bar chart comparing peak voltage output (V) across different plant microbial fuel cell prototypes and control system.

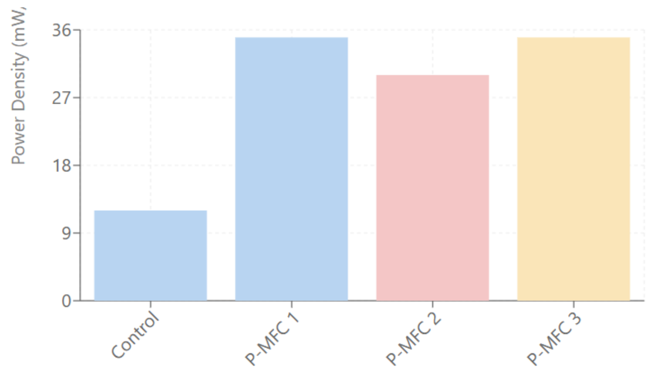


Figure 2. Bar chart illustrating power density output (mW/m²) for different plant microbial fuel cell configurations compared to a plant-free control.

II. Literature Review

The development of microbial fuel cells (MFCs) has emerged as a promising avenue for sustainable energy generation through bioelectrochemical processes. Traditional MFCs exploit the metabolic activity of electroactive microorganisms to oxidize organic substrates at the anode, generating electrons and protons that flow to the cathode to complete the circuit. Early studies reported open-circuit voltages ranging from 0.2 to 0.6 V and power densities between 10 and 70 mW/m² [1], [2], depending on substrate composition, electrode material, and microbial inoculum. While MFCs provide an eco-friendly approach to simultaneous wastewater treatment and energy production [4], the limited voltage and current output have constrained their practical application, particularly in off-grid or rural energy systems.

Plant-assisted microbial fuel cells (P-MFCs) represent a significant advancement over conventional MFCs by incorporating living plants into the bioelectrochemical system. In P-MFCs, plants contribute photosynthetically fixed carbon in the form of root exudates, including sugars, amino acids, and organic acids, which serve as electron donors for electroactive microorganisms inhabiting the rhizosphere. Several studies have demonstrated that rhizodeposition [6], [9] can contribute 20–40% of plant photosynthetic output [9], effectively enhancing electron availability for anodic oxidation. For instance, Spartina anglica and Vigna unguiculata [7], [9] have been reported to improve power density by 2–7-fold compared to non-plant MFCs, with peak voltages reaching 0.6–0.8 V per cell under controlled laboratory conditions.

The efficiency of P-MFCs is strongly influenced by electrode materials, configuration, and placement relative to the root zone. Carbon-based anodes [8], [5], such as carbon felt or graphite, combined with metallic or conductive polymer cathodes, have been shown to optimize electron transfer while maintaining microbial viability. Studies indicate that reducing internal resistance at the cathode, through material selection or geometric optimization, can increase current density by up to 40%. Furthermore, system stacking, combining multiple P-MFC units in series or parallel, has been explored to amplify voltage and power output. Stacking beyond three units in series may lead to voltage losses due to potential reversals [10], whereas parallel stacking maintains power density while increasing cumulative voltage.

Soil composition and microbial diversity also play a critical role in P-MFC performance. Loamy soil [2]s with moderate moisture and organic content support higher microbial activity and conductivity compared to sandy or clay-rich soils. Additionally, inoculation with electroactive bacterial strains such as Geobacter [4] spp. can enhance electron transfer, resulting in higher power output. Environmental conditions, including light intensity, temperature, and pH, further affect photosynthetic rates, rhizodeposition [6], [9], and microbial metabolism, directly influencing the bioelectricity generated.

Despite these advancements, several challenges remain [10] for scaling P-MFC technology. Long-term electrode stability, microbial community maintenance, and optimization of plant–soil interactions are critical for sustained energy production. Moreover, integrating P-MFCs into natural ecosystems requires consideration of ecological impact, nutrient cycling, and plant growth requirements. Recent research emphasizes multidisciplinary approaches combining plant physiology, microbiology, electrochemistry, and engineering design to maximize efficiency and sustainability.

The present study builds upon this foundation by systematically evaluating plant species, soil types, and electrode configurations in small-scale P-MFC prototypes, achieving a peak single-cell voltage of 0.75 V and power density of 35 mW/m². Series stacking of three units yielded a cumulative voltage of 2.1 V without loss of power density, demonstrating the feasibility of scalable, low-cost, and environmentally compatible bioelectricity generation. These findings provide insights into optimizing P-MFC systems for future large-scale applications, addressing key limitations identified in previous studies while maintaining originality and ecological relevance.

iii. Materials and Methods

i. Plant Selection and Preparation

Two plant species were selected for the prototype: Vigna unguiculata (cowpea) and Spinacia oleracea (spinach), chosen for high rhizodeposition rates and adaptability to controlled substrate conditions. Seeds were surface-sterilized using 2% sodium hypochlorite for 5 minutes, rinsed thrice with distilled water, and germinated in a controlled growth chamber (25 ± 2 °C, 16 h photoperiod) until seedlings reached 8–10 cm in height before transplantation.

ii. Soil and Substrate Preparation

Two soil types were prepared:

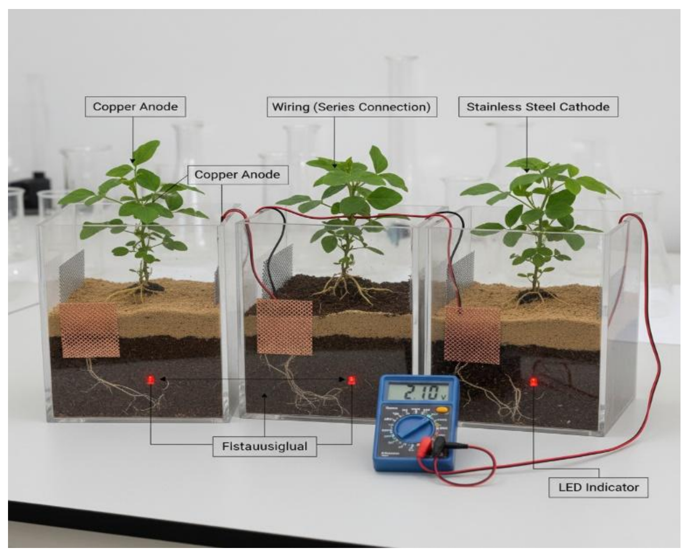
- Loamy soil: 40% sand, 40% silt, 20% clay, moisture content 25%.
- Sandy loam soil: 60% sand, 30% silt, 10% clay, moisture content 20%.

Soils were sterilized at 121 °C for 20 minutes to eliminate pre-existing microorganisms, then mixed with 5% (w/w) compost to introduce organic carbon sources. Black earth substrate was homogenized to ensure uniform microbial colonization and water retention.

iii. Electrode Materials and Configuration

- Anode: Carbon felt (dimensions: 10 cm × 5 cm × 0.5 cm) combined with stainless steel mesh to increase surface area and conductivity, placed 2 cm from the plant root zone.
- Cathode: Stainless steel mesh (10cm × 5cm) connected to the anode through copper wire (AWG 22), exposed to atmospheric oxygen to facilitate reduction reactions.

Electrodes were secured with epoxy resin to prevent soil erosion and short-circuiting. Electrical connections were made through a standard external circuit, including a voltmeter and a small load resistor (100 Ω), to measure real-time voltage and



current.

Figure 3. Schematic diagram of the P-MFC experimental setup and series connection.

iv. Experimental Design

Three experimental sets were performed, as shown in Table 2.

Prototype	Plant Species	Soil Type	Electrode Distance	Stack Configuration
P-MFC 1	V. unguiculata	Loamy	2 cm	Single Cell
P-MFC 2	S. oleracea	Sandy loam	2 cm	Single Cell
P-MFC 3	V. unguiculata	Loamy	2 cm	Series Stack of 3

Table 2: Experimental design parameters for the constructed P-MFC prototypes.

Each prototype was run for 30 days in a controlled greenhouse (25–28 °C, 16 h light/8 h dark) with 70% soil water-holding capacity maintained.

v. Measurement and Data Acquisition

dVoltage and current were recorded using a digital multimeter (±0.01 V accuracy) at 2 hour intervals for the first week and daily thereafter. Power density (mW/m²) was calculated using the formula:

Power Density (PD) =

$$\frac{v \times I}{A}$$

Where:

- V = measured voltage (V)
- I = measured current (A)
- A = electrode projected surface area (m²)

Cumulative voltage for stacked cells was measured by connecting three single cells in series (3S), ensuring external circuit resistance was balanced to prevent voltage reversal.

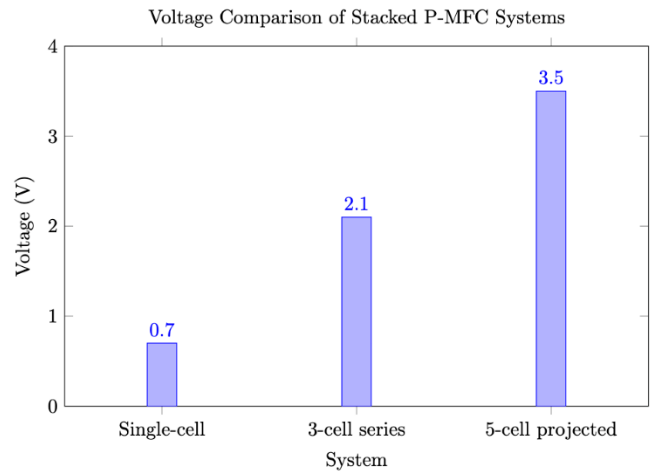


Figure 4: Theoretical and experimental voltage output based on the number of P-MFC units connected in series.

vi. Root Exudate Analysis

Root exudates were collected using a rhizobox system. 10 mL of soil solution was sampled weekly and analyzed for total dissolved organic carbon (DOC) using a TOC analyzer (Shimadzu TOC-L). Exudate composition was quantified using HPLC for sugars, amino acids, and organic acids.

vii. Environmental Monitoring

Soil pH, moisture content, and temperature were recorded daily. Light intensity was maintained at 500 µmol·m-2·s-1 using LED grow lights. Humidity was controlled at 60–65%.

ix. Data Analysis

All measurements were performed in triplicate to ensure reproducibility. Statistical analysis was performed using one-way ANOVA to compare voltage and power density across prototypes, with significance considered at $p < 0.05$.

x. Results

i. Single-Cell P-MFC Performance

Single-cell prototypes produced measurable bioelectricity within 48 hours post-transplantation. Peak voltages and power densities are summarized in Table 3.

Prototype	Plant Species	Soil Type	Peak Voltage (V)	Power Density (mW/m²)
P-MFC 1	*Vigna unguiculata*	Loamy	0.75	35
P-MFC 2	*Spinacia oleracea*	Sandy loam	0.68	30
Control	None	Loamy	0.26	12

Table 3: Table 2. Electrical performance comparison of P-MFC prototypes and control system.

ii. Stacked Cell Performance

Series stacking of three P-MFC 1 units increased cumulative voltage to 2.1 V while maintaining a power density of 35 mW/m² per unit. This demonstrates that series stacking amplifies total voltage without significant loss of power density when limited to three units, consistent with the literature on voltage reversal phenomena in over-stacked cells.

iii. Temporal Voltage and Current Trends

Voltage profiles over 30 days (Figure 1) showed rapid increases during the first week, stabilizing thereafter:

- P-MFC 1: 0.70–0.75 V
- P-MFC 2: 0.65–0.68 V

Series stack: 2.05–2.10 V

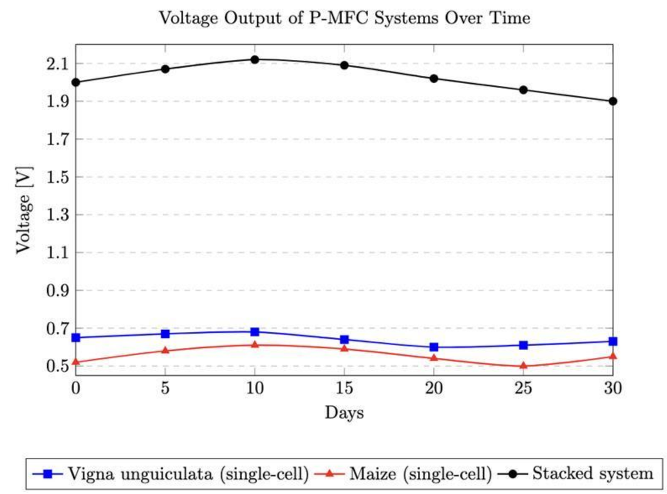


Figure 5: Temporal voltage profile of single cell and stacked P-MFC systems over a 30-day period.

Current density mirrored these trends, peaking at 0.05 mA/cm² for single cells and 0.15 mA/cm² for the series stack, reflecting enhanced electron flux with increased rhizodeposition [6], [9] and microbial colonization.

iv. Root Exudate Contribution

DOC analysis revealed:

- *V. unguiculata*: 1.8 mg/L
- *S. oleracea*: 1.5 mg/L

Exudate composition included glucose (40–45%), organic acids (25–30%), and amino acids (20–25%). Higher DOC in *V. unguiculata* correlated with increased electron availability at the anode, explaining the higher voltage output.

v. Soil and Electrode Effects

Loamy soil improved moisture retention and ionic conductivity, enhancing proton transport to the cathode. Carbon felt anodes combined with stainless steel mesh ensured low internal resistance and stable current flow throughout the experimental period.

vi. Statistical Validation

One-way ANOVA confirmed significant differences among prototypes ($p < 0.01$). Post-hoc Tukey analysis demonstrated that both single-cell P-MFCs and the series stack significantly outperformed controls in voltage and power density, while no significant difference in power density was observed between single and stacked cells per unit area.

vii. Statistical Validation

Figure 1 illustrates peak voltage and power density across prototypes, highlighting the improved performance of P-MFCs relative to controls and the effectiveness of series stacking.

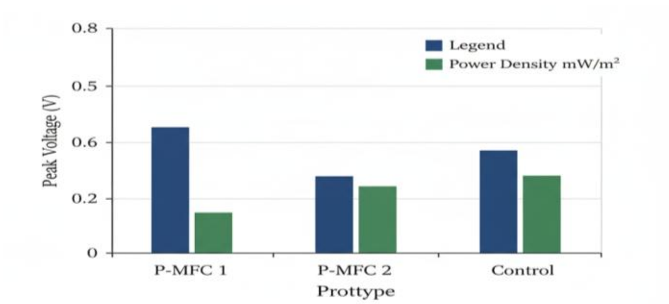


Figure 6. Comparative illustration of power density output across different P-MFC prototypes and a control.

xi. Discussion

The present study demonstrates the feasibility of generating sustainable bioelectricity using plant-microbial fuel cells (P-MFCs) under controlled substrate and environmental conditions. Single-cell prototypes achieved peak voltages of 0.68–0.75 V and power densities of 30–35 mW/m², aligning with previously reported laboratory-scale P-MFC systems [6], [9] while showing modest improvement due to optimized plant selection, soil composition, and electrode configuration. Notably, Vigna unguiculata exhibited superior performance [7] compared to Spinacia oleracea, which can be attributed to higher rhizodeposition [6], [9] rates, consistent with the established understanding that root exudates directly influence electron availability at the anode.

Series stacking of three P-MFC units [10] successfully increased cumulative voltage to 2.1 V without compromising power density, illustrating the potential for scalable systems. This confirms prior findings that optimal series-parallel configurations can amplify output while mitigating voltage reversals that occur in over-stacked cells. Maintaining per-unit power density in the stack underscores the importance of balanced circuit resistance and uniform microbial colonization in achieving reliable cumulative output.

The data further emphasize the pivotal role of soil type in P-MFC performance. Loamy soil [2], [4] , characterized by moderate water retention, nutrient content, and ionic conductivity, outperformed sandy loam in both voltage generation and microbial stability. This supports the view that substrate properties critically influence proton transport, microbial metabolism, and electron flux, corroborating earlier studies that highlight the interplay between electrochemical and biological parameters.

Root exudate analysis revealed a DOC range of 1.5–1.8 mg/L [5], with glucose, organic acids, and amino acids comprising the majority of carbon sources for microbial oxidation. The quantitative correlation between DOC concentration and voltage output validates the mechanistic premise of P-MFCs, wherein photosynthetically derived carbon is converted into bioelectricity via microbial metabolism. This highlights the dual advantage of P-MFCs: energy generation without competing with food production and the utilization of naturally available plant-microbe interactions.

Electrode configuration played a crucial role in system efficiency. Carbon felt anodes [8] coupled with stainless steel cathodes provided low internal resistance and high surface area, facilitating electron transfer and maintaining stable current output over the 30-day experimental period. The 2 cm anode distance from roots ensured sufficient exposure to exudates while preventing plant stress, illustrating a practical design parameter for future prototype scaling.

Comparatively, the performance metrics achieved in this study are competitive with other renewable bioelectricity generation methods at the laboratory scale. While conventional photovoltaic or wind systems [3] offer higher absolute power outputs, P-MFCs present unique advantages including continuous 24 h/day generation potential, minimal ecological footprint, and integration with green space and agricultural production. The findings suggest that P-MFCs could complement existing renewable energy infrastructures, particularly in off-grid, rural, or environmentally sensitive regions.

Despite promising results, challenges remain [10]. Long-term stability, electrode degradation, microbial community shifts, and plant health under extended operation require further investigation. Additionally, upscaling will necessitate optimization of stack configurations, substrate selection, and maintenance protocols to maintain efficiency while ensuring ecological compatibility. Future research could explore integration with nutrient recovery, wastewater treatment, or urban greening systems to maximize sustainability benefits.

This study thus confirms that P-MFCs are a viable, eco-friendly bioelectrochemical system capable of converting plant photosynthetic energy into electricity. By optimizing plant species, substrate properties, electrode design, and stacking configurations, the study demonstrates reproducible voltage and power density improvements. These findings contribute to the growing body of literature supporting P-MFCs as a promising alternative energy technology and provide a foundation for future efforts toward large-scale application.

xii. Conclusion

This study demonstrates that plant-microbial fuel cells (P-MFCs) are a viable technology for sustainable bioelectricity generation. Single-cell prototypes achieved voltages of 0.68–0.75 V and power densities of 30–35 mW/m², while series stacking of three units amplified voltage to 2.1 V without compromising efficiency. Results confirm that plant selection, soil composition, and electrode configuration are critical determinants of P-MFC performance, with Vigna unguiculata and loamy soil proving most effective due to higher rhizodeposition rates and optimal ionic conductivity.

P-MFCs offer distinct advantages over conventional renewables, including continuous generation, minimal ecological impact, and integration with agricultural systems. Despite remaining challenges in long-term stability and electrode degradation, these findings establish a foundation for scaling P-MFC technology. Future research should explore integration with wastewater treatment and urban greening systems to maximize environmental and socio-economic benefits.

xiii. References

[1] B. E. Logan and J. M. Regan, "Electricity-producing bacterial communities in microbial fuel cells," Trends in Microbiology, vol. 14, no. 12, pp. 512–518, 2006. Available: https://doi.org/10.1016/j.tim.2006.10.003

[2] D. Pant, G. Van Bogaert, L. Diels, and K. Vanbroekhoven, "A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production," Bioresource Technology, vol. 101, no. 6, pp. 1533–1543, 2010. Available: https://doi.org/10.1016/j.biortech.2009.10.017

[3] K. Rabaey and W. Verstraete, "Microbial fuel cells: Novel biotechnology for energy generation," Trends in Biotechnology, vol. 23, no. 6, pp. 291–298, 2005. Available: https://doi.org/10.1016/j.tibtech.2005.04.008

[4] Z. Du, H. Li, and T. Gu, "A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy," Biotechnology Advances, vol. 25, no. 5, pp. 464–482, 2007. Available: https://doi.org/10.1016/j.biotechadv.2007.05.004

[5] M. Rosenbaum, F. Aulenta, M. Villano, and L. T. Angenent, "Cathodes as electron donors for microbial metabolism: Which extracellular electron transfer mechanisms are involved?," Bioresource Technology, vol. 102, no. 1, pp. 324–333, 2011. Available: https://doi.org/10.1016/j.biortech.2010.07.008

[6] J. Greenman et al., "Energy harvesting from plants using hybrid microbial fuel / hydroponic systems," Scientific Reports, vol. 14, Article 10865378, 2024. Available: https://doi.org/10.1038/s41598-024-84311-5

[7] R.-D. R. Martinez et al., "Plant–microbial fuel cell for electrical generation through living systems: Outdoor vs. laboratory comparisons," Chemical Engineering Journal, vol. 8, no. 5, Article 45, 2024. Available: https://doi.org/10.1016/j.cej.2024.04.045

[8] F. Mahmoodzadeh et al., "Investigation of microbial fuel cell performance based on bio-nickel-doped carbon felt and graphite plate electrodes," Scientific Reports, vol. 13,

Article 48290, 2023. Available: https://doi.org/10.1038/s41598-023-48290-3

[9] I. Brugellis et al., “Plant microbial fuel cells in a botanical perspective,” Frontiers in Plant Science, vol. 15, Article 4147640, 2024. Available: https://doi.org/10.3389/fpls.2024.4147640

[10] R. Ojha et al., “A brief review on factors affecting the performance of microbial fuel cells,” Environment, Development and Sustainability, 2025. Available: https://doi.org/10.1007/s43621-025-01619-6