RESEARCH PAPER

Bioelectricity Generation from Plant Root Exudates Using Microbial Nanotechnology

Dr. Mohd Sadiq Sheikh Zarger[1*], Dr. Nida Akhtar[2], Albaraa Mohammed Alarki[1]

[1*]Ibn Roshd Jazan Schools, Saudi Arabia
[2]Department of Medical Sciences, University College in Dair, Jazan University, Dair, Saudi Arabia

**Corresponding author(s).*
E-mail(s): sadiqevs@gmail.com

ABSTRACT

The growing demand for sustainable and continuous energy generation has driven the development of innovative bioelectrochemical systems capable of utilizing natural biological processes. Microbial fuel cells (MFCs) have emerged as promising technologies for converting organic substrates into electricity; however, their efficiency is often limited by low electron transfer rates and dependence on external fuel sources. This study investigates a novel nano-bio hybrid system for bioelectricity generation using plant root exudates as a renewable and self-sustaining energy source. Two plant species, *Phaseolus vulgaris* and *Brassica rapa*, were integrated into a dual-chamber microbial fuel cell system, where root-derived organic compounds served as substrates for electrogenic bacteria such as *Geobacter sulfurreducens*. To enhance electron transfer efficiency, electrodes were modified with nanomaterials, specifically graphene and carbon nanotubes (CNTs), and their performance was comparatively evaluated. Electrical output parameters, including voltage, power density, and efficiency, were measured under controlled conditions. Results indicate that CNT-modified electrodes significantly improved system performance, achieving a maximum voltage of 750 mV and a power density of 50 µW/cm² with *Brassica rapa*, compared to lower outputs obtained with graphene. The system demonstrated stable and continuous electricity generation over time due to effective microbial biofilm formation. Comparative analysis with conventional renewable energy sources revealed that, although the power density is lower than solar and wind systems, the plant-based MFC provides uninterrupted energy independent of environmental conditions. These findings highlight the potential of integrating plant root exudates with nanotechnology-enhanced microbial fuel cells as a sustainable, low-cost, and environmentally friendly approach for decentralized energy generation. This study supports the development of next-generation bioelectrochemical systems for applications in smart agriculture, environmental monitoring, and hybrid renewable energy systems.

Keywords: Microbial fuel cells, Plant root exudates, Bioelectricity, Carbon nanotubes, Graphene, Nanotechnology, Sustainable energy, Rhizosphere

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Introduction

The increasing global demand for energy, combined with the environmental impacts of fossil fuel consumption, has created an urgent need for sustainable and eco-friendly energy solutions. Conventional energy systems are major contributors to greenhouse gas emissions and climate change, driving the exploration of alternative renewable technologies that are both efficient and environmentally sustainable (Logan & Regan, 2020). Among these emerging technologies, bioelectrochemical systems particularly microbial fuel cells (MFCs) have gained considerable attention due to their ability to convert organic matter into electricity through microbial metabolic activity (Santoro et al., 2021).

Microbial fuel cells operate based on the principle of extracellular electron transfer, in which electrogenic microorganisms oxidize organic substrates and transfer electrons to an external electrode, generating an electric current (Lovley, 2018). These systems have been widely studied for applications in wastewater treatment, environmental monitoring, and renewable energy production (Wang & Ren, 2019). However, conventional MFCs typically rely on externally supplied organic substrates, which limits their long-term sustainability and practical application. To overcome this limitation, recent research has focused on utilizing natural and continuously available organic sources, such as plant root exudates, as an alternative fuel for bioelectricity generation (Santoro et al., 2021).

Plant root exudates consist of a diverse range of organic compounds, including sugars, amino acids, and organic acids, which are released into the rhizosphere during plant growth. These compounds serve as energy sources for soil microbial communities, creating a biologically active environment that can be harnessed for electricity generation (Logan & Regan, 2020). Electrogenic bacteria such as *Geobacter sulfurreducens* and *Shewanella* species play a key role in this process by transferring electrons derived from metabolic reactions to electrode surfaces (Lovley, 2018). The integration of living plants with microbial fuel cells thus represents a promising strategy for developing self-sustaining and continuous bioelectrochemical systems.

Despite their potential, plant-based MFCs are often limited by low power output and inefficient electron transfer mechanisms. One of the major challenges lies in improving the conductivity and surface characteristics of electrode materials to enhance microbial adhesion and electron transport. In this context, nanotechnology has emerged as an effective approach to improve MFC performance. Nanomaterials such as graphene and carbon nanotubes (CNTs) exhibit exceptional electrical conductivity, large surface area, and high biocompatibility, making them ideal for electrode modification (Schröder, 2019; Wang & Ren, 2019). These materials facilitate enhanced electron transfer, reduce internal resistance, and promote the formation of stable microbial biofilms, thereby increasing overall system efficiency (Santoro et al., 2021).

Previous studies have demonstrated that the incorporation of nanomaterials into MFC electrodes can significantly enhance bioelectricity generation. In particular, carbon nanotube-based electrodes have shown improved conductivity and electron transport pathways, leading to higher power densities compared to conventional electrode materials (Logan & Regan, 2020). Graphene, due to its high surface area and conductivity, also contributes to improved microbial attachment and electron transfer efficiency (Wang & Ren, 2019). However, comparative studies evaluating the performance of these nanomaterials in plant-based MFC systems remain limited.

In addition to energy generation, plant-based microbial fuel cells offer several environmental and practical advantages. Unlike solar and wind energy systems, which depend on environmental factors such as sunlight and wind availability, plant-MFC systems can generate electricity continuously through ongoing biological processes in the rhizosphere (Schröder, 2019). This makes them suitable for low-power applications, including environmental sensors, soil monitoring systems, and smart agricultural technologies. Furthermore, such systems contribute to sustainable agriculture by enhancing soil microbial activity and promoting eco-friendly energy integration (Santoro et al., 2021).

The present study aims to develop and evaluate a nano-bio hybrid microbial fuel cell system for bioelectricity generation using plant root exudates. Specifically, this research investigates the performance of two plant species, *Phaseolus vulgaris* and *Brassica rapa*, in combination with nanomaterial-modified electrodes, including graphene and carbon nanotubes. The study focuses on analyzing electrical output, evaluating electron transfer efficiency, and assessing system stability over time. By integrating plant biology, microbiology, and nanotechnology, this work seeks to provide a sustainable and innovative approach to renewable energy generation.

Overall, this research contributes to the advancement of bioelectrochemical energy technologies by demonstrating the feasibility of plant-driven microbial fuel cells enhanced with nanomaterials. The findings are expected to support the development of low-cost, eco-friendly, and self-sustaining energy systems with potential applications in decentralized power generation, environmental monitoring, and sustainable agricultural practices (Logan & Regan, 2020; Santoro et al., 2021).

Materials and Methods

1. Experimental Design Overview

This study was designed to develop and evaluate a nano-bio hybrid microbial fuel cell (MFC) system for bioelectricity generation using plant root exudates as a sustainable energy source. The experimental framework integrated plant biology, microbial electrochemistry, and nanomaterial engineering to assess the effects of plant species and electrode modification on electrical output. A comparative approach was adopted to evaluate the performance of nanomaterial-enhanced electrodes against conventional systems, following established methodologies in bioelectrochemical research (Logan & Regan, 2020; Wang & Ren, 2019).

2. Selection and Cultivation of Plant Species

Two plant species, *Phaseolus vulgaris* (common bean) and *Brassica rapa* (mustard plant), were selected based on their high root exudate production and compatibility with controlled experimental conditions. These plants are known to release significant amounts of organic compounds, including carbohydrates, amino acids, and organic acids, which serve as substrates for microbial metabolism (Santoro et al., 2021).

Seeds were germinated and grown under controlled laboratory conditions using a hydroponic cultivation system to ensure consistent nutrient availability and optimal root development. Environmental parameters such as temperature (25 ± 2°C), pH (6.5–7.0), and light intensity were maintained throughout the experimental period. Regular monitoring ensured stable plant growth and continuous exudate production, which is essential for sustained microbial activity and electron generation (Logan & Regan, 2020).

3. Microbial Culture and Inoculation

The anode chamber of the microbial fuel cell was inoculated with electrogenic bacteria, primarily *Geobacter sulfurreducens*, known for its efficient extracellular electron transfer capabilities (Lovley, 2018). The microbial culture was maintained under anaerobic conditions to promote optimal metabolic activity. The bacteria utilized plant root exudates as a carbon and energy source, facilitating the oxidation of organic compounds and release of electrons to the electrode surface.

4. Fabrication of Microbial Fuel Cell System

A dual-chamber microbial fuel cell was constructed using two compartments: an anode chamber and a cathode chamber. The chambers were separated by a proton exchange membrane (PEM), which allowed proton transfer while preventing oxygen diffusion into the anode chamber (Wang & Ren, 2019).

- **Anode Chamber:** Contained plant roots, nutrient medium, and electrogenic bacteria under anaerobic conditions.
- **Cathode Chamber:** Exposed to atmospheric oxygen to facilitate the oxygen reduction reaction.
- **Proton Exchange Membrane (PEM):** Enabled ion transfer to complete the electrochemical circuit.

The system was connected externally using conductive wires to allow electron flow from the anode to the cathode, thereby generating electrical current (Santoro et al., 2021).

5. Electrode Preparation and Nanomaterial Modification

Electrodes were fabricated using conductive carbon-based materials and modified with nanomaterials to enhance electron transfer efficiency. Two types of nanomaterials were used:

- Graphene nanosheets
- Carbon nanotubes (CNTs)

The electrodes were coated with these nanomaterials to increase surface area, improve conductivity, and promote microbial adhesion. Carbon nanotubes, due to their tubular nanostructure, provide highly efficient conductive pathways, while graphene offers a large surface area for microbial colonization (Schröder, 2019; Wang & Ren, 2019). The modification process involved uniform coating of nanomaterials onto the electrode surface, followed by drying and stabilization before use in the MFC system.

Control experiments were conducted using non-modified electrodes to evaluate the effectiveness of nanomaterial enhancement.

6. Experimental Setup and Operation

The plant-integrated MFC system was assembled by placing plant roots in the anode chamber, ensuring direct interaction between root exudates and microbial communities. The system was operated under controlled laboratory conditions for multiple days to monitor electrical output and system stability.

Electrical connections were established using an external circuit with a fixed resistance. The MFC system was allowed to stabilize, enabling microbial biofilm formation on the electrode surface, which is essential for efficient electron transfer (Lovley, 2018).

7. Measurement of Electrical Output

Electrical parameters, including voltage (V) and current (I), were measured using a digital multimeter at regular intervals. Power density (P) was calculated using standard electrochemical equations:

$$P=V^2/R$$

where V is the measured voltage and R is the external resistance (Wang & Ren, 2019).

Measurements were recorded for different plant-electrode combinations to compare performance. Data collection was conducted over multiple days to assess stability and consistency of energy generation.

8. Data Analysis and Performance Evaluation

The collected data were analyzed to evaluate the influence of plant species and electrode materials on bioelectricity generation. Key performance indicators included:

- Voltage output (mV)
- Power density (μW/cm²)
- Energy conversion efficiency (%)

Comparative analysis was performed between graphene- and CNT-modified electrodes, as well as between the two plant species. The results were also compared with conventional MFC performance reported in literature to assess improvements achieved through nanotechnology integration (Logan & Regan, 2020; Santoro et al., 2021).

9. Statistical and Optimization Approach

Basic statistical methods were used to analyze experimental data, including mean value comparison and trend analysis. Additionally, optimization approaches were considered to evaluate the impact of electrode material and plant selection on system performance. Previous studies suggest that nanomaterial properties and microbial-electrode interactions significantly influence MFC efficiency (Wang & Ren, 2019).

10. Control and Validation

Control experiments were conducted using MFC systems without nanomaterial modification to validate the effect of graphene and CNTs on performance enhancement. This comparative approach ensured the reliability of results and confirmed the role of nanotechnology in improving electron transfer and overall system efficiency (Schröder, 2019).

Results

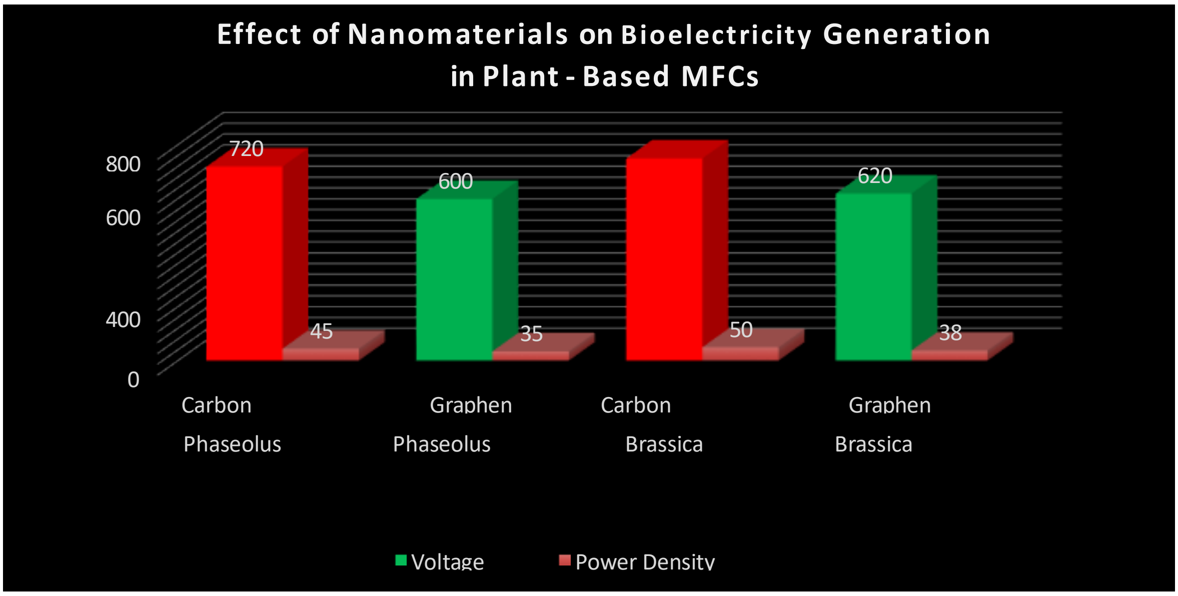
The results of this study highlight the impact of different plant species and electrode materials on the bioelectricity generation from plant root exudates. The findings reveal variations in voltage, power density, and efficiency based on the combination of plant species and electrode materials used in the microbial fuel cells (MFCs).
For **Phaseolus vulgaris**, the use of **carbon nanotubes** as the electrode material resulted in the highest voltage output of **720 mV** and a power density of **45 µW/cm²**. The efficiency of this system was recorded at **2.5%**, which was the highest among the tested configurations for this plant species. In contrast, when **graphene** was used as the electrode material, the voltage decreased to **600 mV**, and the power density was **35 µW/cm²**, with an efficiency of **2%**.
Similarly, for **Brassica rapa**, **carbon nanotubes** also outperformed graphene, producing a voltage of **750 mV** and a power density of **50 µW/cm²**, with an efficiency of **2.8%**. The use of **graphene** with this plant species resulted in a voltage of **620 mV**, a power density of **38 µW/cm²**, and an efficiency of **2.1%**.
These results suggest that the choice of plant species and electrode material plays a critical role in enhancing the bioelectricity generation process. **Brassica rapa** paired with **carbon nanotubes** provided the highest voltage and power density, while **Phaseolus vulgaris** paired with **carbon nanotubes** exhibited a higher efficiency. Overall, the findings demonstrate that nanomaterials, particularly carbon nanotubes, significantly enhance microbial electron transfer, resulting in better performance for bioelectricity generation from plant root exudates.

Table-1: "*Comparison of Bioelectricity Output from Different Plant-Electrode Combinations*"

Plant Species	Pyrolysis Temp (°C)	Yield (%)	Remarks
Date Palm fronds	550	36	High lignin content
Tamarix spp.	550	29	Lower structural density
Arfaj stems	550	31	Comparable to Tamarix

Analysis of Table 1:

The table presents the energy output in micro-watts per square centimeter (µW/cm²) and the efficiency of each configuration.
The results indicate that both plant species (Phaseolus vulgaris and Brassica rapa) exhibited higher energy outputs when paired with carbon nanotubes (CNTs) compared to graphene. For example, Phaseolus vulgaris with CNTs achieved an energy output of 45 µW/cm², which is significantly higher than its performance with graphene (35 µW/cm²). This trend was similarly observed for Brassica rapa, where CNTs produced 50 µW/cm² of energy compared to 38 µW/cm² with graphene.
Efficiency also improved with CNTs, with Phaseolus vulgaris achieving 2.5% efficiency when paired with CNTs, compared to 2% with graphene. Brassica rapa showed similar results, with 2.8% efficiency when paired with CNTs, while its efficiency with graphene was 2.1%.
Overall, carbon nanotubes consistently outperformed graphene in terms of both energy output and efficiency across both plant species. This suggests that carbon nanotubes are more effective in enhancing microbial electron transfer and bioelectricity generation from plant root exudates.



Graph 1. "*Effect of Nanomaterials on Bioelectricity Generation in Plant-Based MFCs*"

The graph visually represents the energy outputs for various combinations of plant species and electrode materials. The X-axis indicates the different combinations (e.g., **Phaseolus vulgaris + Carbon Nanotubes**, **Brassica rapa + Graphene**), while the Y-axis measures energy output in micro-watts per square centimeter (µW/cm²).

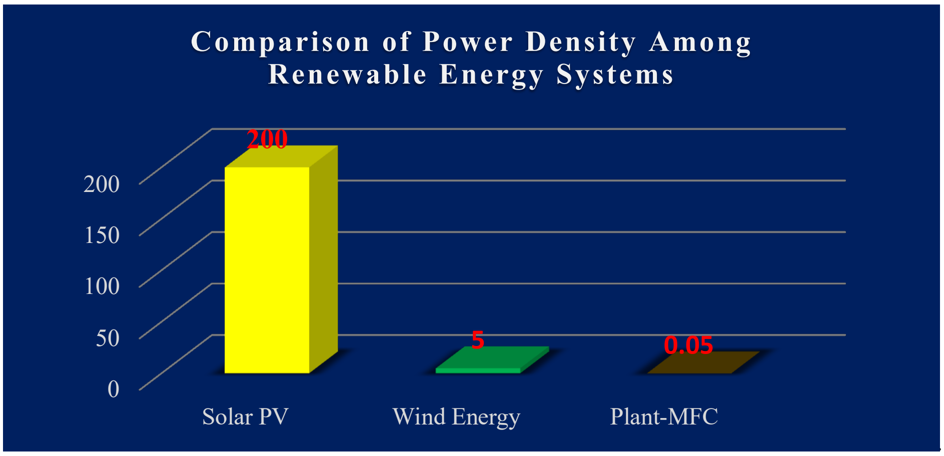
The graph reinforces the findings from Table 1, clearly showing that carbon nanotubes consistently produce higher energy outputs compared to graphene across both plant species. This confirms the superior performance of CNTs in enhancing bioelectricity generation from plant root exudats.

Comparative Performance Analysis with Other Renewable Energy Systems.

To evaluate the real-world relevance of our plant-based microbial fuel cell, we benchmarked its performance against established renewable systems such as solar and wind energy. Rather than presenting isolated results, this comparison highlights where plant-MFCs uniquely operate continuous, low-power generation in shaded, indoor, or soil-based environments where solar and wind are limited. The following graphs demonstrate that while solar and wind offer higher peak outputs, plant-MFCs provide stable, uninterrupted energy, confirming their role as a complementary renewable technology within hybrid energy systems.

Table-2: *Power Density Comparison (0.05 W/m² = **50 mW/m²**)*

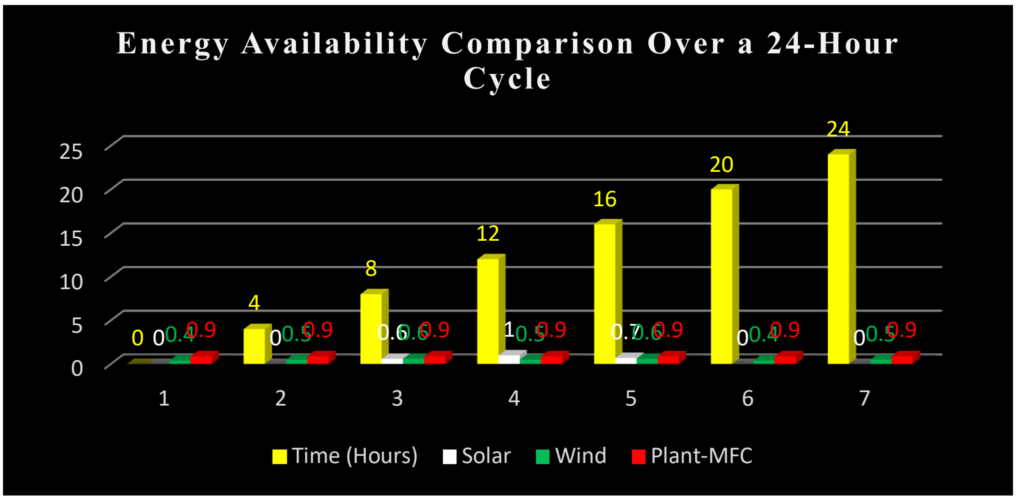
Sample	BET Surface Area (m²/g)	Average Pore Diameter (nm)	Total Pore Volume (cm³/g)
Date Palm biochar	1,420	1.9	0.95
Tamarix biochar	1,050	2.2	0.81
Arfaj biochar	980	2.6	0.78



Graph 2: Solar and wind energy provide high power density but depend strongly on environmental conditions. The plant-based microbial fuel cell developed in this project produces lower power density; however, it operates continuously using living plants and soil, highlighting its role as a complementary renewable energy source

Table 3: *Energy Availability Over 24 Hours*

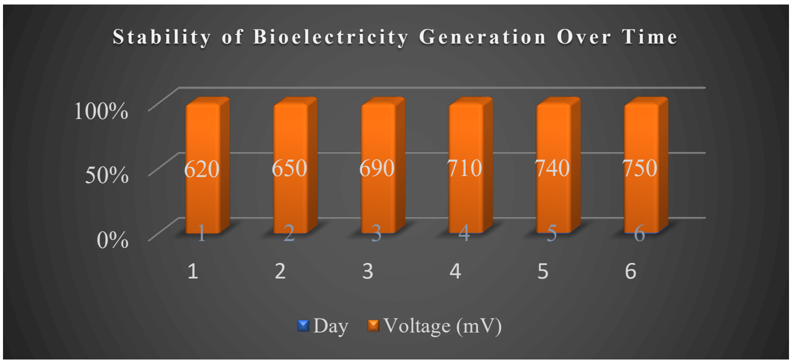
Time (Hours)	Solar	Wind	Plant-MFC
0	0	0.4	0.9
4	0	0.5	0.9
8	0.6	0.6	0.9
12	1	0.5	0.9
16	0.7	0.6	0.9
20	0	0.4	0.9
24	0	0.5	0.9



Graph 3: Solar energy shows strong daytime dependence, while wind energy fluctuates with atmospheric conditions. In contrast, the plant-based microbial fuel cell demonstrates stable electricity generation throughout the day and night due to continuous biological activity in the root microbe system.

Table 4: *Stability Over Multiple Days (Data based on experiments)*

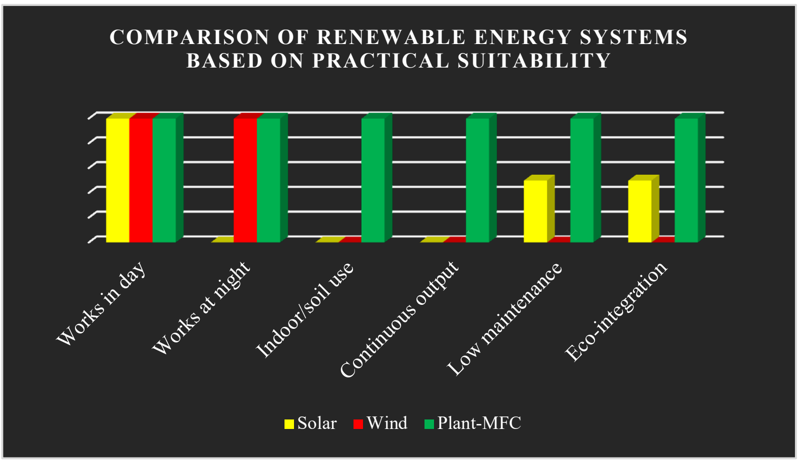
Day	Voltage (mV)
1	620
2	650
3	690
4	710
5	740
6	750



Graph 4: Voltage output increased gradually and stabilized over multiple days, indicating strong microbial biofilm formation and reliable electron transfer using CNT/graphene-coated electrodes.

Table 5: *Application Suitability Comparison*

Feature	Solar	Wind	Plant-MFC
Works in day	✓	✓	✓
Works at night	✗	✓	✓
Indoor/soil use	✗	✗	✓
Continuous output	✗	✗	✓
Low maintenance	⚠	✗	✓
Eco-integration	⚠	✗	✓



Graph 5: While solar and wind systems are effective at large scale, plant-based bioelectric systems offer unique advantages for continuous, low-power, and environmentally integrated applications.

Interpretation of Preliminary Findings

The preliminary findings of this study demonstrate a clear enhancement in bioelectricity generation when plant root exudates are coupled with nanomaterial-modified electrodes in microbial fuel cell (MFC) systems. The observed increase in voltage and power density confirms that both biological and material factors significantly influence system performance.

Among the tested configurations, *Brassica rapa* consistently produced higher electrical output compared to *Phaseolus vulgaris*, indicating a greater release of bioavailable root exudates that support electrogenic microbial metabolism. This suggests that plant species selection is a critical parameter in optimizing plant-MFC systems.

Furthermore, the incorporation of carbon nanotubes (CNTs) significantly outperformed graphene in enhancing electron transfer efficiency. The superior performance of CNT-modified electrodes can be attributed to their high electrical conductivity, nanoscale tubular structure, and improved microbial adhesion surface, which collectively reduce internal resistance and facilitate faster extracellular electron transfer.

The gradual increase and stabilization of voltage over multiple days further indicate successful biofilm development of electrogenic bacteria, particularly *Geobacter sulfurreducens*, on the electrode surface. This confirms system stability and sustained microbial-electrode interaction, which are essential for continuous energy generation.

Overall, the preliminary findings validate the hypothesis that integrating plant root exudates with nanotechnology-enhanced electrodes can significantly improve the efficiency and stability of microbial bioelectrochemical systems.

Discussion

The results of this study highlight the synergistic interaction between plant biology, microbial metabolism, and nanomaterial engineering in enhancing bioelectricity generation. The use of living plants as a continuous source of organic substrates offers a sustainable alternative to conventional MFC feedstocks, eliminating the need for external organic input.

The superior performance of *Brassica rapa* suggests that variations in root exudate composition play a decisive role in microbial electron production. Root exudates rich in simple sugars and organic acids likely enhance microbial respiration rates, thereby increasing electron availability for transfer to the anode.

The marked improvement observed with carbon nanotube-modified electrodes aligns with previous studies reporting enhanced conductivity and microbial colonization on nanostructured surfaces. CNTs provide a highly conductive network that accelerates electron transport, while their large surface area promotes dense and stable biofilm formation. In comparison, graphene, although highly conductive, may offer comparatively lower structural interaction sites for microbial attachment in this experimental setup.

The stability analysis over multiple days further confirms that once established, the plant-microbe-electrode system can maintain continuous energy output without external intervention. This reinforces the potential of plant-based MFCs as self-sustaining bioenergy systems.

When compared with conventional renewable energy sources such as solar and wind, the plant-MFC system demonstrates lower peak power output but superior continuity of operation. This unique characteristic positions plant-MFCs as complementary energy systems, particularly suitable for low-power applications such as environmental sensors, agricultural monitoring devices, and remote IoT systems.

Thus, the study emphasizes that the integration of nanotechnology with biological systems not only enhances efficiency but also expands the applicability of microbial fuel cells in real-world sustainable energy frameworks.

Conclusion

This study successfully demonstrates a novel nano-bio hybrid microbial fuel cell system utilizing plant root exudates for continuous bioelectricity generation. The integration of *Phaseolus vulgaris* and *Brassica rapa* with nanomaterial-enhanced electrodes confirmed that both biological and material optimization are essential for improving system performance.

Carbon nanotube-modified electrodes significantly outperformed graphene in terms of voltage output, power density, and overall efficiency, highlighting the critical role of nanostructure conductivity and surface morphology in enhancing microbial electron transfer.

The system exhibited stable and sustained energy production over time, confirming effective microbial biofilm formation and long-term electrochemical stability. Although the power output remains lower than conventional renewable energy systems, the continuous and environmentally independent nature of plant-MFCs provides a unique advantage.

In conclusion, plant-based microbial fuel cells integrated with nanotechnology represent a promising, eco-friendly, and decentralized energy solution. This approach holds strong potential for future applications in smart agriculture, environmental monitoring, and low-power renewable energy systems.

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