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Plant microbial fuel cells: A new frontier in sustainable agriculture

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Intricacies of the topic

The increasing demand for renewable energy and sustainable agricultural technologies has encouraged scientists to explore innovative biological systems capable of producing clean electricity. Among these emerging technologies, Plant Microbial Fuel Cells (PMFCs) have attracted considerable attention because they integrate plant biology, soil microbiology, and electrochemistry into a single environmentally friendly system. Unlike conventional renewable energy technologies that require dedicated infrastructure, PMFCs utilize the natural biological processes occurring around living plant roots to generate electricity continuously without affecting plant growth. This remarkable technology not only provides a source of green energy but also offers exciting opportunities for precision agriculture, real-time crop monitoring, and early disease diagnosis (Strik *et al.*, 2008; Martinez, 2024).

What is a plant microbial fuel cell?

A Plant Microbial Fuel Cell (PMFC) is a bioelectrochemical device that converts solar energy stored by plants into electrical energy through the metabolic activity of naturally occurring electrogenic microorganisms present in the rhizosphere. The technology exploits the intimate interaction between plant roots and soil microorganisms to harvest electrons that are naturally released during microbial respiration. Plants absorb sunlight through photosynthesis and convert carbon dioxide into carbohydrates. While a significant proportion of these carbohydrates is utilized for plant growth, nearly 20–40% of the photosynthetically fixed carbon is transported to the roots and released into the surrounding soil as root exudates. These exudates contain sugars, amino acids, organic acids, alcohols, and other carbon-rich compounds that serve as food for rhizospheric microorganisms. Under oxygen-limited conditions, electrogenic bacteria metabolize these compounds through anaerobic respiration, releasing electrons, protons, and carbon dioxide. Instead of transferring electrons to oxygen, these specialized bacteria donate electrons directly to an electrode (anode) buried near the plant roots. The electrons subsequently flow through an external electrical circuit to a cathode, where they react with oxygen and protons to produce water, thereby generating electricity without disturbing the normal physiology of the plant (Strik *et al.*, 2008; Nair and Sreedharan, 2023; Martinez, 2024). The concept of generating electricity from living plants was first demonstrated by Dr. David P.B.T.B. Strik and colleagues, who established that plant-microbe interactions could serve as a sustainable source of renewable energy.

Working principle of plant microbial fuel cells

The operation of a Plant Microbial Fuel Cell involves a sequence of biological and electrochemical processes occurring naturally in the rhizosphere.

Photosynthesis and carbon fixation

The process begins with photosynthesis, during which green plants capture solar energy and convert carbon dioxide and water into carbohydrates. These carbohydrates represent stored solar energy and serve as the primary energy source for plant metabolism. Photosynthesis therefore acts as the fundamental driving force behind electricity generation in PMFCs because all subsequent microbial activities depend upon the carbon compounds synthesized by plants (Strik *et al.*, 2008).

Rhizodeposition: Feeding the underground microbial community

Plants transport a substantial proportion of photosynthetically synthesized carbon to their root systems. Approximately 20–40% of this fixed carbon is naturally released into the rhizosphere in the form of root exudates, including glucose, sucrose, amino acids, phenolic compounds, and organic acids. These organic molecules nourish millions of microorganisms inhabiting the soil around the roots, creating a biologically active rhizosphere (Strik *et al.*, 2008).

Anaerobic microbial oxidation

Within waterlogged or oxygen-deficient soil, electrogenic bacteria such as Geobacter, Shewanella, and related microorganisms metabolize these root exudates through anaerobic respiration. During microbial oxidation, carbohydrates are broken down into carbon dioxide while simultaneously releasing electrons and protons. These microorganisms possess specialized extracellular electron transfer mechanisms that enable them to donate electrons directly to conductive materials instead of molecular oxygen (Tongphanpharn *et al.*, 2021; Nair and Sreedharan, 2023).

Electron capture by the anode and electricity generation at the cathode

An electrically conductive anode is strategically positioned within the anaerobic root zone. Electrogenic bacteria transfer their released electrons onto the surface of this electrode, effectively converting microbial metabolic activity into electrical energy. Because oxygen is absent around the anode, microorganisms utilize the electrode as their terminal electron acceptor, initiating continuous electron flow (Azizul Moqsud, 2024). The electrons collected by the anode travel through an external electrical circuit toward the cathode, thereby generating an electric current. Simultaneously, protons produced during microbial metabolism migrate through the surrounding soil or a proton exchange membrane toward the cathode. At the cathode, oxygen from the atmosphere combines with incoming electrons and protons to form water, completing the electrochemical circuit. Since this entire process relies on naturally occurring biological activities, electricity can be generated continuously without harming the plant or the surrounding ecosystem (Martinez, 2024).

Applications of plant microbial fuel cells

Sustainable energy generation for agriculture

One of the most promising applications of PMFC technology is decentralized renewable energy production directly within agricultural ecosystem

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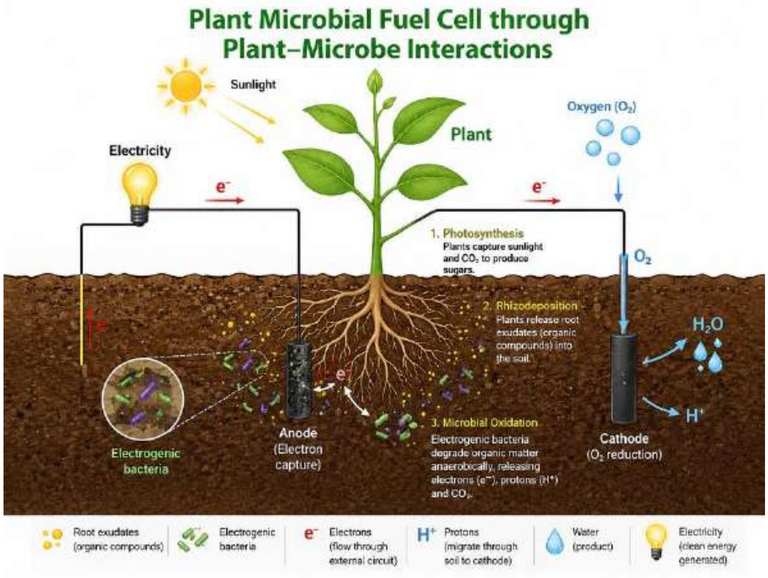
Fig 1: Plant Microbial Fuel Cell through plant–microbe interactions



Unlike solar panels or wind turbines, PMFCs utilize existing crop plants to generate electricity without requiring additional land or external fuel sources. Paddy fields, wetlands, and irrigated agricultural lands are considered ideal environments because they naturally provide anaerobic conditions favorable for electrogenic microorganisms. Consequently, farmers can simultaneously cultivate crops and generate renewable electricity from the same field, thereby improving overall land-use efficiency (Chen, 2024; Rusyn *et al.*, 2025).

Self-powered precision agriculture

Precision agriculture increasingly depends on continuous monitoring of environmental parameters such as soil moisture, temperature, humidity, electrical conductivity, and nutrient availability. Conventional sensor systems require batteries that demand periodic replacement and contribute to electronic waste. PMFCs provide an attractive alternative by continuously supplying low-power electricity capable of operating wireless sensor networks (WSNs), Internet of Things (IoT) devices, and environmental monitoring systems. This creates self-powered smart farms with reduced maintenance costs and improved environmental sustainability (Osorio de la Rosa *et al.*, 2019).

Plant disease monitoring and early diagnosis

Plant Microbial Fuel Cells also function as highly sensitive biological sensors because electrical output directly reflects root physiology and microbial activity. During pathogen infection, photosynthetic efficiency declines, resulting in reduced carbohydrate transport to the roots and decreased root exudation. Consequently, microbial metabolic activity decreases, leading to measurable reductions in electrical current generation. Soil-borne pathogens alter the composition of rhizospheric microbial communities, disrupting electrogenic bacterial populations and producing characteristic electrical signatures. Such changes may enable farmers to detect disease outbreaks several days before visible symptoms appear, allowing timely implementation of disease management strategies (Chen, 2024; Van Limbergen *et al.*, 2022).

Environmental monitoring

PMFCs can also be employed to monitor environmental changes such as heavy metal contamination, nutrient deficiency, flooding, and soil degradation. Because microbial metabolism rapidly responds to environmental stress, changes in PMFC electrical output provide real-time information regarding soil ecosystem health. This makes PMFC technology valuable for ecological restoration, wetland conservation, and environmental risk assessment.

Advantages of plant microbial fuel cells

PMFC technology offers numerous ecological and agricultural advantages. It generates clean, renewable electricity without emitting greenhouse gases or requiring chemical fuels. Since living plants remain undisturbed throughout the process, crop productivity is not compromised. The technology simultaneously supports food production, environmental monitoring, and renewable energy generation while minimizing battery waste and electronic pollution. Moreover, PMFCs possess enormous potential for integration into future smart farming systems based on IoT, artificial intelligence, and wireless communication networks.

Future perspectives

The future of Plant Microbial Fuel Cells extends far beyond electricity generation. Emerging research is focusing on integrating PMFCs with artificial intelligence, machine learning, electrochemical impedance spectroscopy, and wireless sensor technologies to create intelligent agricultural monitoring systems. Advanced AI algorithms will analyze continuous voltage fluctuations generated by PMFCs to distinguish between drought stress, nutrient deficiencies, fungal infections, bacterial diseases, and other physiological disorders long before visual symptoms appear. Such predictive systems could revolutionize disease surveillance and precision agriculture (Guan et al., 2024; Rusyn et al., 2025).
Simultaneously, researchers are developing nanostructured electrodes with improved conductivity to enhance electron transfer efficiency and power output. Advances in crop breeding and microbial engineering may further optimize root exudation patterns and electrogenic bacterial activity, making commercial PMFC technology more efficient and economically viable.

Conclusion

Plant Microbial Fuel Cells represent one of the most promising examples of bio-inspired renewable energy technology. By utilizing the natural interactions between plant roots and soil microorganisms, PMFCs simultaneously generate electricity, monitor plant health, and support precision agriculture without harming the environment. Although challenges such as low power output and large-scale implementation remain, continued advances in biotechnology, nanotechnology, and artificial intelligence are expected to transform PMFCs into powerful tools for sustainable agriculture. In the coming decades, crop fields may function not only as sources of food but also as intelligent living power stations capable of producing renewable electricity while continuously monitoring plant health and environmental conditions.

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