Journal of Power Sources 656 (2025) 238068

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Review article

Plant microbial fuel cells: An innovative path toward integrated food and energy production for a sustainable future

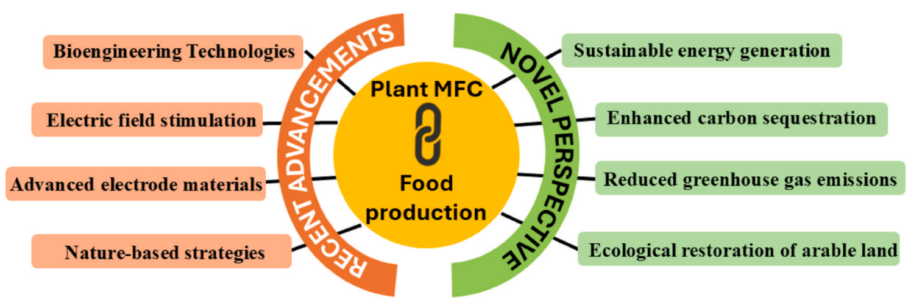
Iryna Rusyn [a], Yamini Mittal [b], Wilgince Apollon [c,d,*]

[a] Department of Ecology and Sustainable Environmental Management, Viacheslav Chornovil Institute of Sustainable Development, Lviv Polytechnic National University, Stepan Bandera St., 12, Lviv, 79013, Ukraine
[b] University of Luxembourg, Faculty of Science, Technology and Medicine, Chair for Urban Water Management 6, Rue Richard Coudenhove-Kalergi, L-1359, Luxembourg
[c] Centro de Investigación en Ciencia Aplicada y Tecnología Avanzada (CICATA), Instituto Politécnico Nacional (IPN), Carretera Tampico-Puerto Industrial Altamira km 14.5, C. Manzano, Industrial Altamira, Altamira, 89600, Mexico
[d] Department of Agricultural and Food Engineering, Faculty of Agronomy, Autonomous University of Nuevo León, Francisco Villa S/N, Ex-Hacienda El Canadá, General Escobedo, Nuevo León, 66050, Mexico

HIGHLIGHTS

- Integration of P-MFCs enables simultaneous food cultivation and bioelectricity generation.
- Advanced electrodes and engineered microbial consortia enhance P-MFC efficiency.
- P-MFCs support smart agriculture via IoT-based monitoring and waste-to-energy systems.
- Nature-based strategies, including smart fertilizers, boost P-MFC output & stability.
- P-MFC integration fuels renewable power, fostering efficient sustainable agriculture.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Carbon neutral
Energy efficiency
Electrochemically active microorganism
Rhizosphere interaction
Smart agriculture
Waste management

ABSTRACT

Plant microbial fuel cells (P-MFCs) offer a promising solution for generating sustainable energy while enhancing agricultural productivity. This mini-review focuses on recent advancements in P-MFCs integrated into food production and innovative technologies aimed at practical applications. Enhancing system efficiency and scalability involves optimization of engineering microbial consortia, nanomaterial-based electrodes, and nature-based strategies such as smart fertilizers, biofertilizers, and the introduction of annelids. This technology enhances soil fertility, enables carbon sequestration, reduces greenhouse gas emissions, contributes towards soil remediation, and arable land restoration, which are key factors for sustainable infrastructure. This mini-review highlights the potential of P-MFCs in developing sustainable, integrated food and energy systems, thereby contributing to a carbon-neutral future. Integrating food crops with P-MFCs in hydroponic cultivation is expected to support vertical farming, enabling the production of clean energy and high-value crops in space-efficient, controlled environments. Additionally, food P-MFCs have the potential to effectively treat organic waste, particularly food residues, advancing circular economy practices by converting waste into renewable electricity.

* Corresponding author. Centro de Investigación en Ciencia Aplicada y Tecnología Avanzada (CICATA), Instituto Politécnico Nacional (IPN), Carretera Tampico-Puerto Industrial Altamira km 14.5, C. Manzano, Industrial Altamira, Altamira, 89600, Mexico.
E-mail address: wilgince.apollon@uanl.edu.mx (W. Apollon).

https://doi.org/10.1016/j.jpowsour.2025.238068
Received 8 June 2025; Received in revised form 29 July 2025; Accepted 5 August 2025
Available online 8 August 2025

Coupling P-MFCs with Internet of Things (IoT) systems could enable smart agriculture through real-time monitoring of soil and plant health, supporting precision farming and resilient resource management.

1. Introduction

Sustainable food systems are essential for promoting environmentally responsible agriculture that protects planetary health while securing equitable access to food for all. Practices such as crop rotation, organic farming, and permaculture improve soil health and reduce chemical inputs, enhance biodiversity, which results in higher-quality food [1]. However, modern agriculture is highly energy-intensive, requiring substantial inputs for field preparation, irrigation, agrochemical application, and mechanized harvesting. These processes still heavily depend on fossil-based energy sources, making food production systems both resource-demanding and environmentally damaging. Consequently, the critical re-evaluation of energy consumption patterns in agriculture and the implementation of renewable, decentralized energy solutions that support both food security and climate resilience present an important challenge of our time.

Sustainable energy systems, which rely on renewable resources such as solar, wind, and hydroelectric power, help reduce greenhouse gas emissions, thereby mitigating the impacts of climate change on global health and food security [2,3]. When effectively integrated, sustainable food and energy systems promote energy efficiency throughout the production, distribution, and consumption stages. This integrated approach ensures a reliable energy supply while reducing dependence on non-renewable fossil fuel resources, thus enhancing long-term energy security [4]. However, these undoubtedly progressive alternative energy infrastructures often impose considerable environmental burdens, manifesting in degraded landscapes and disrupted ecosystems. In this context, the scientific community is increasingly turning its attention to bioelectricity, particularly the implementation of bioelectrochemical systems (BESs), such as plant microbial fuel cells (P-MFCs), within sustainable agro-energy systems.

Researchers at Wageningen University in the Netherlands introduced this innovative technology through P-MFCs in 2008 to enhance the energy production capacity of conventional microbial fuel cells (MFCs) [5]. The applicability of P-MFCs is based on photosynthesis, a process that involves solar-driven, complex biochemical reactions in chlorophyll, producing glucose from CO_2 and water while releasing oxygen [6]. In 2008, Strik and his colleagues [5] aptly suggested using a plant along with an MFC due to their ability to produce photosynthetic exudates and organic compounds that feed electrochemically active bacteria (EAB) known as electrogenic bacteria. In addition, radial oxygen loss through the root creates favorable conditions for rhizosphere bacteria and also affects the redox potential of the system [7]. Thus, the system includes a plant as an integral part of maintaining steady microbial activity at the anode, which enables sustained electron transfer during P-MFC operation. In P-MFCs, EABs perform the same operational function as in MFCs by using anodic organic matter oxidation to create electrons and protons [8]. The electrons move from the anode to the cathode, where they participate in the reduction of protons while producing usable energy. The generated energy is released from the device through an external electrical circuit to run remote equipment [9].

P-MFC integration into sustainable food systems not only contributes to decentralized renewable energy production but also supports biodiversity conservation, while maintaining essential ecosystem services and preserving natural resources for future populations [3]. Such an approach leads to building a more sustainable and equitable world. However, despite the promising results and demonstrated environmental benefits, P-MFC technology continues to face critical challenges, including power density limitations, low economic viability, and difficulties with system scalability. Consequently, the development of advanced P-MFC systems is increasingly focused on key performance-determining factors, including the optimization of plant species, rhizosphere architecture, and the composition of electrogenic microbial communities, to enhance bioelectricity generation [10]. Since the first experiments with P-MFCs using plants such as *Glyceria maxima* [5] and *Oryza sativa* [11,12], numerous studies have explored a wide range of plant species, including C_3, C_4, and Crassulacean Acid Metabolism (CAM) plants, as potential candidates to improve P-MFC performance [13–15]. At the system level, technical limitations remain a critical challenge. Electrode materials properties, electrode surface area, multielectrode design, electrode arrangement, and unit interconnections can alter the efficiency of P-MFCs [16]. New electrode materials based on graphene and nanocarbons, which boost electron transfer speeds as documented by Radeef and Najim [17], open up perspectives for enhancing the efficiency and durability of P-MFC systems under real-world agricultural conditions. In addition, novel functional organic ligands immobilized onto inorganic mesoporous silica frameworks, such as those developed by Awual et al. [18,19] and Shahat et al. [20], as well as conjugated nanomaterials [21,22] with tailored pore structures, can improve biofilm development, ion transport, and surface-mediated electron exchange in P-MFC anodes and significantly enhance the adsorption capacity. Exploring such materials for integration into next-generation P-MFCs may pave the way for more effective power generation, as well as enhanced multifunctionality, including wastewater treatment and real-time environmental sensing. Modern approaches that combine genetically modified plants and engineered microorganism consortia to optimize electron transfer processes show strong potential for developing modular P-MFC units capable of supporting off-grid applications, such as environmental monitoring sensors and irrigation system power. In pilot experiments, P-MFCs offer successful diverse application potentials, including powering biosensing and low-energy digital devices, remediation of polluted sites, and generating electricity on green roofs [23].

This mini-review aims to explore recent advancements in integrating P-MFCs into food production systems that enable the simultaneous cultivation of plants and the generation of renewable energy. Special attention is given to the multifunctional role of P-MFCs in promoting soil health and climate mitigation, as well as to innovative approaches, that may facilitate the sustainable incorporation of P-MFCs into resilient agro-ecosystems, including bioengineering technologies, advanced electrode materials, electric field stimulation, and nature-based strategies such as the application of smart fertilizers, biofertilizers, and the introduction of annelids. The research further seeks to highlight novel perspectives for the integration of P-MFCs into food production systems, contributing to sustainable energy generation, enhanced carbon sequestration, reduced greenhouse gas emissions, and the ecological restoration of arable land within the achievement of climate-smart agriculture.

2. The operation mechanisms of P-MFC

P-MFCs operate through the combined effects of plant-soil microbe-bioelectrochemical system interactions, which produce sustainable bioelectricity. In P-MFC systems, plants perform photosynthesis to produce organic compounds, which are released into the rhizosphere through their roots. These compounds are then broken down by electrochemically active bacteria (EAB), generating electrons for electricity production. The electrons move from the anode to the external circuit before reaching the cathode, thereby completing the electric current generation process (Fig. 1). The system's efficiency depends on several key factors, including the plant species, microbial communities, cultivation conditions, and the technical configuration of the system [100].

2.1. Technical components of P-MFCs

The design of P-MFCs requires an integrated systems approach considering the complex interaction between plant roots and microbial communities within the electrochemical environment. The effective design of P-MFCs relies on a systems-level optimization of all core components to enhance energy generation and long-term functionality in sustainable food-energy production systems. The operational performance of P-MFCs depends heavily on the technical characteristics and the electrode material, because they determine how well electrons transfer throughout the system. The optimization of each component, from electrode composition to interelectrode distance and electrode surface area, must occur to achieve maximum conductivity and low inner resistance. As the electrodes serve as both essential microbial colonization sites and electron transfer locations, materials must also exhibit chemical stability, structural integrity, and compatibility with biological processes [24]. For effective P-MFC operation, it is essential to use materials that ensure high ion conductivity and minimize internal resistance, such as Nafion and FuMA-Tech cation exchange membranes [24]. Although membranes are rarely used in P-MFCs, particularly in soil-based systems, their selection in planted CW-MFCs plays a critical role in determining internal resistance and ion transport efficiency. Technological advances, including the integration of nanostructured carbon materials and next-generation ion exchange membranes, have significantly improved to their electrical output and operational stability. Traditional materials, including graphite felt, carbon cloth, and carbon granules, have been widely used due to their favorable conductivity along with their structural features [5,99]. Advanced materials, including graphene, carbon nanotubes, and metal–organic frameworks, enhance microbial adhesion and electron mobility [17]. Cathodic oxygen reduction is typically enhanced with platinum or alternative sustainable catalysts. Optimizing P-MFC design and substrate conductivity properties is fundamental to reducing energy losses and maximizing power output, making it a central focus of upcoming technological developments.

2.2. Role of plant species in P-MFC performance

The P-MFC technology leverages plants to boost its bioenergy production performance within the system [25]. As we have stated previously in the introduction, plants are the primary sources of exudates or organic compounds that support microbial growth through photosynthesis, while also supplying oxygen (Fig. 2). Recent research has increasingly emphasized the importance of plant species in the performance of P-MFCs. A comprehensive review by Rusyn [26] highlights the contributions of specific plant species and associated microbial consortia in enhancing P-MFC efficiency. The review encompasses more than 90 plant species, including cacti from arid environments and plants tolerant to saline, alkaline, and acidic soils, demonstrating their potential as effective biological drivers in P-MFC systems. A study conducted at Lviv University in Ukraine investigated P-MFC systems based on five plant species. It was found that P-MFC systems based on *Carex hirta*, which exhibited the highest total accumulated dry biomass (including leaves, stems, and roots), also achieved the greatest power output. The power density exceeded that of other plant-based systems by up to 37.9 %, indicating a direct correlation between plant biomass accumulation and the efficiency of bioelectricity generation [27]. Further details reveal that the P-MFC system produces stable energy generation as long as the plant remains alive, as described by Maddalwar et al. [28]. Still, when the plant reaches the end of its useful life, energy generation decreases. The findings underscore the critical role of plant species in determining system functionality.

Numerous studies have investigated the performance of plants with various photosynthetic pathways in P-MFC systems. Although C_4 plants have theoretical physiological advantages through a high rate of CO_2 assimilation, their limited global distribution means that C_3 species remain dominant in P-MFC systems and frequently exhibit efficient bioelectricity generation performance. The first study with C_3 plant reed mannagrass (*Glyceria maxima*) in P-MFC by Strik et al. [5] reached a power density of 67 mW m^{-2}, which was higher than the control (blank) results, which were considered highly promising at the time. P-MFC using *Puccinellia distans* (C_3 plants) demonstrated its potential as an excellent choice for implementing P-MFC technology because it can withstand salt conditions, according to Khudzari et al. [29]. The species outperformed *G. maxima* by 20 % [5] through its higher power density, reaching 83.7 mW m^{-2}.

Tapia et al. [13] conducted a pivotal study that tested seven *Sedum* species for P-MFC operation on semi-arid green roofs under non-water-saturated conditions. This research marked a significant milestone because it introduced the evaluation of CAM plant species for P-MFC technology applications. The research showed overall low P-MFC performance promoted with *Sedum* species, where *S. hybridum* reached the highest power density of 0.092 mW m^{-2}. The current energy production levels of these species are still insufficient to support practical implementation in P-MFC technology under arid conditions.

Other succulent and CAM plants, including four *Opuntia* species (*O. ficus-indica, O. robusta*, *O. albicarpa*, and *O. joconostle*) have also been investigated in P-MFCs [9]. This study not only confirmed the potential of CAM plants for real-time applications but also demonstrated a power density almost sixty times higher for *O. albicarpa* compared to *S. hybridum*, reaching 5.47 mW m^{-2}. The step-by-step process for establishing the P-MFC system in a semi-arid environment is shown in Fig. 2. This involves soil preparation, selecting and pre-cultivating *Opuntia* spp., designing and building the electrodes, planting and installing the electrodes, setting up the experimental units, and integrating data acquisition and voltage monitoring systems [9]. Further research is needed to optimize P-MFC performance, as well as their scalability, when using CAM plants in conjunction with C_3 and C_4 photosynthetic pathway plants. Table 1 describes the plant species commonly exploited in PMFC systems, particularly those involved in

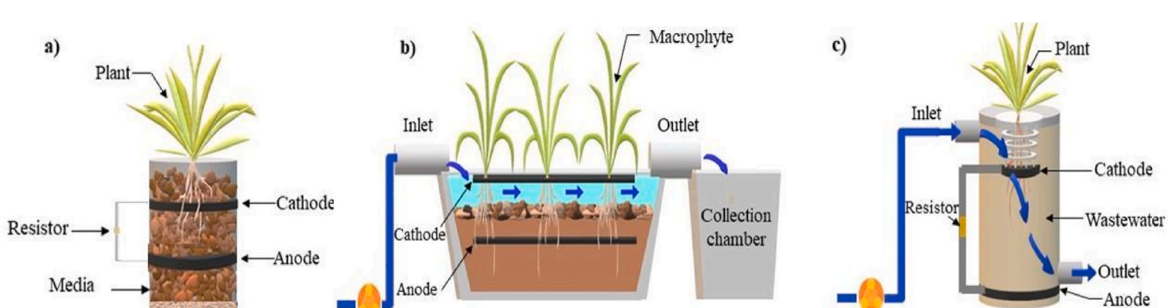


Fig. 1. Schematic representation of P-MFC configurations: (a) conventional system; (b) constructed wetland P-MFC with horizontal subsurface flow (CW-P-MFC); and (c) hydroponic P-MFC system. Adapted from Rusyn and Gómora-Hernández [7] with the permission of Elsevier under license 5914981447352.

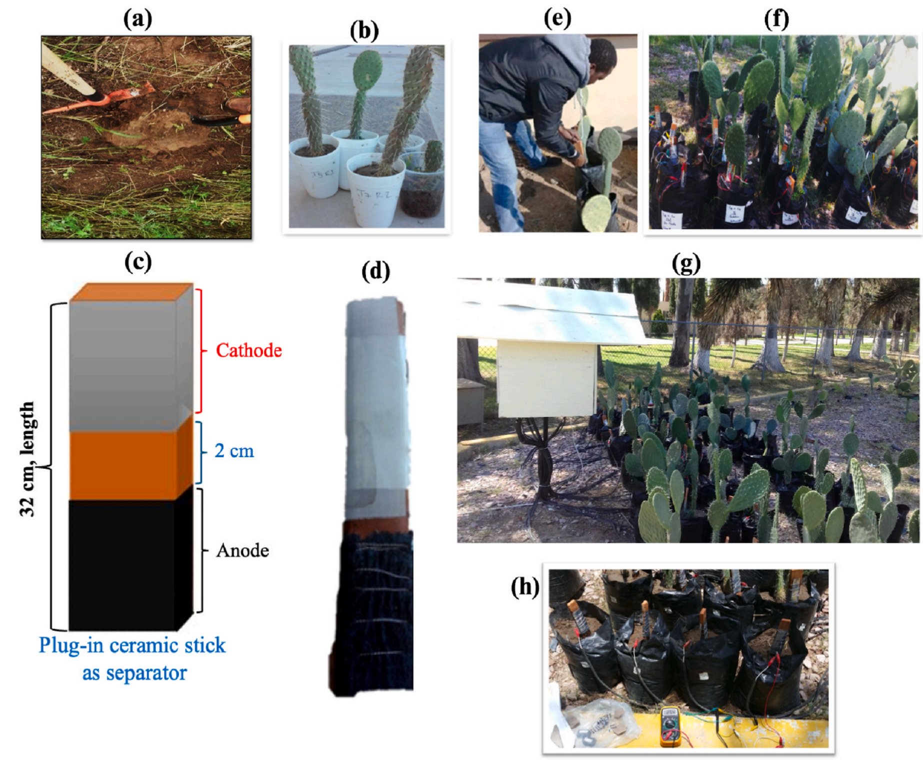


Fig. 2. Stepwise preparation and experimental setup of a P-MFC using *Opuntia* spp [9]. (**a**) Soil preparation prior to planting, (**b**) selection and pre-cultivation of *Opuntia* spp. seedlings, (**c**) schematic design of the plug-in electrode (graphite felt anode, zinc sheet cathode, and ceramic separator), (**d**) fabricated electrode ready for installation, **(e)** planting and embedding of the electrodes in soil, (**f**) establishment of P-MFC experimental units, **(g)** deployment of the data acquisition system in the field, and (**h**) voltage monitoring in both P-MFC and control MFC units (without plants). Created in https://BioRender.com.

food and feed production, in terms of their photosynthetic pathways, physiological and ecological traits, and evaluates their suitability for bioelectrical applications.

Our research group has recently advanced the development of P-MFC technology by integrating agricultural production with bio-electrochemical systems. In a 2022 study, we introduced *Stevia rebaudiana* into livestock urine-based P-MFCs (Fig. 3) and demonstrated, for the first time, a clear synergy between plant growth and power generation [30]. Goat urine yielded the largest stem diameter (0.52 ± 0.01 cm), cow urine significantly promoted root proliferation (95 % increase), and sheep urine supported the greatest plant height (50.08 ± 0.67 cm), while cow urine achieved the highest maximum power density (132 ± 11.6 mW m^{-2}) and maintained long-term operation at 43.68 ± 3.05 mW m^{-2}. Building on these findings, our 2023 study focused on self-sustaining nutrient recovery within the same P-MFC framework, revealing that cow urine enabled the direct reuse of 94 % NH_4^+-N, 98 % PO_4^{3-}, and 33 % K. Meanwhile, goat urine supported the highest long-term power density (46.97 ± 0.67 mW m^{-2}) and sheep urine increased power density by 98 % during polarization tests [31]. This progression of work establishes a strong foundation for low-cost, integrated systems that simultaneously recover nutrients, enhance plant biomass, and generate renewable electricity for sustainable agriculture.

2.3. Contribution of microbial communities to P-MFC functionality

The functionality of P-MFCs critically depends on the activity and diversity of microbial communities. The rhizosphere and the electrode zone serve as habitats for electrochemically active bacteria (EAB) and associated decomposer microorganisms, which utilize root exudates as electron donors. As a result of syntrophy between microorganisms and microbial oxidation of plant-derived substrates, including sugars, amino acids, and organic acids, electrons and protons are released, initiating the bioelectrochemical processes central to P-MFC operation [26]. EAB species, including *Geobacter* and *Shewanella*, are capable of transferring electrons directly or indirectly to the anode surface, enabling current generation [8]. Electrons are captured by the anode and directed through an external circuit, while protons migrate toward the cathode, where they react with oxygen to form water. Sustained electron flow relies on the continuous availability of substrates, supported by root exudates derived from plant photosynthesis [5]. Microbial electron transfer occurs via three main pathways: (i) direct transfer through conductive pili or nanowires, (ii) mediation by redox-active compounds (either endogenous or exogenous), and (iii) electron hopping facilitated by extracellular polymeric substances [10]. Among electrogenic bacteria, *Geobacter sulfurreducens* is notable for producing conductive pili that form electrical conduits between microbial cells and electrodes, thereby enhancing electron transfer efficiency [10]. Although artificial mediators can further boost performance, their use introduces additional costs and design complexity.

Efficient electron transfer is crucial for maximizing the energy output of P-MFCs, and is closely linked to the resilience of the microbial community. Complex and functionally diverse consortia help stabilize electricity production under fluctuating environmental conditions. Recent studies have shown that symbiotic interactions between plants and microbial consortia enhance both electron generation and plant growth by cycling nutrients and suppressing pathogens [14]. Engineering or selecting appropriate microbial communities is, therefore, a promising strategy to enhance P-MFC performance and ensure long-term system sustainability.

Thus, P-MFCs function as an integrated biological-electrochemical system wherein microbial respiration, electrogenesis, and syntrophic interactions are tightly coupled with plant photosynthesis (Fig. 4). Photosynthesis not only provides the primary organic substrates required for microbial metabolism but also helps prevent soil nutrient depletion. To optimize energy generation, it is essential to manage plant health, maintain a stable microbial community, and regulate key

Table 1
Overview of plant species and their suitability for bioelectrical applications for PMFC systems.

Plant species	Photosynthetic pathway	Advantages for PMFC integration	Limitations in PMFC applications	Ref.
Glyceria maxima	C_3	Tolerates prolonged flooding Deep root system (~91 cm) High biomass production Low maintenance Perennial plant	Sensitive to water levels Biofouling risk Invasive potential Seasonal variation	[5]
Oryza sativa	C_3	Deep root system High biomass production High organic matter content	High maintenance Sensitive to environmental conditions High water requirement Short cycle plant - limits long-term PMFC operation	[11] [12]
Acorus calamus	C_3	Tolerance to adverse environments Low maintenance Perennial plant Bioremediation potential	Toxicity concerns	[32]
Canna indica	C_3	High biomass	Regulatory restrictions High water requirement High maintenance Annual plant	[25]
Phragmites australis	C_3	Salt-tolerant High biomass High organic matter content Bioremediation potential Perennial plant	Invasive species	[33]
Trigonella foenum-graecum	C_3	Fast growth rate	Sensitive to water stress Short cycle plant - limits long-term PMFC operation Biofouling issues	[34]
Spartina anglica = *Sporobolus arabicus*	C_4	Salt-tolerance Drought-tolerant Low maintenance Perennial plant High organic matter production	Sensitive to water depth Biofouling risk Invasive potential Seasonal variation	[35]
Zea mays	C_4	High biomass Fast growth rate	Sensitive to water stress High maintenance Short cycle plant - limits long-term PMFC operation	[26]
Phaseolus vulgaris	C_3	Symbiotic nitrogen fixation Fast growth rate	Requires tight evapotranspiration balance (80–120 %) Sensitive to water stress Short cycle plant - limits long-term PMFC operation	[36]
Vigna unguiculata ssp. *sesquipedalis*	C_3	Symbiotic nitrogen fixation Fast growth rate	Short cycle plant - limits long-term PMFC operation	[37]
Solanum lycopersicum	C_3	High biomass Fast growth rate	Sensitive to water fluctuations Seasonal species — limits long-term PMFC operation High maintenance	[38]
Sedum spp	CAM	Drought-tolerant Low maintenance Live in adverse conditions Perennial plant Easy propagination	Low biomass productivity Restricted substrate interaction	[13]
Opuntia spp	CAM	Drought-tolerant Low water need Growth in adverse conditions Perennial plant	Slow growth rate High maintenance Limited root depth	[9]
Stevia rebaudiana.	C3	Bioremediation potential Perennial plant	Sensitive to water stress High maintenance	[39]
Ocimum basilicum	C3	Fast growing Suitable for year-round cultivation under indoor or protected conditions Bioremediation potential	Water-sensitive	[16]
Brassica juncea	C3	High biomass Bioremediation potential	Sensitive to salinity Biofouling risk Short cycle plant - limits long-term PMFC operation High maintenance	[34]
Pandanus amaryllifolius	C3	Perennial plant Bioremediation potential	Low water tolerance Limited distribution	[40]

environmental parameters, including moisture, temperature, and pH.

3. Bioelectricity generation during the cultivation of food crops and additional benefits

Approximately twenty plant species important as food cultures have

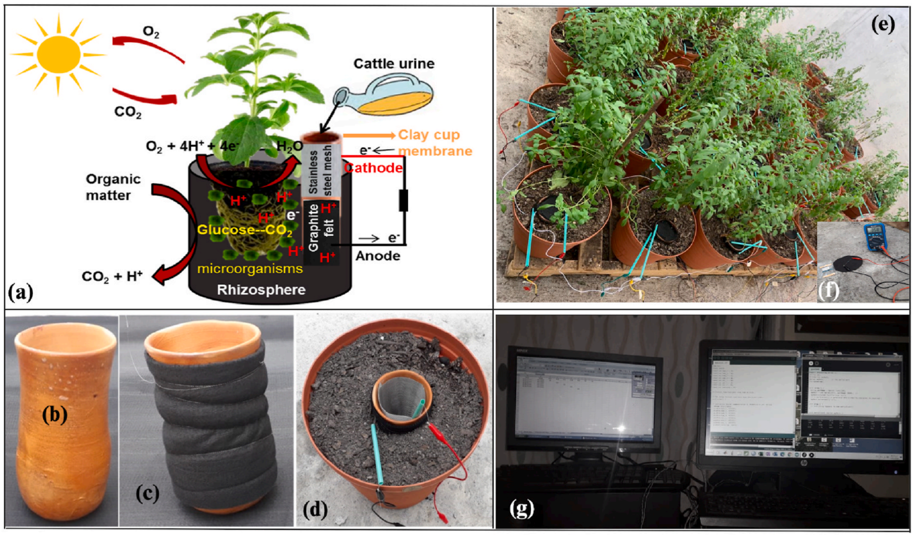


Fig. 3. (**a**) Schematic diagram of the P-MFC system illustrating the roles of photosynthesis, root exudation, microbial activity, and electron flow between the anode and cathode [30,31]. (**b**) Clay cup used as the membrane separator. (**c**) Clay cup wrapped with graphite felt to form the anode assembly. (**d**) Assembled electrode installed in the soil-filled pot. (**e**) Experimental setup with multiple planted units (Stevia plants) in operation. (**f**) Connection to monitoring instruments for voltage and current measurement. (**g**) Data acquisition and processing using dedicated software on a computer system. Created in https://BioRender.com.

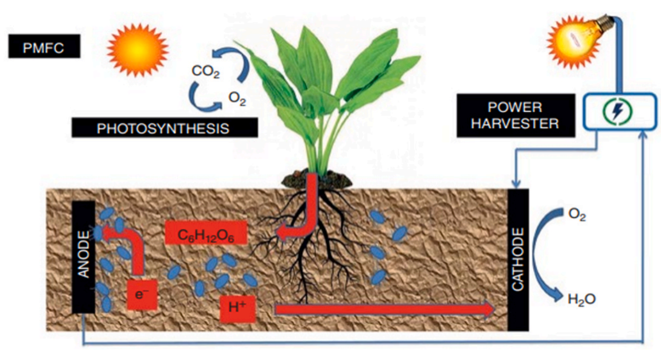


Fig. 4. Schematic illustration of the basic operations of a plant microbial fuel cell. Plants use photosynthesis to create organic compounds, which they release through their roots into the soil, where microbial communities break down these compounds through microbial respiration. The electrons produced by microbial activity move to the anode through direct or mediated electron transfer processes before passing through an external circuit to reach the cathode, generating bioelectricity. The electrodes serve as essential components for maintaining efficient electron transport and system stability. Adapted from Sarma and Mohanty [41], with the permission of John Wiley and Sons under license 6043111200227.

been investigated in P-MFC systems. Among them are key staples such as rice [42,43], tomato [38], bean [37], and maize [26] (Table 2). *Oryza sativa* integrated into P-MFC systems has been the most extensively studied, with continuous research since the technology's inception in 2008 [11,12]. Although the short-cycle seasonal growth of food crops limits their ability to sustain long-term P-MFC operation, these crops can generate efficient electricity during their active growth phases, enabling the operation of environmental sensors essential for their own cultivation.

Matsumoto et al. [43] reported one of the highest bioelectricity outputs from an *O. sativa*-based P-MFC, reaching 130 mW m^{-2}, more than double the output of the control system. This enhancement was achieved by amending the soil with zero-valent iron (Fe^0) supplements, commonly referred to as ZVI, including materials such as magnetite, etc.

Apparently, the microbial community associated with these systems play a key role in enhancing the bioelectricity output. 16S rRNA gene analysis revealed a substantial increase in fermentative and exoelectrogenic bacterial populations responsible for converting plant-derived organic matter into electricity in the iron-amended samples. However, ZVI-P-MFC produces a fluctuating power output, with significantly reduced levels during nighttime. As a result, environmental monitoring systems powered by ZVI-P-MFC may require capacitors for energy storage. Nevertheless, the improved power generation opens possibilities for powering a broader range of sensors, increasing the viability of P-MFCs as an on-site energy source. For instance, twelve P-MFC reactors based on prickly pear, a culturally and agriculturally important crop, demonstrated a power output of 489.02 mW m^{-2} [9] sufficient to power a digital clock and potentially other devices relevant to sustainable agriculture. Likewise, an *Aloe vera*-based P-MFC, a plant valued in food and beverage sectors, demonstrated a boosted voltage of 10.9V when integrated with a power management circuit, sufficient to activate a wireless temperature and humidity sensor, showcasing the system's potential for IoT-enabled environmental monitoring [44].

Aromatic and culinary herbs, including fenugreek and mustard greens [34], lemongrass [45], garlic chives [46], and sweet basil [16], as well as water spinach, a widely consumed edible green in Southeast Asia [47], have also been tested in P-MFC systems. These species generally possess shallow root systems and fast growth cycles, making them well-suited for efficient electron transfer within the rhizosphere. Basil, in particular, has high potential due to its rapid growth and suitability for year-round cultivation in indoor or protected environments. In an annual indoor experiment, two pots of basil successfully replaced a 1.5 V battery to power a 4.3–105.2 μA digital thermometer/hygrometer, while three pots of basil successfully replaced a 3 V battery to power a weather station (10.1–36.4 μA) (Fig. 5) [16]. These findings highlight the practical potential of P-MFCs in households, serving dual aesthetic and practical roles, providing fresh herbs for consumption while powering small electronic devices, and contributing to more sustainable living environments.

The feasibility of cultivating food crops in hydroponic P-MFC systems, as demonstrated for garlic chives [46], lemongrass [45], and tomato [38], presents promising opportunities for integration into vertical farming systems. These approaches eliminate the need for land exploitation and intensive resource use, thereby contributing to more sustainable agricultural practices.

The possibility of wastewater remediation during food cultivation and energy generation constitutes a noteworthy additional benefit of food-energy systems. Several studies have demonstrated the capacity of

Table 2
Bioelectricity generation during the cultivation of food and feed crops.

Plant species	Common name	Potential for food or fodder production	Maximal power output	Additional application	Ref.
Allium tuberosum	*Garlic chives*	Aromatic herb, spice	130.2 mW m^{-2}	Potato-process wastewater treatment, Hydroponics	[46]
Aloe vera	*Aloe*	Food and beverages uses in Mexico, India, China, South Africa, and Thailand	3.49 V	Powering wireless device for remote sensor activation	[44]
Acorus calamus	*Sweet flag*	Food flavoring Currently prohibited for food use due to β-asarone toxicity	46.63 mW m^{-2}	Cr(VI)-containing wastewater treatment	[48]
Brassica juncea	*Mustard greens*	Aromatic herb, spice	69.32 mW m^{-2}	–	[34]
Cymbopogon Citratus	*Lemongrass*	Aromatic herb, tea flavoring	31.9 mW m^{-2}	Wastewater treatment, Hydroponics	[45]
Glyceria maxima	*Reed mannagrass*	Fodder for livestock	80 mW m^{-2}	–	[57]
Ipomea aquatica	*Water spinach*	Popular edible green in Southeast Asia	910 mW m^{-3}	Azo dye wastewater treatment	[51]
Ocimum basilicum	*Sweet basil*	Aromatic herb, spice	160.24 mW m^{-2}/three reactors	Power for digital thermometer/hygrometer, weather station and LEDs	[16]
Opuntia spp	*Prickly pear*	Important local food culture and fodder in arid zones	489.02 mW m^{-2}/twelve reactors	Power for digital clock and LEDs	[9]
Oryza sativa	*Rice*	Important food crop	140 mW m^{-2}	-	[42]
Oryza sativa L. cv. Koshihikari	*Rice*	Important food crop	130 mW m^{-2}	On-site batteries potential for operating low-power environmental sensors	[43]
Pandanus amaryllifolius	*Pandan leaf*	Aromatic herb, spice	[a]CE 95.32 %	-	[58]
Phragmites australis	*Common reed*	Fodder for livestock	3714.08 mW·m^{-2}	Wastewater treatment	[52]
Pistia stratiotes	*Water lettuce*	Local fodder for livestock	6.35 mW m^{-2}	-	[49]
Solanum lycopersicum	*Tomato*	Important vegetable crop	n a, near 84.76 mW m^{-2} - 179.78 mW m^{-2}	Fermented distillery wastewater treatment Hydroponics	[38]
Stevia rebaudiana	*Stevia*	Natural sweetener	46.97 mW m^{-2}	Livestock's urine wastewater treatment	[30]
Trigonella foenum-graecum	*Fenugreek*	Aromatic herb, spice, fodder	80.26 mW m^{-2}	-	[34]
Vigna unguiculata ssp. *sesquipedalis*	*Greenbean*	Important food crop	160.86 mW m^{-2}, a grid of nine PMFCs	-	[37]
Zea mays	*Maize/Corn*	Important corn crop	[b]OCV 1.082V	–	[26]

[a] CE, Coulombic Efficiency.
[b] OCV, Open Circuit Voltage.

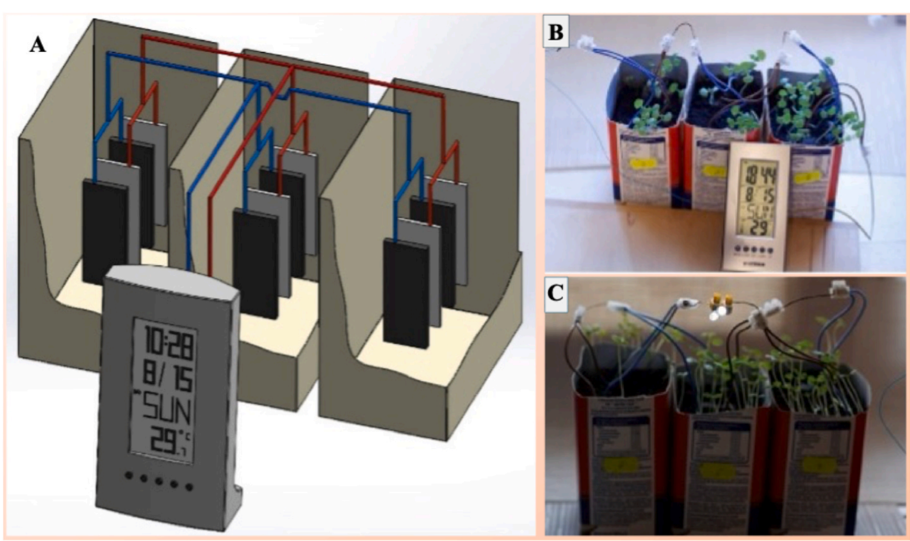


Fig. 5. P-MFC system using two-week-old basil (*Ocimum basilicum*) seedlings as a 3 V biobattery: (**A**) schematic of the P-MFC construction by connecting three biomodules in series. (**B**) powering a 3 V digital indoor weather station (thermometer, clock, calendar). (**C**) powering 3 V LEDs. Adapted from Rusyn and Medvediev [16] with permission from Elsevier under License Number 6070360297734.

crop-based P-MFC to treat Cr(VI)- and azo dye-contaminated wastewater [47,48], as well as domestic wastewater [45]. *Acorus calamus*, recognized for its filtration capabilities and high tolerance to heavy metals, is commonly used in remediation-oriented P-MFC setups. However, due to its tendency to accumulate toxic compounds, it is unsuitable for use as a traditional food flavoring or in any food-related applications. Therefore, the use of non-toxic and biocompatible waste streams becomes critical when integrating P-MFC with food production. In this context, food crop-based P-MFCs utilizing natural organic wastes, such as livestock urine [30], potato-processing effluents [46], and fermented distillery wastewater [46] offer an up-and-coming solution. This strategy enables the utilization of low-cost, waste-derived substrates in food-P-MFCs, aligning with zero-waste agricultural principles and advancing resource circularity and efficiency in sustainable farming systems.

The maximum electricity output of P-MFCs based on food crops ranges between 6.35 and 489.02 mW m^{-2} [49,50] and up to 910 mW m^{-3} [51], which is adequate to support the operation of low-energy on-site devices [50]. Further performance improvements are possible through system enhancements, such as soil amendments with zero-valent iron (ZVI), as previously discussed.

Notably higher electricity yields have been reported for P-MFCs employing *Phragmites australis*, a common livestock fodder species, with output reaching 3714.08 mW m^{-2} [52]. This exceptional performance is likely attributed to the plant's extensive aboveground and belowground (root) biomass, which substantially distinguishes it from other food crops reviewed in this study and plays a crucial role in rhizodeposition, as described by Kabutey et al. [53] and Rusyn et al. [27]. The plant's robust root system fosters the establishment of diverse microbial communities and contributes to reduced internal resistance, while its highly developed aerenchyma facilitates pronounced radial oxygen loss, critical for maintaining a favorable redox potential in the rhizosphere [7]. These findings support the prospect of achieving comparably high performance with *O. sativa*, which exhibits similar morphological characteristics to *P. australis*.

Overall, recent advancements in food crop-based P-MFC technology underscores its potential as a renewable power source capable of supporting ultra-low-energy devices, including those deployed for environmental monitoring and Internet of Things (IoT) applications. P-MFCs can be effectively integrated into various settings, such as agricultural landscapes for powering sensor networks [44,54,55], vertical hydroponic farming systems and sustainable indoor environments [56]. A key advantage of integrating P-MFCs with digital technologies lies in the creation of autonomous energy platforms, which minimize reliance on conventional power sources and minimize battery replacement frequency. This makes them particularly suitable for deployment in remote or infrastructure-limited regions. Although current power outputs remain modest, ongoing efforts are directed at improving the efficiency, reliability, and scalability of P-MFC systems. Additionally, integrating P-MFCs with waste processing streams, particularly those utilizing organic waste from food production, offers a sustainable solution for concurrent energy generation and waste remediation. By utilizing waste streams such as agricultural by-products or wastewater, P-MFCs promote a circular economy model, reduce environmental pollution and deliver renewable energy source for low-power devices. This integrated approach holds substantial potential for enhancing the sustainability of both agriculture and waste management systems.

4. Multifunctional role of P-MFCs in renewable energy, soil health, and climate mitigation

P-MFCs offer a sustainable and renewable pathway for decentralized power generation. In these systems, plant roots naturally release organic exudates, which are utilized by to produce a continuous flow of bioelectricity through P-MFCs [59,60]. As this energy generation process operates independently from external input consumption, it contributes to its long-term sustainability. The technology demonstrates exceptional compatibility with decentralized power systems, which serve off-grid applications particularly well in rural and semi-arid regions lacking access to conventional electricity infrastructure [9]. Importantly, the renewable energy system functions without interfering with plant development, allowing for continuous, non-invasive power production in ecological and agricultural settings [61].

Beyond, electricity generation, P-MFCs contribute positively to soil health through enhanced nutrient cycling and microbial activity in the rhizosphere [62]. The symbiotic plant-microbial relationships enhance rhizosphere nutrient cycling, which leads to better soil structure, increased microbial diversity, and elevated organic matter content [14]. The root exudates act as nutrients for beneficial bacteria [63], creating conditions that make nutrients more accessible while controlling disease-causing pathogens. The natural process creates soil sustainability by lowering chemical fertilizer needs and builds resilient agricultural systems, improving long-term crop production [64].

In addition to improving soil health, P-MFCs serve environmental goals by reducing greenhouse gas emissions and offering potential for wastewater treatment. In contrast to traditional fossil-fuel systems that release significant greenhouse gases, P-MFCs operate as carbon-neutral or even carbon-negative energy systems by leveraging natural soil carbon sequestration processes [65]. Moreover, electrogenic bacteria within P-MFCs can oxidize organic pollutants in wastewater, generating electricity while simultaneously remediating environmental contaminants [66]. The dual function capability positions P-MFCs as a promising technology for achieving multiple sustainable development goals (SDGs), particularly those related to clean energy, water sanitation, and climate action.

P-MFCs have already been deployed in diverse pilot projects across the globe. Researchers at Wageningen University in the Netherlands implemented P-MFC prototypes on green roofs and wetlands to demonstrate decentralized renewable energy generation in urban and semi-urban areas [5,15]. In India, researchers used P-MFCs to power electricity generation in rice paddy fields by utilizing native plant species and natural microbial communities, enhancing both soil quality and crop productivity [67]. In Mexico, studies have demonstrated the suitability of drought-resistant *Opuntia* species for continuous electricity generation in arid climates [9]. Beyond basic power generation, P-MFCs also function as energy sources for environmental monitoring systems, including sensors for real-time soil moisture, temperature, and nutrient levels [68]. Their multifunctionality gives P-MFCs an advantage over conventional renewable systems in agricultural settings. By simultaneously improving soil health and generating electricity, P-MFCs offer a holistic, ecosystem-based solution, aligning with the principles of sustainable agriculture and smart farming [69].

5. Innovative technologies for improving food-energy P-MFC systems

5.1. Plant genetic engineering, synthetic microbial consortia and next-generation electrode materials in food-energy P-MFC systems

Plant biotechnology and materials science advancements have significantly accelerated the development of high-performance P-MFC systems. The application of CRISPR/Cas9 genetic engineering techniques and holo-omics approaches enables scientists to modify plant root systems for producing elevated amounts of particular exudates, which boosts P-MFC energy output [70]. Scientists have worked on building synthetic microbial consortia through the precise selection of electrogenic bacteria and plant growth-promoting bacteria to achieve maximum bioelectricity output and plant health benefits [71]. Bioengineered approaches enable the development of microbial communities that adapt their metabolism to maintain stability under changing environmental conditions, thus enabling stable and scalable P-MFC performance.

The development of nanotechnology has brought new electrode materials, including graphene aerogels, carbon nanotubes, and metal-organic frameworks, which boost electron transfer rates while decreasing internal resistance. A remarkable fivefold enhancement in power density, up to 583.8 W m^{-3}, was achieved through the application of advanced graphene aerogel anodes [69]. Owing to their pronounced hydrophilicity and three-dimensional structure, these materials offer abundant attachment sites and favorable biocompatibility conditions for exoelectrogens, thereby facilitating denser biofilm formation and significantly reducing the start-up times and enhances long-term system performance.

In addition to recently explored graphene-based and carbonaceous materials, several novel and emerging materials hold promise for advancing food-energy P-MFC systems by enhancing biofilm development, electrochemical efficiency, and redox activity. Ligand-imprinted mesoporous composite materials, such as BSBAE (N,N–bis (salicylidene)1,2–bis(2–aminophenylthio)ethane), exhibit excellent surface characteristics that can promote microbial adhesion and increase the electrochemically active surface area, thereby improving electron exchange efficiency within the anode biofilm layer [72–74]. Silicon-based materials, known for their abundance, low toxicity, excellent conductivity, and cost-effectiveness, have been used successfully in sustainable hydrogen generation and are now being explored as electrodes and conductive fillers in P-MFC systems [75,76]. Likewise, biodegradable composites such as chitosan-modified cotton matrices provide an eco-friendly platform for microbial colonization, coupling structural integrity with favorable ion transport properties [77]. Furthermore, direct ligand immobilization onto mesoporous silica has been shown to improve adsorption capacity and selectivity, offering dual functionality in systems designed for simultaneous bioelectricity generation and organic pollutant remediation [78–81]. In pursuit of improving proton conductivity across the system, the development of Nafion–metal oxide hybrid membranes has emerged as a promising strategy. These composite membranes can establish additional proton transport pathways, thereby lowering internal resistance and enhancing overall system efficiency [82]. Finally, integrating innovative photocathodes into P-MFC configurations, such as those based on Ni/Si/MgO photocatalysts, could enhance the oxygen reduction reaction (ORR) under light exposure. This would not only improve cathodic kinetics but also activate supplementary redox processes [83]. Despite their promising electrochemical properties, all electrode materials intended for integrated food-energy P-MFC systems, must be thoroughly evaluated for environmental inertness and the potential release of hazardous compounds, to ensure the safety of agricultural products for end-consumers.

Integrating P-MFCs with Internet of Things (IoT) platforms allows for real-time monitoring and adaptive management of soil health, plant vitality, and system output [68,84]. Innovative agriculture systems optimize bioelectricity generation, boosting crop productivity and environmental sustainability [85]. Combining these advanced technologies leads to commercial opportunities for P-MFCs as essential elements in future food-energy-water nexus solutions.

5.2. Smart inputs, biological agents, and electronic soil for enhancing P-MFC performance

An emerging and underexplored direction in P-MFC optimization is the application of smart fertilizers. Such an approach involves the use of mineral fertilizers or rich substrates, which have been shown to significantly enhance the performance of P-MFCs. Fertilizing *Opuntia*-based P-MFCs with ammonium nitrate resulted in a 94 % increase in power output and a 51 % improvement in plant growth [86]. As demonstrated, the use of mineral fertilizers, particularly, slow-release formulations, enriches both the diversity and abundance of the microbial community [87], which can play a crucial role in electricity generation. For instance, the diversity of fungal species in the soil treated with chemical fertilizer, along with waterlogging, increased by 40.5 % relative to the control [88]. Smart fertilizers or nutrient-enriched substrates may support continuous microbial and root activity, enhancing power output and system resilience during periods of reduced natural nutrient availability, and affect electro-generating microorganisms and the associated decomposer organisms. Furthermore, smart fertilizers promote the plant, another key factor for the stable and efficient performance of P-MFC. As reported by Abdel Hafez et al. [89] and El-Azeiz et al. [90], the treatment has shown a significant effect on improving vegetative growth parameters, such as the number of green leaves per plant and total leaf area (m^2/plant), which is essential for rhizodeposition. Equally important is the use of biofertilizers, which modulate soil microbiome structure and influence soil health and crop performance [67]. Thus, the nutrient supplementation strategy can contribute to the long-term sustainability and performance stability of PMFC systems.

Another promising and nature-grounded strategy includes incorporating annelids into P-MFC systems for improving soil health and creating optimal conditions for both microbial communities and plants. This unconventional solution was demonstrated by Rusyn et al. [91] in a short-term experiment using a *Caltha palustris*-based P-MFC. The introduction of earthworms, *Lumbricus terrestris*, served as a biological enhancer of bioelectricity generation, increasing power output by up to 14.3 % within just one month. Earthworms act as natural bio-boosters by simultaneously supporting plant development and influencing soil microbial dynamics. Their role as active regulators of soil microbiota promotes the proliferation of specific microbial populations, potentially including electrogenic taxa, thus contributing to improved system performance.

A noteworthy and innovative strategy to enhance P-MFC systems involves the application of weak electrical fields. Experimental studies have demonstrated that such stimulation can promote overall plant growth and root development [92] by modulating the architecture of root meristems [93], thereby affecting the functionality of root systems essential for electrogenesis. Additionally, weak electric fields have been shown to influence both the activity and composition of soil microbial communities, increasing microbial diversity [94], improving soil health and fertility, and ultimately enhancing plant productivity, factors that directly contribute to improved P-MFC functionality. Weak electrical stimulation has been reported to strengthen biomass growth of *Chlorella* cultures by 40 % [95], underscoring its potential as a tool for modulating microbial communities across P-MFC systems. Recently, researchers at Linköping University in Sweden developed a "bioelectronic growth scaffold" (eSoil), which enhanced barley seedling growth by 50 % within just 15 days by electrically stimulating the plant root system [96]. This technology represents a particularly promising strategy for integrating P-MFC systems into controlled environments, such as vertical farms and hydroponic or aeroponic settings, where precision agriculture can benefit from electrostimulation techniques.

These emerging bioelectronic solutions, alongside smart fertilizers and the inclusion of beneficial soil fauna such as earthworms (Figs. 6 and 7), offer a powerful toolkit for improving the energy and biomass yields of food-integrated P-MFCs. Integrating such approaches into sustainable agri-energy platforms could significantly advance the performance and resilience of next-generation bioelectrochemical systems.

6. Challenges and future directions

The commercialization of P-MFCs remains constrained by several technical and logistical barriers. The main technical challenge stems from P-MFCs generating lower power density than traditional renewable energy systems, including solar and wind power, as previously reviewed [28]. These energy limitations are primarily attributed to inefficient electron transfer between microbes and electrodes, as well as variable plant exudate production and the use of suboptimal electrode materials. The transition of P-MFCs from laboratory models to field-scale applications creates maintenance problems, along with concerns about biofouling and environmental stability issues [97]. The operational barriers require interdisciplinary collaboration between biologists, material scientists, and engineers to create robust, high-efficiency systems that will operate for extended periods.

The economic viability stands as a significant hurdle that prevents P-MFCs from becoming mainstream technology. Combining expensive electrode materials, ion-exchange membranes, and system integration technologies leads to increased capital costs that surpass traditional agricultural practices [17]. Future research should concentrate on developing affordable, durable materials and system design optimization for modular deployment to resolve these problems. Further research must explore plant-microbe-electrode interactions to improve power generation and system stability in actual operational environments. Bioelectrochemical technology acceptance by society, along with

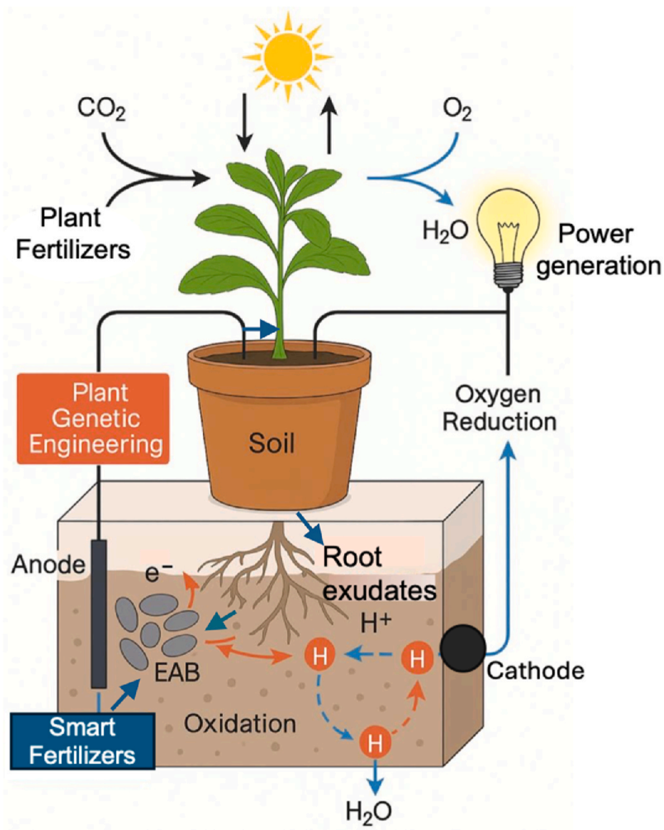


Fig. 6. Schematic diagram demonstrating how genetic engineering plant boosts root exudate production, while smart fertilizers maintain microbial activity and enhance soil health. The combination of these strategies has the potential to significantly improve the performance, efficiency, and long-term stability of P-MFCs. Created in https://BioRender.com.

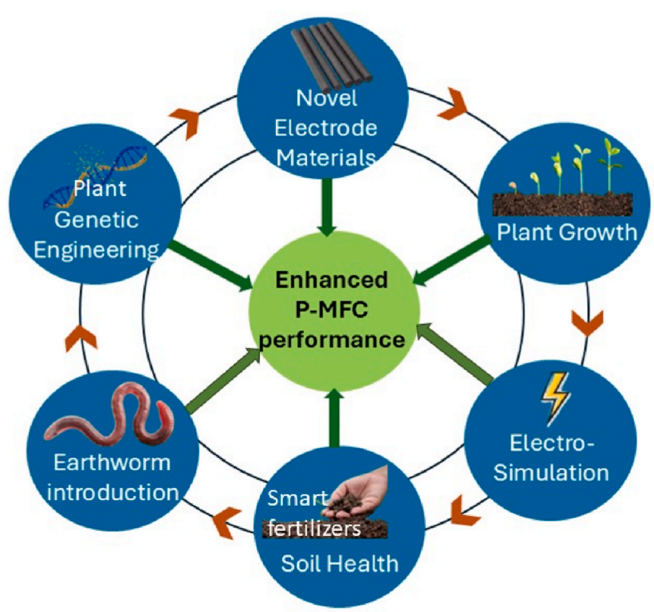


Fig. 7. Biointegrated and technologically advanced solutions to enhance food-energy integrated P-MFC systems performance.

supportive policies, will drive the adoption of P-MFC systems. Smart agriculture frameworks will integrate P-MFCs through real-time IoT--based monitoring and adaptive management systems that optimize both energy production and crop productivity [98]. The solution to these challenges will establish P-MFCs as fundamental technologies for building sustainable global food and energy systems.

In summary, future research should build on recent advancements in livestock urine-based P-MFCs (as demonstrated with *Stevia rebaudiana*) for nutrient recovery, and compact systems for growing culinary plants indoors (as shown with *Ocimum basilicum*) and develop advanced nanomaterial electrodes to address ongoing challenges such as low power density, high material costs, and limited scalability. The main focus should be on plant genetic engineering to create crop varieties that produce more root exudates, as current evidence suggests that higher biomass output leads to better power generation. Additionally, designing synthetic microbial consortia for stable electrogenesis in field conditions will help resolve performance variability issues seen in pilot systems. It is also crucial to develop cost-effective, eco-friendly nanostructured electrodes, along with Nafion–metal oxide hybrid membranes, to improve electron transfer efficiency and lower internal resistance. Furthermore, smart fertilizers and biofertilizers offer practical solutions for maintaining rhizosphere activity and microbial diversity during long-term operations while addressing nutrient depletion observed in extended trials. Finally, implementing IoT-enabled monitoring systems and bioelectronic stimulation methods (such as weak electrical fields and e-Soil technologies) can enhance plant growth and electron flow, reducing performance fluctuations seen in current designs. Combining these research directions will support the transition of P-MFCs from experimental setups to scalable, sustainable food–energy production systems.

7. Conclusions

P-MFCs present a groundbreaking solution to transform the worldwide food-energy relationship through their ability to generate sustainable bioelectricity while boosting agricultural output. The natural partnership between plants and electrogenic microbes in P-MFCs enables renewable energy production while improving soil health, carbon sequestration, and arable land restoration. Enhancing system efficiency and scalability involves optimization of engineering microbial consortia, nanomaterial-based electrodes, and nature-based strategies such as smart fertilizers, biofertilizers, and the introduction of annelids. Integration of P-MFCs with smart agriculture tools, including IoT-based monitoring and waste-to-energy frameworks, offers pathways for precision farming and resource-efficient food-energy systems. Moreover, the coupling of P-MFCs with hydroponic and vertical farming setups opens new possibilities for space-efficient, controlled-environment agriculture that produces both clean energy and high-value crops.

Nevertheless, the system faces major obstacles because of its low power density, expensive materials, and limited scalability. The solution to these challenges demands teamwork between plant science and microbiology experts, materials engineering, and data science fields. The adoption of P-MFCs will depend heavily on public acceptance and policy incentives. The advancement of research will transform P-MFCs into essential components of sustainable agroecosystems, which support worldwide sustainability targets and reduce climate change impacts. The successful implementation of P-MFC technologies as foundational elements of sustainable food and energy systems requires ongoing efforts to optimize and scale up these technologies.

CRediT authorship contribution statement

Iryna Rusyn: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Yamini Mittal:** Writing – review & editing, Validation, Data curation. **Wilgince Apollon:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

WA expresses gratitude for the support received from the Secretariat of Science, Humanities, Technology and Innovation (SECIHTI, its Spanish acronym) for the postdoctoral fellowship (Grant No. 4500144/Ref. No. 878025) and to the Centro de Investigación en Ciencia Aplicada y Tecnología Aplicada (CICATA, Altamira) at the Instituto Politécnico Nacional (IPN).

Data availability

No data was used for the research described in the article.

References

[1] J. Reiff, H.F. Jungkunst, K.M. Mauser, S. Kampel, S. Regending, V. Rösch, J. G. Zaller, M.H. Entling, Permaculture enhances carbon stocks, soil quality and biodiversity in Central Europe, Commun. Earth Environ. 5 (2024) 305, https://doi.org/10.1038/s43247-024-01405-8.

[2] S.G. Nnabuife, A.K. Hamzat, J. Whidborne, B. Kuang, K.W. Jenkins, Integration of renewable energy sources in tandem with electrolysis: a technology review for green hydrogen production, Int. J. Hydrogen Energy 107 (2025) 218–240, https://doi.org/10.1016/j.ijhydene.2024.06.342.

[3] A. Time, N. Gomez-Casanovas, P. Mwebaze, W. Apollon, M. Khanna, E. H. DeLucia, C.J. Bernacchi, Conservation agrivoltaics for sustainable food-energy production, Plants People Planet 6 (2024) 558–569, https://doi.org/10.1002/ppp3.10481.

[4] R. Jayabal, Towards a carbon-free society: innovations in green energy for a sustainable future, Results Eng. 24 (2024) 103121, https://doi.org/10.1016/j.rineng.2024.103121.

[5] D.P.B.T.B. Strik, H.V.M. Hamelers (Bert), J.F.H. Snel, C.J.N. Buisman, Green electricity production with living plants and bacteria in a fuel cell, Int. J. Energy Res. 32 (2008) 870–876, https://doi.org/10.1002/er.1397.

[6] T. Lawson, A.L. Milliken, Photosynthesis – beyond the leaf, New Phytol. 238 (2023) 55–61, https://doi.org/10.1111/nph.18671.

[7] I. Rusyn, J.C. Gómora-Hernández, Constructed wetland microbial fuel cell as enhancing pollutants treatment technology to produce green energy, Biotechnol. Adv. 77 (2024) 108468, https://doi.org/10.1016/j.biotechadv.2024.108468.

[8] B.E. Logan, B. Hamelers, R. Rozendal, U. Schröder, J. Keller, S. Freguia, P. Aelterman, W. Verstraete, K. Rabaey, Microbial fuel cells: methodology and technology, Environ. Sci. Technol. 40 (2006) 5181–5192, https://doi.org/10.1021/es0605016.

[9] W. Apollon, S.-K. Kamaraj, H. Silos-Espino, C. Perales-Segovia, L.L. Valera-Montero, V.A. Maldonado-Ruelas, M.A. Vázquez-Gutiérrez, R.A. Ortiz-Medina, S. Flores-Benítez, J.F. Gómez-Leyva, Impact of Opuntia species plant bio-battery in a semi-arid environment: demonstration of their applications, Appl. Energy 279 (2020) 115788, https://doi.org/10.1016/j.apenergy.2020.115788.

[10] R. Shaikh, A. Rizvi, M. Quraishi, S. Pandit, A.S. Mathuriya, P.K. Gupta, J. Singh, R. Prasad, Bioelectricity production using plant-microbial fuel cell: present state of art, South Afr. J. Bot. 140 (2021) 393–408, https://doi.org/10.1016/j.sajb.2020.09.025.

[11] L. De Schamphelaire, L. Van den Bossche, H.S. Dang, M. Höfte, N. Boon, K. Rabaey, W. Verstraete, Microbial fuel cells generating electricity from rhizodeposits of rice plants, Environ. Sci. Technol. 42 (2008) 3053–3058, https://doi.org/10.1021/es071938w.

[12] N. Kaku, N. Yonezawa, Y. Kodama, K. Watanabe, Plant/microbe cooperation for electricity generation in a rice paddy field, Appl. Microbiol. Biotechnol. 79 (2008) 43–49, https://doi.org/10.1007/s00253-008-1410-9.

[13] N.F. Tapia, C. Rojas, C.A. Bonilla, I.T. Vargas, Evaluation of Sedum as driver for plant microbial fuel cells in a semi-arid green roof ecosystem, Ecol. Eng. 108 (2017) 203–210, https://doi.org/10.1016/j.ecoleng.2017.08.017.

[14] E.R. Ballestas, E.C. Bortoluzzi, A.H. Hamad Minervino, H.H. Palma, A. Neckel, C. G. Ramos, A.L. Moreno-Ríos, Power generation potential of plant microbial fuel cells as a renewable energy source, Renew. Energy 221 (2024) 119799, https://doi.org/10.1016/j.renene.2023.119799.

[15] J. Greenman, R. Thorn, N. Willey, I. Ieropoulos, Energy harvesting from plants using hybrid microbial fuel cells; potential applications and future exploitation, Front. Bioeng. Biotechnol. 12 (2024), https://doi.org/10.3389/fbioe.2024.1276176.

[16] I. Rusyn, O. Medvediev, Stacking and design optimization of novel plant microbial fuel cell based on dwarf indoor decorative and culinary plants as a compact biobattery for a low energy consumption devices, Bioresour. Technol. Rep. 26 (2024) 101860, https://doi.org/10.1016/j.biteb.2024.101860.

[17] A.Y. Radeef, A.A. Najim, Microbial fuel cell: the renewable and sustainable magical system for wastewater treatment and bioenergy recovery, Energy 360 (1) (2024) 100001, https://doi.org/10.1016/j.energ.2024.100001.

[18] M.R. Awual, A. Islam, M.M. Hasan, M.M. Rahman, A.M. Asiri, M.A. Khaleque, M. C. Sheikh, Introducing an alternate conjugated material for enhanced lead (II) capturing from wastewater, J. Clean. Prod. 224 (2019) 920–929.

[19] M.R. Awual, M.M. Hasan, J. Iqbal, M.A. Islam, A. Islam, S. Khandaker, A.M. Asiri, M.M. Rahman, Ligand based sustainable composite material for sensitive nickel (II) capturing in aqueous media, J. Environ. Chem. Eng. 8 (2020) 103591.

[20] A. Shahat, K.T. Kubra, M.S. Salman, M.N. Hasan, M.M. Hasan, Novel solid-state sensor material for efficient cadmium (II) detection and capturing from wastewater, Microchem. J. 164 (2021) 105967.

[21] M.R. Awual, A facile composite material for enhanced cadmium (II) ion capturing from wastewater, J. Environ. Chem. Eng. 7 (2019) 103378.

[22] M.R. Awual, Solid phase sensitive palladium (II) ions detection and recovery using ligand based efficient conjugate nanomaterials, Chem. Eng. J. 300 (2016) 264–272.

[23] P.L. Chong, J.H. Chuah, C.O. Chow, P.K. Ng, Plant microbial fuel cells: a comprehensive review of influential factors, innovative configurations, diverse applications, persistent challenges, and promising prospects, Int. J. Green Energy (2024), https://doi.org/10.1080/15435075.2024.2421325.

[24] R. Agrahari, B. Bayar, H.N. Abubackar, B.S. Giri, E.R. Rene, R. Rani, Advances in the development of electrode materials for improving the reactor kinetics in microbial fuel cells, Chemosphere 290 (2022) 133184, https://doi.org/10.1016/j.chemosphere.2021.133184.

[25] I. Brugellis, M. Grassi, P. Malcovati, S. Assini, Plant microbial fuel cells in a botanical perspective: nomenclatural constraints and new insights on plant traits potentially affecting bioelectrical perfomance, Heliyon 10 (2024) e38733, https://doi.org/10.1016/j.heliyon.2024.e38733.

[26] I. Rusyn, Role of microbial community and plant species in performance of plant microbial fuel cells, Renew. Sustain. Energy Rev. 152 (2021) 111697, https://doi.org/10.1016/j.rser.2021.111697.

[27] I. Rusyn, O. Fihurka, V. Dyachok, Effect of plants morphological parameters on plant-microbial fuel cell efficiency, Innovat. Biosyst. Bioeng. 6 (2023) 161–168, https://doi.org/10.20535/ibb.2022.6.3-4.273108.

[28] S. Maddalwar, K. Kumar Nayak, M. Kumar, L. Singh, Plant microbial fuel cell: opportunities, challenges, and prospects, Bioresour. Technol. 341 (2021) 125772, https://doi.org/10.1016/j.biortech.2021.125772.

[29] J. Md Khudzari, J. Kurian, Y. Gariépy, B. Tartakovsky, G.S. V Raghavan, Effects of salinity, growing media, and photoperiod on bioelectricity production in plant microbial fuel cells with weeping alkaligrass, Biomass Bioenergy 109 (2018) 1–9, https://doi.org/10.1016/j.biombioe.2017.12.013.

[30] W. Apollon, J.A. Vidales-Contreras, H. Rodríguez-Fuentes, J.F. Gómez-Leyva, E. Olivares-Sáenz, V.A. Maldonado-Ruelas, R.A. Ortiz-Medina, S.-K. Kamaraj, A. I. Luna-Maldonado, Livestock's urine-based plant microbial fuel cells improve plant growth and power generation, Energies 15 (2022) 6985.

[31] W. Apollon, A.I. Luna-Maldonado, S.-K. Kamaraj, J.A. Vidales-Contreras, H. Rodríguez-Fuentes, J.F. Gómez-Leyva, V.A. Maldonado-Ruelas, R.A. Ortiz-Medina, Self-sustainable nutrient recovery associated to power generation from livestock's urine using plant-based bio-batteries, Fuel 332 (2023) 126252.

[32] Z. Yan, H. Jiang, H. Cai, Y. Zhou, L.R. Krumholz, Complex interactions between the macrophyte Acorus Calamus and microbial fuel cells during pyrene and benzo[a]pyrene degradation in sediments, Sci. Rep. 5 (2015) 10709, https://doi.org/10.1038/srep10709.

[33] H. Kahrizi, S.E.H. Garmdareh, R. Abbassi, Simultaneous removal of heavy metals and electricity generation from wastewater in constructed wetland-microbial fuel cells, Process Saf. Environ. Prot. 190 (2024) 921–929, https://doi.org/10.1016/j.psep.2024.07.076.

[34] A.C. Sophia, S. Sreeja, Green energy generation from plant microbial fuel cells (PMFC) using compost and a novel clay separator, Sustain. Energy Technol. Assessments 21 (2017) 59–66, https://doi.org/10.1016/j.seta.2017.05.001.

[35] M. Helder, D.P.B.T.B. Strik, H.V.M. Hamelers, A.J. Kuhn, C. Blok, C.J.N. Buisman, Concurrent bio-electricity and biomass production in three plant-microbial fuel cells using Spartina anglica, Arundinella anomala and Arundo donax, Bioresour. Technol. 101 (2010) 3541–3547, https://doi.org/10.1016/j.biortech.2009.12.124.

[36] R.D.R. Martinez, Plant–microbial fuel cell for electrical generation through living plants: an internal resistance insight into the plant species used, Clean Energy 8 (2024) 45–53, https://doi.org/10.1093/ce/zkae053.

[37] K.R.S. Pamintuan, A.M.C. Katipunan, P.A.O. Palaganas, A.R. Caparanga, An analysis of the stacking potential and efficiency of plant-microbial fuel cells growing green beans (Vigna ungiculata ssp. sesquipedalis), Int. J. Renew. Energy Dev. 9 (2020) 439–447, https://doi.org/10.14710/ijred.2020.29898.

[38] P. Chiranjeevi, R. Chandra, S.V. Mohan, Ecologically engineered submerged and emergent macrophyte based system: an integrated eco-electrogenic design for harnessing power with simultaneous wastewater treatment, Ecol. Eng. 51 (2013) 181–190, https://doi.org/10.1016/j.ecoleng.2012.12.014.

[39] M. Karimi, A. Ahmadi, J. Hashemi, A. Abbasi, S. Tavarini, L. Guglielminetti, L. G. Angelini, The effect of soil moisture depletion on Stevia (Stevia rebaudiana Bertoni) grown in greenhouse conditions: Growth, steviol glycosides content, soluble sugars and total antioxidant capacity, Sci. Horticult. 183 (2015) 93–99. https://doi.org/10.1016/j.scienta.2014.11.001.

[40] P. Han, P. Kumar, B.-L. Ong, Remediation of nutrient-rich waters using the terrestrial plant, Pandanus amaryllifolius Roxb, J. Environ. Sci. 26 (2014) 404–414, https://doi.org/10.1016/S1001-0742(13)60426-X.

[41] P.J. Sarma, K. Mohanty, An insight into plant microbial fuel cells, in: Bioelectrochemical Interface Engineering, 2019, pp. 137–148, https://doi.org/10.1002/9781119611103.ch8.
[42] N. Ueoka, N. Sese, M. Sue, A. Kouzuma, K. Watanabe, Sizes of anode and cathode affect electricity generation in rice paddy-field microbial fuel cells, J .Sustain. Bioenergy Syst .06 (2016) 10–15, https://doi.org/10.4236/jsbs.2016.61002.
[43] A. Matsumoto, M. Nagoya, M. Tsuchiya, K. Suga, Y. Inohana, A. Hirose, S. Yamada, S. Hirano, Y. Ito, S. Tanaka, A. Kouzuma, K. Watanabe, Enhanced electricity generation in rice paddy-field microbial fuel cells supplemented with iron powders, Bioelectrochemistry 136 (2020) 107625, https://doi.org/10.1016/j.bioelechem.2020.107625.
[44] P.L. Chong, A.K. Singh, S.L. Kok, Potential application of Aloe Vera-derived plant-based cell in powering wireless device for remote sensor activation, PLoS One 14 (2019), https://doi.org/10.1371/journal.pone.0227153.
[45] R.K. Yadav, P. Chiranjeevi, Sukrampal, S.A. Patil, Integrated drip hydroponics-microbial fuel cell system for wastewater treatment and resource recovery, Bioresour. Technol. Rep. 9 (2020) 100392, https://doi.org/10.1016/j.biteb.2020.100392.
[46] C. Sato, W. Apollon, A.I. Luna-Maldonado, N.E. Paucar, M. Hibbert, J. Dudgeon, Integrating microbial fuel cell and hydroponic technologies Using a ceramic membrane separator to develop an energy–water–food supply system, Membranes 13 (9) (2023) 803, https://doi.org/10.3390/membranes13090803.
[47] S. Dewanjee, S. Joardar, N. Bhattacharjee, T.K. Dua, S. Das, J. Kalita, P. Manna, Edible leaf extract of Ipomoea aquatica Forssk. (Convolvulaceae) attenuates doxorubicin-induced liver injury via inhibiting oxidative impairment, MAPK activation and intrinsic pathway of apoptosis, Food Chem. Toxicol. 105 (2017) 322–336, https://doi.org/10.1016/j.fct.2017.05.002.
[48] S. Liu, D. Qiu, F. Lu, Y. Wang, Z. Wang, X. Feng, S.-H. Pyo, Acorus calamus L. constructed wetland-microbial fuel cell for Cr(VI)-containing wastewater treatment and bioelectricity production, J. Environ. Chem. Eng. 10 (2022) 107801, https://doi.org/10.1016/j.jece.2022.107801.
[49] K.R.S. Pamintuan, J.A.A. Clomera, K.V. Garcia, G.R. Ravara, E.J.G. Salamat, Stacking of aquatic plant-microbial fuel cells growing water spinach (Ipomoea aquatica) and water lettuce (Pistia stratiotes), in: IOP Conf Ser Earth Environ Sci, Institute of Physics Publishing, 2018, https://doi.org/10.1088/1755-1315/191/1/012054.
[50] W. Apollon, A.I. Luna-Maldonado, S.-K. Kamaraj, J.A. Vidales-Contreras, H. Rodríguez-Fuentes, J.F. Gómez-Leyva, J. Aranda-Ruíz, Progress and recent trends in photosynthetic assisted microbial fuel cells: a review, Biomass Bioenergy 148 (2021) 106028, https://doi.org/10.1016/j.biombioe.2021.106028.
[51] Z. Fang, X. Cao, X. Li, H. Wang, X. Li, Biorefractory wastewater degradation in the cathode of constructed wetland-microbial fuel cell and the study of the electrode performance, Int. Biodeterior. Biodegrad. 129 (2018) 1–9, https://doi.org/10.1016/j.ibiod.2017.12.003.
[52] F. Xu, F. Cao, Q. Kong, L. Zhou, Q. Yuan, Y. Zhu, Q. Wang, Y. Du, Z. Wang, Electricity production and evolution of microbial community in the constructed wetland-microbial fuel cell, Chem. Eng. J. 339 (2018) 479–486, https://doi.org/10.1016/j.cej.2018.02.003.
[53] F.T. Kabutey, Q. Zhao, L. Wei, J. Ding, P. Antwi, F.K. Quashie, W. Wang, An overview of plant microbial fuel cells (PMFCs): configurations and applications, Renew. Sustain. Energy Rev. 110 (2019) 402–414.
[54] E. Osorio de la Rosa, J. Vázquez Castillo, M. Carmona Campos, G.R. Barbosa Pool, G. Becerra Nuñez, A. Castillo Atoche, J. Ortegón Aguilar, Plant microbial fuel cells–based energy harvester system for self-powered IoT applications, Sensors 19 (6) (2019) 1378. https://doi.org/10.3390/s19061378.
[55] P.L. Chong, A.K. Singh, F.Y. Kong, J.P. Diraja, U. Aziz, K. Lumpur, W. Persekutuan, Renewable Energy from Living Plants to Power Iot Sensor for Remote Sensing, 2022.
[56] I.B. Rusyn, B.T. Valko, Container landscaping with *Festuca arundinaceae* as bioelectrical minisystems in modern buildings, Int. J. Energy Clean Environ. 20 (3) (2019) 211–229. https://doi.org/10.1615/InterJEnerCleanEnv.2019026674.
[57] R.A. Timmers, M. Rothballer, D.P.B.T.B. Strik, M. Engel, S. Schulz, M. Schloter, A. Hartmann, B. Hamelers, C. Buisman, Microbial community structure elucidates performance of glyceria maxima plant microbial fuel cell, Appl. Microbiol. Biotechnol. 94 (2012) 537–548, https://doi.org/10.1007/s00253-012-3894-6.
[58] T.H. Cheng, K.B. Ching, C. Uttraphan, Y.M. Heong, Electrical energy production from plant biomass: an analysis model development for Pandanus amaryllifolius plant microbial fuel cell, Indonesian J.Electrical Eng.Computer Sci. 18 (2020) 1163–1171, https://doi.org/10.11591/ijeecs.v18.i3.pp1163-1171.
[59] O. Guadarrama-Pérez, T. Gutiérrez-Macías, L. García-Sánchez, V.H. Guadarrama-Pérez, E.B. Estrada-Arriaga, Recent advances in constructed wetland-microbial fuel cells for simultaneous bioelectricity production and wastewater treatment: a review, Int. J. Energy Res. 43 (2019) 5106–5127, https://doi.org/10.1002/er.4496.
[60] R.D.R. Martinez, M.E.A. Bermudez, Production of electrical energy from living plants in microbial fuel cells, Clean Energy 7 (2023) 408–416, https://doi.org/10.1093/ce/zkac092.
[61] A.G. Olabi, K. Elsaid, K. Obaideen, M.A. Abdelkareem, H. Rezk, T. Wilberforce, H. M. Maghrabie, E.T. Sayed, Renewable energy systems: comparisons, challenges and barriers, sustainability indicators, and the contribution to UN sustainable development goals, Int. J.Thermofluids 20 (2023) 100498, https://doi.org/10.1016/j.ijft.2023.100498.
[62] D. Bose, R. Bhattacharya, P. Ganti, A. Rizvi, G. Halder, A. Sarkar, Bioelectricity production and bioremediation potential of Withania somnifera in plant microbial fuel cells, Energy Nexus 15 (2024) 100314, https://doi.org/10.1016/j.nexus.2024.100314.
[63] L. Chen, Y. Liu, The function of root exudates in the root colonization by beneficial soil rhizobacteria, Biology 13 (2) (2024) 95, https://doi.org/10.3390/biology13020095.
[64] P. Sharma, P. Sharma, N. Thakur, Sustainable farming practices and soil health: a pathway to achieving SDGs and future prospects, Dis. Sustain. 5 (2024) 250, https://doi.org/10.1007/s43621-024-00447-4.
[65] T.A. Kurniawan, M.H.D. Othman, X. Liang, M. Ayub, H.H. Goh, T.D. Kusworo, A. Mohyuddin, K.W. Chew, Microbial Fuel Cells (MFC): a potential game-changer in renewable energy development, Sustainability 14 (2022), https://doi.org/10.3390/su142416847.
[66] V. Ancona, C. Cavone, P. Grenni, G. Gagliardi, C. Cosentini, D. Borello, A. Barra Caracciolo, Plant microbial fuel cells for recovering contaminated environments, Int. J. Hydrogen Energy 72 (2024) 1116–1126, https://doi.org/10.1016/j.ijhydene.2024.05.457.
[67] T. Kumar, S.E. Jujjavarapu, Carbon dioxide sequestration and wastewater treatment via an innovative self-sustaining algal microbial fuel cell, J. Clean. Prod. 415 (2023) 137836, https://doi.org/10.1016/j.jclepro.2023.137836.
[68] N.N. Thilakarathne, M.S. Abu Bakar, P.E. Abas, H. Yassin, Internet of things enabled smart agriculture: current status, latest advancements, challenges and countermeasures, Heliyon 11 (2025) e42136, https://doi.org/10.1016/j.heliyon.2025.e42136.
[69] J. Li, Y. Yu, D. Chen, G. Liu, D. Li, H.-S. Lee, Y. Feng, Hydrophilic graphene aerogel anodes enhance the performance of microbial electrochemical systems, Bioresour. Technol. 304 (2020) 122907, https://doi.org/10.1016/j.biortech.2020.122907.
[70] S. Singh, W. Ramakrishna, Application of CRISPR–Cas9 in plant–plant growth-promoting rhizobacteria interactions for next Green Revolution, 3 Biotech 11 (2021) 492, https://doi.org/10.1007/s13205-021-03041-x.
[71] Y. Besset-Manzoni, L. Rieusset, P. Joly, G. Comte, C. Prigent-Combaret, Exploiting rhizosphere microbial cooperation for developing sustainable agriculture strategies, Environ. Sci. Pollut. Control Ser. 25 (2018) 29953–29970, https://doi.org/10.1007/s11356-017-1152-2.
[72] M.S. Salman, M.N. Hasan, K.T. Kubra, M.M. Hasan, Optical detection and recovery of Yb (III) from waste sample using novel sensor ensemble nanomaterials, Microchem. J. 162 (2021) 105868.
[73] M.M. Hasan, M.S. Salman, M.N. Hasan, A.I. Rehan, M.E. Awual, A.I. Rasee, R. M. Waliullah, M.S. Hossain, K.T. Kubra, M.C. Sheikh, Facial conjugate adsorbent for sustainable Pb (II) ion monitoring and removal from contaminated water, Colloids Surf. A Physicochem. Eng. Asp. 673 (2023) 131794.
[74] M.E. Awual, M.S. Salman, M.M. Hasan, M.N. Hasan, K.T. Kubra, M.C. Sheikh, A. I. Rasee, A.I. Rehan, R.M. Waliullah, M.S. Hossain, Ligand imprinted composite adsorbent for effective Ni (II) ion monitoring and removal from contaminated water, J. Ind. Eng. Chem. 131 (2024) 585–592.
[75] A. Islam, S.H. Teo, M.T. Islam, A.H. Mondal, H. Mahmud, S. Ahmed, M. Ibrahim, Y.H. Taufiq-Yap, M.L. Hossain, M.C. Sheikh, Harnessing visible light for sustainable biodiesel production with Ni/Si/MgO photocatalyst, Renew. Sustain. Energy Rev. 208 (2025) 115033.
[76] A. Islam, M.T. Islam, S.H. Teo, H. Mahmud, A.M. Swaraz, A.I. Rehan, A.I. Rasee, K.T. Kubra, M.M. Hasan, M.S. Salman, Progress in silicon-based materials for emerging solar-powered green hydrogen (H2) production, Adv. Colloid Interface Sci. (2025) 103558.
[77] M.S. Salman, M.C. Sheikh, M.M. Hasan, M.N. Hasan, K.T. Kubra, A.I. Rehan, M. E. Awual, A.I. Rasee, R.M. Waliullah, M.S. Hossain, Chitosan-coated cotton fiber composite for efficient toxic dye encapsulation from aqueous media, Appl. Surf. Sci. 622 (2023) 157008.
[78] M.R. Awual, M.M. Hasan, M.A. Khaleque, M.C. Sheikh, Treatment of copper (II) containing wastewater by a newly developed ligand based facial conjugate materials, Chem. Eng. J. 288 (2016) 368–376.
[79] M.R. Awual, New type mesoporous conjugate material for selective optical copper (II) ions monitoring & removal from polluted waters, Chem. Eng. J. 307 (2017) 85–94.
[80] M.S. Hossain, M.A. Shenashen, M.E. Awual, A.I. Rehan, A.I. Rasee, R. M. Waliullah, K.T. Kubra, M.S. Salman, M.C. Sheikh, M.N. Hasan, Benign separation, adsorption, and recovery of rare-earth Yb (III) ions with specific ligand-based composite adsorbent, Process Saf. Environ. Prot. 185 (2024) 367–374.
[81] M.M. Hasan, K.T. Kubra, M.N. Hasan, M.E. Awual, M.S. Salman, M.C. Sheikh, A. I. Rehan, A.I. Rasee, R.M. Waliullah, M.S. Islam, Sustainable ligand-modified based composite material for the selective and effective cadmium (II) capturing from wastewater, J. Mol. Liq. 371 (2023) 121125.
[82] A. Islam, A. Malek, M.T. Islam, F.Y. Nipa, O. Raihan, H. Mahmud, M.E. Uddin, M. L. Ibrahim, G. Abdulkareem-Alsultan, A.H. Mondal, Next frontier in photocatalytic hydrogen production through CdS heterojunctions, Int. J. Hydrogen Energy 101 (2025) 173–211.
[83] A. Islam, M. Shahriar, M.T. Islam, S.H. Teo, M.A.R. Khan, Y.H. Taufiq-Yap, S. C. Mohanta, A.I. Rehan, A.I. Rasee, K.T. Kubra, Advances in filler-crosslinked membranes for hydrogen fuel cells in sustainable energy generation, Int. J. Hydrogen Energy 140 (2025) 745–776.
[84] P. Rewatkar, D. Nath, P.S. Kumar, M.E. Suss, S. Goel, Internet of things enabled environmental condition monitoring driven by laser ablated reduced graphene oxide based Al-air fuel cell, J. Power Sources 521 (2022) 230938, https://doi.org/10.1016/j.jpowsour.2021.230938.

[85] J. Ke, B. Wang, Y. Yoshikuni, Microbiome engineering: synthetic biology of plant-associated microbiomes in sustainable agriculture, Trends Biotechnol. 39 (2021) 244–261, https://doi.org/10.1016/j.tibtech.2020.07.008.
[86] W. Apollon, L.L. Valera-Montero, C. Perales-Segovia, V.A. Maldonado-Ruelas, R. A. Ortiz-Medina, J.F. Gómez-Leyva, M.A. Vázquez-Gutiérrez, S. Flores-Benítez, S.-K. Kamaraj, Effect of ammonium nitrate on novel cactus pear genotypes aided by biobattery in a semi-arid ecosystem, Sustain. Energy Technol. Assessments 49 (2022) 101730, https://doi.org/10.1016/j.seta.2021.101730.
[87] I. Rusyn, M. Malovanyy, I. Tymchuk, S. Synelnikov, Effect of mineral fertilizer encapsulated with zeolite and polyethylene terephthalate on the soil microbiota, pH and plant germination, Ecol. Quest. 32 (2020), https://doi.org/10.12775/EQ.2021.007.
[88] L. Deng, L. Fu, K. Zhang, Y. Shen, G. Feng, L. Zhang, H. Li, C. Liu, Effects of fertilizer and waterlogging on the diversity and functioning of the microbial community in greenhouse cultivation soil, Chem. Biol.Echnol. Agriculture 9 (2022) 31, https://doi.org/10.1186/s40538-022-00298-z.
[89] K.S. Abdel Hafez, S.M. El-Massry, O.A. Khodair, M.A. Mohmmed, Effect of different rates of slow-release potassium fertilizers on growth and fruiting of banana var. grand nain plants, Archiv.Agriculture Sci. J. 7 (2024) 139–147, https://doi.org/10.21608/aasj.2024.376857.
[90] E. Abd El-Azeiz, R. El Mantawy, A. Albakry, Effect of different forms and rates of slow release urea fertilizers on growth, yield and quality of maize plants (Zea mays L.) تأثيرصور ومعدلات مختلفه من اسمدة اليوريا بطيئة الذوبان على نمو ومحصول وجودة الذرة الشامية, J. Soil Sci. Agricultural Eng. 12 (2021) 639–645, https://doi.org/10.21608/jssae.2021.205761.
[91] I.B. Rusyn, V.V. Vakuliuk, O.V. Burian, Prospects of use of Caltha palustris in soil plant-microbial eco-electrical biotechnology, Regul Mech.Biosyst. 10 (2019) 233–238, https://doi.org/10.15421/021935.
[92] K. Grzelka, A. Matkowski, S. Ślusarczyk, Electrostimulation improves plant growth and modulates the flavonoid profile in aeroponic culture of Scutellaria baicalensis Georgi, Front. Plant Sci. 14 (2023), https://doi.org/10.3389/fpls.2023.1142624.
[93] W. Wawrecki, B. Zagórska-Marek, Influence of a weak DC electric field on root meristem architecture, Ann. Bot. 100 (2007) 791–796, https://doi.org/10.1093/aob/mcm164.
[94] F. Li, S. Guo, S. Wang, M. Zhao, Changes of microbial community and activity under different electric fields during electro-bioremediation of PAH-contaminated soil, Chemosphere 254 (2020) 126880, https://doi.org/10.1016/j.chemosphere.2020.126880.
[95] H. Sun, W. Zhao, X. Mao, Y. Ren, T. Wu, F. Chen, Cost-effective wastewater treatment in a continuous manner by a novel bio-photoelectrolysis cell (BPE) system, Bioresour. Technol. 273 (2019) 297–304, https://doi.org/10.1016/j.biortech.2018.11.045.
[96] V.K. Oikonomou, M. Huerta, A. Sandéhn, T. Dreier, Y. Daguerre, H. Lim, M. Berggren, E. Pavlopoulou, T. Näsholm, M. Bech, E. Stavrinidou, eSoil: a low-power bioelectronic growth scaffold that enhances crop seedling growth, Proc. Natl. Acad. Sci. 121 (2024) e2304135120, https://doi.org/10.1073/pnas.2304135120.
[97] I.B. Rusyn, K.R. Hamkalo, Use of Carex hirta in electro-biotechnological systems on green roofs, Regul Mech.Biosyst. 10 (2019) 39–44, https://doi.org/10.15421/021906.
[98] S. Safeer, G. De Mastro, C. Pulvento, IoT based climate smart agriculture succeeded by blockchain database—A bibliometric analysis, Front. Sustain. Food Syst. 8 (2024), https://doi.org/10.3389/fsufs.2024.1406871.
[99] Y. Mittal, P. Srivastava, N. Kumar, M. Kumar, S.K. Singh, F. Martinez, A.K. Yadav, Ultra-fast and low-cost electroactive biochar production for electroactive-constructed wetland applications: A circular concept for plant biomass utilization, Chem. Eng. J. 452 (2023) 138587.
[100] S. Gupta, A. Patro, Y. Mittal, S. Dwivedi, P. Saket, R. Panja, T. Saeed, F. Martínez, A.K. Yadav, The race between classical microbial fuel cells, sediment-microbial fuel cells, plant-microbial fuel cells, and constructed wetlands-microbial fuel cells: Applications and technology readiness level, Sci. Total Environ. 879 (2023) 162757.