Energy Reports 14 (2025) 268–281

Contents lists available at ScienceDirect

Energy Reports

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

Review article

Energy harvesting from living plant: A review on past research and way forward

Sk Rakibur Rahman [a], Ngu Eng Eng [a,c], Muhammad Aqeel Ashraf [a], Wai-Leong Pang [d], Kar Ban Tan [e], Ajay Kumar Singh [f], Kah-Yoong Chan [a,b,*,1]

[a] Faculty of Artificial Intelligence and Engineering, Multimedia University, Persiaran Multimedia, Cyberjaya, Selangor 63100, Malaysia
[b] Centre for Advanced Devices and Systems, COE for Robotics and Sensing Technologies, Multimedia University, Persiaran Multimedia, Cyberjaya, Selangor 63100, Malaysia
[c] Centre for Electric Energy and High Voltage Engineering, COE for Robotics and Sensing Technologies, Multimedia University, Persiaran Multimedia, Cyberjaya, Selangor 63100, Malaysia
[d] School of Engineering, Faculty of Innovation and Technology, Taylor's University, Subang Jaya, Selangor 47500, Malaysia
[e] Department of Chemistry, Faculty of Science, Universiti Putra Malaysia, Serdang, Selangor 43400, Malaysia
[f] Faculty of Electronics and Communications Engineering, NIIT University, Rajasthan, India

ARTICLE INFO

Keywords:
PBC
PMFC
Plant-Based Energy
Living Plant
Electrode Potential
Energy Harvesting
Low-Energy

ABSTRACT

In the face of the global warming crisis, reliance on non-renewable energy sources poses significant ecological threats, prompting the international community to explore renewable alternatives. Numerous alternative energy sources are currently being studied, including solar, wind, hydropower, geothermal, plant-based, and biomass. This review highlights recent advancements in extracting energy from living plants by looking at 70 peer-reviewed research studies published from 2010 to 2025, including 15 that focused on Plant-Based Cells (PBCs), 24 on Plant Microbial Fuel Cells (PMFCs), and 21 that examined the physical traits of plants that influence how efficiently energy can be harvested. PMFC harnesses electron generation through the interaction of plant roots and soil bacteria during organic matter decomposition, while PBC captures electrical energy directly from the plant's metabolic processes via embedded electrodes. PMFCs typically generate lower voltage and power, whereas PBCs achieve significantly higher outputs, up to 3.5 V and 58.8 mW. The analysis examines key factors influencing energy efficiency, including plant species, age, soil composition, electrode materials, environmental conditions, and circuit design, and addresses scalability and integration challenges. The findings underscore the necessity for further research on optimal sizing, aging effects, and practical applications. Overall, this review aims to provide a solid foundation for advancing green energy technologies and their deployment in low-energy devices, such as IoT sensors, in smart farming and remote areas.

1. Introduction

The overdependence on non-renewable resources like coal, oil and natural gas has caused many issues such as environmental crisis, increased prices, and depletion of available resources (Xu and Zhao, 2023). The burning of fossil fuels retains and increases the emission of greenhouse gases, for example carbon dioxide (CO_2), which worsens climate change and global warming, and to a very large extent damages ecological health (Bertrand, 2021). This activity results in the loss of ecological balance and biodiversity because of acid rains, soil erosion, and habitat destruction. This also leads to fossil fuel extraction and usage pollution for air and water systems, which severely affects ecosystems and human health (Abas et al., 2015). Shifting to plants, geothermal, hydropower, biomass, wind, and solar energy helps overcome this issue and becomes essential in achieving sustained development (Gayen et al., 2024;Tan and Chan, 2024;Haram et al., 2023;Haram et al., 2021). As these alternatives lower greenhouse gas emissions and slow down climate change, they become economically feasible, which decreases dependence on established sources of energy. This greatly strengthens global energy security while reducing the impact on the environment (Paraschiv and Paraschiv, 2023).

It's a well-known fact that plants have incredible abilities,

* Corresponding author at: Faculty of Artificial Intelligence and Engineering, Multimedia University, Persiaran Multimedia, Cyberjaya, Selangor 63100, Malaysia.
E-mail address: kychan@mmu.edu.my (K.-Y. Chan).
[1] ORCID ID: 0000-0003-1076-5034

https://doi.org/10.1016/j.egyr.2025.06.021
Received 4 March 2025; Received in revised form 26 May 2025; Accepted 14 June 2025
Available online 18 June 2025
2352-4847/

particularly in their ability to convert solar energy to chemical energy via photosynthesis (Muladi et al., 2021). Besides their ecological and agricultural importance, other recent research examined plant structures and found their capacity to serve as renewable energy sources capable of generating electric energy. The method of getting electrical energy from living plants, called plant-based energy, uses the unique ways plants work, like the movement of ions, sugars, and other substances, to create energy without harming the plants much. This innovative method of energy harvesting is noteworthy (Teng et al., 2018). It provides a reasonable solution for use in micro energy applications, particularly where conventional renewable energy approaches, such as solar panels and wind turbines, are impractical because of infrastructural constraints, high costs, or inconsistent performance. Plant-based energy systems are generally more autonomous compared to the prevalent systems designed for medium to large-scale power generation. They are capable of operating without dependence on the sun or wind, using biological phenomena that require minimal interference. For this reason, they are a less intrusive and environmentally integrated alternative to sustainable energy generation.

Plant-derived energy systems hold enormous promise in solving modern global problems, such as acting as renewable and decentralized power sources with a significantly reduced carbon footprint, lower environmental impact, and climate change mitigation (Singh, 2022). Research indicates that the emerging technologies use the bio-electrochemical processes of plants to create alternative energy systems that are dependable and require little maintenance, particularly in remote or off-grid areas with no access to traditional energy infrastructure (De La Rosa et al., 2019). Plant-based energy enables innovation with environmental monitoring and precision agriculture, and aids the creation of green urban infrastructure, which helps foster sustainability and innovation (Leoni et al., 2022a). Because of how easy this technology is to scale and adapt, it can target a wide range of applications, from small-scale IoT and sensor devices (Ting and Chan, 2024; Lokman et al., 2024) to urban projects, thus making it a leader in developing sustainable energy solutions. Recent research has proven that PMFCs and PBCs are viable sources of low-energy electricity for powering agricultural processes. In other words, *Aloe vera* and some other plants have the capacity to support rural agriculturally connected microgrids. This study shows how plant-derived energy is necessary to reduce the use of non-renewable resources and the satisfaction of growing electricity demand brought about through sustainable means.

Researchers have thoroughly studied new ways to use living plants to generate electrical energy, looking at methods like electrode potential, triboelectric, piezoelectric, electrostatic, electromagnetic, and thermal energy harvesting. Particularly popular among scholars are the Plant Microbial Fuel Cell (PMFC) and the Plant-Based Cell (PBC), which are both classified under the electrode potential method (Lajis et al., 2021). The PMFC further enhances the interdependence between plant roots and microorganisms in the soil: the bacteria decompose organic materials, which generate electrons, and the electrodes capture the energy to convert it to electricity (Martinez and Bermudez, 2023). In comparison, the PBC extracts electricity from the metabolic activities of plants and uses electrolytes, which are the metabolic waste products the plant produces within the system, and electrodes are placed in plant tissues like leaves or stems (Guesmi et al., 2022).

The use of live plants as energy sources has numerous social, environmental, and financial benefits, including the reduction of carbon emissions and air pollution, improved power grid resilience, and enhanced energy access for remote populations. Unlike fossil fuels, plant-based energy sources provide a locally sourced, environmentally protective alternative with minimal risks and corresponding impacts (Ying Ying and Dayou, 2016). Moreover, the development of renewable energy research technologies like PMFC and PBC suggests the existence of further plant-based power generation systems for sustaining energy development. This illustrates the ability to harness natural environmental resources to produce electricity while fostering ecological and societal benefits.

Many studies concentrating on PBC and PMFC have contributed to the body of research related to these technologies and renewable energy capturing. Discussions have thoroughly tackled issues such as the species of the plants to be used, electrodes, soil type, the influence of environmental factors, and the scalability of the systems. However, important aspects, such as the impact of plant size and maturity and the reliability of PBC and PMFC systems over time, have not been adequately addressed, requiring additional work to enhance their effectiveness and sustainable use in renewable energy.

This review aims to clarify the questions around the gaps in the existing literature by documenting what has already been done and what did not get the attention it required. It covers all the previous research while highlighting new work, like the mix of PMFC and PBC techniques, which could help boost energy generation from waste in customized structures or devices used in IoT applications. The review is structured to present a foundational overview of relevant technologies in Section 2, followed by an analysis of state-of-the-art advancements and their limitations in Section 3. Section 4 identifies new research domains, emphasizing potential developments and challenges. Finally, Section 5 concludes the key insights and outlines future research directions.

1.1. Methodology of literature selection

This review consolidates findings from 70 peer-reviewed publications published from 2010 to 2025. The literature was sourced from Scopus, Web of Science, IEEE Xplore, and additional academic databases by searching for the terms "Plant Microbial Fuel Cell," "Plant-Based Cell," "plant electricity," "photosynthetic bioelectricity," and "electrode potential." The inclusion criteria were: (i) research focusing on PMFC or PBC technologies; (ii) evidence of power generation via living plants or plant–microbe systems; (iii) system-level performance metrics such as power output or integration feasibility; and (iv) publication in journals, conference proceedings, books, or encyclopaedias following peer review.

Among the 70 studies, 15 examined PBC, 24 investigated PMFC, and 21 analyzed the physiological, structural, or morphological characteristics of plants affecting energy harvesting efficiency. This review aims to evaluate methods based on electrode potential, focusing on their low invasiveness and material requirements in natural or remote environments. Studies that did not present experimental validation or lacked direct relevance to plant-based energy generation were excluded.

2. Introduction of related technologies

The goal of this section is to present the approaches and techniques for energy harvesting from living plants, particularly with an emphasis on the biological and electrochemical actions. The energy harvesting process in plants begins with photosynthesis, which is the same as the natural process taking place in the plants where the sunlight is captured by the plants and then turned by them into chemical energy, which gives the plant-based energy harvesting a head start. Thereafter, plant-based energy harvesting processes are discussed; the focus shifts to PMFCs and discusses how soil microorganisms and plant roots work synergistically to produce energy. The section concludes with a discussion of PBC technology, which harnesses a plant's metabolic activity and ionic movement to produce electricity.

Using a living plant's biochemical properties, the electrode potential method can be employed to harvest energy, making it a feasible alternative option for energy extraction from plants. This energy harvesting mechanism requires an implantable understanding of how these organisms produce electrical energy first. This outcome is achieved by the process of photosynthesis, as one of the most essential fundamental processes providing chemical energy from sunlight to the living systems is photosynthesis. Electrochemistry and botany have an undeniable synergy, enabling tremendous possibilities here for energy-growing opportunities in long-term sustainability (Najhi et al., 2024).

2.1. Basic photosynthesis

Photosynthesis is how plants produce food. This important biological process takes place mainly in the leaves, where the green part of plants, called chlorophyll, captures light energy. In plants, photosynthesis takes place in a specialized organelle called the chloroplasts, which are plentiful in the leaf tissues. Plants absorb water (H_2O) from the soil through their vascular system, in particular through the xylem, and supply it to their leaves. Simultaneously, leaves absorb carbon dioxide (CO_2) from the air through tiny openings known as stomata. In addition to this, we must also consider that carbon dioxide (CO_2) is also released from natural and anthropogenic processes such as respiration, oxidation of organic matter, and fossil fuels source combustion Fig. 1.

The water (H_2O) and carbon dioxide (CO_2) undergo a chemical reaction essential for photosynthesis, which commences once the plant's leaves assimilate all three requisite components. In this process, light energy is absorbed by water molecules, producing hydrogen (H_2) and oxygen (O_2). The released oxygen is expelled through the stomata of the leaves, leaving behind hydrogen and carbon dioxide for further reactions. The energy derived from sunlight is pivotal in catalyzing this transformation, ultimately converting the resultant mixture into glucose ($C_6H_{12}O_6$), a fundamental plant energy source. Glucose acts as a critical nutrient, facilitating growth and development within the plant organism (Gurram and Kothapalli, 2017).

$$6H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2 \quad (1)$$

Leaves face a serious problem because of the structure and function of leaf tissues. The walls of leaf cells are thin, and the air captured in the spaces between leaf cells is water vapor. To fix CO_2, leaves need to balance the very high CO_2 capture and photosynthetic air volume proportions at leaf surface temperature. To make just 1 g of sucrose, the plant needs roughly 5000 L of air. This means that there can be a great loss of water vapor through the stomata when CO_2 is being captured. To counteract this problem, certain plants, particularly desert or semi-arid region drought-tolerant plants, have developed Crassulacean Acid Metabolism (CAM) photosynthesis. In such cases, to avoid loss of water, stomata remain closed in the daytime. Stomata will open at night to facilitate gas exchange. Thus, transpiration is reduced, and a greater water efficiency capacity is achieved. CAM is viewed as an important adaptation strategy, as shown by the fact that about 5–10 % of plants may use this system (Leegood, 2004).

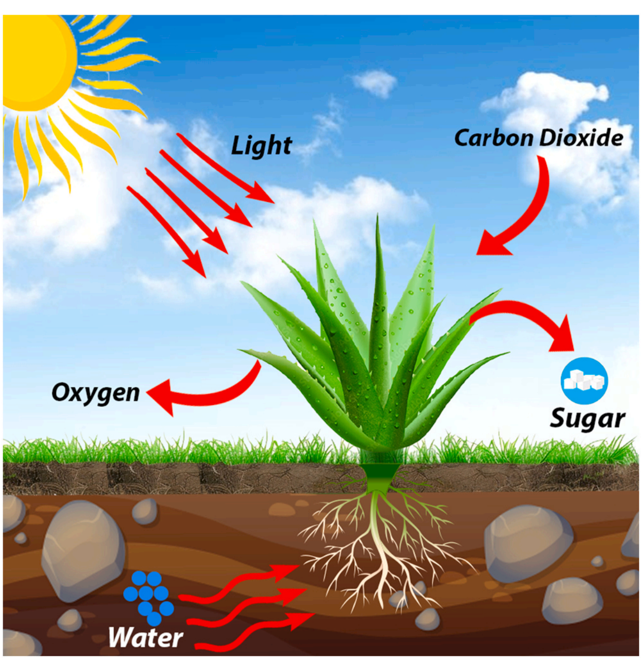

Fig. 1. Photosynthesis (Overview of photosynthesis process) (Wikipedia contributors, 2024).

In arid conditions, CAM plants show a special adaptation by separating the photosynthetic process into separate day and night cycles, so reducing water loss. Under this physiological approach, stomata—microscopic openings on the leaf surface—are opened during the cooler, more humid nighttime hours (Chen and Blankenship, 2021), so fixing CO_2. These plants create phosphoenolpyruvate (*PEP*) as a byproduct as the chloroplasts synthesize starch and sucrose throughout the day. Though it fixes atmospheric CO_2 into oxaloacetate (*OAA*), which is then reduced to malate and stored in vacuoles as malic acid ($C_4H_6O_5$), this *PEP* plays a pivotal role in the fixation of CO_2 (Guesmi et al., 2022). Besides pointing out the efficiency of this metabolic adaptation is that the Calvin cycle is dependent on adenosine triphosphate (*ATP*) and nicotinamide adenine dinucleotide phosphate (*NADPH*), byproducts of the light-dependent process, absent during the night cycle.

Nighttime reaction:

$$PEP + CO_2 \rightarrow PEP \rightarrow OAA \rightarrow C_4H_6O_5 \quad (2)$$

$$C_4H_6O_5 \rightarrow \text{Stored in vacuoles} \quad (3)$$

Daytime reaction:

$$C_4H_6O_5 \rightarrow CO_2 + \text{Pyruvate} \rightarrow PEP \quad (4)$$

$$CO_2 + RuBP \rightarrow PGA \rightarrow C_6H_{12}O_6 \quad (5)$$

Where *OAA* is oxaloacetate, *PEP* stands for phosphoenolpyruvate carboxylase, *RuBP* denotes Ribulose-1,5-bisphosphate, and *PGA* is for 3-phosphoglycerate. *RuBP* and *PGA* are key molecules in the Calvin cycle.

2.2. Plant microbial fuel cell (PMFC)

The PMFC is a sustainable technology that exploits the rhizosphere's symbiotic relationship between living plants and their accompanying microbial communities to generate electricity. This process leverages organic matter released by plants during photosynthesis (Martinez and Bermudez, 2023), where, notably, they utilize only about 30 % of the glucose ($C_6H_{12}O_6$) produced, with the remaining 70 % exuded through the roots into the surrounding soil. This surplus organic material is a substrate for microbial activity, producing electrical energy. Importantly, the extraction of this excess glucose does not compromise the health or vitality of the plants, thereby offering a method to harness renewable energy while maintaining the ecological balance (Teng et al., 2018).

PMFCs are sophisticated energy harvesting systems consisting of two electrodes, which allow for the transfer of electrons. The anode is placed near the plant roots, where the oxidation half-reaction occurs. The cathode is away from the anode and is usually in air or water. There, the reduction half-reaction occurs. An ion exchange membrane or separator is often incorporated to guarantee that the anode stays the main electron acceptor and is not influenced by oxidizing agents, such as oxygen. This membrane divides the cell into two separate chambers and helps to preserve electron flow, so enabling proton migration from the anode to the cathode (Martinez and Bermudez, 2023). Single- and double-chamber configurations (Deng et al., 2012) define PMFCs most essentially Fig. 2.

The double-chamber architecture uses a proton exchange membrane to divide the anodic and cathodic chambers, allowing selective proton transfer and avoiding catalyst and oxygen diffusion to the anode. On the other hand, the single-chambered PMFC highlights the basic ideas of microbial fuel cell operation, employing its different structural

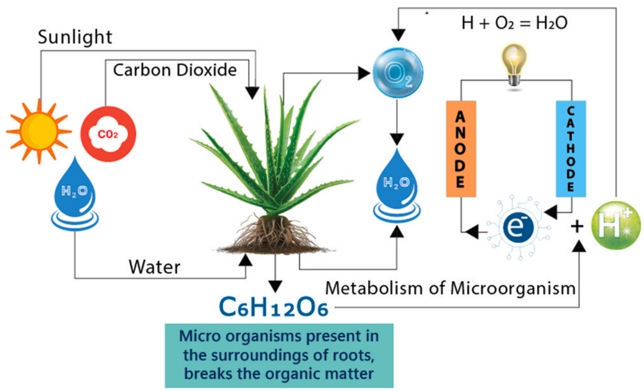

Fig. 2. Schematic diagram of PMFC technology to explain the process (Gurram and Kothapalli, 2017).

configurations since it lacks a membrane and consists just of an anode chamber coupled with a cathode chamber. Two main processes define the PMFCs (Martinez and Bermudez, 2023).

2.2.1. Rhizodeposition of organic compounds ($C_6H_{12}O_6$)

Plant roots release various organic compounds into the soil through a process known as rhizodeposition. This includes water-soluble exudates such as sugars, organic acids, vitamins, and water-insoluble materials like cell walls and cellular debris. Additionally, roots secrete complex carbohydrates and enzymes—collectively termed rhizodeposits—that nourish soil microbes and influence nutrient cycling (Lynch and de Leij, 2012).

2.2.2. Electricity generation

Approximately 70 % of glucose is exuded into the soil as rhizodeposits via root systems. This trait makes soils an important resource for incorporation into biological treatment systems, mainly due to the presence of many, often overwhelming numbers, of available naturally occurring bacteria, which can be used as substrates in PMFC processes. This glucose ($C_6H_{12}O_6$) serves as a substrate that gives chemical energy obtained by the naturally occurring electrochemically active bacteria found in the soil food web as a part of their metabolic processes, with the byproducts of CO_2, protons (H^+), and electrons (e^-). As electrons are produced, anodic oxidation occurs, an important process in PMFC processes. A half-reaction can be utilized to represent the relationship between rhizodeposits and electrochemical functioning within the soil matrix Fig. 3.

$$12H_2O + C_6H_{12}O_6 \rightarrow 6HCO^{3-} + 3H^+ + 24e^- \quad (6)$$

Electrons are transformed from the cathode of an electrochemical cell, which is a major feature of electrochemical reactions. Protons that are released at the anode will eventually get to the cathode, where the protons react with oxygen gas (O_2) and the electrons (e^-) that have been transferred to generate water (H_2O). This process may be summarized by the following half-reaction that characterizes the process of reduction of oxygen to water at the cathodic location. Thus, highlighting the dynamic of protons, electrons and molecular oxygen to carry out the reaction:

$$6O_2 + 24H^+ + 24e^- \rightarrow 12H_2O \quad (7)$$

In PMFC, the anode, situated within a substrate rich in microbial populations, plays a critical role in electron capture. During this electrochemical process, electrons generated by microbial metabolism traverse an external circuit towards the cathode, which is generally positioned above the soil and exposed to ambient oxygen. This configuration enables the efficient generation of electricity, as electrons flow through the external circuit while protons migrate through an ion exchange membrane (Martinez and Bermudez, 2023). Here, electrons

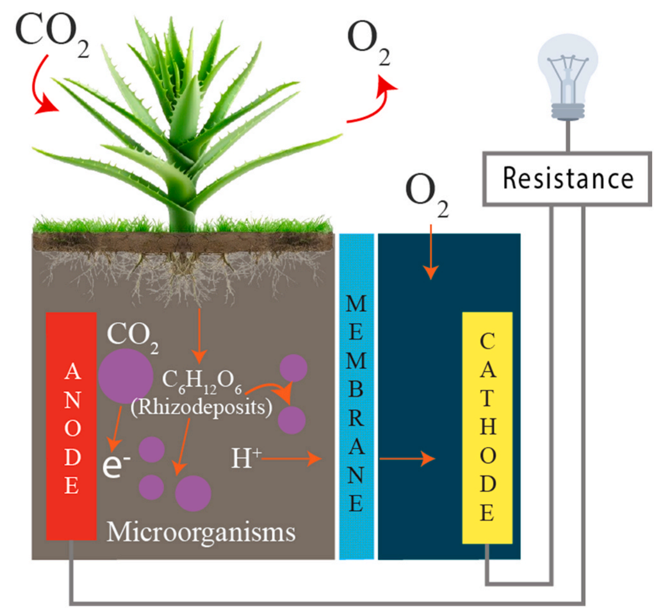

Fig. 3. Scheme of a plant-microbial fuel cell with external resistance (Martinez and Bermudez, 2023).

through an external circuit, Protons through an ion exchange membrane, and O_2 as the terminal acceptor are reduced to water in the cathode.

The condition of plant roots plays a crucial role in the surrounding soil ecosystem, particularly through its influence on organic matter availability for microbial activity. Healthy and decomposing roots enhance the accessibility of organic compounds, specifically glucose ($C_6H_{12}O_6$), which serves as a substrate for microbial metabolism. While decomposed roots contain significant cellulose content (ranging from 35 % to 50 %), bacteria do not directly utilize this material for energy production. However, the decomposition process yields low-molecular-weight organic molecules derived from hydrolyzed cellulose, facilitating energy generation (Liu et al., 2018). Furthermore, the breakdown of dead roots increases rhizodeposits and substrates, providing essential resources for microbial food synthesis and electron release. In instances of plant mortality, accumulating these substrates within the soil matrix may extend the viability of the microbial community, thereby sustaining ecological functions in the system (Martinez and Bermudez, 2023).

The decay of organic matter from plant rhizodeposition is supported by a bacterial community composed of a wide variety of organisms. These organisms are able to utilize the substrates to make energy and transfer electrons to the anode. The substrate is metabolized through two primary metabolic groups: anaerobic does not require oxygen, and aerobic does. Organisms oxidize energy-rich substrates in aerobic metabolism to fulfil nutritional needs, resulting in non-electrochemical byproducts due to the metabolic reactions involved. This process illustrates the wide variability and complexity of microbial behavior and energy production under various environmental conditions. In the process, they produced electrochemically inactive byproducts, which are part of this reaction:

$$6O_2 + C_6H_{12}O_6 \rightarrow 6CO_2 + 6H_2O \quad (8)$$

In conditions of limited oxygen, bacteria employ enzymatic processes to release electrons for the degradation of rhizodeposits. This response demonstrates the point effectively:

$$6CO_2 + 24H^+ + 24e^- \rightarrow C_6H_{12}O_6 + 6H_2O \quad (9)$$

The effective operation of a PMFC necessitates the preservation of selectivity within the anaerobic metabolic system. This requirement underscores the critical importance of aerobic reactions in facilitating the growth and development of microorganisms responsible for electron transfer into the surrounding medium. Consequently, promoting anaerobic metabolic pathways to mitigate competition for glucose resources is essential rather than depleting the oxygen necessary for aerobic metabolism. Such an approach is fundamental to optimizing the overall efficiency and functionality of the microbial fuel cell ecosystem (Martinez and Bermudez, 2023).

In conclusion, PMFC technology has great potential as a sustainable and renewable energy source that demands more research. The performance of PMFC systems is much influenced by several factors, including plant species, soil conditions, the choice of electrode materials, and the structural design of the operation. Particularly, PMFC voltage generation is much influenced by elements including root shape, biomass composition, and microbial exudation. The practical application of this technology depends on the promotion of more resilient plant species displaying consistent rhizodeposition and the engineering of buildings enabling effective electron transfer rates (Muladi et al., 2021).

2.3. Plant-based cell (PBC)

The PBC system represents another electric bioenergy generation technique relying on the direct use of electrical energy from living plants, through their natural biological processes as a living organism. In the PBC system, electrodes made from conductive materials, including zinc and copper are inserted into the tissues of the plants through the roots, stems and leaves (Teng et al., 2018;Singh, 2022;Leoni et al., 2022a; Guesmi et al., 2022; Najhi et al., 2024; Singh and Kumar, 2021; Chong et al., 2018; Chong et al., 2019; Nouhalla and Adepoju, 2022; Concepcion et al., 2023). The electrodes are positioned as electrical bridges that may harness the electricity generated via metabolism by the plant and convert biological energy to usable electric energy. This is a clear example of combining plant biology with electrical engineering to create electricity with a bioenergy configuration Fig. 4.

The operational principles of PBC are founded on the electrochemical phenomena that occur at the interface of plant cells, establishing a potential difference between paired electrodes (Choo et al., 2014). During photosynthesis, plants synthesize carbohydrate sugars and other chemical compounds transported through the vascular system (Encyclopaedia Britannica, 2024). This process generates a small electrical potential due to the movement of ions and electrons, which the electrodes convert into current for the external load circuit. Given the inherently low power output of PBCs, integrating electrochemical and photosynthetic processes is essential for enhancing their energy output and ultimately generating practical electricity (Ying Ying and Dayou, 2014).

Plants possess sap primarily consisting of water, sugars, nutrients, hormones, and various organic compounds (Encyclopaedia Britannica, 2024). The ionic components, particularly potassium (K^+), sodium (Na^+), and chloride (Cl^-), in conjunction with organic compounds, contribute to the conductive properties of plant sap. The properties outlined are critical for the electrochemical processes involved in plant-based energy harvesting. In these systems, sap serves a dual role as both the electrolyte and the medium for ionic transfer, particularly in configurations that include electrodes (Ying Ying and Dayou, 2016).

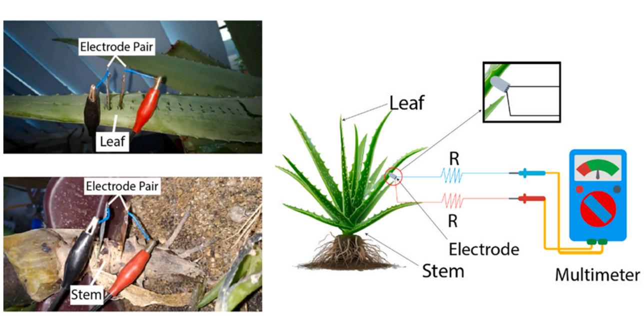

Fig. 4. Experiment setup for embedding electrodes in the leaf and stem of *Aloe vera* (Chong et al., 2018).

The action of two electrodes made of dissimilar materials creates a dichotomous reactivity and electrochemical potential between the electrodes. These potentials lead to the simultaneous electrochemical processes of oxidation at the anode and reduction at the cathode. In this case, positive ions enable electrons to be released at the anode (LibreTexts, 2024). With an applied voltage across the electrodes, there is now an external circuit that allows electrons to travel to the cathode. Once there, dissolved oxygen (O_2) from the sap is available for reduction, water is formed across the electrodes.

$O_2 + 4\,H^+ + 4e^- \rightarrow 2\,H_2O$ (10)

A variety of ion species in plant sap (i.e., K^+, Na^+, Cl^-) permit efficient movements of charge particles between the two electrodes in the circuit. The external current travels through the circuit connecting the electrodes, which elicits the internal current due to the movement of ions occurring in the plant. This is how the external and internal circuits work collaboratively, reinforcing the vital role of ionic species in increasing conductivity and maintaining electrical activity in the plant (Ying Ying and Dayou, 2016; Choo et al., 2014; Encyclopaedia Britannica, 2024; Ying Ying and Dayou, 2014; LibreTexts, 2024).

Voltage differences are utilized to monitor plant activity and are thought to arise from multiple sources. The "Streaming potential" mechanism is the most significant among these, as it elucidates the generation of voltage resulting from sap flow. The mathematical representation of this mechanism is as follows:

$$Vsapstream = \frac{\varepsilon_0 \varepsilon_r}{\sigma \eta} \Delta P \cdot \zeta \quad (11)$$

where, ΔP is the pressure difference between ends of the capillary, σ is the typical conductivity, η is the viscosity, and Zeta (ζ) is the voltage difference due to flow difference in the center of the capillary (Teng et al., 2018).

Transroot potential is the potential difference between the roots and the soil. This potential occurs from complex biochemical activity in the xylem sap, which involves charged gradients of H^+, K^+, and Ca^{2+} ions (De Boer and Volkov, 2003; Weisenseel and Meyer, 1997). It has been shown that both glucose and H^+, the activity of K^+ ions, can raise transroot potentials by approximately 50 mV (Wegner and Zimmermann, 2002) when moving in opposing directions (Wright and Fisher, 1981). This suggests that trees inherently can generate electrical energy. Hence, trees with substantial ionic flux and dissolved nutrient sap conductivity can act as bio-generators, particularly with suitable electrode materials.

3. State of arts research

The harvesting of energy from living plants has emerged as a critical area of research, particularly in advancing sustainability and renewable energy objectives. This innovative approach leverages the organic metabolic processes of plants to generate low-power electricity in an environmentally friendly and carbon-neutral manner. Such a technique establishes a continuous and self-sustaining energy source, which is particularly advantageous for decentralized power systems in remote locations. Furthermore, it aligns with the increasing demand for renewable energy solutions. Additionally, integrating this plant-based energy system within the IoT ecosystem enhances its significance, as it enables the powering of low-energy devices, such as sensors used in smart city frameworks, precision agriculture, and environmental monitoring. Implementing plant-derived energy sources may reduce reliance on external power supplies and batteries, promoting energy-efficient and sustainable practices across various sectors.

In electrochemical studies, PBC and PMFC are pivotal technologies exhibiting significant potential. Both methodologies leverage the inherent biological processes associated with plants, which are intrinsically linked to the interactions between vegetative systems and soil-dwelling microorganisms, particularly bacteria. This symbiotic relationship underpins the electrochemical mechanisms that facilitate energy conversion and substrate utilization, highlighting the critical role of microbial activity in enhancing plant performance and sustainability within these innovative approaches.

Extensive research has been conducted on energy harvesting from living plants utilizing PBC and PMFC methodologies. Six key focus areas have emerged within this domain, highlighting the considerations most pertinent to advancing this technology. These areas include: 1) plant and leaf morphology, soil condition and chemistry, electrode material selection, and their spatial arrangement; 2) the influence of weather conditions; 3) scalability of energy harvesting systems; 4) the effects of decay and aging on energy production; 5) the potential of hybrid systems that integrate multiple energy sources; and 6) the practical applications of harvested energy in various fields.

3.1. Living plant investigation

Previous research has shown that several factors influence plants' energy harvesting potential, including plant species selection. A 2017 experiment applying the PMFC method to rice plants achieved a maximum power density of 1.1 W/m^2. This result demonstrates that PMFC technology is 16 times more efficient than traditional biomass electricity generation, underscoring its potential as a sustainable energy source (Gurram and Kothapalli, 2017).

Subsequently, in 2019, two trials were conducted on grassy potted plants. Both works underwent the PMFC technique. The diverse potted plants exhibited the greatest voltage level (Di Lorenzo et al., 2019). The areas they examined include plant selection, soil conditions, artificial and natural light availability, unhealthy plants, and environmental factors. This indicated that if a single plant is in poor condition, the entire network of connections will see a reduction in voltage. Furthermore, the system operates effectively in wet soil, reducing internal resistance (Di Lorenzo et al., 2019; Imbrogno et al., 2019). Several research studies indicate that succulent plants produce greater energy due to the substantial volume of sap (fleshy) within their stems and leaves, which acts as an electrolyte. Consequently, *Aloe vera* and *Cactus* species are favored by numerous researchers, despite the existence of many other plants with higher sap content (Teng et al., 2018; Singh, 2022; Leoni et al., 2022a; Guesmi et al., 2022; Singh and Kumar, 2021; Chong et al., 2018; Chong et al., 2019; Nouhalla and Adepoju, 2022; Concepcion et al., 2023; Pechsiri and Puengsungwan, 2022; Leoni et al., 2022b). In 2018 and 2019, two successive studies were conducted on the *Aloe vera* plant. Nevertheless, these two works were executed via the PBC approach. The researchers examined many experimental parameters, including plant selection, dimensions, leaf size, and types (Chong et al., 2018; Chong et al., 2019).

Some researchers administered glucose externally when the PMFC was installed in the stem bark the subsequent year. Implementing PMFC in the stem bark instead of the rhizosphere constituted a diversified strategy. The bacterial habitat was also introduced there (Lu et al., 2020). Employing the PMFC methodology, a separate study was executed in the same year, wherein researchers endeavored to hybridize the MFC and PMFC systems utilizing *Trigonella foenum* (terrestrial) and *Azolla* (aquatic) plants, elucidating the factors influencing each system independently, with soil conditions being a focal point of investigation (DAVE et al., 2020).

In 2021, an experiment employing the PBC approach was conducted with four succulent plants, wherein the *Sansevieria* exhibited superior performance (Singh and Kumar, 2021). In the same year, researchers expanded their focus from small plants to investigate seven tropical forest species using the PBC method. The voltage stability was evaluated, yielding maximum output from the Sengon tree, while other trees exhibited performance fluctuations (Muladi et al., 2021).

Subsequently, in 2022, an extensive investigation was conducted consecutively. The ideal plant from the preceding investigation was utilized. To achieve optimal yield, the researchers evaluated leaf type and size, soil conditions, ambient factors, and other variables. Numerous investigations highlighted the dimensions of plants and leaves as well (Singh, 2022; Martinez and Bermudez, 2023; Chong et al., 2018; Chong et al., 2019; Nouhalla and Adepoju, 2022; Pechsiri and Puengsungwan, 2022; Lu et al., 2020; Moqsud and Okamoto, 2023). They recorded the size during the experimentation but demonstrated no effects attributable to the size, except for one instance. If the leaf breadth of the Sansevieria plant is less than 4 cm, power increases; if it exceeds 5 cm, a drop in power is observed. Nonetheless, power stays invariant when the leaf width is maintained between 4 cm and 5 cm (Singh, 2022). In 2022, the PMFC system was tested with a 1.30 m avocado plant and effectively extracted energy (Pechsiri and Puengsungwan, 2022). Another experiment with PMFC was conducted that year, utilizing corn plants under various environmental variables (Leoni et al., 2022b). In 2022, an additional PMFC-based system was tested with two flowering plants, yielding results in several areas, including soil chemistry, external variables, and others (Luong and Thomas, 2022). Nonetheless, multiple tests with PBC were also performed in the same year. A cohort of researchers conducted experiments on prickly pear plants. They conducted tests on parameters such as leaf thickness. They compared prickly pear and non-prickly pear plants, finding that they generate more energy than their non-prickly pear plants (Guesmi et al., 2022). A separate study emphasized the plant soil to examine the variations in output power. The state of the soil is a variable that can influence output, particularly in the context of PMFC. Acidic soil is the most efficient conductor of electricity (Singh, 2022; Leoni et al., 2022a).

The next year, in 2023, two study teams witnessed plants harvesting energy using a PMFC-based system, as per our findings. One group examined the plant's size and various other characteristics under diverse external conditions, including solar radiation, mean temperature, and precipitation (Moqsud and Okamoto, 2023). Another group examined the power variation among five plant species concerning several environmental conditions (Martinez and Bermudez, 2023). This year, a PBC-based energy harvesting system was also examined. The researchers selected the dragon fruit plant for investigation (Concepcion et al., 2023).

In 2024, several researchers established a differentiation between large outdoor non-succulent plants and succulent plants, categorizing them into seven separate varieties. They were employed in a PBC-based energy-obtaining system during various weather conditions, where the maximum voltage was derived from the succulent one (Najhi et al., 2024). In the same year, a PMFC-based experiment was undertaken by a group of researchers using six distinct flowering plants, focusing on soil mixtures, various bacteria, and individual plant efficiency, among other factors. This study showed that various plants connected in series had the highest power output. Flowering specimens exhibit a voltage of 2.050 V (Ballestas et al., 2024).

According to the literature, some plant species, particularly succulents, have enhanced electrical outputs due to the electrolyte-rich composition of their sap. Prickly pear plants produce far more energy than non-prickly pear plants. Despite the corn plants exhibiting minimal microbial activity, their yield was significantly enhanced using bamboo charcoal as an electrode. Pot plants frequently generate the highest voltage; flowering plants can generate up to 2.050 V, but rice plants may obtain a power density of 1.1 W/m^2. Recent advancements have enhanced plant selection, electrode materials, soil conditions, and environmental parameters in PMFC systems, which harness microbial activity at plant roots to generate energy.

3.2. Electrode

The output power exhibits the greatest variability due to the utilization of electrode materials. Copper (*Cu*) is the most used electrode material due to its conductivity. Numerous studies have employed electrode pairs rather than individual electrodes (Singh, 2022; Guesmi et al., 2022; Chong et al., 2018; Chong et al., 2019; Nouhalla and Adepoju, 2022). Zinc (*Zn*) constitutes an optimal electrode pair with Copper (*Cu*). The *Zn-Cu* electrode pair is identified as the optimal combination for maximizing electron capture (Guesmi et al., 2022; Najhi et al., 2024; Chong et al., 2018; Chong et al., 2019; Nouhalla and Adepoju, 2022).

In 2022, the maximum power of 58.8 mW was extracted from prickly pear plants utilizing *Zn-Cu* electrode pairs embedded in the leaves (Guesmi et al., 2022). A notable combination identified is Aluminium (*Al*) and Copper (*Cu*) (Singh, 2022; Chong et al., 2018; Pechsiri and Puengsungwan, 2022; Leoni et al., 2022b). Graphite was the predominant material utilized in PMFC systems due to its accessibility, low cost, and efficacy (Martinez and Bermudez, 2023)., (Lu et al., 2020; DAVE et al., 2020; Ballestas et al., 2024). Nonetheless, the maximum voltage was produced utilizing titanium or gold as the anode and carbon felt-coated titanium or gold as the cathode, albeit at a significant cost (Di Lorenzo et al., 2019). Graphene Quantum Dots (*GQDs*) are substances that sequester electrons, augment plant metabolic processes and energy output, and generate potential changes between electrodes (Xu et al., 2021). Alternatively, bamboo charcoal was used as the electrode material due to its superior sustainability and natural properties. The most advantageous aspect is that this electrode is reusable (Moqsud and Okamoto, 2023).

The dimensions and configuration of the electrode are also significant factors to consider. The dimensions and configuration of the electrodes substantially influence output power (Teng et al., 2018; Leoni et al., 2022a; Martinez and Bermudez, 2023; Guesmi et al., 2022; Gurram and Kothapalli, 2017; Chong et al., 2018; Chong et al., 2019; Nouhalla and Adepoju, 2022; Di Lorenzo et al., 2019; DAVE et al., 2020; Moqsud and Okamoto, 2023; Ballestas et al., 2024). Rectangular electrodes augment output power (Leoni et al., 2022a). Smaller electrodes exhibited superior output compared to bigger electrodes (DAVE et al., 2020).

The positioning of electrodes also affects the output power (Teng et al., 2018; Singh, 2022; Leoni et al., 2022a; Martinez and Bermudez, 2023; Guesmi et al., 2022; Singh and Kumar, 2021; Chong et al., 2018; Chong et al., 2019; Nouhalla and Adepoju, 2022; Concepcion et al., 2023; Leoni et al., 2022b). Placing electrodes within the same leaf increases the voltage (Singh and Kumar, 2021). Inserting electrodes into the outermost edges of the soft leaves of two distinct plants increases output power (Singh, 2022). Positioning the electrode horizontally alongside the plant yields the maximum voltage (Moqsud and Okamoto, 2023). Nonetheless, a novel approach was implemented by inserting the electrodes within the intercellular spaces of the vascular bundle (icVB) and inter-parenchyma cells (iPC). The researchers established that optimal output is attained when electrodes are embedded in the iPC region. The peak voltage recorded was 20.7 V, and pin-type *Ag*-coated *Cu* electrodes were positioned in the intercellular regions of the dragon fruit plant in 2023 (Concepcion et al., 2023).

A significant alteration in power is observed, fluctuating the distance between the electrodes (Teng et al., 2018; Singh, 2022; Martinez and Bermudez, 2023; Guesmi et al., 2022; Singh and Kumar, 2021; Chong et al., 2018; Chong et al., 2019; Nouhalla and Adepoju, 2022; Concepcion et al., 2023). In the PMFC system, the electrodes are typically positioned with one (anode) in the rhizosphere and the other (cathode) external to the soil. The inter-electrode spacing can affect the output (Martinez and Bermudez, 2023; Gurram and Kothapalli, 2017). A reduced distance between electrodes correlates with increased power in the PBC system (Singh, 2022; Chong et al., 2018). The current increment transpires without voltage variation when the distance is reduced (Guesmi et al., 2022). The open circuit voltage rises as the distance decreases, leading to a drop in internal resistance (Di Lorenzo et al., 2019). Notably, distance changes have shown no substantial alteration in output power for urban tropical forest plants (Muladi et al., 2021).

The study on electrodes indicates that electrode materials are essential for improving plant output power. Copper (*Cu*) is the most prevalent material owing to its conductivity, although zinc (*Zn*) and copper (*Cu*) constitute the optimal electrode pairings. Graphite and bamboo charcoals are also utilized, with Graphene Quantum Dots (*GQDs*) facilitating organic species reactions and augmenting output power. The dimensions and configuration of electrodes also influence output power, with rectangular designs improving output. The positioning of electrodes affects output power, with smaller electrodes yielding superior performance as well. The distance between electrodes also influences power, with reduced distances yielding greater power and enhanced open circuit voltage.

3.3. Life cycle

A notable property of plants is their life cycle, which has been studied in only two publications considering distinct external variables (Martinez and Bermudez, 2023; Concepcion et al., 2023). Research on the life cycle of plants in energy harvesting, particularly with PBC and PMFC, is still scarce. A more thorough research with varied configurations is required. Although certain studies have shown the potential of PMFCs for prolonged application in agricultural or environmental monitoring contexts, there are deficiencies in understanding their durability and efficacy across lengthy plant growth phases and seasonal variations. The root of a plant is an essential component of the PMFC system. As this root commences to decompose, the system is inclined to deteriorate, concluding the plant's life cycle and the system itself. Research primarily examines plant characteristics and microbial interactions that enhance PMFC energy production. Nevertheless, comprehensive research examining life cycle effects, including the impact of aging or size on total energy yield, is limited.

The study of the plant's life cycle reveals a deficiency in comprehending the aggregate effect of the complete life cycle on energy harvesting efficiency. This underscores the necessity for longitudinal studies to enhance plant selection and system integration for practical applications, which will be elaborated upon in Section 4.2.

3.4. Environmental condition

Environmental variables can substantially affect production power, as the biological systems of plants are contingent upon their surroundings. *Moss* emerges as the most resilient plant, exhibiting superior power output relative to *Aloe vera*, *Tomato*, *Corn*, and *Bean* plants under normal and extreme drought and flooding conditions (Martinez and Bermudez, 2023). Power often escalates when the plant is consistently irrigated under natural light conditions. However, the power diminishes under artificial light and drought conditions (Imbrogno et al., 2019). Humid conditions provide increased energy, but exposure to artificial illumination and drought times diminish the short-circuit current (Di Lorenzo et al., 2019). Voltage generation escalates with increased solar radiation but diminishes with increased precipitation (Moqsud and Okamoto, 2023). In sunny environments, photosynthesis in plants is enhanced due to increased organic matter. Utilized in both PBC as an electrolyte and PMFC in the bacterial metabolic process. Furthermore, other researchers conducted their tests under precise environmental settings, both indoors and outdoors. Nonetheless, no evidence of impact from environmental factors has been established thus far.

Various studies have analyzed environmental factors to identify specific parameters under which the plant can achieve enhanced output. Regular watering in natural light, humid conditions, and sunny weather enhances photosynthesis, increasing organic matter formation in plants that aid the PBC and PMFC in energy extraction. Moreover, certain factors also diminish the yield, including drought and flood situations, artificial light, extreme precipitation, etc. Nonetheless, the precise effects of environmental factors remain ambiguous despite several controlled tests.

3.5. Integration

The quantitative performance metrics across PMFC and PBC highlight their complementary strategies for enhanced collaboration in Table 1. Research indicates that PMFCs can produce a voltage output between 0.2 and 2.05 V, with a current output of 3.5 mA and a power density of approximately 1.1 W/m^2 (Gurram and Kothapalli, 2017; Di Lorenzo et al., 2019; Ballestas et al., 2024). PBCs found on succulent species like prickly pear and *Aloe vera* exhibit peak voltages of 20.7 V, a power output of 58.8 mW, and a current of 2.1 mA (Guesmi et al., 2022; Singh and Kumar, 2021; Concepcion et al., 2023). All these outcomes indicate that PMFC offers a more stable and reliable system over the long term, albeit with a slower, more consistent energy pulse, while PBC experiences higher energy surges. Despite the numerous benefits these technologies appear to provide, they remain inadequate in addressing or adapting to varying energy demands when functioning under real-world conditions. The integration of these two technologies offers a method to achieve voltage control over extended durations, all while adhering to the low-power demands characteristic of IoT systems utilized in agricultural monitoring and smart environments.

The independent generation of electricity by PBCs and PMFCs, stemming from their interactions with plants or plant metabolism, suggests that their integration could enhance and sustain power output through synergistic pathways. PBCs utilize the inherent metabolic systems of the plant, whereas PMFCs are contingent upon the microbial activity present in the rhizosphere. The integration of these technologies could lead to reduced maintenance needs and more sustainable alternatives for powering low-energy devices, such as IoT sensors utilized in agricultural applications. However, a clear effort to effectively merge these technologies into a unified energy harvesting system seems significant, as one study indicated the potential for integrating these technologies within the aquaponics framework (Lajis et al., 2021).

No efforts have been undertaken to merge PBC and PMFC; nonetheless, a single study has suggested a framework. The integration of these two systems allows for a more effective tracking of output. Most studies concentrated on energy extraction from plants utilizing either PBC or PMFC. The advancement of these two systems develops independently. This represents a significant opportunity for exploration within this context. Further technical specifics will be disclosed in Section 4.3.

3.6. Scalability

A significant alteration in captured power is observed due to circuit configurations for scalability. Leaves arranged in series provide more voltage, whereas those configured in parallel yield greater current. Optimal power is achieved by integrating series and parallel circuits (Chong et al., 2018). The same cohort of researchers advanced their study by developing a power management circuit that enhances the output (Chong et al., 2019). Various studies indicated that increased electrode pairs connected in series across distinct leaves correlate with enhanced power output. Conversely, the same connection manifests differently when situated within the same leaf. With the leaves arranged in opposition, they function similarly in parallel. Nonetheless, the combination of series and parallel connections elevates the power to a distinct level (Guesmi et al., 2022). Optimal production is achieved when many plants are interconnected in series (Singh, 2022; Ballestas et al., 2024). However, connecting additional PMFCs in parallel yields increased power output. Optimal production is achieved by connecting pot plants in certain series and parallel configurations (Di Lorenzo et al., 2019). A power management circuit with boosters improves output; nevertheless, its efficacy diminishes as the discharge duration extends (Imbrogno et al., 2019).

Beyond circuit-level enhancements, tackling real-world scalability and enduring performance decline necessitates more comprehensive strategies. The selection of resilient plant species, including *Sansevieria*, *Aloe vera*, and Prickly Pear, is crucial, as these species exhibit stable voltage outputs across various environmental conditions, attributable to their high sap content, thick leaves, and drought resistance (Singh, 2022; Guesmi et al., 2022; Singh and Kumar, 2021). Additionally, the integration of hybrid PMFC–PBC architectures has been suggested to utilize microbial and photosynthetic pathways simultaneously, potentially improving voltage sustainability under varying field conditions (Lajis et al., 2021). Emerging electrode materials, including reusable bamboo charcoal and cost-effective graphite-based systems, demonstrate long-term durability and environmental compatibility (Martinez and Bermudez, 2023; Guesmi et al., 2022; Moqsud and Okamoto, 2023). The use of energy storage components such as supercapacitors and DC-DC converters facilitates the intermittent capture and buffered delivery of energy, aligning with the duty cycles of practical IoT and smart farming devices (Najhi et al., 2024; Chong et al., 2019).

According to the analysis of the scalability of power extraction from plants, series-parallel connections are crucial for optimizing the system. These two connectors were employed in various circuit configurations throughout multiple PBC studies. Nevertheless, the amalgamation of these two connections amplifies the overall output. Furthermore, the power management circuit enhances the output significantly. This power management circuit maintains consistent and regulated electricity. Nonetheless, the system's efficiency suffers due to numerous power management circuits. The circuit configurations must be equilibrated in conjunction with the power management circuits Fig. 5.

Table 1
Comparative performance metrics of PMFC, PBC, and hybrid plant-based energy systems.

Parameter	PMFC	PBC	Hybrid/Other
Voltage Output (V)	0.2–2.05 V	0.5–20.7 V (peak)	Variable
Current Output (mA)	0.1–3.5 mA	0.05–2.1 mA	Prototype-stage
Power Output (W/m^2)/(mW)	0.05–1.1 W/m^2	Up to 58.8 mW (transient)	Conceptual only
Electrode Materials	Graphite, Copper (*Cu*), Zinc (*Zn*), Titanium (*Ti*), Carbon Felt	*Zn-Cu*, *Al-Cu*, Bamboo charcoal, *Ag*-coated *Cu*, GQDs	Mixed
Notable Plants	Rice, Corn, Flowering Plants, Avocado	*Aloe vera*, Prickly Pear, Dragon Fruit, *Sansevieria*	*Trigonella foenum*, *Azolla*
Typical Applications	LEDs, Capacitors, Sensors, 5 G Boosters, Commercial Street lighting	LEDs, calculators, nanoscale IoT sensors (proposed)	Aquaponics (experimental)
References	(Gurram and Kothapalli, 2017; Di Lorenzo et al., 2019; Imbrogno et al., 2019; Pechsiri and Puengsungwan, 2022; Leoni et al., 2022b; Lu et al., 2020; DAVE et al., 2020; Moqsud and Okamoto, 2023; Luong and Thomas, 2022; Ballestas et al., 2024)	(Muladi et al., 2021; Singh, 2022; Leoni et al., 2022a; Guesmi et al., 2022; Najhi et al., 2024; Singh and Kumar, 2021; Chong et al., 2018; Chong et al., 2019; Nouhalla and Adepoju, 2022; Concepcion et al., 2023)	(Lajis et al., 2021; DAVE et al., 2020)

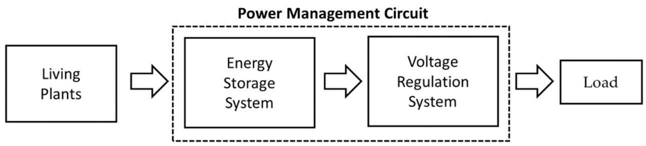

Fig. 5. Block diagram of the energy harvesting system (Chong et al., 2019).

3.7. Application and commercialization

In terms of applications, there are some real-life experimented applications, whereas some proposed applications also exist. In 2017, more than 300 LED streetlights were introduced by the plant-e company (Gurram and Kothapalli, 2017). After two years, in 2019, researchers employed the captured energy to charge capacitors and operate temperature and humidity sensors (Chong et al., 2018; Chong et al., 2019; Imbrogno et al., 2019). LED was also illuminated by the minimal power produced in 2020 (DAVE et al., 2020). In 2021, plant-derived energy enhanced 5 G signals (Xu et al., 2021). The acquired energy was employed to energize sensor nodes for soil detection (Pechsiri and Puengsungwan, 2022), to activate a remote sensor for theoretical measurement of ambient temperature and humidity (Nouhalla and Adepoju, 2022), to power LEDs, calculators, and capacitors (Guesmi et al., 2022), and to charge a 100 μF capacitor in 2022. Numerous studies have suggested harnessing power for specific applications. Providing power as a battery source for WSN and IoT applications, particularly in remote regions, as well as in precision farming and environmental monitoring, to energize nanoscale sensors, advance computing in agriculture and alternative energy sectors, develop prototypes capable of powering electronics, illuminate gardens at night, and operate aquaponics systems, among other applications (Teng et al., 2018; Singh, 2022; Leoni et al., 2022a; Lajis et al., 2021; Guesmi et al., 2022; Najhi et al., 2024; Chong et al., 2019; Nouhalla and Adepoju, 2022; Concepcion et al., 2023; Di Lorenzo et al., 2019; Pechsiri and Puengsungwan, 2022; Luong and Thomas, 2022).

Within the commercialisation framework, the PMFC approach was employed by the company Plant-e Green Business. Wageningen University's PMFC technology possesses the capacity to transform the worldwide electricity industry by utilizing plants as an energy source. This technology can augment national competitiveness and become a European electricity export commodity. Plant-e, a spin-off enterprise, is developing tubular and modular solutions for extensive electricity generation and plant trays. The company's initial implementation is a green electricity roof, and they have also developed DIY boxes for educational purposes. In 2014, Plant-e initiated its "Starry Sky" project, comprising 100 m^2 installations equipped with 400 modules illuminating over 300 LED streetlights at two locations in Amsterdam. The PMFC's environmental performance is anticipated to improve with elevated power output (Gurram and Kothapalli, 2017). Nonetheless, no commercialization has been identified with PBC till now.

Insights derived from application and commercialization studies indicate that plant-based energy can enhance 5 G signals and power LEDs, sensors, and capacitors; proposals also suggest its use in environmental monitoring, precision agriculture, and IoT applications. Through PMFC technology, Plant-e has led commercialization, encompassing projects such as "Starry Sky," which features 300 illuminated LED streetlights, modular systems, and green electricity roofs.

Although PMFC systems, such as the Starry Sky project, show significant promise, there is a notable lack of explicit life-cycle assessments (LCA) and thorough techno-economic analyses (TEA) in the peer-reviewed literature referenced. Indirect evidence from referenced studies enables the inference of multiple dimensions of feasibility.

In the research conducted by Osorio De La Rosa et al. (2023), it was shown that PMFC systems can function continuously for prolonged periods while providing stable power to low-consumption devices (Osorio-de-la-Rosa et al., 2023). Bataillou et al. (2024) highlighted the importance of system modularity and scalability, especially in outdoor configurations subjected to natural environmental conditions. The observations indicate technical feasibility and suggest operational sustainability (AHMAD et al., 2025).

Osorio De La Rosa et al. (2023) reported the application of PMFC in green infrastructure, such as rooftops, utilizing low-cost, biodegradable materials like bamboo charcoal electrodes (De La Rosa et al., 2019). This example illustrates cost-effective design by intention, aligned with sustainability principles, though not explicitly framed in formal LCA or TEA terms. Plant-e's Starry Sky project, which installed over 300 LED streetlights utilizing PMFC technology, exemplifies an economic reality, albeit lacking published life cycle assessment metrics. PMFC demonstrates market potential, although PBC is yet to be marketed.

3.7.1. Practical feasibility of PMFC and PBC in IoT and smart farming

Numerous applications have been proposed; however, a significant question remains: do PMFC and PBC systems possess the capability to meet the energy demands of current IoT and smart farming applications in practical settings? Their feasibility has been thoroughly examined in several experimental studies.

Multiple studies have experimentally confirmed that both PMFC and PBC systems are effective in terms of reliability and in providing sufficient power to low-energy IoT components, including those used in smart farming and environmental monitoring. An example is the power output of PBC-based setups utilizing *Aloe vera* (Chong et al., 2019), which achieved 1.1 mA and 3.49 V. In PMFC-based configurations (Ballestas et al., 2024), the output was recorded at 2.05 V and approximately 1 mW. The generated power is adequate to operate standard DHT11 temperature and humidity sensors, as well as LoRa-based transceivers that function with power management circuitry designed for 3.3 – 5 V and < 2 mW during active transmission. Several studies demonstrate the adequacy of harvested energy, either directly or indirectly, for the remote powering of sensors, LED lights, and amplifiers for 5 G signals (Guesmi et al., 2022; Najhi et al., 2024; Chong et al., 2019; Xu et al., 2021).

The operational feasibility is supported by literature on the low power requirements of such IoT components. DHT11 sensors operate effectively at power levels below 2.5 mW, while LoRa (SX1278) modules transmit at power levels of ≤ 100 mW, both of which fall within the output ranges of PMFC and PBC (Zrioual et al., 2024; Bataillou et al., 2024). The findings endorse the utilization of plant-based systems within decentralized smart agriculture frameworks that operate independently of batteries.

The results generally indicate the progress of PMFC and PBC systems as effective and efficient power sources for low-power applications in smart agriculture and environmental monitoring.

3.7.2. Comparative power output vs. device requirements

A direct comparison of the demonstrated energy outputs of PMFC and PBC technologies with the electrical requirements of typical IoT and sensor devices is essential for evaluating their practical readiness. Table 2 provides a comparison based on selected peer-reviewed experiments. The analysis quantifies the disparity or congruence between plant-derived energy sources and actual device consumption profiles.

Table 2 presents a comparative analysis highlighting significant operational differences between PMFC and PBC technologies in their application for powering low-energy devices in IoT and smart farming. PMFC systems, exemplified by a 900-day outdoor deployment in a beehive monitoring setup, exhibit significant long-term reliability and environmental resilience. Modular units maintain voltages up to 2.05 V and currents exceeding 3 mA over prolonged durations (AHMAD et al., 2025). The strong performance, enhanced by scalable architectures and microbial synergy, positions PMFCs favorably for unattended sensor applications in agriculture and forestry.

PBC systems demonstrate superior voltage and power density per plant, with optimized *Zn–Cu* electrodes reaching 58.8 mW and peak

Table 2
Comparative analysis of PMFC and PBC for IoT and smart farming applications.

Parameter	PMFC	PBC	Reference
Energy Source	Rhizodeposition + microbial metabolism	Electrolyte-rich plant sap or tissues	(AHMAD et al., 2025)
Voltage Range	0.6–2.1 V (up to 2.05 V in multi-plant setups)	0.7–3.49 V (boosted to 10.9 V using converters)	(AHMAD et al., 2025; De La Rosa et al., 2019)
Current Output	0.5–3.9 mA (stable in modular systems)	0.1–1.1 mA (plant- and load-dependent)	(AHMAD et al., 2025; De La Rosa et al., 2019)
Power Output	0.15–5.8 mW (validated under field conditions)	0.9–58.8 mW (lab tested with boosted configurations)	(Osorio-de-la-Rosa et al., 2023; De La Rosa et al., 2019)
Power Management	Parallel PMFCs with DC/DC boost circuits	*Zn–Cu* leaf-array with boost converter circuitry	(AHMAD et al., 2025; De La Rosa et al., 2019)
IoT Applications Demonstrated	Beehive monitoring, BLE sensors, environmental loggers	Smart greenhouses, IoT relays, and sensor activation in WSN	(AHMAD et al., 2025; De La Rosa et al., 2019)
Scalability Evidence	900 + days of stable output in outdoor deployments	High power from > 160 *Zn–Cu* pairs across 20 leaves	(AHMAD et al., 2025; De La Rosa et al., 2019)
Long-Term Durability	Stable performance with minimal degradation	Susceptible to load fluctuations and material fatigue	(AHMAD et al., 2025; Osorio-de-la-Rosa et al., 2023)
Limitations	Soil microbe variability, anode fouling	Voltage drop under load, plant damage under electrode strain	(Osorio-de-la-Rosa et al., 2023; De La Rosa et al., 2019)

voltages of 10.9 V after boosting, adequate for activating IoT controllers and smart greenhouse components (De La Rosa et al., 2019). These configurations, while exhibiting increased sensitivity to load and material fatigue, show significant compatibility with capacitor banks and remote data transmission modules.

PMFCs demonstrate superior endurance and prolonged deployment, whereas PBCs offer power-dense, scalable options suitable for intermittent or high-burst applications. Future research should focus on hybridization strategies that integrate the long-term stability of PMFCs with the superior output efficiency of PBCs to meet the varied energy demands of IoT-based agricultural systems (Osorio-de-la-Rosa et al., 2023).

4. New areas of research

Despite considerable progress in plant-based energy harvesting, our understanding and application of these technologies remain constrained by certain critical, undiscovered domains. Specifically, there has been limited research on the effects of sizing, particularly about how *Aloe vera* leaves of the same dimensions but varying ages influence energy-harvesting efficiency. Additional research is required about the effects of aging, which pertains to the alterations in a plant's attributes across its life cycle and their influence on energy production. To enhance energy efficiency and reliability, considerable knowledge about integrating PBC and PMFC must be acquired. These unexamined opportunities promote additional research to improve plant-based energy systems' scalability and practical application.

4.1. Sizing effects of plants and leaves

Although numerous studies have explored the utilization of diverse plant species for energy harvesting in PMFC and PBC systems, insufficient focus has been directed toward the impact of plant size and leaf area on energy output. There has been no comprehensive investigation into how these physical attributes influence a plant's capacity to capture energy efficiently throughout its life cycle Fig. 6.

Multiple tests utilized plants and leaves of various sizes. Nonetheless, further examination is warranted, as it is conceivable that numerous plants of the same species may possess leaves at varying phases of the life cycle yet exhibit identical dimensions. Although there is an age disparity, the leaves are identical in size.

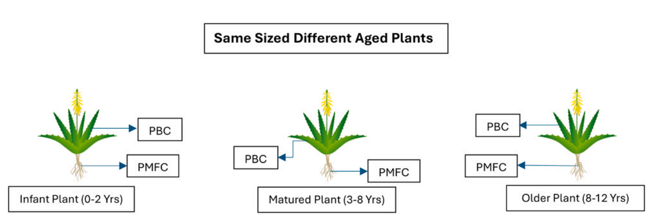

Fig. 6. Sizing Effect Test.

Broader leaves often possess an increased surface area for sunlight interception, potentially enhancing photosynthetic rates due to more chloroplasts and stomata (Evans, 1999; Niinemets and Sack, 2006). The quantity of stomata present enhances a plant's ability to absorb CO_2. The quantity of carbon accessible to the plant escalates with the concentration of CO_2. Rubisco is a crucial enzyme in photosynthesis, and its efficacy is enhanced in the presence of abundant carbon. Its interaction with Ribulose-1,5-bisphosphate and CO_2 in the Calvin cycle promotes the synthesis of phosphoglycerate-3 (Hamilton, 2019). Furthermore, increased CO_2 facilitates the plant in attaining its optimal light saturation threshold. Another advantage is the more effective utilization of water and nutrients. Guard cells, responsible for regulating the opening and closing of stomata, contain chloroplasts. Chloroplasts in guard cells can be modified to increase photosynthesis (Kucheli, 2024).

Because of having more extensive root and vascular systems and enlarged canopies (Hikosaka, 2003; Qaderi et al., 2019), larger plants also boost photosynthetic rates. Physiological differences may cause plants of different ages, even similar in size, to show different photosynthetic capacities (Bielczynski et al., 2017). Furthermore, the age of a succulent plant may affect its ability to store nutrients and water. The soft leaves' thickness and internal composition may change with age. Younger plants may thus not be as good at retaining nutrients and water as older ones (England and Attiwill, 2006). Plants change in their metabolic activities as they grow. Older plants may possess elevated levels of internal chemicals, potentially influencing physiological functioning (Choi and Chung, 2003).

Furthermore, although plants may exhibit similar above-ground dimensions, their root systems generally expand and become increasingly efficient as they mature. Older plants may possess a more advanced root system, facilitating superior access to water and nutrients and influencing their physiological stability relative to younger plants (Twyman, 2003). Plant internal physiology varies over multiple life cycles while maintaining the same size. This affects the metabolic processes in plants, which are expected to impact the output of PBC and PMFC as well.

The discrepancy is substantial since the plant's size probably influences the mechanisms of energy transfer and the amount of energy that can be extracted. Examining changes in plant size can provide essential insights for enhancing the efficiency of PMFC and PBC systems.

4.2. Aging effect

The predominant focus of existing research has been on short-term energy harvesting trials, with insufficient consideration given to the variations in the long-term energy output of plants as they progress through distinct life stages. In prior research, particular aged plants were chosen for experimentation. Significant knowledge must be acquired regarding potential fluctuations in energy output over extended periods, especially in plants with prolonged life cycles Fig. 7.

The three fundamental stages of post-embryonic plant growth and development are juvenile, adult vegetative, and adult reproductive. Plants undergo a "phase change" or "phase transition" to progress from one phase to another. Both internal and external influences induce transitions. The shift from the juvenile to the adult stage is physiologically significant as it determines the "body plan," or the structural configuration of each plant species, affecting biomass production, environmental interactions, and subsequent crop output (Gioppato and Dornelas, 2021).

The duration to manifest these transitions is extended. These transitions influence the internal mechanisms of plants and the energy extracted from them. As plants develop, the structures facilitating electron movement, such as vascular tissues and root networks, proliferate, augmenting energy transmission within the organism (Jung et al., 2008). The xylem is a vascular tissue responsible for moving water and minerals from the roots to the leaves and providing mechanical support to the plant (Brodribb and Mencuccini, 2016). A phloem is a vascular tissue that translocates nutrients from the leaves to various plant parts, including the roots, flowers, and fruits (Swamy et al., 2022). The greater the development of the xylem and phloem, the more efficiently they will execute their functions. Their productive endeavors will enhance the rate of photosynthesis. Furthermore, the plant can increase chemical energy (glucose) when photosynthesis intensifies. Moreover, an increase in the chemical energy of the plant correlates with an increase in the harvested energy.

This research will address a notable deficiency in the literature by examining the influence of plant aging and growth on the stability and consistency of energy accumulation throughout the year.

4.3. Integration of two methods

PBC and PMFC technologies have progressed markedly. Nonetheless, a solitary study suggested integrating these two systems inside an aquaponics framework (Lajis et al., 2021), and no comprehensive effort has been undertaken to amalgamate them into a unified energy harvesting system.

Their integration can significantly enhance the energy obtained from PBC and PMFC systems. Series and parallel configurations can be utilized to integrate these systems. The series configuration is optimal for elevating voltage, whereas the parallel configuration is optimal for augmenting current (Power-Sonic Team, 2022). For a series connection, the currents of the two outputs must be equivalent, while for a parallel connection, the voltages must be equal. Connecting many voltage sources in parallel may result in significant issues. The source with the highest voltage will dictate the voltage for the entire circuit. The elevated voltage source may excessively supply current to the lower voltage sources, potentially causing overload or considerably reducing lifespan (StudySmarter, 2022). In a series connection, the current remains constant. Consequently, two separate current values linked in series are invalid (Testbook, 2022). Nonetheless, despite the differing voltage and current values of the PMFC and PBC systems, they can be integrated using a power management circuit to combine their outputs efficiently, and numerous devices will be utilized for experimentation (Naamane and Msirdi, 2013).

The design must account for the particular specifications and characteristics of both PBC and PMFC energy harvesting circuits. The energy circuit for PBC typically employs electrodes put into the leaves or stems to monitor bio-electrochemical reactions inside the plant tissues. In this scenario, low-resistance electrodes, an optimal placement strategy, and a voltage regulator to regulate the inherently low and variable voltage are critical components Fig. 8.

The PMFC circuit primarily focuses on microbial activity at the interface of soil and plant roots. An external resistor is frequently necessary to control current flow, a proton exchange mechanism, and electrodes for electron transfer from microorganisms. PMFC systems require amplification circuits to enhance their practicality in real-world applications, as they often deliver little current while maintaining relatively steady voltage.

Compatibility and efficiency should be considered in a unified energy circuit for both PBC and PMFC. The outputs of the PBC and PMFC can be managed separately by multiple input stages in an integrated design before amalgamation into a singular processing circuit. A central energy management unit, DC-DC converters for voltage regulation, and diode-based current isolators are necessary. Supercapacitors and other energy storage systems can mitigate power fluctuations and provide a reliable power supply for subsequent applications.

The consistency between theoretically and practically acquired findings can be compared using the following equations (Ballestas et al., 2024):

$$I = \frac{v}{R} \tag{12}$$

where I is the intensity (A), v is the output voltage, and R is the resistance.

$$P = vI \tag{13}$$

where P is the electric power (watts), v is the output voltage, and I is the output current.

$$J = \frac{I}{a} \tag{14}$$

where J is the current density (A / m^2), I is the output current, and a is the area.

$$\phi = \frac{P}{a} \tag{15}$$

where ϕ is the power density (W / m^2), P is the output power, and a is the area.

$$Pv = \frac{P}{v} \tag{16}$$

Pv is the volumetric power (W/m^3), P is the output power, and v is the output voltage.

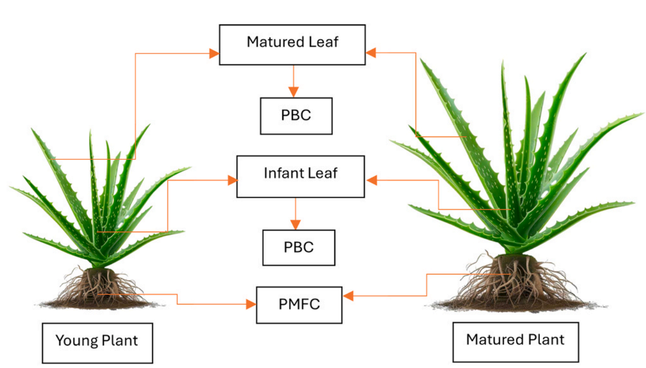

Fig. 7. Aging Effect Test.

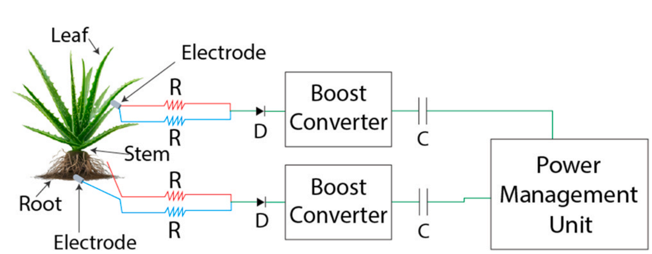

Fig. 8. Implementation of Integrated Energy System.

Integrating the microbial interactions of the PMFC with the metabolic activities of the PBC may yield advantageous results and enhance energy output. This work aims to address a notable research deficiency due to the absence of comparable investigations by developing a hybrid system to optimize energy production. This hybrid method harnesses the advantages of both strategies while mitigating their shortcomings.

4.4. Technical and economic challenges in PBC vs. PMFC systems

PBCs and PMFCs both utilize bioelectricity generated by living plants; however, they exhibit notable differences in technical complexity and economic viability, exhibited in Table 3.

PBC systems provide economic benefits through the use of low-cost materials and simplified architecture, rendering them attractive for decentralized and temporary IoT applications. Nonetheless, they typically generate intermittent and less stable power. Conversely, PMFCs demonstrate superior performance in continuous energy generation and environmental applications, such as wastewater remediation. However, they present technical complexities and higher economic costs associated with maintenance and microbial dependencies.

Table 3
Comparative analysis of technical and economic barriers between PBC and PMFC.

Barrier Category	PMFC	PBC	Reference
System Complexity	Requires soil-microbe-plant integration, electrode burial, and root-microbe interaction.	Simpler setup using leaf/stem electrodes.	(Maddalwar et al., 2021)
Material Cost	Graphite, carbon felt, or precious metals like platinum increase the cost.	Often uses cheaper materials like copper, zinc, and aluminium.	(Jadhav et al., 2021)
Power Output	Stable long-term output, but lower peak voltage without boosters.	Higher peak voltages with short-term outputs and boosters.	(Chiranjeevi et al., 2019)
Scalability	Difficult due to complex microbe-plant dependency and soil variability.	Easier to scale using modular arrays of leaves/plants.	(Nitisoravut and Regmi, 2017)
Maintenance	Sensitive to microbial health, soil moisture, and root aging.	Less biologically dependent, easier to maintain.	(Cahyani et al., 2020)
Cost per Watt	Higher due to complex setup and slower electron transfer.	Lower due to simpler design and fewer biological dependencies.	(Maddalwar et al., 2021)

5. Conclusion

Innovative techniques such as PMFC and PBC have advanced the development of alternative energy harvesting architectures that utilize the inherent biological and electrochemical mechanisms present in living plants. This review examines 70 peer-reviewed articles published between 2010 and 2025, focusing on trends, challenges, and validation related to energy generation, electrode materials, system design, and environmental conditions. The findings indicate that PMFCs utilizing specialized microbial-rich soil and specific electrode configurations can achieve power densities of 1.1 W/m^2. In contrast, PBCs, especially those involving fleshy plants like *Aloe vera* and Prickly Pear, yield voltage outputs exceeding 3.4 V and power outputs of approximately 58.8 mW when subjected to optimal environmental conditions. So far, PMFC demonstrates an advanced level of maturity and evidence of operational, commercial-scale applications, such as the "starry sky" project implemented by the Dutch company Plant-e, which supplies electricity to over 300 LED lights. PBC systems are currently in an experimental phase, demonstrating feasibility primarily for powering small IoT sensors and capacitors, pending further long-term validation and commercialization efforts. PMFCs demonstrate a superior potential for long-term and sustainable energy production in outdoor or wetland settings when compared to PBCs, owing to their compact design and modular stack mounting configuration suitable for indoor or greenhouse applications. Various application areas with potential include precision farming, environmental monitoring, smart farming that is both decentralized and automated, as well as WSNs. Experimental frameworks have demonstrated the capability to energize sensors for the measurement of temperature and humidity, activate remote transmitters, and supply power to capacitors in low-energy circuits. An examination of scalability, voltage regulation, long-term performance issues, and various constraints such as displacement selection, life cycle effects, hybrid integration, and advanced materials integrated research indicates that targeted research will bridge the gap between real-world applications and lab-scale feasibility. By concentrating on impact and resilience, it is possible to construct sustainable and low-impact energy systems through the integration of these systems with other renewable technologies. Plant-powered systems, particularly PMFCs, are poised to significantly impact the future by providing essential energy solutions for both urban and rural environments that require advanced green technologies.

CRediT authorship contribution statement

Sk Rakibur Rahman: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Kah-Yoong Chan:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ngu Eng Eng:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis. **Wai-Leong Pang:** Writing – review & editing, Visualization, Validation. **Muhammad Aqeel Ashraf:** Writing – review & editing, Visualization, Validation. **Kar Ban Tan:** Writing – review & editing, Visualization, Validation. **Ajay Kumar Singh:** Writing – review & editing, Visualization, Validation.

Declaration of Competing Interest

I hereby affirm that this review manuscript is original, has not been published or submitted for consideration elsewhere, and has been prepared in compliance with the ethical guidelines established by the journal. All authors have granted their approval for the submission, and there are no conflicts of interest to declare.

I sincerely appreciate your time and consideration regarding this submission, and I eagerly anticipate your feedback. Please feel free to contact me if any additional information is required.

Acknowledgement

We would like to acknowledge Telekom Malaysia Research and Development (TM R&D) for the financial support with TM R&D Research Fund (Grant No: RDTC/231080, Project ID: MMUE/230009)

Data availability

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

References

Abas, N., Kalair, A., Khan, N., 2015. Review of fossil fuels and future energy technologies. Futures 69, 31–49. https://doi.org/10.1016/j.futures.2015.03.003 (May).

Ahmad, Y.A., Mustapa, N.S., Razaman, A.H., Hamid, M.N.A.A., Malik, N.A., Jamlos, M. F., 2025. Integration of Lora IOT with cloud platform in stingless beehive remote monitoring system. IIUM Eng. J. 26 (1), 373–397. https://doi.org/10.31436/IIUMEJ.V26I1.3531.

Ballestas, E.R., et al., 2024. Power generation potential of plant microbial fuel cells as a renewable energy source. Renew. Energy 221. https://doi.org/10.1016/j.renene.2023.119799.

Bataillou, G., Ondel, O., Haddour, N., 2024. 900-Days long term study of plant microbial fuel cells and complete application for powering wireless sensors. J. Power Sources. https://doi.org/10.1016/j.jpowsour.2023.233965.

S. Bertrand, "Climate, Environmental, and Health Impacts of Fossil Fuels (2021)," Washington, D.C., Dec. 2021. [Online]. Available: ⟨https://www.eesi.org/papers/view/fact-sheet-climate-environmental-and-health-impacts-of-fossil-fuels-2021⟩.

Bielczynski, L.W., Łaçki, M.K., Hoefnagels, I., Gambin, A., Croce, R., 2017. Leaf and plant age affects photosynthetic performance and photoprotective capacity. Plant Physiol. 175 (4), 1634–1648. https://doi.org/10.1104/pp.17.00904 (Oct.).

Brodribb, T., Mencuccini, M., 2016. Xylem. In: in Encyclopedia of Applied Plant Sciences, 2nd ed, 1. Elsevier Inc, pp. 141–148. https://doi.org/10.1016/B978-0-12-394807-6.00074-5 (ch. Physiology | Xylem).

D. Cahyani, A. Haryanto, D.S. Marpaung, and R. Fil'aini, "Sel Bahan Bakar Berbasis Mikroba-Tanaman (P-MFC) Sebagai Sumber Energi Listrik; Prinsip Kerja, Variasi Desain, Potensi dan Tantangan," vol. 9, no. 2, pp. 112–121, Jun. 2020, doi: 10.23960/JTEP-L.V9I2.112-121.

Chen, M., Blankenship, R.E., 2021. Photosynthesis | Photosynthesis. Encyclopedia of Biological Chemistry III, 3rd ed. Elsevier, pp. 150–156. https://doi.org/10.1016/B978-0-12-819460-7.00081-5. 2.

Chiranjeevi, P., Yeruva, D.K., Kumar, A.K., Mohan, S.V., Varjani, S., 2019. Plant-microbial fuel cell technology. Microbial Electrochemical Technology, 1st ed. Elsevier, pp. 549–564. https://doi.org/10.1016/B978-0-444-64052-9.00022-4 (ch. PMFC Technology).

Choi, S., Chung, M.H., 2003. A review on the relationship between Aloe vera components and their biologic effects. Semin. Integr. Med. 1 (1), 53–62. https://doi.org/10.1016/S1543-1150(03)00005-X.

Chong, P.L., Singh, A.K., Kok, S.L., 2018. Characterization of Aloe Barbadensis Miller leaves as a potential electrical energy source with optimum experimental setup conditions. PLoS One 14 (6). https://doi.org/10.1371/journal.pone.0218758.

Chong, P.L., Singh, A.K., Kok, S.L., 2019. Potential application of Aloe vera-derived plant-based cell in powering wireless device for remote sensor activation. PLoS One 14 (12). https://doi.org/10.1371/journal.pone.0227153 (Dec.).

Choo, Y.Y., Dayou, J., Surugau, N., 2014. Origin of weak electrical energy production from living-plants. Int. J. Renew. Energy Res. Jedol Dayou Et. al 4 (1), 198–203. https://doi.org/10.20508/ijrer.v4i1.1082.g6265 (Feb.).

Concepcion, R., Francisco, K., Janairo, A.G., Baun, J.J., Izzo, L.G., Dec. 2023. Genetic atom search-optimized in vivo bioelectricity harnessing from live dragon fruit plant based on intercellular two-electrode placement. Renew. Energy 219. https://doi.org/10.1016/j.renene.2023.119528.

DAVE, K., Darji, P., Gandhi, F., Singh, S., Jadav, D., 2020. Bioelectrochemical system: an eco-friendly approach to generate electricity utilizing plants and microorganisms. Biosci. Biotechnol. Res. Asia 18 (1), 147–161. https://doi.org/10.21203/rs.3.rs-64793/v1 (Oct.).

De Boer, A.H., Volkov, V., 2003. Logistics of water and salt transport through the plant: structure and functioning of the xylem. Plant Cell Environ. 26 (1), 87–101. https://doi.org/10.1046/j.1365-3040.2003.00930.x.

De La Rosa, E.O., et al., 2019. Plant microbial fuel cells-based energy harvester system for self-powered IoT applications. Sensors 19 (6). https://doi.org/10.3390/s19061378.

Deng, H., Chen, Z., Zhao, F., 2012. Energy from plants and microorganisms: progress in plant-microbial fuel cells. ChemSusChem 5 (6), 1006–1011. https://doi.org/10.1002/cssc.201100257.

Di Lorenzo, R., Grassi, M., Assini, S., Granata, M., Barcella, M., Malcovati, P., 2019. Electrical energy harvesting from pot plants. Lecture Notes in Electrical Engineering, Sensors. CNS 2018. Springer, Cham, pp. 545–550. https://doi.org/10.1007/978-3-030-04324-7_65, 539.

Encyclopaedia Britannica., "Photosynthesis | Definition, Formula, Process, Diagram, Reactants, Products, & Facts." Accessed: Sep. 20, 2024. [Online]. Available: ⟨https://www.britannica.com/science/photosynthesis/Energy-efficiency-of-photosynthesis⟩.

England, J.R., Attiwill, P.M., Jan. 2006. Changes in leaf morphology and anatomy with tree age and height in the broadleaved evergreen species, Eucalyptus regnans F. Muell. Trees Struct. Funct. 20 (1), 79–90. https://doi.org/10.1007/s00468-005-0015-5.

Evans, J.R., 1999. Leaf anatomy enables more equal access to light and CO_2 between chloroplasts. N. Phytol. 143 (1), 93–104. https://doi.org/10.1046/j.1469-8137.1999.00440.x.

Gayen, D., Chatterjee, R., Roy, S., 2024. A review on environmental impacts of renewable energy for sustainable development. Int. J. Environ. Sci. Technol. 21 (5), 5285–5310. https://doi.org/10.1007/s13762-023-05380-z.

Gioppato, H.A., Dornelas, M.C., 2021. Plant design gets its details: modulating plant architecture by phase transitions. Plant Physiol. Biochem. 163, 1–14. https://doi.org/10.1016/j.plaphy.2021.03.046.

Guesmi, H., Ajjel, R., Alqahtani, T., Algarni, S., 2022. Towards renewable green energy produced by prickly pear living plant. Int. J. Sustain. Eng. 15 (1), 253–265. https://doi.org/10.1080/19397038.2022.2140223.

Gurram, S.P.G., Kothapalli, N.S., 2017. A Novel Electricity Generation with Green Technology by Plant-e from Living Plants and Bacteria. 2017 6th International Conference on Computer Applications in Electrical Engineering - Recent Advances (CERA). Roorkee, India: IEEE, pp. 146–151. https://doi.org/10.1109/CERA.2017.8343317 (Oct.).

Hamilton, T.L., 2019. The trouble with oxygen: the ecophysiology of extant phototrophs and implications for the evolution of oxygenic photosynthesis. Free Radic. Biol. Med. 140, 233–249. https://doi.org/10.1016/j.freeradbiomed.2019.05.003 (Aug.).

Haram, M.H.S.M., Lee, J.W., Ramasamy, G., Ngu, E.E., Thiagarajah, S.P., Lee, Y.H., 2021. Feasibility of utilising second life EV batteries: applications, lifespan, economics, environmental impact, assessment, and challenges. Alex. Eng. J. 60 (5), 4517–4536. https://doi.org/10.1016/j.aej.2021.03.021 (Oct.).

Haram, M.H.S.M., Sarker, M.T., Ramasamy, G., Ngu, E.E., 2023. Second Life EV Batteries: technical evaluation, design framework, and case analysis. IEEE Access 11, 138799–138812. https://doi.org/10.1109/ACCESS.2023.3340044.

Hikosaka, K., 2003. A model of dynamics of leaves and nitrogen in a plant canopy: an integration of canopy photosynthesis, leaf life span, and nitrogen use efficiency. Am. Nat. 162 (2), 149–164. https://doi.org/10.1086/376576 (Aug.).

Imbrogno, F., Assini, S.P., Granata, M., Lorenzo, R.Di, Malcovati, P., 2019. Experimental characterization of the electrical energy produced by microbial fuel cells supplied by pot plants. 2019 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor), Portici. IEEE, Italy. https://doi.org/10.1109/MetroAgriFor.2019.8909234.

D.A. Jadhav, D. Ghosal, A.D. Chendake, S. Pandit, and T.K. Sajana, "Plant Microbial Fuel Cell as a Biomass Conversion Technology for Sustainable Development," Springer, Cham, 2021, pp. 135–147. doi: 10.1007/978-3-030-65017-9_5.

Jung, J.H., Kim, S.G., Seo, P.Joon, Park, C.M., 2008. Molecular mechanisms underlying vascular development. Adv. Botan. Res. Academic Press Inc., pp. 1–68. https://doi.org/10.1016/S0065-2296(08)00401-1, 48.

B. Kucheli, "The Role of Guard Cells Chloroplasts toward the Enhancement of Plant Growth," in Chloroplast Structure and Function, M. S. Khan, Ed., 2024. doi: 10.5772/intechopen.114204.

Lajis, G.A., Jasni, J., Azis, N., Mohd Radzi, M.A., Mohtar, M.N., Salim, N.A., 2021. Bioelectricity harvesting at aquaponics system: current and future challenges. ICPEA 2021 - 2021 IEEE International Conference in Power Engineering Application. Institute of Electrical and Electronics Engineers Inc, pp. 85–90. https://doi.org/10.1109/ICPEA51500.2021.9417840 (Mar).

Leegood, R.C., 2004. Photosynthesis. Encyclopedia of Biological Chemistry. Elsevier eBooks, pp. 330–335. https://doi.org/10.1016/b0-12-443710-9/00487-7, 3.

Leoni, A., Ferri, G., Stornelli, V., Colaiuda, D., 2022b. Micro Energy Harvesting from the Soil of Indoor Living Plants. 2022 7th International Conference on Smart and Sustainable Technologies (SpliTech), Split / Bol. IEEE, Croatia. https://doi.org/10.23919/SpliTech55088.2022.9854259.

Leoni, A., Ferri, G., Ursini, D., Zompanti, A., Sabatini, A., Stornelli, V., 2022a. Towards Smart Sensor Systems for Precision Farming: Electrode Potential Energy Harvesting from Plants' Soil. ICECS 2022 - 29th IEEE International Conference on Electronics, Circuits and Systems, Proceedings. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ICECS202256217.2022.9970911

LibreTexts., "Electrode Potentials," Chemistry LibreTexts. Accessed: Dec. 24, 2024. [Online]. Available: https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Instrumental_Analysis_(LibreTexts)/22%3A_An_Introduction_to_Electroanalytical_Chemistry/22.03%3A_Electrode_Potentials.

Liu, B., Ji, M., Zhai, H., Oct. 2018. Anodic potentials, electricity generation and bacterial community as affected by plant roots in sediment microbial fuel cell: effects of anode locations. Chemosphere 209 (1), 739–747. https://doi.org/10.1016/j.chemosphere.2018.06.122.

Lokman, M.L., Chan, K.Y., Ting, Y.T., Liang Lee, C., Chung, G.C., Pang, W.L., 2024. "LoRa based IoT enabled sensor networks for plantations. J. Eng. Technol. Appl. Phys. 6 (1), 16–24. https://doi.org/10.33093/jetap.2024.6.1.

Lu, Z., et al., 2020. Power-generating trees: Direct bioelectricity production from plants with microbial fuel cells. Appl. Energy 268. https://doi.org/10.1016/j.apenergy.2020.115040 (Jun.).

Luong, T., Thomas, S.J., 2022. Towards the plant-based sensor: agricultural energy harvesting and sensing experiments. SenSys 2022 - Proceedings of the 20th ACM Conference on Embedded Networked Sensor Systems. Association for Computing Machinery, Inc, pp. 1116–1122. https://doi.org/10.1145/3560905.3568418 (Nov).

Lynch, J.M., de Leij, F., 2012. Rhizosphere. Encyclopedia of Soils in the Environment, 1st ed. Wiley, pp. 507–512. https://doi.org/10.1002/9780470015902.a0000403.pub2. 3.

Maddalwar, S., Nayak, K.K., Kumar, M., Singh, L., 2021. Plant microbial fuel cell: opportunities, challenges, and prospects. Bioresour. Technol. 341, 125772. https://doi.org/10.1016/J.BIORTECH.2021.125772.

Martinez, R.D.R., Bermudez, M.E.A., Apr. 2023. Production of electrical energy from living plants in microbial fuel cells. Clean. Energy 7 (2), 408–416. https://doi.org/10.1093/ce/zkac092.

Moqsud, M.A., Okamoto, T., 2023. Bioelectricity generation from corn plant microbial fuel cell (PMFC) using natural bamboo charcoal as electrodes and Shewanella oneidensis. Bioresour. Technol. Rep. 24. https://doi.org/10.1016/j.biteb.2023.101611 (Dec.).

Muladi, M., et al., 2021. An experimental study of generating electricity from urban tropical forest plants. Journal Physics: Conference Series. IOP Publishing Ltd. https://doi.org/10.1088/1742-6596/1825/1/012099.

Naamane, A., Msirdi, N., 2013. Improving multiple source power management using state flow approach. Smart Innov. Syst. Technol. 22, 779–785. https://doi.org/10.1007/978-3-642-36645-1_69.

Najhi, B.M.T.Ahmad Zun, Habaebi, M.H., Islam, M.R., Sep. 2024. Living plant energy harvesting for WSN & IoT devices. 9th International Conference on Mechatronics Engineering (ICOM'24). Institute of Electrical and Electronics Engineers (IEEE), pp. 107–111. https://doi.org/10.1109/icom61675.2024.10652478.

Niinemets, Ü., Sack, L., 2006. Structural determinants of leaf light-harvesting capacity and photosynthetic potentials. Progress in Botany. Springer-Verlag Berlin Heidelberg, pp. 385–419. https://doi.org/10.1007/3-540-27998-9_17, 67.

Nitisoravut, R., Regmi, R., 2017. Plant microbial fuel cells: a promising biosystems engineering. Renew. Sustain. Energy Rev. 76, 81–89. https://doi.org/10.1016/J.RSER.2017.03.064 (Sep.).

Nouhalla, B., Adepoju, A., 2022. Application of aloe vera-derived plant-based cell in powering wireless Iot devices in a smart greenhouse. Int. Uni-Sci. Res. J. 3 (19), 126–172. https://doi.org/10.59271/s44768.022.2010.19.

Osorio-de-la-Rosa, E., et al., 2023. Plant microbial fuel cells as a bioenergy source used in precision beekeeping. Sustain. Energy Technol. Assess. https://doi.org/10.1016/j.seta.2023.103499 (Dec.).

Paraschiv, L.S., Paraschiv, S., Sep. 2023. Contribution of renewable energy (hydro, wind, solar and biomass) to decarbonization and transformation of the electricity generation sector for sustainable development. Energy Rep. 9, 535–544. https://doi.org/10.1016/j.egyr.2023.07.024.

Pechsiri, T., Puengsungwan, S., 2022. Energy harvesting based on living plants for smart farming. ASEAN J. Sci. Eng. 3 (1), 47–56. https://doi.org/10.17509/ajse.v3i1.43721 (Mar.).

Power-Sonic Team, 2022 "How to Connect Batteries in Series and Parallel," Power-Sonic. [Online]. Available: ⟨https://www.power-sonic.com/blog/how-to-connect-batteries-in-series-and-parallel/⟩.

Qaderi, M.M., Martel, A.B., Dixon, S.L., 2019. Environmental factors influence plant vascular system and water regulation. Plants 8 (3). https://doi.org/10.3390/plants8030065.

Singh, A.K., 2022. Plant base renewable energy to power nanoscale sensors. In: Dudem, B., Venkateswaran, V., Chandrasekhar, A. (Eds.), Nanogenerators and Self-Powered Systems. IntechOpen. https://doi.org/10.5772/intechopen.105365.

Singh, A.K., Kumar, N., 2021. Renewable and sustainable electrical energy harvested from living plants: an experimental study. 2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME). IEEE, Mauritius, Mauritius. https://doi.org/10.1109/ICECCME52200.2021.9590928.

StudySmarter, 2022 "Voltage Sources in Parallel," StudySmarter UK. [Online]. Available: ⟨https://www.studysmarter.co.uk/explanations/physics/electromagnetism/voltage-sources-in-parallel/⟩.

Swamy, M.J., Bobbili, K.B., Mondal, S., Narahari, A., Datta, D., 2022. Cucurbitaceae phloem exudate lectins: purification, molecular characterization, and carbohydrate binding characteristics. Phytochemistry 201. https://doi.org/10.1016/j.phytochem.2022.113251.

Tan, J.Y., Chan, K.Y., 2024. Solar-based nighttime electric power generator based on radiative cooling. Energy Rep. 12, 5155–5162. https://doi.org/10.1016/j.egyr.2024.11.024 (Dec.).

Teng, H., Kok, B., Uttraphan, C., Yee, M., Raja, P., Pahat, B., 2018. A review on energy harvesting potential from living plants: future energy resource. Int. J. Renew. Energy Res. 8 (4). https://doi.org/10.20508/ijrer.v8i4.8807.g7546.

Testbook, 2022 "If Two Sources with Different Currents Are Connected in Series." [Online]. Available: ⟨https://testbook.com/question-answer/if-i1-and-i2-are-two-current-sources-that-are-conn–63fde2f8da9602a89afc35ec⟩.

Ting, Y.T., Chan, K.Y., 2024. Optimising performances of LoRa based IoT enabled wireless sensor network for smart agriculture. J. Agric. Food Res. 16. https://doi.org/10.1016/j.jafr.2024.101093.

Twyman, R.M., 2003. Root Development | Genetics of primary root development. Encyclopedia of Applied Plant Sciences. Elsevier, pp. 1096–1101. https://doi.org/10.1016/B0-12-227050-9/00038-7.

Wegner, L.H., Zimmermann, U., 2002. On-line measurements of K^+ activity in the tensile water of the xylem conduit of higher plants. Plant J. 32 (3), 409–417. https://doi.org/10.1046/j.1365-313x.2002.01426.x (Jul.).

Weisenseel, M.H., Meyer, A.J., 1997. Bioelectricity, gravity, and plants. Planta 203 (S1), S98–S106. https://doi.org/10.1007/pl00008122 (Jan.).

Wikipedia contributors, "Photosynthesis," Wikimedia Foundation. Accessed: Oct. 24, 2024. [Online]. Available: ⟨https://en.wikipedia.org/wiki/Photosynthesis⟩.

Wright, J.P., Fisher, D.B., 1981. Measurement of the Sieve tube membrane potential. Plant Physiol. 67 (4), 845–848. https://doi.org/10.1104/pp.67.4.845.

Xu, Y., Lu, Y., Zhu, X., 2021. Toward plant energy harvesting for 5G signal amplification. ACS Sustain. Chem. Eng. 9 (3), 1099–1104. https://doi.org/10.1021/acssuschemeng.0c08453 (Jan.).

Xu, Y., Zhao, F., 2023. Impact of energy depletion, human development, and income distribution on natural resource sustainability. Resour. Policy 83. https://doi.org/10.1016/j.resourpol.2023.103531.

Ying Ying, C., Dayou, J., 2014. Increasing the energy output from living-plants fuel cells with natural photosynthesis. Adv. Environ. Biol. 8 (14), 20–23. ⟨http://www.aensiweb.com/AEB/⟩.

Ying Ying, C., Dayou, J., 2016. Modelling of the electricity generation from living plants. J. Teknol. (Sci. Eng.) 78 (6), 29–33. https://doi.org/10.11113/jt.v78.3704.

Zrioual, H., Toluwalase Adewale, I., Bahaa Eddine, C., 2024. Remote environmental monitoring system using DHT11. Int. J. Innov. Sci. Res. Technol. 386–392. https://doi.org/10.38124/ijisrt/IJISRT24NOV200.