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Submission date: 28-May-2026 07:37PM (UTC+0530)

Submission ID: 2971292158

File name: milsi.docx (5.4M)

Word count: 12518

Character count: 75362

**“Construction of Shared-Soil Stacked Plant Microbial Fuel Cell
using Nutrient Film Technology in Hydroponics for Bioelectricity
Production and its Performance Evaluation”**

²⁴
A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS OF THE DEGREE
OF
MASTER OF TECHNOLOGY
IN
INDUSTRIAL BIOTECHNOLOGY

Submitted by
Milsa Pal
(24/IBT/04)

⁶
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July 2026



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ACKNOWLEDGEMENT

The success of this project is an outcome of the enormous help from many people. My deepest thanks to Prof Jai Gopal Sharma, Project Guide, for inspiring and allowing me to conduct this work, and for his instant and constant support and valuable guidance. I would like to thank him ⁵ for his persistent support and incomparable guidance, and most of all his unmatched patience, attention, and care. His efforts far outweigh any of my efforts put into his project, and for making corrections as and when required. I am profoundly grateful to him. I am also grateful and thankful to all my lab mates for their continuous assistance during my practical work.

I would like to extend my thanks to Mr. CB Singh, Mr. Jitendra Singh, and other non-teaching staff members for supporting me throughout the project tenure. Finally, I am ⁵ thankful to my family and friends for their continuous engagement throughout the project process. The accomplishments would not have been possible without them.

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DECLARATION

⁶ Paridhi (Roll No. 24/IBT/06), a student of Master of Technology (Industrial Biotechnology), hereby declare that the Project Dissertation titled **“Construction of Shared-Soil Stacked Plant Microbial Fuel Cell using Nutrient Film Technology in ¹Hydroponics for Bioelectricity Production and its Performance Evaluation”** submitted to the Department of Biotechnology, Delhi Technological University, Delhi, in fulfilment of the requirements for the award of the degree of Master of Technology, is original and has not been copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma, Associateship, Fellowship, or any other similar title or recognition.

Place: Delhi

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CERTIFICATE

I hereby certify that the Project Dissertation titled “Construction of Shared-Soil Stacked Plant Microbial Fuel Cell using Nutrient Film Technology in Hydroponics for Bioelectricity Production and its Performance Evaluation”, submitted by Milsa, Roll No. 24/IBT/04, Department of Biotechnology, ² Delhi Technological University, Delhi, in partial fulfilment of the requirements for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted, in part or in full, for any degree or diploma to this University or elsewhere.

Prof. JAI GOPAL SHARMA

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ABSTRACT

The world is currently facing a critical power crisis, necessitating the urgent development of sustainable sources of energy. Among the various alternative energy solutions, Plant Microbial Fuel Cell (PMFC) technology has been explored as a potential means of electricity generation. However, the electricity output from traditional PMFC setups remains insufficient. In this research, we present an innovative approach by integrating microbial fuel cells with nutrient film channels, harnessing hydroponics technology. The proposed design incorporates carbon fibre cloth as an efficient conductor for the anode and the cathode, resulting in improved electrical conductivity. Additionally, from the wetlands of Tughlaqabad Biodiversity Park (New Delhi, India), containing electrochemically active facultative anaerobic bacteria, is introduced to enhance electron transfer processes. The novel PMFC design achieves tenfold higher efficiency compared to conventional PMFCs while occupying a smaller footprint. By connecting plants with diverse cathodes in series, a gradual increase in current was observed. Experimental analysis involved tomato and morning glory plants, with their respective performances assessed. The research demonstrates a remarkable maximum power generation of 28 W/m² within 50 days. Furthermore, the electricity generation can be further augmented by employing plants with fibrous root systems. A polarization curve analysis was used to thoroughly test the PMFC prototype, giving important information about its operating features. The findings from this research present significant progress in sustainable energy production, potentially transforming the future of bioelectricity generation through hydroponics technology.

Key Words:



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CHAPTER-1

1. Introduction of the Study

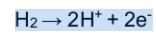
The overuse of non-renewable resources, including coal, and ⁷the depletion of fossil fuels are the main causes of the global energy crisis. Overuse of fossil fuels also contributes to the serious problem of climate change and global warming. Researchers from all over the world are actively investigating new methods for producing sustainable ¹⁵and renewable energy sources. They are also working to lessen the impact of environmental problems like climate change and global warming. One notable method for producing clean, green energy is the plant microbial fuel cell. By exchanging CO₂ and O₂ with the environment, it also contributes to environmental protection.

For a more sustainable future, PMFC's strategy seeks ²¹to address the twin crises of energy scarcity and climate change. The development ²⁷of microbial fuel cells led to the creation of the plant microbial fuel cell. Anaerobic bacteria feed on organic matter in ²¹microbial fuel cells, which are electrochemical systems that release protons and electrons and enable the production of bioelectricity. Potter and M.C. originally revealed the idea of MFCs in 1911, and the Royal Society of London's Proceedings reference it. The substrate used in this bioelectrochemical system is a disadvantage of MFCs, though. A plant, an anode in an anaerobic environment, and a culture of exoelectrogenic bacteria, or EABs, are the main components of ⁹Plant Microbial Fuel Cells (PMFCs), which are an integration of plant and microbial cells that ensures a continuous supply of substrate to microbes and addresses the issue of substrate limitation. PMFCs have an impressive capability of generating 18 times more power than conventional MFCs (Strik et al., 2008S).

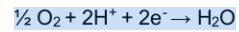
A biofilm of exoelectrogenic bacteria, also known as electrochemically active bacteria (EAB), contributes to the electrochemical processes within the system at the anode. Plants are essential to this energy-generation process because they use carbon dioxide from the environment to convert it into glucose or acetate through metabolic reactions aided by sunlight or photosynthesis. However, not all produced sugar is assimilated for plant metabolism, resulting in the excretion of excess glucose through the roots; this organic matter is known as rhizodeposits. Rhizodeposits are accumulated in a specific zone known as the rhizosphere, which is present in the anode area of PMFC.

The microbial community, especially exoelectrogenic bacteria, flourishes on these rhizodeposits within the rhizosphere. As a consequence of their oxidation of organic materials, these bacteria release protons and electrons. While the electrons move via an external circuit to produce electricity, the liberated protons move across the proton exchange membrane from the anode to the cathode. Because of the special interaction between microbial activity and plant metabolism, PMFC is a viable substitute for producing sustainable and renewable energy. The following illustrates the plant microbial fuel cell's (PMFC) total chemical reaction:

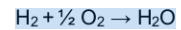
At the anode,



At the cathode,



Overall reaction,



CHAPTER-2

2. Motivation of the Study

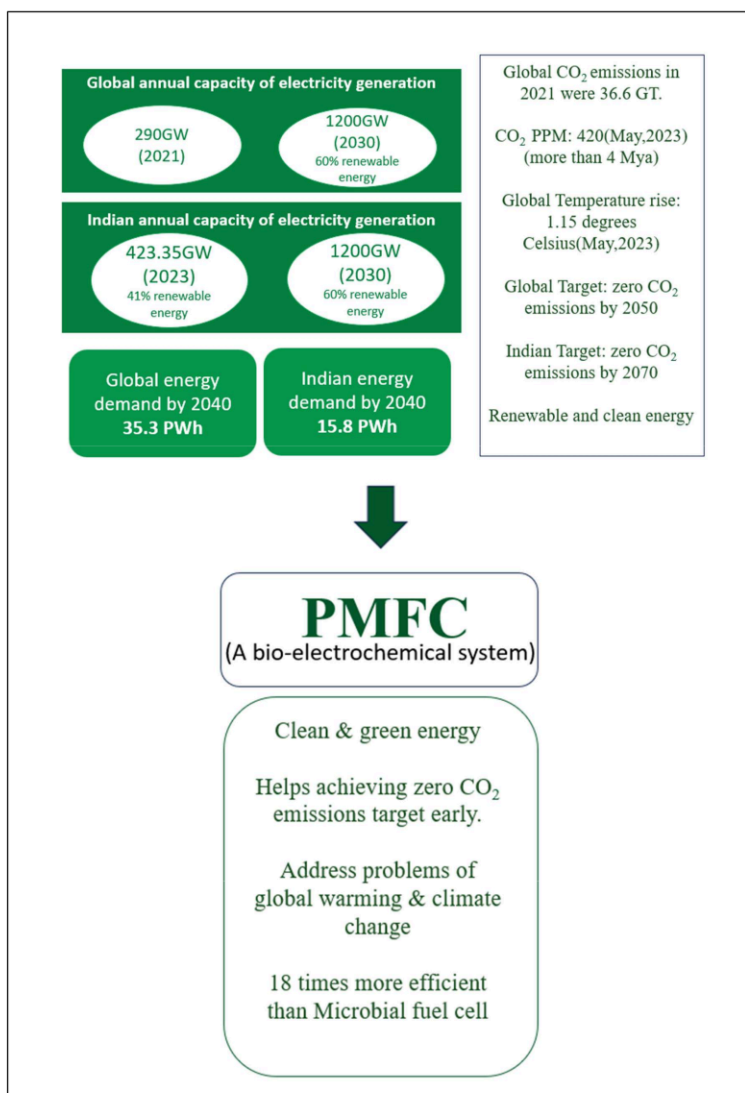


Figure 34: Motivation of the study; explaining needs and PMFC as a solution

The increasing demand for energy worldwide and the urgent need to reduce carbon dioxide emissions are the driving forces behind this study. It is critical to investigate novel and sustainable energy sources because the International Energy Agency (IEA) projects that worldwide power generation capacity will increase significantly, reaching 290GW in 2021 and starting at 1200 GW by 2030 (IEA et al., 2021). In addition, India hopes to achieve 60% renewable energy by 2030 and greatly increase its yearly electricity output capacity from 423.35 GW in 2023 to 1200 GW by 2030 (Ministry of Power et al., 2023). These challenging objectives emphasize how urgent it is to find greener and more sustainable energy sources.

I. Energy Demand and Carbon Emissions:

The IEA projects that the world's energy demand will reach 35.3 PWh by 2040, indicating how quickly the energy environment is changing. By the same year, India's energy consumption is predicted to reach 15.8 PWh (IEA et al., 2023). These forecasts highlight how urgently sustainable energy sources are needed to meet the growing demand while reducing their negative effects on the environment. Furthermore, immediate action is needed to lessen the negative consequences of climate change because global carbon dioxide emissions reached 36.6 gigatons in 2021, and atmospheric CO₂ concentrations skyrocketed to 420 parts per million (PPM) as of May 2023 (NASA et al., 2023).

II. Global Climate Targets:

As of May 2023, the Earth's temperature has risen by 1.15 degrees Celsius, making the current situation of the ecosystem concerning (IPCC et al., 2021). In order to meet global climate targets, such as the challenging target of zero CO₂ emissions by 2050, these environmental issues call for quick and practical solutions (IPCC et al., 2021). India has established its own goal to achieve zero CO₂ emissions by 2070 after realizing how serious the situation is (IPCC et al., 2021). Clean and green energy sources that can considerably reduce global warming and climate change are vital for addressing these issues and moving toward a sustainable future.

III. Plant Microbial Fuel Cells (PMFCs) as a solution:

Plant Microbial Fuel Cells (PMFCs) are a novel and promising way to address the twin problems of rising energy consumption and carbon emissions. PMFCs function

as biochemical systems that produce clean, green energy⁹ by utilizing the inherent synergy between soil bacteria and plants. In addition to supporting the global movement for sustainable practices, this technology provides a workable solution to the current environmental problems.

IV. Efficiency of PMFCs:

PMFCs are more efficient than conventional microbial fuel cells, which is one of their main advantages. According to research, PMFCs can outperform their microbial counterparts by up to 18 times. PMFCs are a competitive option for large-scale energy generation because of their improved efficiency, which results in a larger power output. The efficiency of PMFCs makes them an important part of the clean energy transition as we work to reach the challenging goals set by national and international energy policy.

V. Environmental Benefits of PMFCs:

PMFCs provide advantages for the environment that go beyond their effectiveness. PMFCs provide a sustainable and renewable energy source by utilizing soil microbial activity and plant photosynthesis. PMFCs lessen the influence on climate change since, in contrast to fossil fuels, they do not contribute to greenhouse gas emissions during the generation of energy. Furthermore, PMFCs can contribute to the circular economy and lessen the load on conventional waste disposal techniques by turning soil organic matter into power (Logan et al., 2006).

CHAPTER-3

3. Objective of the Study

3.1 General Objective

To assess the possibility of a Plant Microbial Fuel Cell (PMFC) combined with a Nutrient Film Technique (NFT) hydroponic system for concurrent plant growth and bioelectricity production.

3.2 Specific Objective

- I. To set up and run a PMFC that is connected to an NFT hydroponic system.
This goal is to create an integrated system that combines microbial fuel cell technology with plant growth. This system was created to promote healthy plant development while offering ideal conditions for microbial activity, nutrient circulation, and electricity production.
- II. To assess *Ipomoea* and *Solanum lycopersicum* growth and acclimatization in hydroponic environments.
Before the chosen plant species are incorporated into the PMFC system, this objective is to investigate their successful germination, establishment, and adaptation in the hydroponic environment. Maintaining plant health and guaranteeing the continual flow of root exudates necessary for microbial metabolism depend on proper acclimatization.
- III. To measure the PMFC system's electrical performance in terms of power density, voltage, and current density.
Monitoring and evaluating the electrical output produced by the PMFC is the goal. The effectiveness of electron transport and overall system performance was assessed by measuring parameters like voltage, current density, and power density.
- IV. To evaluate the possibility of producing bioelectricity from *Solanum lycopersicum* and *Ipomoea purpurea*.
This goal is to assess how the two-plant species' electrical output differs. In order to determine a species' suitability for PMFC applications, the comparison aids in identifying which species supports higher microbial activity and power generation.
- V. To determine whether hydroponic farming and PMFC technologies can be used to provide sustainable energy.

This goal is to ascertain whether PMFC-NFT integration can function as a sustainable strategy for concurrent crop production and renewable energy production. The study investigates this technology's potential as an eco-friendly substitute that integrates the production of bioelectricity with agriculture.

CHAPTER-4

4. Selection of Plants

4.1. *Ipomoea purpurea*

Ipomoea purpurea was chosen because it produces a lot of resin glycosides (RGs), which are amphiphilic secondary metabolites mainly made up of C14-C16 acyl sugars (Magana et al., 2022). These substances are essential to the plant's ability to withstand biotic and abiotic stress and support its medicinal qualities. RGs are useful for research on antibiotic development since they also function as chemosensitizers, lowering microbial resistance by blocking multidrug efflux pumps (King et al., 2014). Gene duplication events that promote specialized metabolism and diversify the generation of secondary metabolites assist the species' high evolutionary flexibility (Rafiqi & Kevan et al., 2020). *Ipomoea purpurea* is a promising option for PMFC systems, where root activity and metabolic secretion directly affect microbial relationships and electron transfer, due to its very strong competitive ability and genetic variety, particularly in features related to stress and competition.

Key supporting points include:

- High genetic diversity influences plant fitness and competitive tolerance (Baucom & Mauricio, 2008).
- Resin glycosides contribute to chemical defense and therapeutic potential (Magaña et al., 2022).
- Gene duplication enhances metabolic specialization (Rafiqi & Kevan, 2020).
- RGs show biomedical potential by sensitizing bacteria to antibiotics through the efflux pump inhibition (King et al., 2014).

These qualities are the reason that *Ipomoea purpurea* can be used in PMFC applications, where strong rhizosphere interactions and complex root exudates can boost microbial activity and power production.

4.2. *Solanum lycopersicum*

The tomato, or *Solanum lycopersicum*, has been extensively researched in PMFC systems and has been demonstrated to provide power densities of roughly 17 mW/m² in experimental settings (Helder et al., 2010). Generally speaking, current output rises with plant maturity but falls with senescence or wilting, suggesting that PMFC

performance is significantly affected by liveliness. The species is nevertheless valuable because of its active rhizodeposition and well-established physiology, even though tomato-based PMFCs typically have shorter operational lifespans.

Secondary metabolites are abundant in tomato plants, particularly lycopene, which makes up almost 85% of all carotenoids and has potent antioxidant properties (Giovannucci, 2002). In addition to lycopene, tomatoes also provide vitamins B, C, and K, potassium, calcium, and riboflavin - substances linked to heart protection, bone health, cancer prevention, migraine alleviation, enhanced immunity, UV protection, and vasodilation.

Solanum lycopersicum was chosen for the following reasons:

- Strong antioxidant qualities and a high lycopene concentration (Giovannucci et al., 2002).
- A Nutritional composition that promotes immunological, cardiovascular, and bone health (Wilcox et al., 2003).
- Proven application in PMFC studies and consistent rhizosphere behavior (Helder et al., 2010).
- Exudates from roots that can support electrogenic microbial populations.

Solanum lycopersicum is a good comparator species for assessing PMFC efficacy across various plant physiological profiles because of these biological and metabolic characteristics taken together.

CHAPTER-5

5. Literature Review

Research on bioelectrochemical technologies, particularly ⁴¹Microbial Fuel Cells (MFCs), which use electrochemically active microorganisms to oxidise organic substrates and generate electrons, has increased due to growing demand for renewable and decentralized systems worldwide. Within this field, Plant Microbial Fuel Cells (PMFCs) have drawn attention due to their unique capacity to produce bioelectricity using living plants and the microbial consortia that naturally thrive in the rhizosphere. A low-carbon electricity-generating path that is sustainable. PMFCs, which were first proposed in the middle of the 2000s, showed that plant root exudates might operate as an ongoing carbon supply for electrogenic bacteria, allowing for long-term current production without the need for external organic inputs (De Schampelaire & Verstraete et al., 2009).

Plant ⁴Microbial Fuel Cells (PMFCs) represent a promising bioelectrochemical system for sustainable energy generation by leveraging the interaction between plant roots and electroactive rhizospheric microbes. Over recent years, researchers have investigated a wide array of plant species to evaluate their potential in PMFC configurations, assessing parameters like power density, operational longevity, and compatibility with various fuel cell architectures.

Among aquatic macrophytes, *Canna indica* ²⁸in Constructed Wetland-Microbial Fuel Cell (CW-MFC) setups has demonstrated high volumetric power densities, reaching up to ²⁵320.08 mW/m³ (Srivastava et al., 2015). Similarly, *Phragmites australis*, a common wetland plant, has been widely studied across different designs. In a CW-MFC system, it delivered 25.14 mW/m², while in a PMFC setup, power densities varied depending on the study conditions, ranging from 15.14 mW/m² to 22 mW/m² (Song et al., ¹⁴2016; Wetser et al., 2017; Yang et al., 2020).

Herbaceous terrestrial crops have also gained attention in recent years. *Triticum aestivum* (wheat) in a PMFC exhibited one of the highest reported surface power densities, reaching ²⁵291.23 ± 7.50 mA/m² (Arulmani et al., 2021). Similarly, *Amaranthus viridis*, another fast-growing leafy vegetable, reported 185.13 ± 1.71 mA/m² in a 150-day operation (Arulmani et al., 2021), making these species promising candidates for dual-use systems integrating bioelectricity generation with edible biomass production.

In the domain of short-duration studies, plants like *Canna stuttgart* demonstrated an impressive

output of 222.54 mW/m² in just 30 days of PMFC operation (Sophia and Sreeja, 2017). Meanwhile, *Trigonella foenum-graecum* (fenugreek), another edible plant, yielded 80.26 mW/m² under similar time frames, indicating the potential of leguminous species in rapid-cycling energy systems (Sophia and Sreeja, 2017).

Conversely, several *Sedum* species reported extremely low power outputs (often < 0.01 mW/m²), suggesting limited rhizospheric microbial activity or low root exudate profiles that do not sufficiently support electrogenic biofilms (Tapia et al., 2017). Despite being hardy, their physiological traits make them suboptimal for energy generation applications.

In terms of novel species explored, *Punernianthe alopecuroides* stood out, producing 467.94 ± 17.65 mW/m², the highest surface power density among all reviewed studies (Guan and Yu, 2021). Similarly, *Wachendorfia thyrsiflora* yielded a high volumetric power output of 130.6 ± 9.9 mW/m³, indicating its robust microbial interactions and efficient electron transfer capabilities in PMFC conditions (Gulamhussein and Randall, 2020).

Across the board, power generation capacity appears to be influenced by multiple factors, including root structure, the quantity and quality of root exudates, microbial consortia diversity, and operational parameters like water saturation and electrode placement. CW-MFCs generally reported volumetric power densities, while PMFCs emphasized surface-based power, making direct comparisons nuanced but informative.

Despite their potential, conventional PMFC designs have intrinsic drawbacks such as low power density, inefficient electron transmission, and spatial restrictions that make scaling difficult. Strategies to improve system performance, such as better electrode materials, have been the subject of numerous studies.

Using plant species with dense root systems, adjusting anode-cathode spacing, and maximizing soil conductivity. Because of their large surface area and biocompatibility, conductive materials, including carbon felt, carbon cloth, and graphite granules, are widely utilized to enhance electron transmission (Helder et al., 2012). Another important factor is the makeup of the soil; anaerobic wetland soils that are high in electrogenic bacteria, such as *Shewanella* and *Geobacter* species, have been demonstrated to greatly enhance current production (Timmers et al., 2013).

Stacking several PMFC units, which enables voltage uplift and higher power output, is another developing tactic. According to earlier studies, linking PMFC modules in parallel or series can significantly increase electrical yield; however, internal resistance and ion transport constraints frequently decrease effectiveness (Kaku et al., 2008). In order to facilitate microbial networking and enhance electron distribution among stacked modules, systems with shared anode environments have been proposed more recently. Although there is currently little research on shared-soil systems, they may lower internal energy losses by allowing collective electron transport through connected anode zones.

Interest in combining PMFCs with hydroponic technology has increased concurrently with these advancements. The controlled environment that hydroponics provides for root development, oxygen control, and fertilizer distribution can have a direct impact on the production of bioelectricity. Of the different hydroponic systems, the thin, oxygenated nutrient films supported by the Nutrient Film Technique (NFT) encourage better root systems with wide surface areas- conditions that boost electron transfer routes and encourage microbial colonization (Resh et al., 2013). Although there are yet few practical investigations in this field, integrating NFT with PMFCs could result in hybrid systems that capitalize on the advantages of both technologies.

PMFC performance is also significantly influenced by plant selection. Plants with dense, fibrous root systems typically produce more exudates and offer more microbial attachment sites, which enhances the production of electricity. According to studies, species including *Phragmites* and *Oryza sativa*, high power outputs can be supported by *Australis* and *Ipomoea aquatica* because of their strong rhizosphere activity (Helder et al., 2010). By coordinating energy output with agricultural productivity, the utilisation of crop plants like *Solanum lycopersicum* significantly broadens the practical applications of PMFCs.

In order to understand internal resistance, electrode kinetics, and operational constraints, polarization curve analysis has been frequently used to characterize PMFCs. This approach aids in determining the ideal operating conditions and evaluating how design changes affect system performance (Logan et al., 2006).

Innovative system configurations, cutting-edge electrode materials, plant selection, and integration with controlled culture systems like hydroponics all show great promise for enhancing PMFC performance, according to the research. However, little study has been done

on shared-soil stacking PMFCs combined with NFT hydroponics, leaving a big knowledge vacuum about how improved root habitats and microbial connectivity work together to affect the production of bioelectricity. By creating a shared-soil stacked PMFC system in conjunction with hydroponic NFT channels and assessing its long-term performance and power generation efficiency, the current work fills this gap.

5.1. Technological challenges in design and prototype manufacture

Despite the promise of PMFCs as a sustainable bio-energy source, several challenges continue to limit their efficiency. A key issue is the maintenance of anaerobic conditions at the anode, which is essential for the activity of exoelectrogenic bacteria like *Geobacter*. These microbes require an oxygen-free environment to effectively transfer electrons; any oxygen intrusion can severely hamper their performance. Proper soil depth, insulation, and moisture control help preserve the needed anoxic zone (Roy et al. 2023).

Another major factor is the choice of electrode materials. Traditional carbon-based materials often suffer from limitations in conductivity and surface area. Recent advances involve using nanostructured electrodes like nickel silicide-coated nickel foam, which promote better bacterial adhesion and electron flow, significantly improving output (Hosseini et al. 2025). However, even with better materials, achieving a stable and uniform output of current and voltage remains a challenge. Power fluctuations hinder real-world applications. Novel configurations such as iCiS-MFCs (internally connected series setups) have shown promise in stabilizing energy generation by enhancing internal connectivity (Walter et al., 2020). The uniformity and health of the biofilm also play a critical role. Bacteria must form a stable, even biofilm on the anode surface to ensure effective electron transfer. Uneven growth, biofilm degradation, or nutrient imbalances can lead to poor performance. Factors like external resistance, material texture, and pH levels influence biofilm formation (Grzegorz et al. 2018).

Finally, the most persistent hurdle is the overall low power output of PMFCs. While these systems are capable of generating energy, it's usually in the micro- to milliwatt range, far below what's needed for practical applications. Researchers are experimenting with voltage booster circuits and modular designs to overcome this limitation, though commercial viability is still distant (Koffi et al. 2018).

CHAPTER-6

6. Working of a plant microbial cell

One kind of microbial fuel cell that uses the symbiotic link between ⁸plants and soil ⁷bacteria to produce electricity is the plant microbial fuel cell (PMFC). The following crucial procedures are part of a PMFC's operating principle:

6.1. Plant Photosynthesis

Photosynthesis in green plants is the first step in the operation of a Plant Microbial Fuel Cell (PMFC). In this mechanism, plants transform light energy into chemical energy by absorbing sunlight through the chlorophyll pigments found in their leaves (Taiz et al., 2015). To create glucose and other organic compounds, roots take water and use atmospheric carbon dioxide. A consequence of this process is the emission of oxygen. The main energy source for plant growth, metabolism, and root development is the glucose created during photosynthesis. Some of this fixed carbon is carried to the roots, where root exudation makes it accessible to soil microbes (Strik et al., 2008). Therefore, the primary energy source that powers the production of electricity in PMFC systems is photosynthesis.

6.2. Root Exudation

Root exudation is the process by which plants discharge a range of organic chemicals into the surrounding rhizosphere region (Dakora and Phillips et al., 2002). Sugars, amino acids, organic acids, proteins, vitamins, and secondary metabolites are all present in the root exudates. Naturally occurring soil microbes use the released chemicals as a source of nutrients. Plant species, nutrient availability, environmental stress, and microbial interactions are some of the elements that affect root exudation. These organic substances serve as biodegradable substrates for electroactive microbes in PMFC systems (Timmers et al., 2010). A steady supply of organic matter is ensured by the constant discharge of root exudates, which supports ongoing microbial metabolism and the production of electricity.

6.3. Microbial Activity

Different populations of microorganisms, including bacteria, fungi, and archaea, can be found in the rhizosphere area that surrounds plant roots (Rabaey and Verstraete et al.,

2005). The organic substances found in root exudates are used by these microbes as sources of carbon and energy. Through biochemical processes, complex organic molecules are reduced to simpler chemicals during microbial metabolism. Electrons produced during metabolism can be transferred by some electroactive bacteria to external surfaces like electrodes (Logan et al., 2006). Soil moisture, temperature, pH, oxygen content, and nutrient availability all have a significant impact on microbial activity. Stable PMFC performance and sustained electron production depend on effective microbial metabolism.

6.4. Electron Transfer

Electrons and protons are generated as byproducts of oxidation processes when electroactive bacteria break down root exudates (Logan et al., 2008). These electrons are moved from the microbial fuel anode electrode to the cathode either directly via membrane protein or indirectly via electron shuttles made by microorganisms. In anaerobic environments, the anode functions as an electron acceptor. Microbial biofilm development, electrode conductivity, and system internal resistance all affect effective electron transport (Pant et al., 2010). Because they offer high conductivity and a broad surface area for microbial adhesion, materials like graphite and carbon fibre cloth are frequently employed as anodes.

6.5. Electricity Generation

An electric current is produced as the electrons are sent to the anode and travel through an external electrical circuit in the direction of the cathode (Rabaey and Verstraete et al., 2005). Concurrently, protons (H^+ ions) generated by microbial metabolism permeate the soil or electrolyte in the direction of the cathode chamber. Voltage and current are measurements of usable electrical energy produced by the flow of electrons across the external circuit. In the PMFC systems, persistent microbial activity and long-term power generation are made possible by plants' constant release of root exudates (De Schampelaire et al., 2008). Plant growth, microbial activity, electrode characteristics, and environmental factors all affect how efficiently power is produced.

6.6. Oxygen Reduction Reaction (ORR)

Oxygen from the atmosphere serves as the PMFC system's terminal electron acceptor at the cathode. The oxygen reduction reaction (ORR) produces water when the electrons

from the external circuit mix with the protons and oxygen (Logan et al., 2006). The electrochemical circuit is completed by this reaction, which permits constant electron flow between the electrodes.

Because oxygen reduction events are frequently slower than microbial oxidation reactions at the anode, the cathode is essential to determining total PMFC efficiency (Pant et al., 2010). Therefore, optimizing cathode performance and boosting power generation requires the use of catalytic materials and appropriate aeration.

6.7. Power Output

Electrical power that can be used for low-energy applications is produced by the constant flow of electrons from the anode to the cathode via an external circuit (Helder et al., 2012). Voltage, current density, and power density are typically used to quantify the generated power output. Biosensors in distant areas, small electrical devices, and environmental sensors can all be powered by PMFCs. Plant type, microbial population, electrode material, nutrient availability, pH, temperature, and system internal resistance are some of the variables that affect power generation efficiency. (Timmers et al., 2010). Because PMFC technology simultaneously promotes plant growth, carbon cycling, wastewater treatment, and the generation of renewable bioelectricity, it is regarded as sustainable.

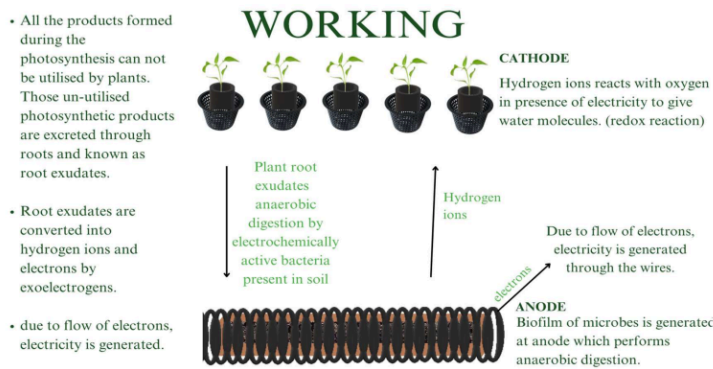


Figure 2: Working of PMFC

CHAPTER-7

7. Materials and Methods:

7.1. Materials Used:

I. Seeds

For the germination study, tomato (*Solanum lycopersicum*) and *Ipomoea purpurea* seeds were utilized. To guarantee consistent germination, mature, healthy, and disease-free seeds were chosen (Copeland and McDonald et al., 2001). The stiff seed coat of *Ipomoea purpurea* seeds may cause physical dormancy and decrease water absorption (Jha et al., 2015). Under the right circumstances, tomato seeds, which are tiny, flattened, and typically not dormant, germinate quickly (Bewley et al., 2013). Since environmental temperature has a significant impact on seed germination, a thermometer was also utilized to keep an eye on the temperature (Tokić et al., 2023). The tomato seeds were collected from the Indian Agricultural Research Institute (IARI), Pusa, New Delhi. The materials used guaranteed appropriate and regulated circumstances for examining the germination behavior of tomato and *Ipomoea purpurea* seeds.



Figure 35: Tomato Seeds



Figure 36: Morning Glory Seeds

II. Net Pots

The primary support structure for plant growth in hydroponic systems was chosen to be net pots. These pots are made of perforated plastic that provides adequate aeration and nutrient uptake while allowing roots to develop freely (Resh et al., 2013). To ensure constant growing conditions, net pots of the same size, 2.5 inches in diameter, were

employed. Because hydroponic plants rely solely on dissolved nutrients for growth, a hydroponic nutrient solution including critical macro and micronutrients was created (Jones et al., 2016). The net pots were filled with an inert growing media like cocopeat, to provide seedlings with physical support without compromising the availability of nutrients (Savvas and Gruda et al., 2018). The electrode, which acted as the cathode, was also placed in the net pot.



Figure 37: Hydroponics Net Pot (2 inches)

III. Support Medium

The hydroponic system's support material consisted of cocopeat and balls of LECA (Light Expanded Clay Aggregate). Because of its high-water holding capacity, excellent aeration, and potential to promote root growth, cocopeat- a naturally occurring fibrous substance derived from coconut husk- is utilized extensively (Abad et al., 2002). Additionally, it keeps the area around plant roots sufficiently moist while avoiding waterlogging. Lightweight, porous clay pellets called LECA balls give the root system superior drainage and aeration (Resh et al., 2013). Their porous structure increases the availability of oxygen, which is necessary for nutrient absorption and root respiration. Both media are chemically stable and inert, meaning they do not significantly alter nutrient composition in the hydroponic solution (Jones et al., 2016). Cocopeat and LECA balls were thoroughly washed with distilled water before use to remove dust impurities. These support media provided physical stability to seedlings and ensured suitable conditions for healthy root development in the hydroponic setup.



Figure 38: Support Medium- Light Expanded Clay Aggregate (LECA) balls



Figure 39: Support Medium- Compressed Cocopeat derived from coconut husk

IV. Water Pump

¹⁵The Nutrient Film Technique (NFT) hydroponic system employed a water pump to move the nutrient solution through the channels continuously. For nutrient uptake and plant growth, the pump guaranteed a ⁴steady supply of water with dissolved nutrients to plant roots (Resh et al., 2013). To provide consistent nutrient delivery throughout the system, a submersible electric pump with an appropriate capacity is chosen. Additionally, constant circulation prevented the nutritional solution from stagnating and maintained oxygen availability around the roots (Jones et al., 2016). To move the nutritional solution from the reservoir to the NFT channels, flexible tubing was attached to the outlet. To prevent contamination and clogging, the pump was cleaned before use. In the hydroponic system, effective nutrient delivery and robust root growth were guaranteed by the water pump's proper operation.



Figure 40: Submersible Water Pump

V. RO Pipe

The hydroponic NFT channel system included RO pipe connectors to link pipes and guarantee the nutrient solution moved smoothly throughout the setup. These connectors are often composed of sturdy plastic that is impervious to chemical deterioration and water leaks (Resh et al., 2013). Depending on how the pipes were arranged in the system, various connector types, including elbow joints, T-connectors, and straight connectors, were utilized. For optimal nutrient circulation and plant growth, the connectors assisted in maintaining a steady flow of nutrient solution between the reservoir, water pump, and NFT channels (Jones, 2016). In order to preserve system efficiency and stop nutrient solution loss, leak-proof fittings were chosen. To prevent contamination or blockage, connectors were properly cleaned prior to installation. Stable water flow and efficient hydroponic system operation were guaranteed by properly installed RO pipe connectors.



Figure 41: uPVC RO Pipe



Figure 42: RO Pipe Connector

VI. Reservoir

The hydroponic NFT system employed a ¹⁵reservoir to hold the nutrient solution needed ¹⁵for plant growth and development. A water pump was used to move the nutrient solution through the channels from the reservoir, which served as the primary container (Resh et al., 2013). To avoid chemical interaction with the nutrient solution, a clean, non-reactive plastic container with an appropriate volume was chosen (Jones et al., 2016). The reservoir assisted in ensuring that plant roots had a steady supply of water and dissolved nutrients. Additionally, it helped ensure that nutrients were evenly distributed

throughout the system and properly mixed. To lessen the contamination, evaporation, and algae development brought on by sun exposure, the container was covered (Resh et al., 2013). Hygienic conditions and effective hydroponic setup operation were ensured by thoroughly cleaning the reservoir before usage.

VII. Titanium Wires

The electrodes of the Plant Microbial Fuel Cell (PMFC) system were connected electrically by titanium wire. Because of its superior corrosion resistance in aqueous settings, high conductivity, and low electrical resistance, titanium is a popular choice (Logan et al., 2006). These characteristics improve power generation efficiency in PMFC systems by facilitating effective electron transport [from the anode to the cathode](#) (Pant et al., 2010). Additionally, titanium wire boosts the system's longevity and long-term performance since it is chemically stable and doesn't readily react with nutritional solutions or microbial metabolites (Rabeay and Verstraete et al., 2005). Its flexibility and mechanical strength make it simple to connect electrodes without breaking. To guarantee correct electrical contact in the PMFC setup and to eliminate contaminants, the wire was properly cleaned before use.



Figure 43: Titanium Wire

VIII. Carbon Fibre Cloth

The Plant Microbial Fuel Cell (PMFC) system employed carbon fibre cloth as the electrode material due to its surface area and strong electrical conductivity (Logan et al., 2006). Carbon fibre cloth's porous structure facilitates electroactive microorganisms' effective adhesion and development, which improves electron

transmission during the production of electricity (Rabaey and Verstraete et al., 2005). Power output is increased by its low electrical resistance, which facilitates ⁸the transfer of electrons from microorganisms to the electrode (Pant et al., 2010). Carbon fibre fabric is appropriate for long-term PMFC applications because it is lightweight, chemically stable, and corrosion-resistant in damp and nutrient-rich conditions. Additionally, the material's flexibility makes system installation simple. To ensure efficient electrical performance in the PMFC system, the fabric was thoroughly cleaned before usage to get rid of contaminants. The carbon fibre cloth used was of 200 GSM strength.



Figure 44: Carbon Fibre Cloth

IX. Multimeter

In the PMFC setup, electrical characteristics like voltage, current, and resistance produced throughout the experiment were measured using a multimeter. This device assisted in precisely monitoring and accessing the PMFC system's electrical output (Logan et al., 2006). Because of its great sensitivity, precision, and convenience of reading measurements, a digital multimeter was chosen. To monitor the flow of electrons caused by microbial activity, conductive wires were used to link the multimeter to the electrode circuit. ²⁷For microbial fuel cells to calculate power generation efficiency, voltage and current measurements are crucial (Pant et al., 2010). Additionally, the gadget assisted in determining changes in resistance and circuit continuity within the configuration. Throughout the experiment, accurate and dependable electrical measurements were guaranteed by cautious multimeter handling and calibration.



Figure 45: Multimeter

X. Hoagland Nutrient Medium

In the hydroponic and PMFC systems, Hoagland nutrient medium was utilized to supply vital nutrients needed for plant growth and development. In addition to micronutrients like Iron, manganese, zinc, copper, boron, and molybdenum, the medium has balanced amounts of ³ macronutrients including nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur (Hoagland and Arnon et al., 1950). These nutrients aid in physiological functions, including enzyme activity, root formation, and photosynthesis.

Because it provides nutrients in easily accessible ionic forms that guarantee effective uptake by plant roots, the Hoagland solution is frequently utilized in hydroponic research (Resh et al., 2013). To prevent contamination from undesirable salts or contaminants, distilled water was used to prepare the solution. Throughout the investigation, steady experimental conditions and healthy plant growth were ensured by maintaining proper pH and nutrient content.

XI. NFT Channels

In order to promote plant growth and provide a constant flow of nutrient solution around the roots, NFT channels were employed in the hydroponic system. To avoid chemical contact with the nutritional solution, the channels were constructed of non-reactive PVC material (Resh et al., 2013). To accommodate net pots holding the plants, tiny holes were made in the upper surface of the channels. Plant roots always had access to water, nutrients, and oxygen because of NFT channels, which kept a thin layer of

nutrient-rich water running along the base (Jones et al., 2016). Water stagnation around the roots is avoided, and nutrient uptake is enhanced by this design. Additionally, the consistent flow of nutritional solution throughout the system was aided by the channel's smooth inner surface. The channels were completely cleaned before usage to prevent contamination and guarantee the hydroponic arrangement operated effectively.



Figure 46: Nutrient Film Technique Channel

7.2. Cultivation of Plants

I. Germination of seeds

The biological process by which a seed becomes a young seedling under the right environmental circumstances is known as seed germination. *Ipomoea purpurea* (common name: morning glory) seeds are physically dormant due to a strong seed coat that prevents them from absorbing water (Jha et al., 2015). Natural weathering and scarification increase the proportion of germination and break dormancy (Haddock et al., 2025). Temperatures between 15 degrees Celsius and 25 degrees Celsius are ideal for *Ipomoea purpurea* germination; Temperatures beyond 35 degrees Celsius considerably inhibit germination (Haddock et al., 2025). Since the seeds can sprout in both bright and dark environments, light is not a necessary component (Jha et al., 2015). Water absorption during germination triggers enzymes that start breathing and the growth of the embryo. The plumule, which forms the shoot, follows the radicle, which first appears and grows into the root system (Bewley et al., 2013).

Seeds of tomato (*Solanum lycopersicum*) germinate more easily and take less time as they are not usually dormant like morning glory. Temperature, moisture content, and oxygen availability all have a significant impact on germination (Copeland and McDonald et al., 2001). The ideal temperature range for tomato seed germination is between 21 degrees Celsius to 29 degrees Celsius, with 25 degrees Celsius producing the greatest results (TomatoFest, 2024). Seeds sprout in five to ten days under ideal circumstances (TomatoFest 2024). Seed viability and seedling vigor are adversely affected by extremely high or low temperatures (Tokić et al., 2023). While too much water can lower oxygen availability and lead to seed decomposition, adequate moisture is required for imbibition (Copeland and McDonald et al., 2001). Although light is not necessary for tomato seed germination, seedlings need enough sunlight for photosynthesis and optimal growth once they emerge (Cornell Garden-Based Learning et al., 2022). *Ipomoea purpurea* exhibits dormancy mechanisms, while tomato seeds germinate quickly under favourable conditions. Therefore, both *Ipomoea purpurea* and *Solanum lycopersicum* seeds require appropriate environmental conditions for successful germination.



Figure 47: Seedling of tomato on the 7th day of Germination

II. Acclimatization

Before being moved to the experimental setting, tomato plants (*Solanum lycopersicum*) were acclimated in a different hydroponic chamber. The purpose of the acclimatization technique was to lessen transplant stress and assist the plant in progressively adjusting to hydroponic conditions (Resh, 2013). Under carefully

regulated environmental conditions, healthy seedlings were put in the hydroponic systems with a nutritional solution.

In order to ensure an efficient supply of dissolved nutrients necessary for plant growth and root development, the nutrient medium was kept at an electrical conductivity (EC) of 1000 $\mu\text{S}/\text{cm}$ (Jones et al., 2016). The nutrient solution's pH was brought to 6.0, which is thought to be ideal for tomato plants' effective nutrient absorption at the initial stage (Hoagland and Arnon et al., 1950). To ensure that the roots had enough oxygen available, the nutrient solution was continuously aerated and circulated. This stage of acclimatization enhanced tomato plants' ability to adapt to the hydroponic environment and encouraged the formation of strong roots.



Figure 48: A plant in acclimatization phase



Figure 49: All plants in acclimatization phase

III. Transfer to Microbial Fuel Cell integrated with Nutrient Film Technique Channel

Healthy tomato plants (*Solanum lycopersicum*) were carefully moved to the Plant Microbial Fuel Cell (PMFC) combined with Nutrient Film Technique (NFT) channels for experimental investigations after being acclimated in a different hydroponic chamber. Since healthy root systems are crucial for nutrient uptake and microbial interactions in PMFC systems, the transfer procedure was done carefully to avoid mechanical damage to roots and lessen transplant shock (Resh et al., 2013). The plants and support medium were placed in net pots that were securely fastened into the NFT channel apertures.

By enabling a ¹⁷ thin layer of nutrient solution to continuously flow down the channel base, the NFT system made sure that roots were always in contact with water, dissolved nutrients, and oxygen (Jones et al., 2016). The nutrient solution used in the integrated setup was maintained at an electrical conductivity (EC) range of 3000-5000 $\mu\text{S}/\text{cm}$ to provide a higher concentration of nutrients required for active plant development and metabolic activity. Electrical conductivity was regularly monitored during the experiment to guarantee nutritional stability.

Slightly acidic conditions in tomato plants can improve the nutrient solubility and absorption in tomato plants; this is why the pH of the nutrient solution was changed and kept at 6.0 (Hoagland and Arnon et al., 1950). To ensure uniform nutrient distribution and prevent stagnation, a water pump was used to keep the nutrient solution continuously circulating. To sustain dissolved oxygen levels surrounding the roots, which are crucial for root respiration and effective microbial activity within the PMFC system, adequate aeration was also provided. The successful establishment of tomato plants in the combined hydroponic and microbial fuel cell environment was guaranteed by this transfer phase.



Figure 50: PMFC Chamber

7.3. Experimental Setup and Design

Biological, electrochemical, and engineering components had to be carefully combined throughout the design and construction of the Plant Microbial Fuel Cell (PMFC) integrated with the nutrient film technique (NFT) hydroponic system. By taking advantage of the natural interaction between plant roots and electroactive microorganisms, the system was designed to enable simultaneous plant development and bioelectricity generation (Logan et al., 2006). In order to maintain the operating needs of both PMFC and NFT technologies, the experimental setup was created to provide favourable circumstances for microbial metabolism, nutrient circulation, root development, and electron transfer.

A rectangular hollow wooden block that functioned as the system's lower compartment made up the PMFC unit. Soil served as the substrate for microbial activity and growth in this compartment. Naturally occurring electroactive bacteria that can oxidise organic molecules and transport electrons to the electrode surface found a favourable environment in the soil (Rabaey and Verstraete et al., 2005). To optimize microbial electron transfer efficiency, the carbon fibre cloth anode electrode was carefully inserted into the soil matrix under comparatively anaerobic

conditions (Lovely et al., 2006). Because of its superior conductivity, low resistance, mechanical robustness, and resistance to corrosion in damp environments, titanium wire was utilized to create electrical connections (Pant et al., 2010).

To facilitate plant cultivation, a Nutrient Film Technique (NFT) hydroponic channel was built above the PMFC compartment. In order to enable a continuous thin film of nutritional solution to pass through the plants' root zone, the NFT channel was built utilising non-reactive PVC material (Resh et al., 2013). Net pots with support media, such as cocopeat and LECA (Light Expanded Clay Aggregate) balls, were inserted into apertures on the NFT channel's upper surface. According to Savvas and Gruda (2018), these support media gave the plants mechanical stability while preserving sufficient hydration and aeration around the root system.

Because of their strong root growth and capacity to transfer organic chemicals into the rhizosphere, two plant species- *Ipomoea purpurea* (morning glory) and *Solanum lycopersicum* (tomato)- were chosen for the study. Prior to being moved to the integrated PMFC-NFT system, these plants underwent regulated hydroponic conditions for germination and acclimatization. Their roots reached into the NFT channels, where they interacted with the nutrient solution continuously and indirectly supplied the microbial population with organic substrates (Limmers et al., 2010).

Standard Hoagland nutrient medium, which contains vital macronutrients and micronutrients needed for plant growth, was used to prepare the nutrient solution flowing through the NFT channel (Hoagland and Arnon et al., 1950). To guarantee the best possible nutrient availability and uptake by plant roots, the solution was kept at a pH of roughly 6.0 (Trejo-Télez and Gómez-Merino., 2012). In order to promote steady microbial activity and good plant growth, electrical conductivity (EC) was routinely measured and kept within the intended range. Through RO pipes and connectors, a reservoir linked to a submersible water pump continuously supplied the nutrient solution to the NFT channels, guaranteeing continuous circulation and consistent nutrient distribution throughout the system (Jones et al., 2016).

To promote oxygen reduction reactions, the cathode electrode was placed in an area of the setup that was rich in oxygen. The anode collected the electrons produced by microbial metabolism in the soil compartment and carried them to the cathode via

an external circuit, where they joined forces⁸ with protons and oxygen to make water (Logan et al., 2006). To track the voltage, current, and resistance produced throughout the experiment, a digital multimeter was linked to the electrode system. To guarantee steady plant growth, microbial activity, and electrical performance, the complete system was kept under controlled environmental conditions.

A sustainable platform for assessing the concurrent generation of plant biomass and renewable bioelectricity was made available by the combined PMFC-NFT architecture. Continuous nutrient recycling, effective root development, microbial colonization, and long-term power generation were all made possible by the configuration without the need for additional organic substrates. According to Helder et al. (2012), these integrated systems offer a viable way to combine hydroponic farming with the production of green energy and environmental sustainability.

7.3.1. Design Components

I. Anode Placement

To optimize contact with the soil and microbial life, the anode electrode was placed in the lower part of the Nutrient Film Technique (NFT) channel. For effective electron capture during microbial metabolism, this location proved crucial. Because carbon fibre fabric has a wide surface area, high conductivity, and is suitable for microbial adhesion, it was used as the anode (Logan et al., 2006). The setup's lower section offered comparatively anaerobic conditions, which are ideal for the development of electroactive microorganisms that can move electrons⁸ to the electrode (Lovley et al., 2006). Electron transfer resistance was reduced by positioning the anode directly within the soil matrix, enhancing overall electrical performance. The configuration promoted microbial colonization and enabled the PMFC system to generate power continuously.

II. Rectangular hollow wooden block

The lower compartment of the PMFC system was a rectangular hollow wooden block that was filled with soil to support microbial growth and activity. The soil contained naturally occurring microorganisms, such as electroactive bacteria that could oxidise organic compounds and release electrons during metabolic processes (Rabaey and

Verstraete et al., 2005). The soil's porous nature allowed water, nutrients, oxygen gradients, and microbial populations to move, creating favourable conditions for bioelectrochemical reactions. The anode and cathode regions were combined, and the soil matrix acted as a medium of proton transport between them. Hence, A crucial role in sustaining microbial metabolism and electricity generation was played by a combination of wooden block and soil.

III. Integration of Plants

Two plant species, *Ipomoea purpurea* (morning glory) and *Solanum lycopersicum* (tomato), were the two plants included in the upper section of the NFT channel. These plants were chosen due to their extensive root systems, rapid growth, and capacity to discharge organic compounds into the rhizosphere (Timmers et al., 2010). It was possible to assess the impact of two distinct plant species on microbial activity and the production of electricity in the PMFC system. Microbial metabolism used the sugars, amino acids, and organic acids found in the root exudates that the plant released (Dakora and Phillips et al., 2002). Microbial activity around the electrode surface was increased, and electron production was encouraged by this plant-microbe interaction. Additionally, the dual-plant approach offered comparative insights into the potential of various plant species to generate bioelectricity.

IV. Nutrient Film Technique (NFT)

The experimental plants were grown hydroponically using the nutrient Film Technique (NFT). This method involved a constant flow of a thin layer of nutrient-rich solution across the plants' root zone and through the channel (Resh et al., 2013). The flowing fertilizer solution maintained sufficient oxygen availability around the roots while providing vital macronutrients and micronutrients needed for plant growth. NFT systems, in contrast to traditional soil cultivation, offer direct nutrient availability, leading to effective nutrient uptake and enhanced plant growth (Jones et al., 2016). In addition to lowering water use, the nutrient solution's constant recirculation preserved steady growth conditions. The simultaneous production of hydroponic crops and renewable electricity inside a single sustainable agricultural system was made possible by the integration of NFT with PMFC technology.

The diagram illustrates the components and layout of the hydroponic system. On the left, individual components are shown: a **NET POT** (a black mesh container), a **CATHODE** (a black cylindrical container), a layer of **SOIL** (brown granular material), a **WATERPROOF WOODEN FRAME** (a rectangular frame with dimensions 90 cm by 6 cm and a 0.5 cm gap), and an **ANODE** (a black cylindrical container). On the right, the assembled system is shown, featuring five pots with green plants, connected by a network of tubes and valves, with a grey rectangular frame at the bottom.

V. Hoagland Media Formulation:

To reduce contamination from undesirable ions and contaminants, distilled water was used to prepare the nutrient solution. Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), and Sulphur (S) were among the formulation's important macronutrients. These elements are crucial for plant metabolism, photosynthesis, cell division, protein synthesis, and root development (Taiz et al., 2015). Micronutrients like iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and molybdenum (Mo) were also present in the solution. These elements are necessary in trace amounts but are crucial for physiological processes and enzyme activity (Trejo-Téllez and Gómez-Merino et al., 2012).

NUTRITION MEDIA COMPOSITION

Nutrients	Amount (mg/L)
Macro	
KNO ₃	323
Ca(NO ₃) ₂	434.6
NH ₄ NO ₃	8
KH ₂ PO ₄	109
K ₂ HPO ₄	52
MgSO ₄ /7H ₂ O	184.5
NaCl	11.7
Micro	
(NH ₄) ₆ Mo ₇ O ₂₄ /4H ₂ O	0.05
H ₃ BO ₃	1.5
MnSO ₄ /4H ₂ O	2
CuSO ₄ /5H ₂ O	0.25
ZnSO ₄ /7H ₂ O	1
Sequestered Fe 136	10

STOCK A- 1/2 KNO₃ + Ca(NO₃)₂ + NH₄NO₃

STOCK B- 1/2 KNO₃ + Other macronutrients salts

STOCK C- Fe Salt

STOCK D- Other micronutrients

pH

Optimum pH for tomato= 6-8

optimum pH for morning glory=6-6.8

Hence, pH range of media is 6-6.8 for this system.

EC

Optimum range of TDS is 800-1200 ppm.

Figure 52: Hoagland Media Composition and its Formulation

A submersible water pump was used to continually circulate the prepared nutritional solution throughout the NFT channels while it was kept in a reservoir. This maintained consistent fertilizer distribution throughout the hydroponic system and guaranteed a steady supply of nutrients to the plant roots (Jones et al., 2016). The nutritional solution was kept at a pH of 6.0 and an electrical conductivity (EC) of about 1000 μ S/cm during the acclimatization phase. The EC was raised to a range of 3000-5000 μ S/cm after transfer to the PMFC-integrated NFT system in order to enable improved plant growth and metabolic activity while keeping the pH at 6.0. To ensure the best possible nutrient availability and uptake by the plants, these conditions were routinely checked (Sonneveld and Voogt et al., 2009).

Ipomoea purpurea and *Solanum lycopersicum* were given a stable and nutrient-rich environment by the continuous flow of Hoagland solution through the NFT channel. Microbial activity within the PMFC system was supported by healthy plant growth, which also encouraged root development and boosted root exudation. As a result, the Hoagland nutrient medium was essential for preserving plant health and indirectly supporting the production of bioelectricity through improved interactions between microbes and plants.

CHAPTER-8

8. Operational Dynamics

Plant physiological processes, microbial metabolism, and electrochemical reactions combine to power the integrated Plant Microbial Fuel Cell (PMFC)-Nutrient Film Technique (NFT) system. A thin layer of nutrient-rich solution constantly passes through the hydroponic channels in the NFT component, giving the plant the vital nutrients, water, and oxygen they need for growth and development (Jones et al., 2016). In addition to absorbing these nutrients, the roots release a range of organic chemicals into the surrounding rhizosphere that are referred to as root exudates. Sugars, amino acids, organic acids, and other carbon-rich substances that act as substrates for soil microbes are among these exudates (Dakora and Phillips et al., 2002).

A soil matrix and electrode assembly that make up the PMFC unit are located in the lower compartment of the integrated system. The organic chemicals produced by plant roots are broken down by microorganisms in the rhizosphere. Protons and electrons are produced as byproducts of microbial respiration during the oxidation of these substances (Logan et al., 2008). These electrons are moved in the direction of the soil-embedded anode electrode by electroactive bacteria, such as those that can transfer electrons extracellularly (Lovely, 2006). In anaerobic environments, the anode functions as an electron acceptor, absorbing electrons produced during microbial metabolism.

An electric current is produced when the electrons gathered at the anode are moved towards the cathode via an external electrical circuit (Rabaey and Verstraete et al., 2005). The PMFC system's electrical output is represented by this electron flow, which may be quantified in terms of voltage, current, and power density. Concurrently, the protons generated during microbial oxidation move toward the cathode region through the moist soil environment (Strik et al., 2008).

The terminal electron acceptor at the cathode is atmospheric oxygen. The electrochemical circuit is completed when electrons from the external circuit interact with oxygen and protons to generate water through the oxygen reduction reaction (ORR) (Logan et al., 2006). Electrode conductivity, oxygen availability, microbial community structure, nutrient concentration, and ambient conditions are some of the variables that affect this process's efficiency (Pant et al., 2010).

Long term power generation without the requirement for external fuel addition is made possible by growing plants' constant discharge of root exudates, which guarantees a consistent supply of organic substrates for microbial metabolism (Timmer et al., 2010).

Additionally, plant growth strengthens the symbiotic interaction between microorganisms and plants by fostering rhizosphere expansion and microbial colonization (Helder et al., 2012). Thus, while preserving nutrient recycling and environmental sustainability, simultaneous crop culture and renewable energy production are made possible by the combination of NFT hydroponics with PFC technology (De Schampelaire et al., 2008; Kaku et al., 2008).

CHAPTER-9

9. Results and Discussion

1. For *Ipomoea purpurea*

Ipomoea purpurea was used as the experimental plant species to assess the Performance of the Plant Microbial Fuel Cell (PMFC) integrated system. To evaluate the effectiveness of bioelectricity generation, electrical output was tracked for 50 days. The findings showed that electrical performance gradually increased with plant establishment and rhizosphere microbial activity.

Effective electron transport from electroactive microorganisms to the anode electrode was demonstrated by the maximum voltage obtained throughout the experiment, which was 762.3 mV. Enhanced root development and increased root exudate output, which functioned as substrate for microbial metabolism, may be responsible for the voltage increase over time (Strik et al., 2008). Higher voltage generation was the outcome of better electron transfer efficiency as the microbial population grew on the electrode surface (Logan et al., 2006).

Effective electron transport over the external circuit was demonstrated by the maximum current density of 806 $\mu\text{A}/\text{m}^2$. The availability of biodegradable organic compounds in the rhizosphere and the metabolic activity of electroactive microorganisms are closely linked to current production in PMFC systems (Rabaey and Verstraete et al., 2005). *Ipomoea purpurea*'s vast root system probably helped to maintain microbial activity by continuously providing the local microbial community with organic substrates.

Similarly, after 50 days of operation, the maximum power density attained was 641.41 W/m^2 . Increased plant growth, sustained microbial colonization, and effective electrode operation all contributed to improved electrical performance, which was reflected in the rise in power density (Pant et al., 2010). The steady increase in power output over the course of the investigation indicates that a synergistic link between plant roots and electroactive microorganisms has been successfully established. These results show that *Ipomoea purpurea* can efficiently support the production of electricity in PMFC systems and could be a good option for the production of sustainable bioenergy.

Plant development stage, root biomass, nutrient availability, and microbial population dynamics all have a major impact on PMFC efficacy, according to the observed electrical output. A larger amount of organic carbon became available for microbial oxidation as root exudation increased with plant maturity, resulting in

improved electron production and power generation (Timmers et al., 2010). The findings thus demonstrate *Ipomoea purpurea*'s potential for long-term bioelectricity generation in integrated hydroponic-PMFC systems.

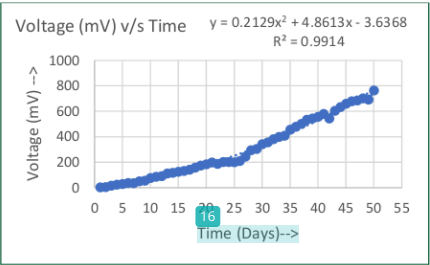


Figure 53: Voltage as a Function of Time in *Ipomoea purpurea*

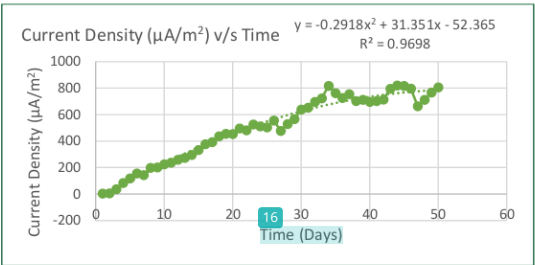


Figure 54: Current Density as a Function of Time in *Ipomoea purpurea*

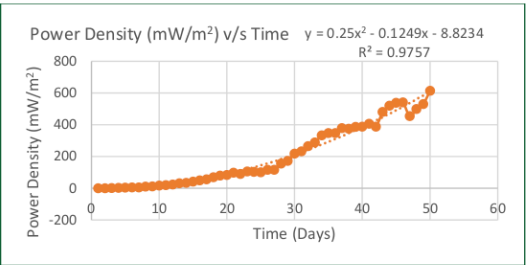


Figure 55: Power Density as a Function of Time in *Ipomoea purpurea*

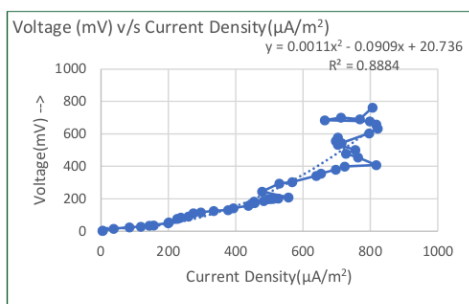


Figure 56: Polarization Curve in *Ipomoea purpurea*

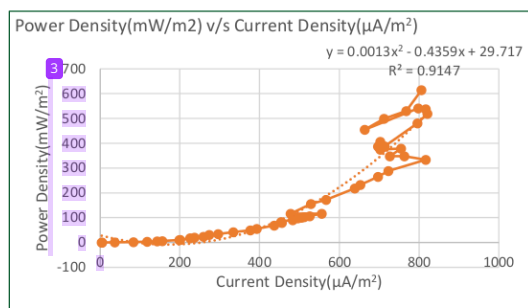


Figure 57: Power Density as a Function of Current Density in *Ipomoea purpurea*

II. For *Solanum lycopersicum*

Solanum lycopersicum (tomato) was used as the experimental plant species to assess the efficacy of the Plant Microbial Fuel Cell (PMFC) integrated system. To ascertain the effectiveness of bioelectricity generation, electrical parameters were tracked during the experiment. The findings showed that the PMFC system's microbial activity and electron production were successfully supported by tomato plants.

With a maximum voltage of 753.8 mV, it demonstrated effective electron transport from rhizospheric bacteria to the anode electrode. The continual production of root exudates, which provided electroactive bacteria with a supply of organic carbon, is

responsible for the voltage generation seen ⁹ in the system (Strik et al., 2008). The efficiency of electron transfer increased when microbial colonies settled on the electrode surface (anode), leading to stable voltage generation during the experiment (Logan et al., 2006).

At 889 $\mu\text{A}/\text{m}^2$, the greatest current density recorded was higher than that of *Ipomoea purpurea*. This finding implies that the PMFC system has increased microbial metabolic activity and more effective electron transport. The amount and makeup of root exudates that are assessable for microbial breakdown, along with the number of electroactive microorganisms in the rhizosphere, have a direct impact on current density (Rabaey and Verstraete et al., 2005). Tomato plants' well-developed root system might have helped to improve microbial colonization around the electrode surface and increase substrate availability.

The study's highest overall electrical performance was recorded at a maximum power density of 670.13 W/m². Effective nutrient uptake, rapid root growth, and ongoing microbial activity in the PMFC environment may be linked to the higher power density (Pant et al., 2010). Long-term electron generation and steady electricity production were supported by the steady supply of biodegradable organic compounds from tomato roots.

Additionally, the steady rise in electrical output throughout the course of the experiment showed that plant-microbe interactions had been successfully established within the PMFC system. The increased activity of the rhizosphere and root biomass encouraged more microbial oxidation of organic substrates, which boosted electron release and power production (Timmers et al., 2010). These results show that *Solanum lycopersicum* is an appropriate plant species for PMFC applications and that, when combined with hydroponic culture systems, it has a great deal of promise for producing sustainable bioelectricity.

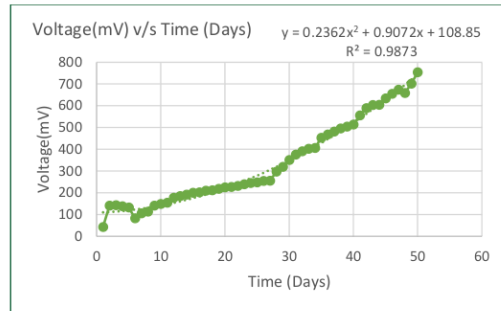


Figure 58: Voltage as a Function of Time in *Solanum lycopersicum*

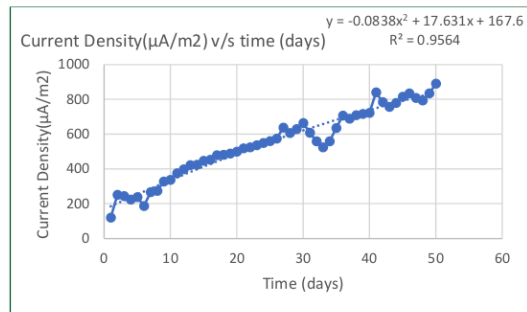


Figure 59: Current Density as a Function of Time in *Solanum lycopersicum*

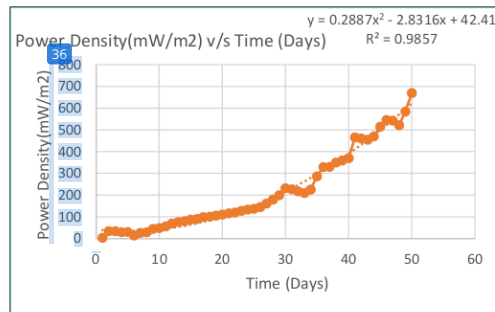


Figure 60: Power Density as a Function of Time in *Solanum lycopersicum*

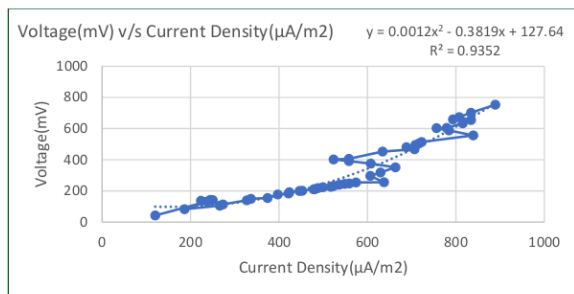
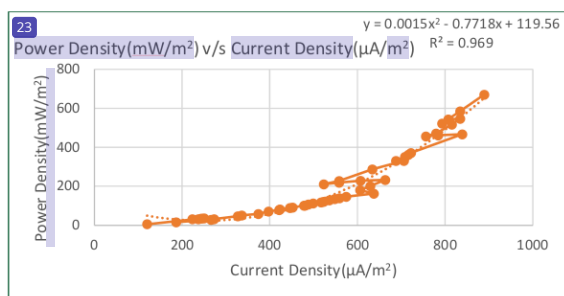


Figure 61: Polarization Curve in *Solanum lycopersicum*



11
 Figure 62: Power Density as a function of Current Density in *Solanum lycopersicum*

CHAPTER-10

10. Conclusion and Future Scope

The design, development, and operation of a novel Plant Microbial Fuel Cell (PMFC) combined with a Nutrient Film Technique (NFT) hydroponic system for concurrent plant growing and bioelectricity generation were effectively demonstrated in this work. The integrated system creates a sustainable platform that can generate renewable electrical energy while promoting plant growth by combining the benefits of hydroponic crop cultivation with microbial fuel cell technology. Without the need for external organic substrates, the system produced energy by utilizing the natural interaction between soil microbes, plant roots, and electrochemical processes. This strategy is an energy-efficient and ecologically beneficial substitute for traditional energy production techniques.

Ipomoea purpurea (morning glory) and *Solanum lycopersicum* (tomato) were used as model plant species in the experiment. Both plants supported microbial activity in the PMFC compartment while successfully establishing and growing within the NFT hydroponic channels. For electrochemically active microbes, the plant's root exudates offered a steady supply of biodegradable organic compounds. These microbes produced energy by metabolizing the organic chemicals and moving electrons to the anode electrode. The Hoagland nutrient solution's constant supply of nutrients promoted plant development and indirectly supported steady electrical output and microbiological activity. (Turner & Croteau, 2004)

The study's findings proved the integrated PMFC-NFT system's efficacy. The highest voltage, current density, and the power density measured for *Ipomoea purpurea* were 762.3 mV, 806 $\mu\text{A}/\text{m}^2$, and 641.41 W/m^2 . These numbers show that the PMFC system has stable microbial activity and effective electron transfer. *Ipomoea purpurea*'s vast root system probably helped to maintain a favourable environment for microbial metabolism and electron generation by continuously releasing root exudates. The measured electrical performance demonstrates this plant species potential for sustainable bioelectricity generation and validates its appropriateness for PMFC applications.

In a similar vein, *Solanum lycopersicum* performed exceptionally well in the integrated system. The highest voltage, current density, and power density attained were 753.8 mV, 889 $\mu\text{A}/\text{m}^2$, and 670.13 W/m^2 , respectively. The tomato plants generated a higher current density and power density, despite the maximum voltage being somewhat lower than that of *Ipomoea purpurea*. Differences in root architecture, root biomass, and the amount and composition of root exudates released into the rhizosphere could all contribute to higher power production. The efficiency of electron transmission may possibly have been enhanced by increased microbial colonization surrounding the root zone. Tomato plants have a great deal of promise for integration into PMFC systems intended to maximize electricity output, according to the superior current and power density values obtained from *Solanum lycopersicum*.

The performance attained in the current study was significantly better than that of previously published PMFC investigations. Due to restrictions in electrode design, microbial activity, internal resistance, and nutrient availability, numerous previous PMFC systems have reported lower voltage outputs and power densities (Strik et al., 2008; Helder et al., 2012). The innovative system architecture, effective nutrient circulation via the NFT channel, the thoughtful positioning of the anode inside the soil compartment, and the utilization of highly conductive materials like carbon fibre cloth and titanium wire are all responsible for the enhanced performance seen in this investigation. Additionally, the incorporation of hydroponic technology guaranteed ideal circumstances for plant growth, leading to increased microbial activity and root exudation.

The study also showed that combining hydroponic farming with the production of renewable energy is feasible. The PMFC system uses naturally existing organic molecules obtained from plants as fuel for microbial metabolism, in contrast to traditional microbial fuel cells that necessitate the constant addition of organic substrates. As a result, the technology is eco-friendly and self-sustaining. The system contributes to sustainable farming practices and lessens reliance on fossil fuel-based energy sources by promoting plant growth, nutrient recycling, and carbon sequestration in addition to producing power.

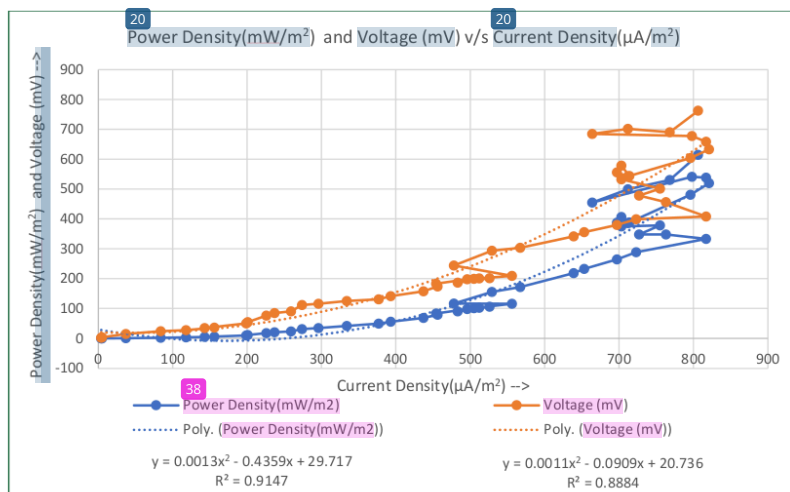


Figure 63: Representation of polarization curve and Power Density for *Ipomoea purpurea*

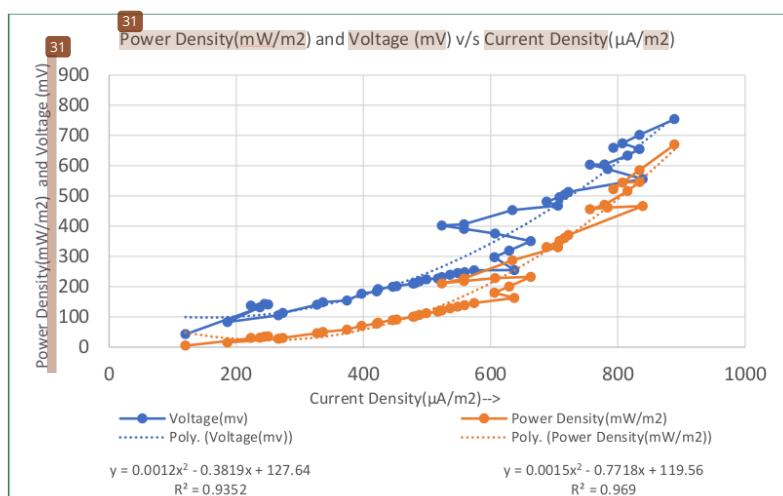


Figure 64: Representation of polarization curve and Power Density for *Solanum lycopersicum*

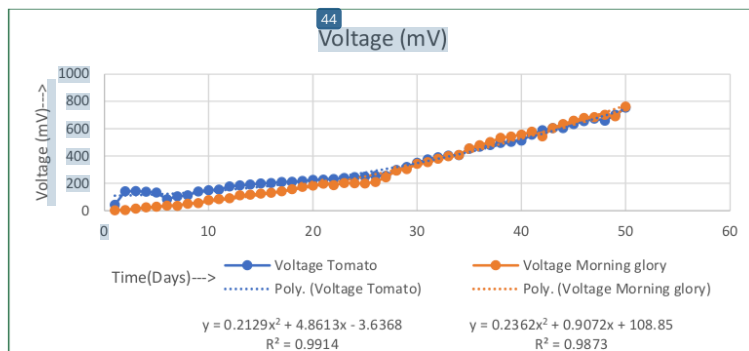


Figure 65: Comparison of Voltage as a Function of Time in *Solanum lycopersicum* and *Ipomoea purpurea*

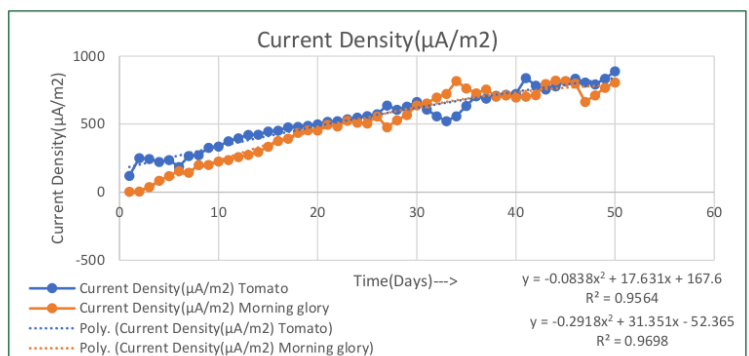


Figure 66: Comparison of Current Density as a Function of Time in *Solanum lycopersicum* and *Ipomoea purpurea*

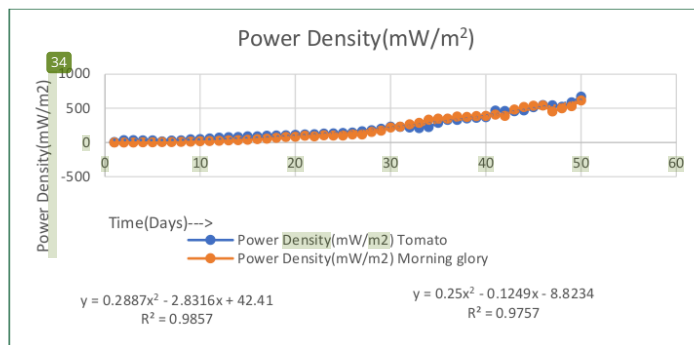


Figure 67: Comparison of Power Density as a Function of Time in *Solanum lycopersicum* and *Ipomoea purpurea*

The PMFC-NFT system still has a lot of room for refinement and optimization, despite the encouraging outcomes. The anaerobic chamber's efficiency is one of the main factors influencing the production of power. Future research should concentrate on creating more effective and sealed anaerobic compartments that reduce oxygen intrusion while preserving ideal conditions for microbial metabolism, as electrochemically active bacteria thrive in oxygen-limited environments. Enhancing electron recovery and lowering energy losses from competing aerobic processes are two benefits of improved anaerobic conditions.

In order to enhance microbial adhesion and electron transfer efficiency, future studies may also look into the use of cutting-edge electrode materials with more conductivity, greater surface area, and superior biocompatibility. Materials like carbon nanotubes, biochar-based electrodes, graphene-coated electrodes, and modified carbon composites have demonstrated promise for improving PMFC performance and may be investigated in further research. Power output may be further increased by optimizing electrode shape, electrode spacing, and external resistance.

Additionally, PMFC performance can be greatly impacted by the choice of plant species. To find plants capable of generating higher electrical output, future studies should assess a wider variety of plant species with vast root systems and high rates of root exudation. Incorporating various plant species into a single system may also increase microbial diversity and boost overall system efficiency and stability.

Increased plant production and microbial activity may result from further optimization of nutrient composition, electrical conductivity (EC), pH, flow rate, and environmental factors, including temperature and humidity. In order to assess system durability, seasonal fluctuations, electrode longevity, and large-scale applicability under field settings, long-term studies are also necessary.

	<i>Ipomoea purpurea</i>	<i>Solanum lycopersicum</i>
Maximum Voltage(mv)	762.3	753.8
Maximum Current Density($\mu\text{A}/\text{m}^2$)	806	889
Maximum Power Density (W/m^2)	614.41	670.13

In summary, the innovative PMFC-NFT system created in this work showed effective bioelectricity generation while concurrently promoting plant development. The efficacy of the integrated design is demonstrated by the high voltage, current density, and power density values achieved from both *Solanum lycopersicum* and *Ipomoea purpurea*. PMFC technology has a great deal of potential to become a sustainable and eco-friendly method for producing renewable energy, smart agriculture, and future green energy applications with additional optimization of anaerobic chamber design, electrode materials, microbial activity, and plant selection.

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