Pakistan Journal of Engineering Technology and Science (PJETS)
Volume 12. Issue.02, PP. 65-73, December 2024
https://doi.org/10.22555/pjets.v12i2.1187
E-ISSN 2224-2333
P-ISSN 2222-9930

Harnessing Synergy of Microbial and Plant-Based Systems for Enhanced Bioelectricity Generation in Sustainable Power Systems

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Abstract:

The exploration of sustainable and renewable energy sources parallels the computational modeling and simulation of biological systems, both driven by the increasing energy demands of modern society. One promising area of research is the utilization of microorganisms for electricity generation, leveraging their inherent metabolic processes. This study investigates two innovative approaches: Microbial Fuel Cells (MFCs) and Plant Microbial Fuel Cells (PMFCs). MFCs harness the electron transfer capabilities of certain bacteria to generate electricity directly from organic matter. This bioelectrochemical system offers a sustainable and environmentally friendly method of energy production. However, the performance of MFCs can be enhanced by incorporating plant-based systems, leading to the development of PMFCs. In this research, we introduce a novel PMFC design based on the Aloe vera plant, demonstrating improved stability and increased bioelectricity generation compared to traditional PMFCs. We evaluate the impact of incorporating plants and compost on bioenergy production in PMFCs and present an automated testing framework for the electrical characterization of these systems. By harnessing the synergy between microorganisms and plant systems, this study aims to contribute to the ongoing efforts to develop clean and sustainable energy solutions. The proposed approaches not only address the depletion of fossil resources but also mitigate environmental degradation, aligning with the global sustainability goals.

Keywords: *Bioenergy generation, Chemical energy conversion, Eco-friendly energy, Electron flow, MEA (Membrane electrode assemblies), Microbial Fuel Cells (MFCs).*

I. INTRODUCTION

The data provided along with the comparison gives a thorough look at the present global energy needs., the challenges posed by reliance on non-renewable fossil fuels [1], and the promising role of Plant-Microbial Fuel Cells (PMFCs) in reducing these challenges [2-3]. The above data portrays a world that is experiencing general improvement in well-being, hence faster population growth [4, 5] and a consequent boost in energy consumption. Notably, the consumption of electricity has increased; this electricity is hitherto generated from non-renewable sources in the form of fossil fuels [6]. Due to their availability, ease of access, and initial investment and infrastructure in place, fossil fuels form the basis for this dependence [7]. However, because of its uneven distribution, rising reliance comes with tough questions such as resource exhaustion, environmental, social, and economic costs, and geopolitical tensions [8].

This is because the use of fossil energy is accredited to have negative impacts on the environment and resource depletion. There is an increase in global awareness towards green energy. It is required to act fast because of the pollution crisis, climatic change, and the fact that the resources of hydrocarbons are limited [9–10]. The following reasons can be noted for the requirements of sustainable energy solutions: expenditure of fossil resources, increase in energy demand due to growth in population and industrialization [11], and the harm caused to the environment and human beings by climate change.

Renewable sources of power such as hydropower, geothermal power, wind, and solar energy are among some of the sources that seem to have the potential to cut out carbon emissions and other detrimental impacts on the environment. However, [12] they have some drawbacks. Nevertheless, they have certain drawbacks yet, but we will discuss them later in this paper. Thus, their widespread usage is impossible because of problems such as dependence on weather circumstances, hydropower supply shortage, geographic limitations, high investment costs, and other challenges, which stimulate the search for new possibilities for creating energy. In the middle of a perpetual search for green replacements, Microbial Fuel Cells (MFCs) have emerged as an exciting innovation. With the use of chemical energy provided by microorganisms, mostly bacteria, to convert organic matter to electrical energy, MFCs offer a new approach to producing energy. A benefit of these gadgets is the fact that garbage and soil microbes are transformed into energy; they minimize their impact on the environment, yet they offer reliable, long-term power solutions with minimal or no maintenance at all. A proton exchange membrane is used to divide the anode and cathode of a typical MFC [16]. These particulate matter are protons and electrons which are created into existence through the breakdown of organic compounds by microbes. Electricity is created through some of these electrons from the anode to the cathode through a circuit that is usually connected. The choice of the organic substrate to be used in MFCs is not as limited since microorganisms act as biocatalysts in the conversion of different organic substrates into energy[17].

Building from this fundamental of MFC technology, scientists have considered how it is possible to incorporate plants into the anode zone to design Plant-Microbial Fuel Cells or PMFCs [18]. Plants are introduced to PMFCs as a supply of substrates to the microorganisms with a view of benefiting from the energy-generating bacteria [20]. As a new technology derived from the natural phenomena of plant-microbe symbiosis, this technology is as cost-effective and eco-friendly as it can be in terms of energy generation. The research to develop MFCs and PMFCs is multi-disciplinary, including microbiology, plant science, electrochemistry, and different branches of engineering [20]. These technologies have potential in a wide range of systems, for example, in treating wastewater, for agriculture, for electricity in remote areas, and for cleaning the environment. MFCs and PMFCs have been integrated into various systems like sewage treatment plants and agricultural fields, which clearly show how this technology can be beneficial in providing energy to people all over the globe and, at the same time, be friendly to the environment. This research proposed plays a role in extracting electric energy from plants. Inserted electrodes induce an electrochemical response in plants, changing chemical energy to electrical energy. The oxidation-reduction reaction happens at the anode and cathode electrodes, enabling electron flow and electricity generation [21-22]. In the Plant-Based Cell (PBC) system, the plant's organic matter acts as an electrolyte. Factors like electrode material, number of pairs, and connection technique affect electricity output.

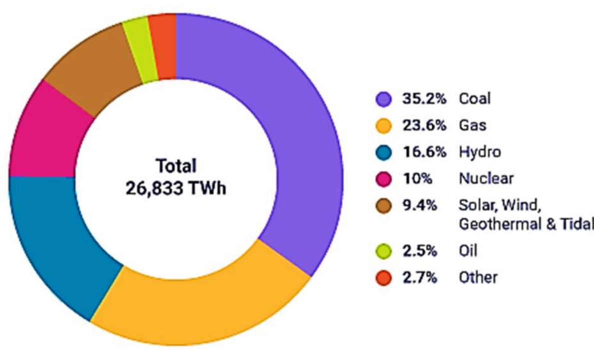

Figure 1: Energy Generation

As researchers continue to explore and refine various configurations and enhancements to augment the efficiency and practicality of MFC technology, the paper is structured to delve into the proposal of a discussion on the research methodology in Section II. The experimental setup is elucidated in Section III, while Section IV presents the experimental results, showcasing the functionality of MFCs and PMFCs in harnessing bacteria's power to convert it into electrical energy. Finally, Figure 1 shows a summary of the results and a discourse on the applicability and limitations of the approach undertaken for various energy considerations.

II. RESEARCH METHODOLOGY

Figure 2 represents the different stages of a process. It begins with PMFCs (Proton Exchange Membrane Fuel Cells), which lead to power generation, power conversion, and load distribution.

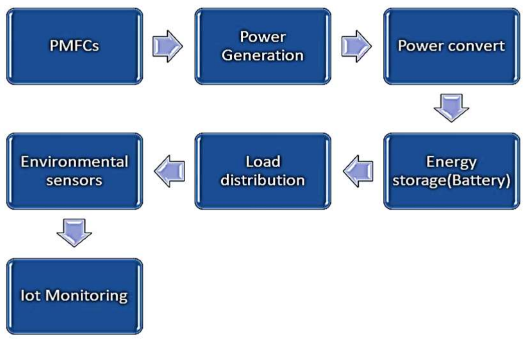

Figure 2: Flow chart of PMFCs

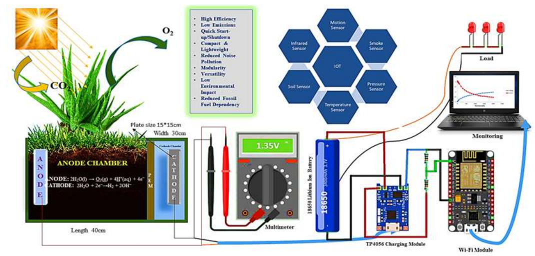

Figure 3: Flow Chart of PMFCs

Environmental sensors and IoT Monitoring are integrated into the process as shown in Figure 3. The flowchart indicates that power is generated, converted, distributed, and stored in batteries, while environmental sensors and IoT monitoring play a role in the process. Overall, it outlines a system that integrates fuel cell technology with power management, storage, and monitoring in an IoT context. IoT-based monitoring offers real-time data on current and voltage, enabling efficient energy management and proactive maintenance measures.

Table 1: Soil and Compost Characteristics

Soil	Plant	Leaf	Electrode	Bacteria	Chemical
Manure	Aloe Vera	Aloe Vera Leaf	Lead Acid plates	Proteobacteria Firmicutes Actinobacteria Bacteriodetes	Sucrose
			Copper & Zinc Plates		
Sandy soil			Lead Acid plates		

A. Setup to investigate the types of electrodes

Table 1 explores the most efficient anode and cathode pair for voltage and current extraction from Aloe Vera plants. Copper and zinc in leaves and electrodes in Aloe Vera roots form a Plant-Based Cell. Constant variables include electrode dimensions (2.5 cm length, 2 cm width, and 1mm thickness), 1 cm electrode separation, and 1.5 cm penetration depth. Additionally, we include Lead oxide (PbO2) and lead electrodes in Aloe Vera roots to form a Plant-Based Cell. Electrode dimensions (15 cm length, 15 cm width, and 2mm thickness), 10 cm electrode separation, and 15 cm penetration depth. Figure 4 shows the schematic of the plant and MEA construction.

The Aloe vera plant generates electricity, as shown in the dimensions in Figure 5, which is measured with a multimeter. This electrical output is then directed to an IoT-based monitoring system. Utilizing smart sensors, the IoT system continuously monitors the electricity generated. Users can access this data through any device or smartphone for real-time tracking and analysis.

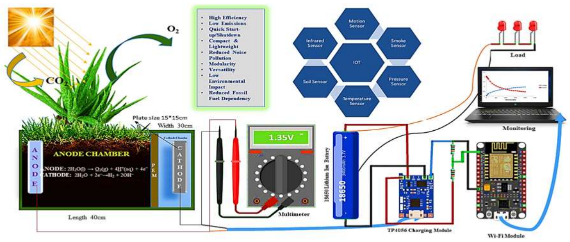

Figure 4: The Schematic of the Plant and MEA Construction

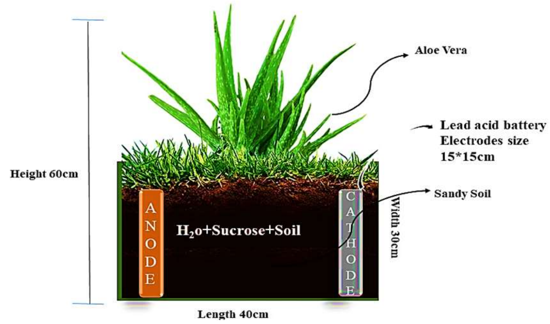

Figure 5: Plant and its dimensions

B. Effect of Distance Between Electrodes

The experiment aims to determine the optimal separation between lead oxide and lead (Anode and cathode) electrodes for maximizing voltage and current extraction from an Aloe Vera plant. The copper electrode is fixed in position near the roots of an Aloe Vera, while the electrode is adjusted incrementally along the root length from 1 to 12 cm, covering its entire span. The electrode penetration size and depth remain constant. Voltage and current measurements are conducted using a high-precision multimeter. Glucose solutions of varying concentrations were injected into the anode of P. macrocarpa for bioelectricity production. Cell voltage was recorded for more than 2 days after each glucose injection. Power, voltage, and current are measured using a digital multimeter. Polarization curves, external resistance changes, and. Operation conditions and characteristics of P-MFC are considered when designing an energy harvester. Duty cycling of IoT nodes for power reduction, with wake-up cycles and sleep periods. Average IoT node power is computed based on the wake-up cycle.

Monitoring of environmental conditions using a data acquisition instrument connected to a personal computer. Online measurements of anode potential, cathode potential, and temperature. Physiological and environmental parameters are considered during P-MFC characterization. Data analysis and fitting were performed using appropriate software. IoT node power needs reduced by duty cycling, with active tasks and long sleep periods. Aggressive reduction of power consumption during sleep periods to optimize energy usage. Computation of average IoT node power considering wake-up cycles and sleep periods. Optimization of energy harvester design based on P-MFC characteristics. Consideration of environmental factors for maximizing energy output. IoT node connectivity expanded via optimized energy harvesting. Exploration of methods for effective P-MFC characterization. Consideration of various parameters influencing P-MFC performance. Ongoing scientific research on the role of clay in P-MFCs. This detailed methodology encompasses various MFC and PMFC setups, plant selections, construction details, measurements, environmental conditions, and data analysis approaches. The systematic and comprehensive nature of the methodology ensures a thorough exploration of bioelectricity production and the potential for IoT node power using microbial fuel cells.

III. EXPERIMENTAL SETUP

An experiment on the Aloe Vera setup in Figure 6 shows energy harvesting conducted in a controlled indoor environment. Aloe Vera, aged 2 years, is chosen for its mature size (60 cm height, 40-60 cm diameter).

A. Exploring the Impact of Series and Parallel Connections on Aloe Vera Leaf Growth and Health

Succulent leaves, 35-40 cm long, 6-7 cm wide, and 2-2.5 cm thick, are exposed to varying light intensity from an adjacent transparent window. The room temperature is maintained at 25-26 degrees Celsius with a relative humidity of 56-61% as shown in Figure 7.

The image depicts a generated electricity series setup with aloe vera plants in various containers, including makeshift rectangular pots, a traditional round pot, and a blue bucket. It is positioned indoors or on a sheltered surface. A Multimeter is attached to the setup of monitoring Voltage. Notably, there's an attempt to integrate electronic devices for plant care. Series connections to electricity generation in the described gardening setup. Additionally, it's mentioned that the chemical sucrose is used in the aloe vera plants. Overall, the scene conveys a mix of traditional gardening and modern technology for plant maintenance, though clarification on electricity generation and sucrose usage is needed.

Figure 6: Simple plant setup

Figure 7: Setup to investigate Series Connection

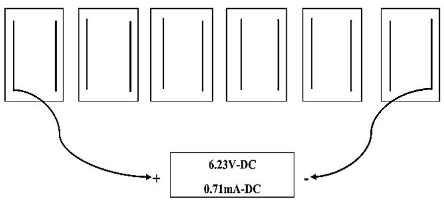

Figure 8: Series connection Voltage & Current

Figure 9: Parallel set up to investigate the voltage

Six Aloe vera setups arranged in series collectively generate a voltage of 6.23V with a current of 0.71mA as shown in Figure 8. This setup harnesses the natural electrical potential of Aloe vera plants to produce renewable energy. The generated electricity is measured using a multimeter, showcasing the effectiveness of this bioelectricity generation method. Additionally, an IoT-based monitoring system is integrated to continuously track and analyze the electrical output of these setups in real time. Utilizing smart sensors, the system ensures efficient energy management and enables proactive maintenance measures. Furthermore, it underscores the importance of exploring eco-friendly alternatives amidst growing concerns over fossil fuel depletion and environmental degradation. Figure 9 shows the parallel setup to investigate the voltage.

The indoor setting displays an experimental setup with aloe vera plants in various containers, including a red rectangular bin and a blue square bin, arranged on a ceramic-tiled floor. Wires from the plant soil connect to a digital multimeter on the red bin, suggesting a potential link to electricity generation or monitoring [23]. Additionally, the chemical sucrose is mentioned as being used in the experiment. It's implied that the setup involves three pots in parallel and three in series, yet the specific electricity generation mechanisms as shown in Figures 10 and 11.

We created six setups with three Aloe vera plants connected in series each. Together, they produced 2.37V and 1.45mA of electricity. This demonstrates Aloe vera's potential for generating power. Connecting them in series boosted voltage output, highlighting their effectiveness and scalability. This experiment highlights the importance of exploring eco-friendly energy sources like Aloe vera to address growing energy needs sustainably. Figure 11 shows the setup to investigate the voltages from aloe vera plant leaves.

Electricity generation is attempted using aloe vera plant leaves. The setup involves placing seven pairs of copper and zinc plates on a single leaf, creating a series connection that yields approximately 1.11 volts. This unconventional approach harnesses the bioelectric potential within the aloe vera plant, with copper and zinc serving as electrodes to facilitate electron flow. The series connection amplifies the voltage output, showcasing the feasibility of utilizing natural resources for sustainable energy production. This innovative system represents an intersection of botanical science and renewable energy exploration, raising possibilities for eco-friendly power sources. The use of aloe vera, known for its hardiness and versatility, underscores the potential for creative solutions in pursuing cleaner and greener energy alternatives. Further experimentation and refinement of such bioelectric setups could contribute to the development of sustainable technologies.

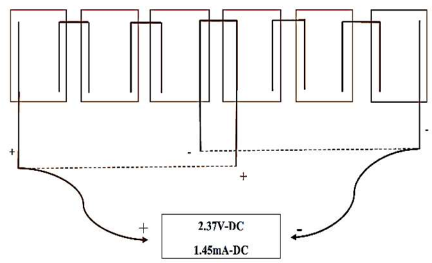

Figure 10: Three of each Series connection Voltage & Current

Figure 11: Setup to investigate the voltages from aloe vera plant leave

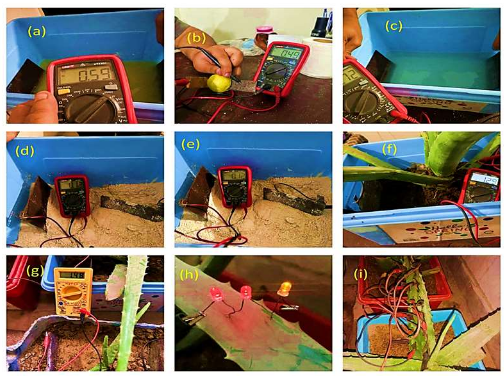

Figure 12: Different types of Soil and Material

The research efforts encompassed numerous experiments involving various soils and materials to explore electricity generation potential in Plant Microbial Fuel Cells (PMFCs) as shown in Figure 12. Across diverse soil types and materials, consistent voltage outputs ranging from 0.42V to 0.51V DC were achieved, reflecting the baseline performance of the PMFCs. However, two notable experiments yielded substantially higher voltage outputs, underscoring the significant influence of specific plant components on electricity generation. In the first experiment, focusing on plant roots, voltage outputs surged remarkably to 6.23V to 6.54V DC, accompanied by currents ranging from 0.71mA to 1.43mA. This considerable increase in electricity generation suggests a potent synergy between the microbial community inhabiting the root zone and the electrochemical processes within the PMFCs. The intricate network of microorganisms associated with plant roots likely contributed to enhanced electron transfer rates and substrate utilization, resulting in elevated power outputs. Similarly, in the second experiment involving aloe vera leaves, a novel approach utilizing seven pairs of copper and zinc plates, a significant voltage of 1.12V DC was attained. This outcome highlights the efficacy of leveraging specific plant structures, such as aloe vera leaves, to augment electricity generation in PMFCs. The inherent electrochemical properties of aloe vera, coupled with the strategic arrangement of electrode materials, facilitated efficient electron transfer and power generation.

When harnessing the natural symbiosis between plants and microorganisms. Further research endeavors should continue to explore and optimize plant-based approaches to maximize electricity generation, ultimately advancing the feasibility and scalability of PMFCs as a renewable energy solution. Through continued innovation and interdisciplinary collaboration, PMFCs hold promise for addressing global energy challenges and promoting a transition towards a more sustainable future.

IV. EXPERIMENTAL RESULTS

The Voltage Time Graph in Figure 13 depicts voltage measurements without load from 10 am to 8 pm at two-hour intervals, with an extra point at 6 pm. Starting at 4.51, the voltage gradually rises to 4.8 at 4 pm, followed by a slight decrease to 4.79 at 6 pm, maintaining consistency during that hour. An additional measurement at 6 pm reaffirms this level. By 8 pm, the voltage dips slightly to 4.78. The graph illustrates a stable pattern with a peak at 4 pm, indicating time-dependent fluctuations.
The Current measured without load (μA) line graph in Figure 14 illustrates electric current fluctuations from 8 am to 8 pm.

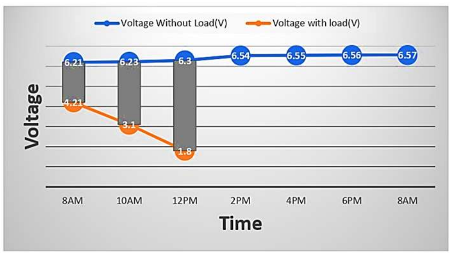

Figure 13: Voltage Time graph

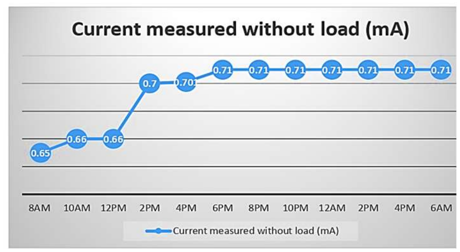

Figure 14: Current Time graph

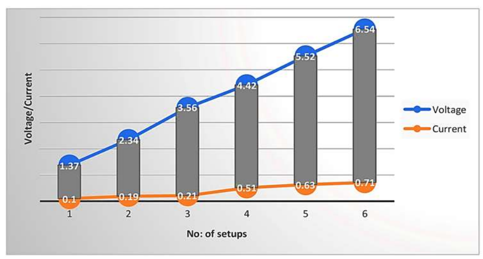

Figure 15: Performance of PMFC, current versus voltage

Starting around 150 μA at 8 am, the current rises to approximately 178 μA at 2 pm, marking the peak. It then slightly declines to about 167 μA by 8 pm, showcasing variations throughout the day. The graph highlights a peak at 2 pm and captures the dynamic nature of current measurements without load, offering a concise overview of the observed trends. The sizes of two different types of plates and their results are shown in Table 2.

Table 2: Different Sizes of Plates

Type Of Plant	Size Of Plates	Depth Of Plates	Distance Between Plates	Voltages
Aloe-Vera	(15*15)cm	12cm	25cm	1.5
Aloe-Vera	(15*15)cm	12cm	8cm	1.38
Aloe-Vera	(12*10)cm	10cm	25cm	1.2
Aloe-Vera	(12*10)cm	10cm	8cm	1.14

The Size of Plates column lists various sizes in the format of height times width. The Depth of Plates column lists the depth. The Distance Between Plates column contains different measurements for each aloe vera type. The final column, "Voltages," lists electric potential differences or voltage measurements associated with each plant setup. Overall, the table appears to be documenting the sizes, distances, and voltages associated with different types of aloe vera plants, possibly for an experiment or demonstration involving electricity generation using these plants.

A. Aloe Vera plant Setup with load (3 white LEDs)

Figure 15 with aloe vera plants showed intriguing voltage and current results. Initially, it produced 6.25V and 1.45mA. Adding one white LED dropped the voltage to 2.1V, and adding two more LEDs further reduced it to 2.35V. This suggests a direct link between LED quantity and voltage drop, indicating increased electrical load. These findings highlight aloe vera's potential in electricity generation, suggesting applications in off-grid lighting and environmental monitoring. Optimizing techniques and integrating them with renewable energy systems could enhance their practicality.

IV. CONCLUSION AND RECOMMENDATIONS

In light of global energy supply and demand and the environmental impact, the study provides a summary of energy in the global context and emphasizes the need for transitions to more sustainable sources and the global energy demand. Plant Microbial Fuel Cells or PMFCs is a unique method of electricity generation, a device where electricity is generated through microbial action. Such concerns as pollution, climate change, and resource depletion by conventional sources of energy could likely be addressed by this discovery. Based on the analysis of the chapters in MFC and PMFC, the subject matter of the research is a combination of many sciences, including engineering, electrochemistry, and microbiology. Thus, the optimization of MFC and PMFC technologies and the broadening of the range of fields of their application are impossible without this or that cross-disciplinary approach. But even with their promise, several obstacles need to be overcome to fully reap the rewards of MFCs and PMFCs But even with their promise, several obstacles need to be overcome to fully reap the rewards of MFCs and PMFCs: Efficiency Optimisation: Hence, MFCs and PMFCs need to be made more efficient to enhance energy generation, as well as using the least resources. To improve the conversion efficiencies of the energy, the following areas should be focused on by researchers: efficiency of microorganisms used in the system, system designs, and electrode materials to be used. Scalability and Cost-effectiveness: This is still the major problem of emulating the larger MFC and PMFC systems to meet large commercial power demands while maintaining inexorable costs. Another factor that would help to increase the usage of these technologies is the development of cheap materials and methods of manufacturing. As for the application of MFC and PMFC systems to specific cases, one must take care of their stability and performance in the long term. To further spread and apply MFCs and PMFCs with efficiency, protocols have to be standardized and easily integrated into the current structure. For the majority of MFC and PMFC-related activities, there must be an adoption of standard procedures and policies, and this requires the concerted effort of independent researchers, industry members, and legislators. Despite these challenges, MFCs and PMFCs can be employed for a host of applications, such as decentralized energy production, applications in environmental management, and agricultural uses. MFCs and PMFCs can evolve as one of the key building blocks of a sustainable energy system if more research and development efforts and international collaborations are directed in this direction. This would benefit the international community by combating climate change and environmental degradation and promoting sustainable environments.

CONFLICT OF INTEREST

There is no conflict of interest between all the authors.

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