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Comparative Estimation of Bioelectrical Performance in Plant Microbial Fuel Cells using Aquatic and Semi-Aquatic Species under Controlled and Solar Environments

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ABSTRACT

Plant Microbial Fuel Cells (PMFCs) offers a sustainable approach for bioelectricity generation by exploiting interactions between plant roots, exudates, and electrochemically active microorganisms. However, system performance relies heavily on plant species selection and ambient light dynamics. This study evaluated the bioelectricity output of three aquatic and semi-aquatic species, which are water lettuce (*Pistia stratiotes*), caladium (*Caladium bicolour*), and hydrilla (*Hydrilla verticillata*), in dual-column PMFC systems. The experiment consisted of two sequential 10-day phases (20 days in total). Phase 1 was under controlled laboratory conditions, and phase 2 was under natural direct sunlight exposure. Aluminium rods and graphite rods were supplied as the anode and cathode, separated by a poly(vinylidene fluoride)-co-poly(vinylimidazole) (PVDF-co-PVIm) ion exchange membrane. Electrical parameters were measured across a fixed external load resistor. In laboratory settings, power density increased linearly over time. Water lettuce achieved the highest output (105 mW), followed by caladium (75 mW) and hydrilla (56 mW). Sunlight exposure in phase 2 significantly enhanced output, yielding peak power outputs of 308 mW (water lettuce), 300 mW (caladium), and 228 mW (hydrilla). Highly branched root systems provided superior surface area for microbial colonisation and exudate transport. These findings highlight species selection and ambient solar radiation as crucial factors for optimising PMFC performance.

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1. INTRODUCTION

The global search for renewable energy as an alternative source has brought PMFCs to the forefront of sustainable technology research. In this context, PMFCs emerged as a unique bioelectrochemical approach that uses aquatic plants. PMFCs further enhance this technology by using living plants to provide organic matter to rhizosphere microorganisms, which in turn generate electricity through metabolic processes. This study evaluates the efficacy of three plants, such as Water Lettuce, Caladium, and Water Thyme, in such a system. PMFCs offer an eco-friendly alternative for sustainable bioelectricity generation by harnessing the natural synergy between plant photosynthesis, rhizodeposition, and electrogenic soil bacteria [1, 2]. According to Shaikh et al. [1] and Greeman et al. [2], photosynthesis captures atmospheric carbon dioxide, discharging as much as 40% in the form of organic rhizodeposits into the soil.

Electroactive microorganisms in the anaerobic root zone then oxidise these exudates, generating electrons that are conveyed to the anode and protons that transfer to the cathode to react with oxygen, yielding water and generating energy. PMFCs represent a crucial, sustainable bioenergy technology that transforms sunlight energy absorbed by plants into clean electricity via interactions between plant root exudates and electrochemically active bacteria [3]. Meanwhile, previous groundwork has investigated aquatic macrophyte performance in PMFCs; direct comparative evaluations of water lettuce (*Pistia stratiotes*), caladium, and water thyme under identical operational conditions remain limited [3, 4]. Existing literature predominantly examines isolated floating or submerged species over short monitoring windows, without systematically comparing how floating root mats versus submerged foliage impact root exudate release, bioelectricity stability, and simultaneous nutrient removal, specifically total nitrogen, and chemical oxygen demand (COD) [5, 6]. To bridge this research gap, this study establishes a standardised comparative framework evaluating all plants over an operational duration of 10 days in a controlled environment and another 10 days in a solar environment [7]. By directly linking structural plant traits and rhizosphere dynamics to power density and pollutant degradation efficiency, this work establishes clear plant selection criteria to optimise long-term, continuous aquatic PMFC performance [8]. PMFCs generate electricity directly from living plants, unlike conventional biomass energy systems that require prior biomass collection. PMFCs operate by leveraging the symbiotic association between plant roots and soil microorganisms to change chemical energy into electrical energy [9]. During photosynthesis, plants emit organic molecules known as root exudates into the surrounding soil or sediment.

Electrochemically active bacteria decompose these substances, releasing electrons in the process. The anode collects these electrons, which subsequently traverse an external circuit to generate bioelectricity and ultimately undergo reduction at the cathode [10]. As reported by Strik 2008 [11], the plant-MFC offers a sustainable and efficient method for bioenergy production in situ, utilizing plants and bacteria to convert solar energy into green electricity. By leveraging rhizodeposits produced by plants, primarily carbohydrates, bacteria transform these substances into electrical energy using Reed mannagrass, this system achieved a maximum electrical power production of 67 mW/m^2 of anode surface. Furthermore, PMFCs are considered environmentally beneficial due to their low carbon emissions and limited ecological impact. The root systems of aquatic and partially submerged plants remain submerged, ensuring continuous interaction with electrodes and bacterial populations. Although research and understanding remain incomplete, these plants are excellent candidates for PMFC applications. Past research has shown that the beneficial effects of PMFC are influenced by bacterial diversity, secretion dynamics, root architecture, and

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plant varieties [3, 12-14]. Species such as *Oryza sativa*, *Glyceria maxima*, and *Canna 'Stuttgart'* show a lot of promise for generating electricity [3, 15, 16]. Insufficient information exists to compare different species under standardised testing conditions. Furthermore, although certain plants, like caladium, boost power generation in membrane-free systems, the longevity of these designs remains to be determined [17].

The application of PMFCs is beyond power production. PMFCs are versatile tools capable of powering ultra-low-power IoT remote sensors, serving as biosensors for water quality or plant health, treating wastewater and facilitating bioremediation of heavy metals and organic pollutants [3]. Water lettuce, caladium and water thyme are the three aquatic plant species studied in this research. Water lettuce, like all species, has its own distinct set of physical characteristics; it can float freely on the water's surface and absorb nutrients rapidly thanks to its long, thread-like roots. The aquatic caladium plant has bulbous roots that can store nutrients effectively. The unusual rhizome system of water thyme, an aquatic plant that grows submerged, ensures the plant's stability and robustness. This study examines the potential of PMFCs in wastewater-to-energy conversion. In this process, microorganisms decompose organic pollutants while simultaneously producing energy [18].

The research aims to identify plant species with desirable characteristics that can enhance the bioelectricity collection capabilities of PMFCs. In this study, the performance of the PEMFC is focused on two key factors regarding electricity generation in which the micro-electricity generation capability of three types of aquatic and semi-aquatic plants, and the effects of maintaining these plants under controlled laboratory conditions versus exposing them to sunlight for ten days each, over a 20-day test period.

2. METHODOLOGY

An aluminium rod serves as the anode in PMFC devices, while a graphite rod serves as the cathode. Daily voltage (mV) and current (mA) measurements were recorded over 10 days using a digital multimeter. Materials and apparatus included a digital multimeter, a two column (2H) microbial fuel cell, an ion exchange membrane (PEM), graphite and aluminium rods, and wastewater, water lettuce, caladium, and water thyme. This study utilised a laboratory-based quantitative experimental strategy to compare the bioelectrical output of PMFC systems with various plant species. Three identical PMFC systems were constructed with dual-column fuel cells. The PMFC device is designed as a two-column H-type system, with a membrane made of synthetic solid polymer electrolyte as a separator [19]. The twin-column fuel cell was subsequently separated using an ion-exchange membrane based on the radiation-induced grafting process, composed of poly(vinylidene fluoride)-co-poly(vinylimidazole) (PVDF-co-PVIm) [20]. The cathode column served as the electrolyte, and the plant was in the anode column; wastewater consists of organic materials, nutrients, pathogens, suspended particles, and contaminants. PMFC cells incorporating water lettuce, caladium, and water thyme were evaluated under two conditions: one in a laboratory setting and the other exposed to direct sunlight. Table 1 presents the properties and features of all plants evaluated, and Fig. 1(i) shows the real photos of the plants.

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Table 1. The list of the plant species and their properties

Plant	**Habits**	**Root Type**	**Key Characteristics**
Water Lettuce (*Pistia stratiotes*)	Floating	Feathery/Dangling	Absorbs nutrients directly from water
Caladium (*Caladium bicolour*)	Terrestrial	Tuberous/Shallow	Stores energy in underground corns
Water Thyme (*Hydrilla verticillate*)	Submerged	Anchoring/Rhizomatous	Produces tubers in sediment

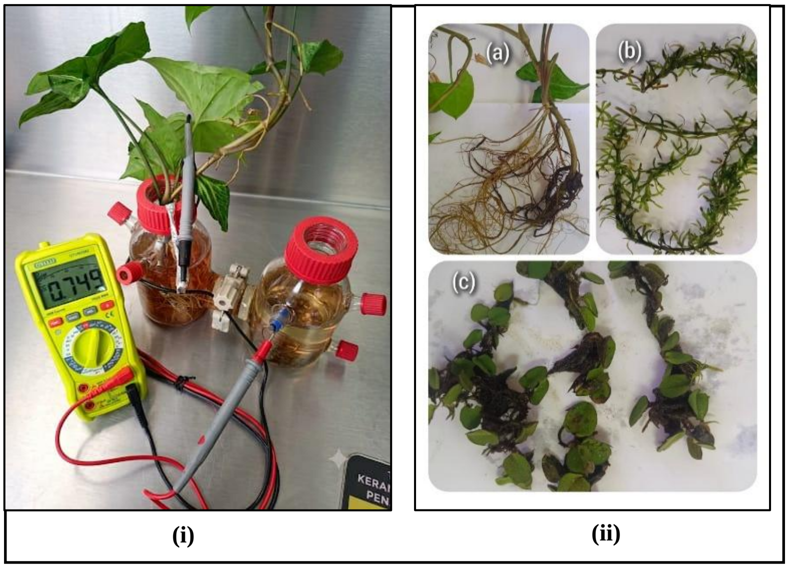

Fig. 1. (i) Plant microbial fuel cell and (ii) Aquatic plants & root type of (a) Caladium (b) Water Thyme & (c) Water Lettuce

The experimental phase extended 10 days to evaluate the bio-electrical potential of three plants. The research was conducted in two unique environments to evaluate the power density outputs. The first habitat was a controlled laboratory setting, while the second was an area exposed to direct sunlight. To establish a baseline for microbial activity in the rhizosphere, plants were kept in the laboratory under conditions consistent with the environment, including uniform light and temperature. To estimate the impact of photosynthetically active radiation on power production, the systems were moved to an external environment once the direct sunlight phase was complete. Daily milliwatts (mW) measurements were taken of the power output for each individual arrangement.

Fig. 1(i) shows the PMFC units comprised dual-column H-type glass reactors with a cylindrical aluminium rod as the anode and a high-density graphite rod as the cathode submerged in liquid volumes of 200 ml each. A radiation-grafted PVDF-co-PVIm proton exchange membrane (10 cm^2 surface area, 0.15 mm thickness) separated the two compartments. Electrodes of anode is cylindrical aluminium rod (r = 3.2 mm, length = 23 cm, submerged surface area = 3.5 cm^2). Cathode with high-density graphite rod (r = 3.2 mm, submerged surface area = 3.5 cm^2). Electrode spacing was fixed at 5 cm from the membrane junction. Then, Fig. 1(ii) displays the aquatic plant together with root pattern for each anode column received 3 healthy aquatic plant specimens of uniform initial wet weight (26.0 to 30.0 ± 1.5 g). Electrical measurements are recorded by multimeter. Cell voltage (V) and current (I) were calculated using a digital multimeter. Power output (P) were calculated using Ohm's Law and Joules Law as in Eq. (1) & (2), respectively.

$$I = \frac{V}{R_{\text{ext}}} \tag{1}$$

$$P = I \times V = \frac{V^2}{R_{\text{ext}}} \tag{2}$$

3. RESULTS AND DISCUSSION

Fig. 2 shows that, over the 10-day testing period, the three plant species produced power output in the order: Water Lettuce, Caladium, and Water Thyme.

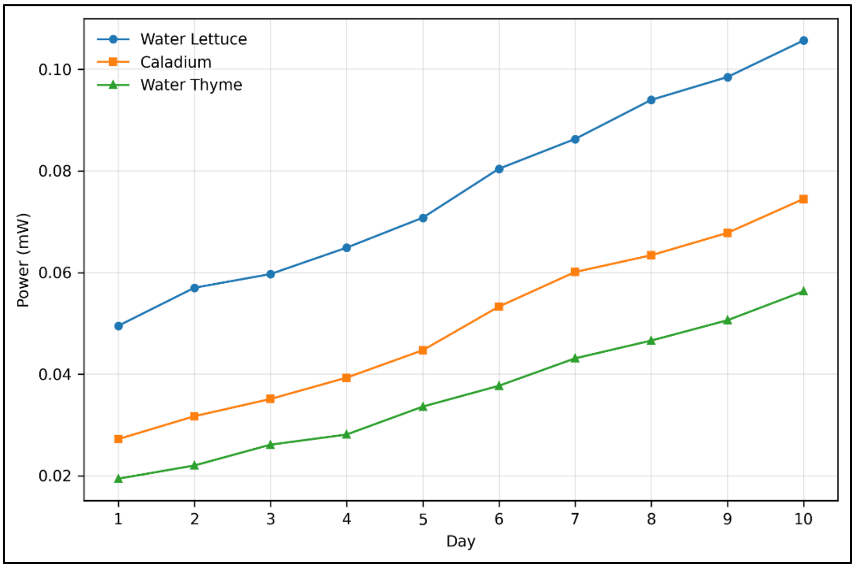

Fig. 2. Power output of respective plant species in a controlled lab environment

Overall, from Day 1 to Day 10, all three systems showed a consistent rise in power output, suggesting that electricity generation improved over the measurement period. Each plant's recorded power values were derived from the matching voltage and current data shown in Table 2.

Table 2. The recorded voltage (V) and current (I) of the plant species at lab-controlled conditions

		Water Lettuce			Caladium			Water Thyme		
Week	**Days**	**Voltage (V)**	**Current (mA)**	**Power (mW)**	**Voltage (V)**	**Current (mA)**	**Power (mW)**	**Voltage (V)**	**Current (mA)**	**Power (mW)**
1	1	0.302	0.164	0.0495	0.241	0.113	0.0272	0.203	0.096	0.0194
1	2	0.314	0.181	0.0570	0.256	0.124	0.0317	0.214	0.103	0.0220
1	3	0.328	0.182	0.0597	0.262	0.134	0.0351	0.221	0.118	0.0261
1	4	0.331	0.196	0.0649	0.275	0.143	0.0393	0.227	0.124	0.0281
1	5	0.347	0.204	0.0708	0.285	0.157	0.0447	0.245	0.137	0.0336
2	6	0.364	0.221	0.8044	0.303	0.176	0.0533	0.262	0.144	0.0377
2	7	0.369	0.234	0.0863	0.318	0.189	0.0601	0.271	0.159	0.0431
2	8	0.382	0.246	0.0940	0.322	0.197	0.0634	0.286	0.163	0.0466
2	9	0.391	0.252	0.0985	0.339	0.200	0.0678	0.291	0.174	0.0506
2	10	0.405	0.261	0.1057	0.342	0.218	0.0745	0.303	0.186	0.0563

Over the observation period, Water Lettuce demonstrated the highest power output among the three plant species. Its power rose by about 113.5%, from 0.0495 mW on Day 1 to 0.1057 mW on Day 10. From Day 5 to Day 6, power rose noticeably, from 0.0708 to roughly 0.0804 mW. This increase persisted until Day 10. Among the three plant species under investigation, Water Lettuce produced the most electrical power under the testing conditions, as evidenced by its consistently higher power output. Over the ten days, the Caladium system showed the second-highest power output. From 0.0272 mW on Day 1 to 0.0745 mW on Day 10, its power gradually increased, for an overall rise of almost 173.9%. With the power reaching 0.0533 mW on Day 6 and then rising to 0.0745 mW by Day 10, the increase was especially noticeable after Day 5. Although Caladium's absolute power output remained lower than Water Lettuce's, its strong relative growth over the measurement period shows a clear upward trend. Water Thyme, on the other hand, generated the least amount of electricity during the trial. Power increased by almost 190.2%, from 0.0194 mW on Day 1 to 0.0563 mW on Day 10. Among the three systems, Water Thyme had the largest relative increase despite having the lowest absolute power. Power output climbed gradually throughout the measurement period, especially starting on Day 5. From Days 6 to 10, it reached 0.0377, 0.0431, 0.0466, 0.0506, and 0.0563 mW, respectively. Overall, the power-output trend was Water Lettuce, followed by Caladium and then Water Thyme across the 10-day observation period. The findings show that while all three plant-based systems demonstrated growing electrical power generation over time, Water Thyme showed the largest percentage gain relative to its initial value, while Water Lettuce provided the highest absolute power output. These results suggest differences in the electrical performance of systems connected to different plant species.

Table 3 illustrates the recorded voltage and current statistics for every aquatic plant between day 11 and day 20. This information was subsequently plotted on a graph, as depicted in Fig. 3. Additionally, Fig. 3 presents a comprehensive comparative analysis of the power production capabilities of three aquatic and semi-aquatic plant species, which are Water Lettuce, Caladium, and Water Thyme, integrated into PMFCs apparatus.

Table 3. The recorded voltage (V) and current (I) of the plant species exposed to sunlight

		Water Lettuce			Caladium			Water Thyme		
Week	**Days**	**Voltage (V)**	**Current (mA)**	**Power (mW)**	**Voltage (V)**	**Current (mA)**	**Power (mW)**	**Voltage (V)**	**Current (mA)**	**Power (mW)**
3	11	0.551	0.402	0.222	0.501	0.344	0.172	0.521	0.41	0.214
3	12	0.567	0.410	0.232	0.437	0.221	0.097	0.532	0.423	0.225
3	13	0.571	0.422	0.241	0.465	0.297	0.138	0.522	0.407	0.212
3	14	0.582	0.426	0.248	0.485	0.355	0.172	0.529	0.397	0.210
3	15	0.589	0.43	0.253	0.493	0.391	0.193	0.531	0.426	0.226
4	16	0.561	0.477	0.268	0.58	0.499	0.289	0.482	0.345	0.166
4	17	0.579	0.501	0.290	0.583	0.509	0.297	0.496	0.351	0.174
4	18	0.730	0.693	0.506	0.576	0.505	0.291	0.507	0.364	0.185
4	19	0.562	0.473	0.266	0.58	0.501	0.291	0.511	0.379	0.194
4	20	0.663	0.443	0.294	0.591	0.507	0.300	0.526	0.382	0.201

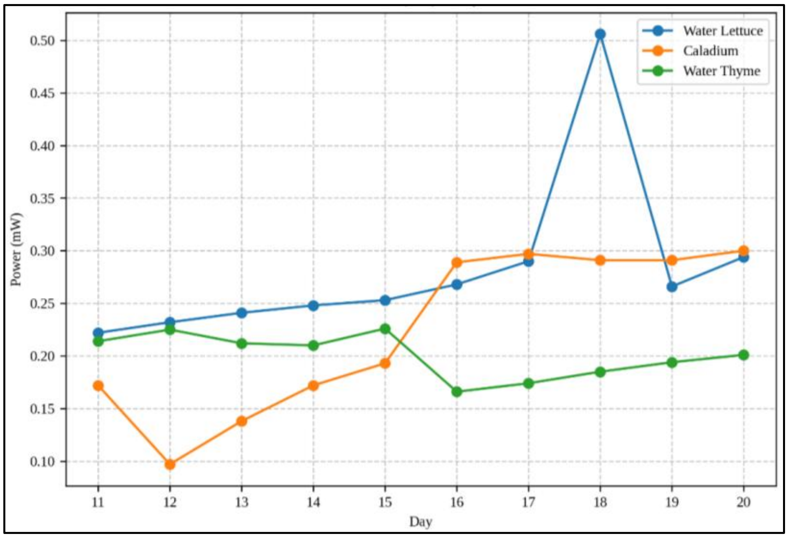

Fig. 3. Power output (mW) vs Day of respective plant species under direct sunlight

The study focuses on a specific ten-day observation window from Day 11 to Day 20, recording critical electrical parameters including voltage (V), current (mA), and power (mW) under sunlight exposure conditions. The primary target of this analysis was to evaluate which species offers the most efficient and stable bio-energy harvesting potential. Through a rigorous examination of daily performance logs and descriptive statistics, it was determined that Water Lettuce is the superior performer among the three candidates. Water Lettuce achieved a mean power production of 0.282 mW, significantly higher than Caladium (0.224 mW) and Water Thyme (0.201 mW). Water Lettuce also dominated peak power output, reaching 0.506 mW on Day 18, with a substantial voltage of 0.730 V and a current of 0.693 mA. Caladium showed a distinctive performance profile, characterised by early-stage volatility followed by a robust, steady increase during the second week of observations, ultimately peaking at 0.300 mW on Day 20. Water Thyme, conversely, reached its maximum output early in the study (Day 15) before declining and slowly recovering in the following days. These findings provide a data-driven foundation for selecting plant species in PMFC applications, highlighting Water Lettuce as the most promising candidate for high-output bio-energy systems within the parameters of this study.

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Water Lettuce is clearly the most efficient species for energy harvesting among those tested. Its ability to reach over 0.5 mW, even if briefly, demonstrates a higher potential for bio-electrical generation. The total power sum of 2.82 mW over ten days makes it the most productive option for a scaled-up system. While Water Lettuce had the highest output, Caladium showed the most impressive growth trend, nearly doubling its output from Week 3 to Week 4. This suggests that Caladium might require a longer "run-in" period but could provide highly stable outputs once established. Water Thyme, despite being consistent in Week 3, showed a worrying trend of decline, making it the least reliable candidate for sustained power production without further optimisation.

The examined species' electrical performance differed greatly. The experiment identified two key factors that helped the three chosen plant species produce more bioelectricity. These factors were direct solar exposure and root type. First, root type affected power production. Because of its large, highly branching root structure, which maximises contact between exudates and the anode surface, water lettuce produced the greatest and most consistent results. Because there was less biological material available in the anodic location, water thyme, on the other hand, generated the least amount. Over the course of the trial, the three-plant species' electrical output changed. In terms of voltage and current, water lettuce consistently produced results, followed by caladium and water thyme, which produced low voltage output. During the first several days of the 10-day trial, electrical output increased and eventually levelled off. Because the PMFC jar is closed and receives light only through windows, sunlight cannot reach the plants inside during PMFC tests in the lab. Put another way, power output is constrained by the amount of sunlight that is shadowed by the building's walls or roof. Solar energy is the main driver of increased power in these systems, as shown by the transition from laboratory to sunny conditions (Fig. 2 vs Fig. 3). While direct sunlight offers substantial yield potential but compromises stability, the laboratory environment offers consistency and linear predictability. Water lettuce is the most promising candidate for real-world use because it maximises power output and resists changes in direct sunlight. Water lettuce's vast, highly branched root system maximises contact between the anode surface, electrochemically active bacteria, and root exudates. These released organic molecules fuel microbial metabolism, driving high electron transfer and resulting in the highest bioelectricity generation across the 10 days (peaking on Day 8 at 0.730 V, 0.693 mA, and 0.506 mW). Meanwhile, Caladium generates moderate bioelectricity because its root structure provides less efficient contact between the anode and rhizosphere microorganisms, slowing electron transmission. Performance steadily increases and stabilises in Week 2, reaching up to 0.591V, 0.507 mA and 0.300 mW on Day 10. However, Water Thyme produces the lowest overall bioelectric output because reduced root-produced organic matter at the anode limits microbial oxidation and electron transfer. Power generation remains consistently low, fluctuating between 0.166 mW and 0.226 mW throughout the trial. The study proves the potential of PMFC systems operating in low-power modes and provides background for future improvements to electrode materials and system structure in sustainable bio-energy production, although a single biofuel cell achieved only a small overall power output. Future research on PMFC systems will examine other factors such as temperature, water quality, electrolyte (nutrients), proton exchange membranes, anode and cathode electrode types, and the role of microbes.

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4. CONCLUSION

This study examined the performance of PMFCs across three species which water lettuce, caladium, and water thyme. The results confirm that factors such as plant selection, root morphology, and light exposure significantly influence electrical output. Water lettuce performed best in both environments, generating 0.106 mW in the laboratory condition and 0.506 mW in direct sunlight for single-cell PMFCs. While direct sunlight increased overall power output, it also caused fluctuations and negatively impacted water thyme's performance after Day 5. By comparison, laboratory conditions yielded lower but more stable, linear power growth, which is ideal for steady-state research. Even with overall power limitations, PMFCs exhibit strong potential for low-power applications, including environmental monitoring and sustainable agriculture. Aquatic plants that take in more sunlight directly boost photosynthetic activity, which brings more organic matter to the root zone to power PMFC operations. Water lettuce is recommended as the primary species for bioelectricity generation.

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6. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted without any self-benefit, commercial, or financial conflicts, and declare no conflicting interests with the funders.

7. AUTHORS' CONTRIBUTIONS

Ashton Valen Alexander Lucas, Danny Darren Simon: Conceptualisation, methodology, formal analysis, investigation and writing-original draft; Muhammad Nabeel Jasni: Conceptualisation, methodology, and formal analysis; Nor Faranaz Shamin Nor Azmi: Lecturer in charge of FSG311 subject, and validation; Ajis Lepit: Conceptualisation, supervision, writing- review and editing, and validation.

8. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) used Gemini Pro, Grammarly, GridArt, SciSpace, & Quillbot to help them write and summarise the FSG311 report.

9. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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10. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed in accordance with the Laboratory Safety protocols of Universiti Teknologi MARA.

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