Preliminary Evaluation of Asparagus Waste as a Substrate in Microbial Fuel Cells (MFCs) for Bioelectricity Generation

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Abstract—**The critical need for renewable energy solutions and effective agricultural waste management presents significant global challenges. This study aimed to evaluate the potential of asparagus waste as a substrate for energy generation in microbial fuel cell. Rich in organic compounds such as carbohydrates, proteins, and bioactive substances, asparagus waste demonstrated remarkable potential as a bioelectricity substrate source. Key findings included a peak power density of 235.213±24.118 mW/cm², a current density of 4.685 A/cm², and an internal resistance of 56.874±4.517 Ω, observed on the thirteenth day of monitoring. Optimal parameters, including a pH of 4.777±0.146 and electrical conductivity of 139.841±4.254 mS/cm, further highlighted its efficiency. Furthermore, connecting three MFCs in series generated a combined voltage of 2.86 V, sufficient to light an LED bulb, demonstrating the technology's scalability. This research offers groundbreaking insights into the use of asparagus waste, setting it apart from other agricultural by-products due to its unique composition and superior energy conversion efficiency. This novel approach not only facilitates waste valorization but also lays the groundwork for sustainable energy systems, especially in asparagus-producing regions such as Peru. By establishing a framework for standardizing MFC parameters, this study contributes to the advancement of scalable renewable energy systems while promoting environmental conservation and delivering economic benefits to agricultural communities. Future investigations could focus on improving system efficiency and expanding its applicability across different contexts.**

Keywords—**asparagus waste, electricity, microbial fuel cell, energy sustainability**

I. Introduction

The food and agricultural sectors will face significant challenges this century due to rapidly increasing population demand [1]. This emerges positions the sector as one of the fastest growing globally [2]. However, such expansion brings multiple issues, with waste management—stemming from the harvesting, marketing, and consumption of products (fruits, vegetables, tubers, and others)—being a primary concern [3, 4]. The Food and Agriculture Organization of the United Nations (FAO) estimates that approximately one-third of all food produced is wasted, amounting to roughly 1.6 million tons and releasing about 3.3 billion tons of carbon dioxide [5, 6]. Furthermore, industries dedicated to producing fruits and vegetables generate even higher volumes of waste—between 25% and 30% of their output—comprising skins, pods, pulp, and peels, among other residues [7]. Simultaneously, global energy demand has grown considerably, spurring the environmentally sustainable development of renewable energy sources [8]. This shift offers hope in the face of winding fossil fuel reserves, with studies indicating that domestic renewable energy generation in countries such as the United States can reduce greenhouse gas emissions by up to one-third [9, 10]. Consequently, policymakers, environmentalists, and stakeholders in the food and agriculture sectors play a crucial role in addressing these challenges and promoting renewable energy solutions.

In this context, advances in Microbial Fuel Cell (MFC) technology have demonstrated significant potential to address both organic waste treatment and electrical energy generation simultaneously [11]. MFCs employ various types of waste as substrates and, through biochemical reactions, convert stored chemical energy into electrical energy [12]. Typically, an MFC consists of an anode and a cathode chamber separated by a membrane and connected externally by a circuit that facilitates electron flow [13]. Crucial parameters such as pH and power density are measured because the electrical output depends on electron transfer driven by microbial metabolism, which is highly sensitive to pH levels [11, 13]. Power density, in turn, provides insight into the amount of electrical power produced per unit area. Recent research has explored the use of food waste in MFCs. For example, Ahmad [14] used potato waste (at a pH of 5) as a substrate, achieving a voltage of 0.154 V, a power density of 1.450 mW/m², and an internal resistance of 724 Ω after 15 days; This study noted that starch is a readily biodegradable carbohydrate that microorganisms can break down into simpler sugars such as glucose. Similarly, red dragon fruit waste has been applied, yielding voltages of 0.46±0.03 V and a power density of 304.33±16.51 mW/cm² at a pH of 4.22±0.09 using metal electrodes to enhance conductivity. Its betalains and other bioactive compounds may further influence microbial activity [15]. Additionally, studies using lettuce waste have reported voltage peaks of 0.959±0.026 V and power densities of 378.145±5.417 mW/cm², with an internal resistance of 87.594±6.226 Ω, attributed to its high content of cellulose and hemicellulose, which are readily biodegradable by microorganisms [16].

Peru, as the world's second-largest exporter of asparagus, produces considerable quantities of agricultural waste during harvesting and processing [17]. This waste presents environmental challenges while offering substantial potential due to its distinctive composition, rich in easily degradable organic compounds such as carbohydrates, dietary fiber, and proteins. The innovative use of asparagus waste in Microbial Fuel Cells (MFCs) offers a sustainable solution to address this local issue while contributing to broader renewable energy initiatives [18]. By leveraging microorganisms to convert organic matter into electricity, MFCs provide dual benefits: efficient waste management and clean energy production. Asparagus waste's unique composition enhances microbial activity and energy conversion efficiency, setting it apart as an ideal substrate for bioelectricity generation. The link between the environmental impact of asparagus waste and its technological utilization in Microbial Fuel Cells (MFCs) underscores the significance and originality of this research [17, 18]. This approach provides a clear pathway toward sustainability, particularly in regions with high asparagus production, such as Peru [19]. Investigating asparagus waste as a substrate in MFCs is especially innovative, offering a distinctive alternative to other agricultural by-products. MFCs rely on microorganisms to convert organic matter into electrical energy, and asparagus waste possesses unique characteristics that make it particularly well-suited for this application [17, 20]. Rich in organic compounds such as carbohydrates, proteins, and fiber, asparagus waste can be efficiently degraded by microorganisms, promoting a high rate of energy conversion and rendering it an ideal substrate for electricity generation [19]. In contrast, other types of waste—such as banana peels, sugarcane bagasse, and corn waste—often have variable compositions, generally high in cellulose, hemicellulose, and lignin, and may require pretreatment to enhance digestibility [21]. Additionally, these alternative wastes typically contain fewer bioactive compounds compared to asparagus waste. Thus, employing asparagus waste in MFCs presents a novel and sustainable opportunity to reuse industrial waste.

The main objective of this study highlights the evaluation of the potential of asparagus waste as a substrate in single-chamber microbial fuel cell. For this purpose, parameters such as electric current, current density, power density, voltage, pH, and electrical conductivity were analyzed. Additionally, the internal resistance of the cell was calculated. This study will provide initial values for the standardization of MFC parameters using asparagus waste. Furthermore, it offers an innovative and sustainable approach that addresses two critical global challenges: agricultural waste management and renewable energy generation. This objective not only helps to minimize environmental impact by reusing industrial waste but also provides a viable solution to mitigate dependence on fossil substrates. The relevance of this approach lies in its ability to leverage the unique composition of asparagus waste, rich in carbohydrates, proteins, and bioactive compounds, optimizing electricity production. Moreover, this work establishes a solid foundation for standardizing MFC parameters, promoting scalability and industrial applications, especially in regions like Peru, where asparagus production is high and energy costs are elevated.

II. Materials and Methods

A. Obtaining Asparagus Waste

Asparagus waste (processing by-products) was obtained from the company CUS SAC (Trujillo, Peru), which is dedicated to collecting agro-industrial waste. The 5 kg of garbage was collected and washed several times to remove any impurities. It was then left to dry at 23.5 °C for 24 h. Then, a liquid waste solution was obtained using an extractor (Labtron, LDO-B10 — USA extractor). Each MFC contained 800 ml of crushed asparagus waste. The environmental parameters were kept constant because the laboratory has specific temperature and humidity controls. Waste consisted primarily of stems (20 %) and leaves (10 %) and fruit (70 %), which are known to contain high levels of lignocellulosic material and secondary metabolites such as saponins and phenolic compounds. These components have been documented to influence microbial activity and biofilm formation, playing a key role in the electrochemical behavior of microbial fuel cells. The predominance of stem biomass contributes structural carbohydrates that may enhance electron donation during microbial degradation, while the leaf fraction offers soluble organic matter that may promote rapid metabolic activation within anodic biofilms.

B. Operationalization of the MFCs

Three single-chamber MFCs with a volume of 100 mL were purchased from SONOTEK Corporation (Milton, USA). The electrodes used inside the MFCs were made of carbon (anode, 30 cm^2) and zinc (cathode, 15.75 cm^2), and a Nafion 117 proton exchange membrane (Wilmington, DE, USA) was used to separate both chambers, where the selection of these electrodes is due to the high porosity of carbon and the high conductivity of metallic materials. The area of the anode electrode was 30 cm^2, and the cathode 15.75 cm^2 (see Fig. 1).

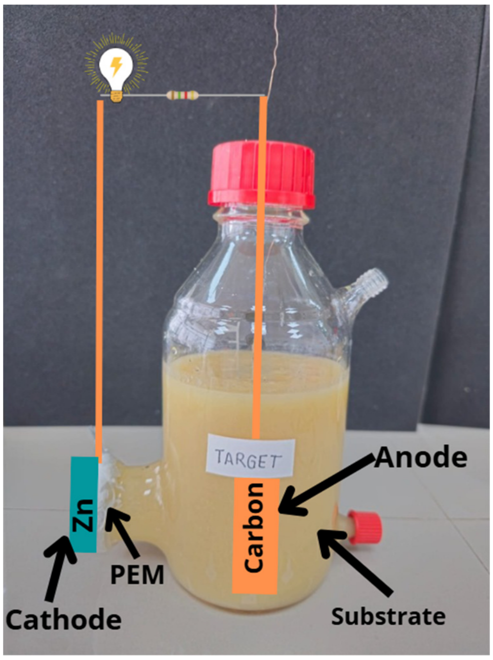
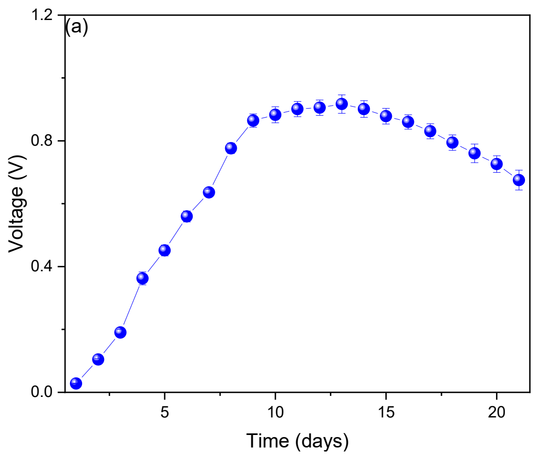


Fig. 1. MFC design used.

The microbial fuel cells were constructed with the cathode electrode sealed at one end and the anode electrode centrally positioned on the lid. Each MFC was filled with 800 mL of processed asparagus waste, prepared and maintained at an ambient laboratory temperature of 21 °C. The external circuit was assembled using tin-soldered 8 mm copper wires, ensuring a strong electrical connection. The copper wire was linked to a 100 Ω external resistor to complete the circuit. This setup was replicated identically for three separate microbial fuel cells. Measurements of current (I) and voltage (V) were obtained using a Truper MUT-830 Digital Multimeter for precision. The chemical oxygen demand (COD) of the asparagus waste was analyzed using the closed reflux colorimetric method in adherence to the NTP 360.502:2016 standard. Internal resistance was evaluated with a Vernier energy sensor, capable of measuring±30 V and±1000 mA. The Power Density (PD) and Current Density (CD) values were calculated using the formulas PD = V^2_{MFC} / (R_{ext}.A) and CD = V_{MFC} / (R_{ext}.A), where V_{MFC} represents the MFC voltage, A is the electrode area, and R_{ext} denotes the external resistors. The resistors used included values of 0.2 (±0.05), 5 (±0.50), 20 (±2.40), 50 (±6.52), 120 (±10.55), 240 (±15.62), 480 (±20.64), 520 (±30.88), 780 (±50.75), and 1000 (±60.55) Ω [22]. To strengthen the scientific validity of the experimental outcomes and ensure consistency in data interpretation, each measurement was performed in triplicate using three identically constructed MFCs under controlled environmental conditions. Data represent mean±SD (*n* = 3), providing a reliable assessment of variability across replicates.

III. Results and Discusión

Fig. 2(a) illustrates the voltage evolution of the MFCs, showing an increase from 0.012±0.001 V on day one to a peak of 0.917±0.029 V on day thirteen, followed by a decline to 0.675±0.035 V on the final day. This trend is attributed in the literature to chemical reactions initiated by the substrate, which generate a potential difference between the electrodes [23]. Similarly, Fig. 2(b) presents the corresponding electric current values. The maximum current of 2.332±0.055 mA was achieved on day thirteen, after which the current decreased to 1.653±0.087 mA by the end of the monitoring period. Initial low current levels are associated with the gradual acclimation of a sparse microbial population; as microorganisms colonize the electrode surfaces and the concentration of electron acceptors increases, a peak current is reached [24, 25]. Reports on using fruit waste—such as banana, lemon, orange, watermelon, and papaya—as substrates in MFCs have recorded peaks of 0.650 V and 0.7 mA over a 35-day period [26]. Moreover, the internal resistance of the system—which includes contributions from the substrate, electrodes, and membranes—directly affects the electrical output. Higher internal resistance reduces electron transfer efficiency, thereby diminishing current flow [25]. Additionally, the conversion of organic acids into acetate, hydrogen, and CO_2 can decrease the availability of readily degradable substrates, leading to lower current if microbial activity slows or inhibitory byproducts accumulate [23, 24].



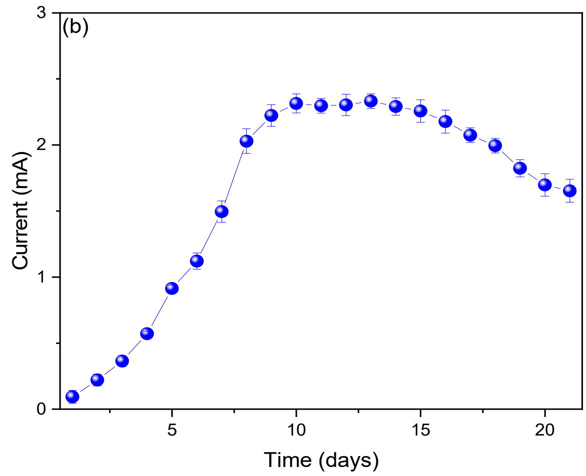


Fig. 2. Monitoring of (a) voltage and (b) electric current values of microbial fuel cell.

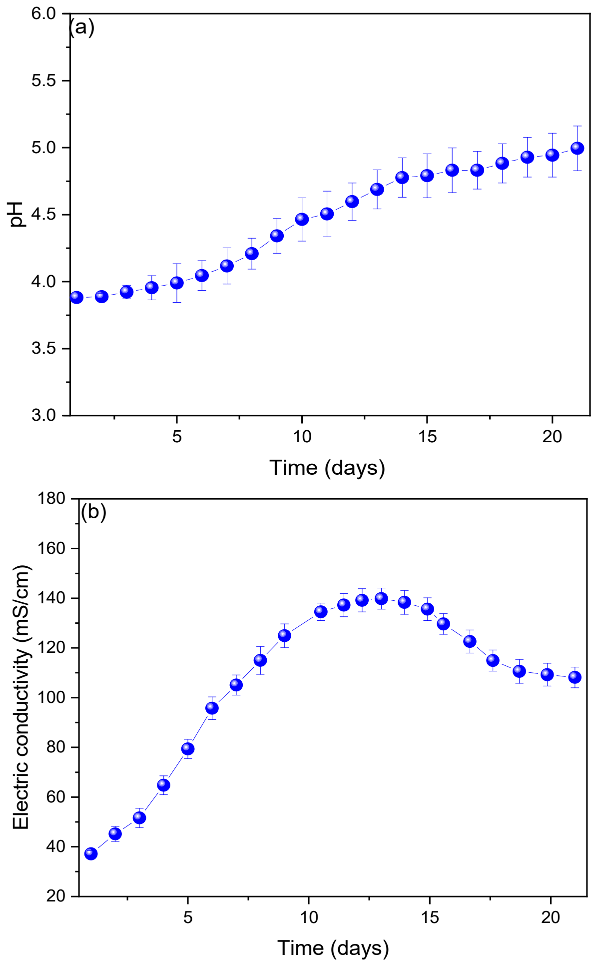


Fig. 3. Monitoring of (a) pH values and (b) conductivity of microbial substrate.

The pH value is critical for the performance of Microbial Fuel Cell (MFC) devices. Fig. 3(a) illustrates the pH measurements over time, revealing that values range from moderately acidic to slightly acidic, with an optimum of 4.777±0.146 recorded on day thirteen. The unique chemical composition of asparagus waste plays a significant role in influencing pH; As microorganisms degrade organic compounds such as carbohydrates, proteins, and dietary fiber, they produce organic acids (e.g., acetic and lactic acids) that subsequently lower the pH [27]. Additionally, variations in pH can be attributed to the hydrolysis and acidification processes that occur during fermentation [28]. Fig. 3(b) displays the electrical conductivity values obtained throughout the study. An increase in conductivity is noted from 37.159±1.332 mS/cm on the first day to 139.841±4.254 mS/cm on the thirteenth day, followed by a gradual decline to 108.135±4.163 mS/cm by the final day. Electrical conductivity in asparagus waste is influenced by the presence of dissolved ions—such as potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), and phosphate (PO_4^{3-})—which contribute substantially to its conductive properties [29]. The subsequent decrease in conductivity is likely due to the sedimentation of residual organic matter during the later stages of monitoring [30]. Typically, optimal MFC performance is achieved within a slightly acidic to neutral pH range of approximately 6.5 to 7.5 [31]. However, this range may vary depending on the microorganisms involved. To maintain consistent pH levels, buffers can be employed, or controlled additions of acids and bases can be used [32].

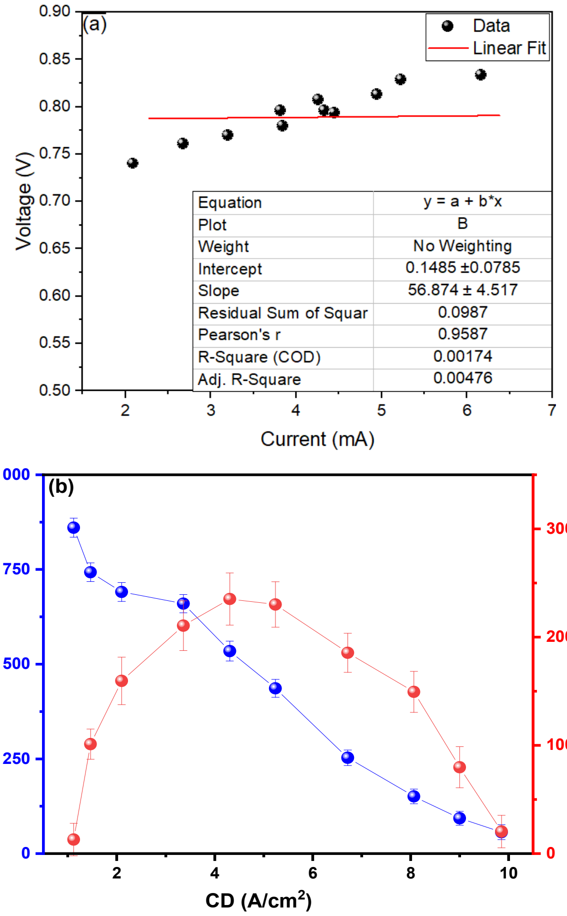


Fig. 4. Values of (a) internal resistance and (b) power density as a function of current density.

Fig. 4(a) presents the average internal resistance of the microbial fuel cell, calculated on the thirteenth day using Ohm's Law (V = RI), which yielded a value of 56.874±4.517 Ω. For comparison, Aleid *et al.* [33] reported an internal resistance of 734 Ω when using mango peel waste as a substrate, noting that copper wire is recommended for the external circuit due to its low cost and high electrical conductivity. Previous studies have shown that employing metallic materials in electrode fabrication can reduce internal resistance because of their inherent high conductivity [34]. In the case of asparagus waste, the degradation of organic matter releases ions and produces organic acids, which can further lower electrical resistance [17]. High system resistance results in greater energy losses as heat, causing a voltage drop and, consequently, a lower current output [35]. The interrelationship between current, resistance, and power in an MFC adheres to Ohm's Law [36], where increasing resistance leads to a decrease in current, thereby reducing the maximum power output. MFCs typically operate within an optimal resistance range that maximizes power generation [37]. Fig. 4(b) illustrates the Power Density (PD) values measured on day thirteen, with a maximum PD of 235.213±24.118 mW/cm², a Current Density (CD) of 4.685 A/cm², and a peak voltage of 860.336±25.155 mV. In comparison, Apollon et al. (2024) used urine as a substrate in their MFCs, achieving 7.60±0.06 mW/m² and demonstrating improved PD values with electrode modifications [38]. The power density of MFCs depends on several factors, including the substrate's composition. Asparagus waste is rich in carbohydrates, proteins, and bioactive compounds that are readily degraded by electrogenic microorganisms, although inhibitory substances (e.g., high concentrations of saponins) may reduce microbial activity and the resulting power density [20, 39]. Furthermore, increasing the anodic electrode area generally enhances PD, although with limitations inherent to the electrode's characteristics. Therefore, detailed studies on electrode types are recommended to determine their maximum potential [39]. Power density remains a critical parameter for assessing MFC performance, and optimizing factors such as microorganism selection, electrode materials, and operating conditions can significantly enhance the efficiency and viability of MFCs as sustainable energy sources [40, 41].

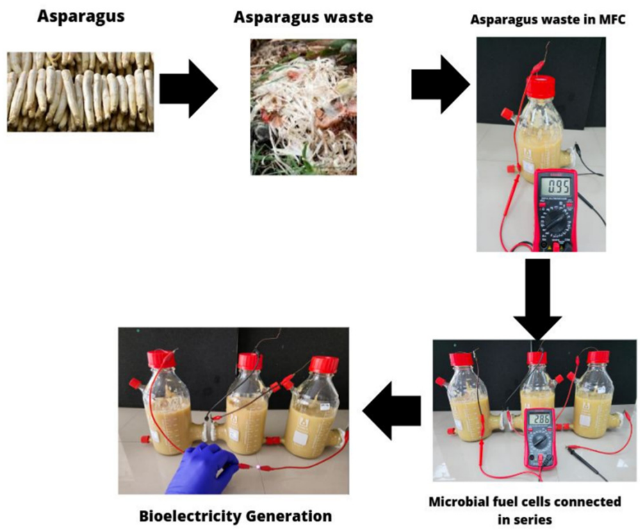


Fig. 5. Schematic of the bioelectricity generation process.

Fig. 5 illustrates the generation of electrical energy from asparagus waste using microbial fuel cells (MFCs). When connected in series, the MFCs produced 2.86 V—sufficient to power the LED network. The economic and financial viability of microbial fuel cells depends on factors such as material costs, energy conversion efficiency, government support, and market demand for renewable energy. Although these devices offer environmental benefits and contribute to sustainability, their large-scale deployment faces economic challenges, including competition from lower-cost energy sources and the requirement for significant upfront investments.

The use of asparagus waste in MFCs presents substantial practical applications, particularly in regions where asparagus is extensively cultivated, such as Peru, China, Mexico, and the United States. For instance, as the world's largest exporter of asparagus, Peru generates considerable waste during harvesting and processing that can be repurposed for MFC applications. To implement large-scale systems, it is essential to integrate them with industrial waste treatment plants to achieve combined energy generation and waste management. However, scaling up the use of asparagus waste introduces challenges, especially during harvest seasons, necessitating storage solutions or co-substrate strategies to maintain continuous operation. Furthermore, the development of this system will require investments in infrastructure, including reactors, electrodes, and monitoring systems.

Table 1 presents a comparison with fruit residues such as banana peel, which in an MFC achieved a peak voltage of 0.650 V and a maximum current of 0.7 mA after 35 days; by contrast, asparagus waste reached 0.917 V and 2.332 mA in just 13 days, representing a 41 % increase in voltage and a 3.3-fold rise in current. Moreover, while banana peel yields power densities on the order of 1 mW/m², asparagus delivered 235 mW/cm²—alongside a very low internal resistance (56.9 Ω)—demonstrating markedly superior bioelectrogenesis efficiency and kinetics. Although dragon fruit pulp exhibits an even higher power density, its peak voltage is 50 % lower, making series stacking of cells more challenging without significantly upsizing external circuitry. Compared with lettuce waste, asparagus achieves a similar peak voltage while sacrificing only 35 % of the power density and simultaneously reducing internal resistance by 35 %, markedly improving electron-transfer efficiency. Taken together, asparagus waste strikes an optimal balance of high voltage, low internal resistance, and rapid attainment of peak output, positioning it as a particularly attractive substrate for scalable bioelectricity applications.

Table 1. Performance comparison of MFCs with different substrates

Substrate	Peak Voltage (V)	Peak Current (mA)	Power Density (mW/cm²)	Internal Resistance (Ω)	Time to Peak (days)
Banana peel [21]	0.650	0.7	~0.000145	Very high (not reported)	35
Dragon fruit Pulp [3]	0.46±0.03	–	304.33±16.51	–	–
Lettuce waste [16]	0.959±0.026	–	378.145±5.417	87.594±6.226	–
Asparagus residue	0.917±0.029	2.332±0.055	235.213±24.118	56.874±4.517	13

IV. Conclusion

The research highlighted the significant potential of asparagus waste as a substrate for microbial fuel cells (MFCs). Over a 21-day monitoring period, the system achieved a maximum power density of 235.213±24.118 mW/cm², accompanied by a current density of 4.685 A/cm² and an internal resistance of 56.874±4.517 Ω. The MFCs reached an average maximum voltage of 0.917±0.029 V and an average current of 2.332±0.055 mA. These values were observed at an optimal pH of 4.777±0.146 and an electrical conductivity of 139.841±4.254 mS/cm on the thirteenth day of operation. Notably, connecting three MFCs in series resulted in a combined voltage of 2.86 V on the same day, which was sufficient to illuminate an LED bulb, demonstrating the scalability and practical applications of the system. To advance this promising technology, future research should prioritize the standardization of critical parameters such as the pH levels identified in this study. Additionally, the implementation of biological catalysts to enhance electrical output warrants exploration. A comprehensive economic cost-benefit analysis is also essential to evaluate the feasibility of MFCs within specific operational contexts.

Further investigations could explore methods to optimize energy efficiency by improving reactor designs and incorporating biological catalysts. Strategies to ensure a stable supply of waste year-round, such as effective storage solutions or the integration of co-substrates, should also be examined. Scaling up these systems within industrial waste treatment facilities offers the dual benefits of renewable energy generation and sustainable agricultural waste management. This approach is particularly promising for asparagus-producing regions like Peru, presenting a transformative step toward renewable energy adoption and environmental conservation.

The research demonstrates a remarkable innovation by showing that asparagus waste, an abundant byproduct along the Peruvian coast, can serve as a highly efficient substrate for electricity generation in microbial fuel cells. Reaching a peak of 0.917 V and 235 mW/cm² in just 13 days, it outperforms other organic wastes such as banana peels or fruit pulp. This superior performance stems from asparagus's rich composition of carbohydrates, proteins, and bioactive compounds, which optimize microbial kinetics and minimize internal resistance. Furthermore, the study standardizes key parameters (pH, conductivity, and resistance), thereby facilitating replication and scale-up.

Exploring the implications for agricultural waste management in Peru reveals enormous potential for circularity: large asparagus plantations could channel their processing residues into integrated MFC facilities within agro-industrial operations. Such an approach would not only alleviate disposal challenges and reduce greenhouse gas emissions but also generate new income streams and clean energy. However, logistical hurdles—such as seasonal fluctuations in waste supply and the requirement for specialized infrastructure—demand a supportive public-policy framework that encourages investment, public-private partnerships, and technical training. In sum, deploying MFCs fueled by asparagus waste could transform Peru's agricultural-waste landscape, aligning its export-focused production with sustainability and circular-economy goals.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

R.-F.S.: Conceptualization; Methodology; Writing -

Original Draft, N.M.-O..: Conceptualization; Supervision; Review & Editing. C.-C.L. and D.L.C.-N.: Conceptualization; Supervision; Review & Editing. All authors had approved the final version.

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