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Obtaining Sustainable Electrical Energy from Pepper Waste

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Abstract: Currently, two significant problems involve the government, population, and environment: the accelerated increase in organic waste and the need to replace conventional energy with environmentally sustainable energy. The sustainable use of organic waste is being intensely investigated to generate energy plants that produce alternative sustainable electrical energy beneficial to the population at a low cost. The novelty of this research is given by the use of pepper waste as fuel in the generation of bioelectricity, giving added value to these types of waste, benefiting farmers and companies dedicated to the export and import of these fruits, because they will be able to generate their own electrical energy using their own waste at a lower cost. For this reason, this research uses pepper waste as fuel in single-chamber microbial fuel cells manufactured at a low cost as its primary objective. The maximum values of the electric current (5.118 ± 0.065 mA) and electric potential (1.018 ± 0.101 V) were shown on the fourteenth day, with an optimal operating pH of 7.141 ± 0.134 and electrical conductivity of 112.846 ± 4.888 mS/cm. Likewise, a reduction in the COD was observed from 1210.15 ± 0.89 mg/L to 190.36 ± 16.58 mg/L in the 35 days of monitoring and with a maximum ORP of 426.995 ± 8.615 mV, whose internal resistance was 33.541 ± 2.471 Ω. The peak power density was 154.142 ± 8.151 mW/cm^2 at a current density of 4.834 A/cm^2, and the *Rossellomorea marisflavi* strain was identified with 99.57% identity.

Keywords: pepper waste; sustainable energy; bioelectricity; microbial fuel cells; organic waste

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1. Introduction

Agroindustry waste increases by a range of 5 to 10% annually, which generates harmful effects on the environment because these wastes do not have an adequate collection system, leading to the contamination of the soil, air, and water [1,2]. In 2023, more than 3.6 billion tons of agricultural waste will be generated due to the high demand for food by the world's population. This large amount of waste originating in the food chain has led to waste agricultural products being converted into by-products to give value to this type of waste, generating a more valuable product [3–5]. Approximately 26% of global greenhouse gas emissions are attributed to food waste when it ferments in the environment [6]. In recent years, governments and researchers have witnessed enormous efforts to make changes in electrical energy generation from an environmental perspective; it has been reported that 83.5% of electrical energy production comes from fossil sources (coal, oil, and gas) [7–9]. In 2022, it was reported that 675.11 TWh was generated using biomass as a source. These values are notable compared to 1999 when no energy was generated from waste [10,11].

Effectively using agroindustry waste to generate electrical energy and dumping it into the environment without causing damage is a cutting-edge and economical solution to these two problems [12]. In this sense, microbial fuel cells (MFCs) are a sustainable technology that can be applied to treating organic waste [13]. This technology is still being developed as a sustainable alternative source of electrical energy generation that uses chemical oxidation–reduction from organic waste used as fuels (substrates) [14,15]. MFCs are composed of two chambers (anodic and cathodic) separated by a proton exchange membrane on the inside and joined by a circuit on the outside [16]. The electrodes inside the chambers are essential because they capture electrons and conduct them through the external circuit, generating electricity. The function of MFCs is to convert organic waste into bioelectricity by using microorganisms (generally found in waste) that act as biocatalysts [17,18]. Verma M. and Mishra V. (2023) used banana peel waste as fuel in their microbial fuel cells, managing to generate peaks of electrical potential and electrical current of 488 $\pm$ 1.5 mV and 0.21 mA on the eighth day of the operation of their MFCs [19]. Lettuce waste has also been used with fuel in single-chamber MFCs, using Zn/Cu as electrodes, managing to generate peaks of electrical potential and power density of 0.959 $\pm$ 0.026 V and 5.697 $\pm$ 0.065 mA on day 14, also achieving identifying with 99.59% certainty the *Stenotrophomonas maltophilia* bacterium in the anodic biofilm [20]. Aleid et al. (2023) generated the maximum values of electric potential and power density of 102 mV and 0.099 mW/m^2 on day 25, using mango waste and an external resistance of 5000 Ω as fuel [21]. Red dragon fruit (pitahaya) waste has also been used as fuel in single-chamber MFCs, achieving a maximum electrical potential and power density of 0.46 $\pm$ 0.03 V and 304.33 $\pm$ 16.51 mW/cm^2 on the tenth day and showing an internal resistance of 75.58 $\pm$ 5.89 Ω [22].

Peppers play an essential role in everyone's diet due to their nutritional value, due to the fact that they contain a high content of vitamins A, C, and E, in addition to protein, fiber, potassium, and magnesium, becoming a reinforcement for the immune system, thus benefiting health [23–25]. The consumption of peppers maintains healthy skin and eyesight and reduces the risk of fatal diseases such as cardiovascular diseases and cancer [26]. Recently, the Food and Agriculture Organization of the United Nations (FAO) reported that in 2020, around 540 thousand metric tons of pepper were produced worldwide, with Brazil, Vietnam, India, Indonesia, and Malaysia being the countries with the highest production, generating a large amount of waste that can fuel microbial fuel cells [27,28]. The novelty of the present study is that no report has been published on the use of pepper waste as fuel in single-chamber microbial fuel cells, where carbon and zinc electrodes were placed vertically to obtain the maximum efficiency of the MFCs. The study identified the microorganisms attached to the biofilm responsible for capturing the electrons. This scientific report is the first research document that uses this technology with this type of substrate.

The main objective of this research is to analyze the capacity of pepper waste as fuel in single-chamber microbial fuel cells. For this, the parameters of electrical conductivity, chemical oxygen demand (COD), electrical potential, electrical current, and power density as a function of current density were evaluated for 35 days. The internal resistance of the MFCs was also found, and the microbes existing on the anode electrode were molecularly identified. This research will generate electrical energy through pepper waste in a sustainable way so that farmers, companies, and governments can use it, generating value from the waste currently found at no cost.

2. Materials and Methods

a Single-chamber microbial fuel cells:

As illustrated in Figure 1, the single-chamber microbial fuel cells (MFCs-SC) were manufactured from prismatic polyethylene, in which a circular hole of a 15 cm radius was made at one end of the prism to place the cathode electrode (Zn) with an area of 148 cm^2; in the center of the MFCs, the 200 cm^2 carbon electrode was placed, and between the cathode electrode and the substrate used, Nafion 117 (Chemours, Wilmington, DE, USA) was placed as a membrane proton exchange, while the electrodes were joined on the outside with a resistance of 100 Ω.

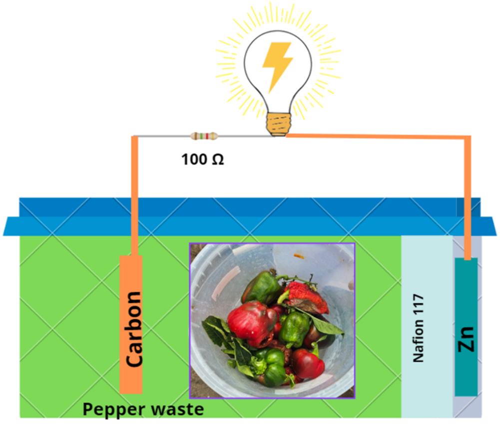

Figure 1. A schematic of the single-chamber microbial fuel cell device.

b. Collection of samples used as substrates

The pepper waste was collected from the Huanchaco, Trujillo, La Libertad, Peru fields, Figure 2. The samples were collected from the soil for subsequent cleaning in the laboratory of Cesar Vallejo University; 2.5 kg was collected and washed several times until all impurities were eliminated. They were allowed to dry at 25 ± 1 °C for 36 h so that 800 mL of pepper extract was obtained using an extractor (extractor, Labtron, Surrey, UK, LDO-B10-USA), the solution used as fuel in the MFCs.

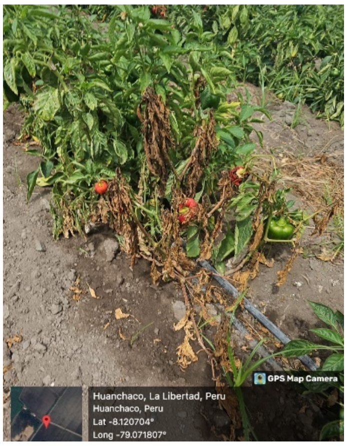

Figure 2. Location of sample collection.

c. Analysis of electrochemical parameters

The voltage and electrical current values were monitored for 35 days using a digital multimeter (Truper MUT—830 Digital Multimeter, Vitrek, CA, USA) and an external resistance of 100 Ω. The COD (chemical oxygen demand) values were measured using the closed reflux colorimetric method according to the NTP 360.502:2016 standard [29]. In contrast, the values of the electrical conductivity, pH, dissolved solids, and oxidation–reduction potential (ORP) were measured using a multiparameter (HI98194 Multiparameter Meter). The internal resistance values of the MFCs were calculated using an energy sensor (Vernier- ± 30 V and ± 1000 mA). PD (power density) and CD (current density) values were calculated using the method of Segundo et al. (2022) using the external resistances of 0.3 (±0.1), 3 (±0.6), 10 (±1.3), 50 (±8.7), 100 (±9.3), 220 (±13), 460 (±23.1), 531 (±26.8), 700 (±40.5), and 1000 (±50.6) Ω [30].

d. Molecular characterization of energy-generating bacteria

The microbiological study was carried out on the electrode of the anodic chamber; the surface of the electrode was rubbed with a sterile swab, and the sample was placed on the surface of the solid culture medium (MacConkey Agar). Meanwhile, with the bacteriological aza, the striation was carried out by exhausting the sample on the surface of the MacConkey. This process was carried out in each sample. The seeded plates were incubated at 35.5 °C × 24 h. The colonies present after incubation were replicated in tubes with slanted nutrient agar to preserve them for the subsequent molecular study of the 16S rRNA gene, which was carried out at the company ECOBIOTECH LAB SAC.

3. Results and Analysis

The values of the electrical potential increased from the first day (0.058 ± 0.005 V), with its maximum value being 1.018 ± 0.101 V on day 14 and then showing a successive decrease until day 35 (0.442 ± 0.194 V), Figure 3a. Due to the large amount of organic matter in the MFCs, the oxidation–reduction chemical processes generate power (voltage) differences between the electrodes in the first days, and the voltage values can increase by introducing oxygen into the anodic region [31,32]. The high voltage values observed are due to the biofilm area formed by the adhesion between the community of microbes present that was diverse and active [33]. On the contrary, the decrease in the electrical potential values is due to the end of the organic oxidation processes, while the decrease in the last days is due to the microbial reduction rate [34]. Furthermore, the literature has reported that the increases in electrical potential are due to the inoculation of fresh waste; organic matter wears out, causing a decrease in potential values [35].

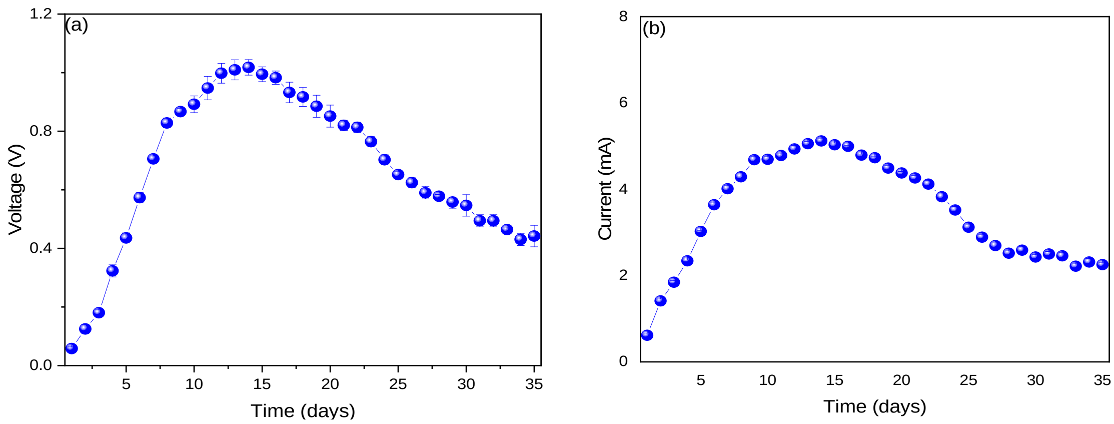

Figure 3. A report on the monitoring carried out of the values of the (**a**) voltage and (**b**) electric current.

The electrical current varied during monitoring; the MFCs on the first day showed 0.615 ± 0.019 mA and then increased to 5.118 ± 0.065 mA on day 14 and then showed a continuous decrease until day 35 (2.252 ± 0.089 mA). The formation of the uniform and porous biofilm is important to capture the electrons generated by the microbes during their metabolism. These electrons, when transmitted through the external circuit, generate a flow, thus producing the electric current [36,37]. The values of the electric current decrease when the organic matter is depleted because the microbes lose their nutrients to carry out their metabolism and release electrons to the medium [38]. Lettuce waste has been reported as substrates in MFCs, generating electrical current peaks of 5.697 ± 0.065 mA, mentioning that the corrosion of the metal electrodes in the last days of the operation of the MFCs influenced the decrease in its current values [39]. Abubakar et al. (2023) reported that the absence or low concentration of exoelectrogenic microbes or other types of microorganisms with high concentrations of organic matter leads to the low efficiency of the MFCs, and the absence of microorganisms is due to the inadequate choice of the standardization of the pH value during the operation of the MFCs [40]. Note that the production of electrons generating electric current is due to the conversion rate of the used substrate (as vegetable waste) into the metabolism of microorganisms and the rate of electron transfer by bacteria to the surface of the anode electrode [41].

The pH values increased from the border of slightly acidic (3.874) to slightly alkaline (9.311 ± 0.417), with an optimal pH value shown on day 14 of 7.141 ± 0.134, Figure 4a. The literature review mentioned that bacteria require a neutral pH for adequate growth, while the reduction process that occurs in the cathode chamber tends to have an alkaline pH [42,43]. The standardization of the pH value is of utmost importance because microbes need an adequate value for their growth and generation of electrons [44]. Compared with previous studies, Verma et al. (2023) used banana waste as a substrate in their MFCs, which operated between values of 5.23 and 7.25, observing that the resistance values of the cells vary with the variation in pH [45]. The literature has observed that with an increase in electrical conductivity, internal resistance values decrease and vice versa [46]. The electrical conductivity values shown during the monitoring of the MFCs show an increase in their values from the first day (53,650 ± 1073 mS/cm) to day 14 (112,846 ± 4888 mS/cm) and then decrease until the last day (48.896 ± 7.471 mS/cm) of monitoring, Figure 4b. As reported by Sreelekshmy et al. (2020), the values of electrical conductivity tend to increase due to the acidic conditions shown by the substrates; as these conditions vary due to various factors, the values decrease [47]. Yaqoob et al. (2022) used local fruit waste from Malaysia, showing an electrical conductivity of 59 µS/cm, where the reduction in electrical conductivity values is due to the increase in the resistance of the substrate used, generally in the last few days of monitoring due to sedimentation observed in used waste [48]. Furthermore, Kebaili et al. (2021) reported an electrical conductivity of 4.3 S/cm in their fermentative fruit juice substrate and also mentioned that the larger the ionic particles the substrate has, the greater the electrical conductivity and the lower the internal resistance of the MFCs [49].

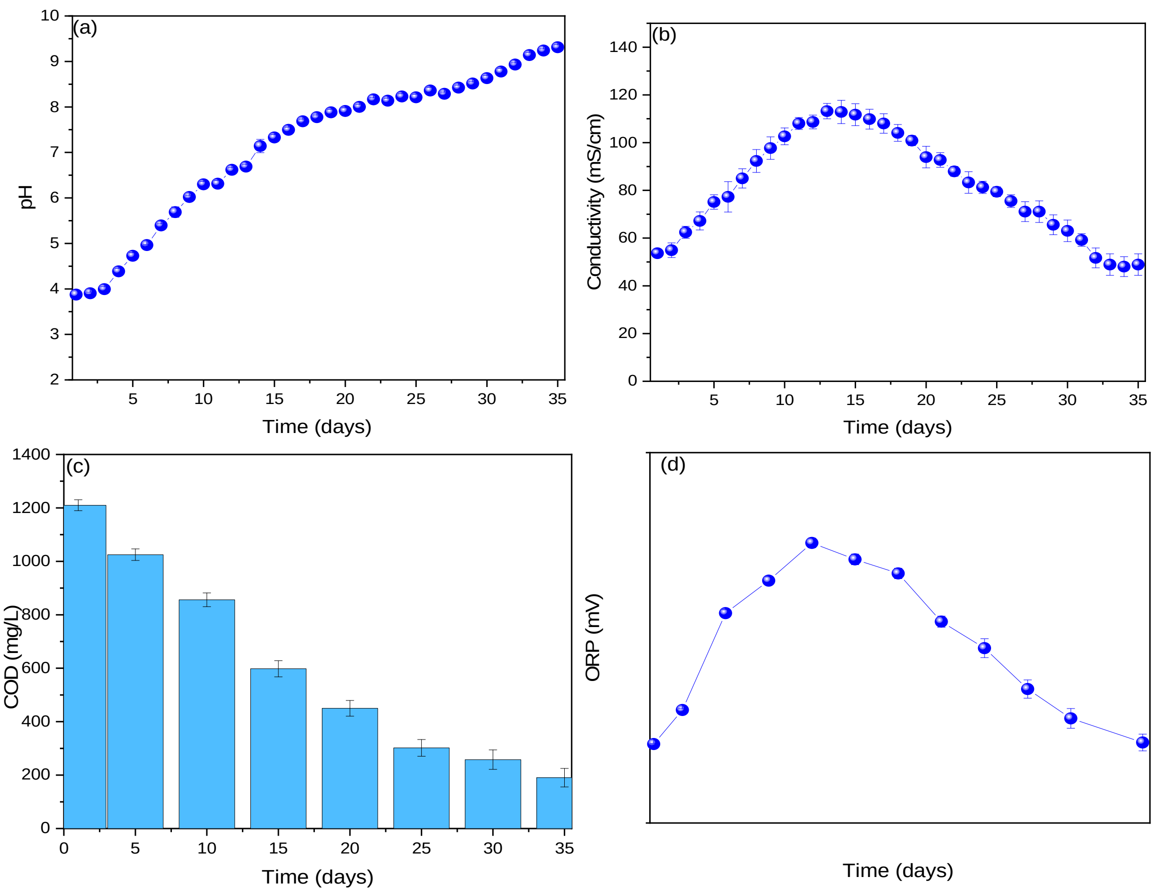

Figure 4. A report on the monitoring carried out of the values of the (**a**) pH, (**b**) conductivity, (**c**) COD, and (**d**) ORP.

Figure 4c shows the monitored COD values, observing a reduction of 84.27 ± 4.51% (190.36 ± 16.58 mg/L) compared to the first day (1210.15 ± 0.89 mg/L). The reduction in the COD confirms that the organic substances were oxidized by the microorganisms present in the substrate and that as the electrons were generated, a continuous decrease in the suspended organic matter occurred [50,51]. Rincón et al. (2022) used banana waste as fuel in their MFCs, managing to reduce the COD by 85.4 ± 1.0% due to the degradation of banana waste where they found salts belonging to the stems and green peels; these salts helped the transport of electrons giving stability to the output potential [52]. The reduction in the COD is related to the drop in voltage due to the decrease in the metabolism of microbes [53]. The ORP values increased from the first day (127.843 ± 1.210 mV) to day 15 (426.995 ± 8.615 mV) and then showed a successive decrease until day 35 (130.391 ± 13.554 mV), Figure 4d. In the literature, it has been reported that electrical energy is released when it is converted from a lower ORP to a higher ORP, which is why the increase in the ORP differential between the anode and cathode leads to an increase in the production of electrical energy [54,55]. Furthermore, a large surface area of the biofilm generates the electrons produced from the reactions within the biofilms, which are transferred directly to the anodic electrode, avoiding the loss of electrons in the anodic solution [56]. Aguero et al. (2023) reported a maximum ORP of 378 mV in their single-chamber MFCs using wastewater waste, where they mention that oxidizing environments facilitate electroactive microbes to grow favorably, leading to an increase in generated electrons, favoring the increase in the values of the electric current [57]. The substrates whose ORP values exceed 100 mV should be considered anaerobic environments; on the other hand, ORP values that are less than 100 mV should be considered aerobic due to the conditions in which microbes must metabolize to produce electrons [58].

The maximum power density generated was 154.142 ± 8.151 mW/cm^2 at a current density of 4.834 A/cm^2 at a maximum potential of 901.894 mV, Figure 5a. The increase in organic matter tends to increase the power density values, as well as the increase in the areas of the electrodes and the adequate spacing of the electrodes, which have increasing PD if the organic matter remains constant [59–61]. A greater amount of oxygen in the cathode chamber of the microbial fuel cell generates a greater number of electrons, improving the values of power density and voltage by encouraging the transfer rates of protons and electrons [62]. Rice-washing wastewater has been used as substrates, showing a power density of 1 mW/m^2 with a power density of 59.4 mA/m^2 in 5 days, attributing the rapid increase in PD values to the rapid formation of anodic biofilm due to the yeast content shown by the substrate used [63]. Organic wastes (tangerine, lime, and orange) have been used as substrate in single-chamber MFCs showing a power density of 72 ± 1.4 mW/cm^2 at a CD of 0.9 mA/cm^2 on the seventh day, reporting that the use of zinc electrodes generate rust and corrosion in the biofilm form, decreasing the effectiveness of the MFC in generating power density [64]. Yaqoob et al. (2022) in their research showed a power density of 41.58 mW/m^2 using food waste as a substrate, mentioning that the PD can be increased by placing catalyzing microorganisms on the substrate to obtain a better conduction of the generated electrons [65].

The internal resistance ($R_{int.}$) shown in Figure 5b was obtained using Ohm's Law (V = IR), where the values of the electric current were placed on the "X" axis while the values of the electric potential were placed on the "Y" axis, where the slope of the linear fit represents the $R_{int.}$ of the MFCs, whose calculated value was 33.541 ± 2.471 Ω. The low resistance found is due to the high electrical conductivity shown in Figure 4b on the fourteenth day, as well as the metallic nature composition of the electrodes that allowed for a low resistance to the passage of electrons from the anodic to cathodic chamber [66,67]. Likewise, the oxidation of organic matter by bacteria generates free electrons that, when flowing through the external circuit and reaching the cathode, react with the protons (which flowed through the PEM) and water, generating O_2; in a greater quantity of these reactions, the higher the PD values will be [68]. When there is a lower internal resistance, the electrons flow more easily, but this mobility is obstructed if the internal resistance of the MFCs is greater than external resistance [69]. Liu et al. (2020) reported an internal resistance of 162.9 ± 3.5 Ω and an electrical potential of 0.63 V using electrogenic bacteria in their MFCs and carbon electrodes as a substrate, showing the importance of reflux and aeration in the cells to increase PD values [70]. The mango waste in single-chamber MFCs has shown an internal resistance of 205.056 ± 25 Ω on the twenty-first day, mentioning that the high resistance value is due to poor biofilm formation due to the corrosion observed, but they showed high values of electric current (7.5948 ± 0.3109 mA) and electric potential (0.84546 ± 0.314 V), but it would be due to the metallic nature of the electrodes used (copper and zinc) that in the first days it did not show corrosion [71].

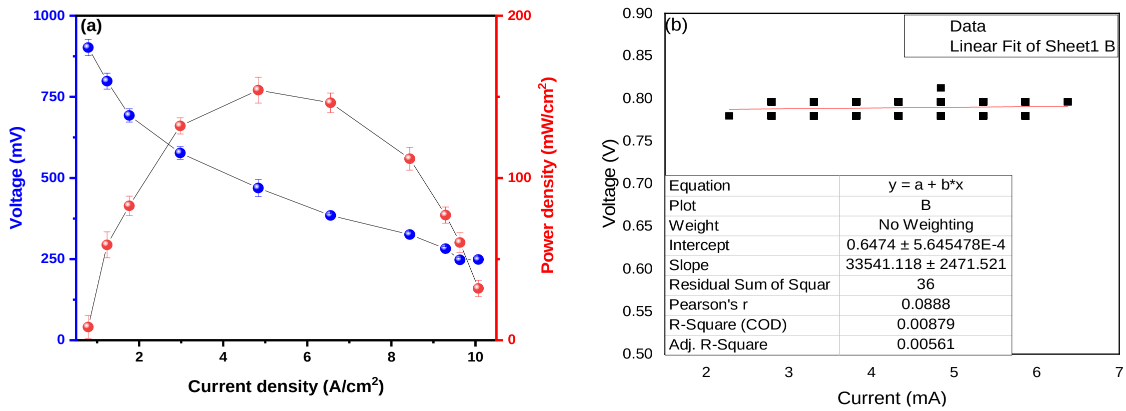

Figure 5. A report on the monitoring carried out of the (**a**) internal resistance and (**b**) power density vs. current density.

The *Rossellomorea marisflavi* strain was identified with an identity percentage of 99.57% (Table 1). These aerobic, spore-forming, mesophilic bacteria have circular colonies. They are mainly found in soil and can live in extreme conditions such as high pH, high temperatures, and high salt content, such as seawater from a tidal flat [72]. Souyung et al. (2019) reported results using red pepper powder (Capsicum annuum) as a substrate and rumen microorganisms in the anodic and cathodic chamber whose phosphate-buffered saline solution operated at pH 7.4, demonstrating that red pepper powder in microbial fuel cells causes an increase in power density from 24 mW/m^2 to 39.6 mW/m^2 ($p < 0.0001$) [73]. Rojas et al. (2023) identified through molecular techniques the species *Yarrowia phangngaensis* and *Pseudomonas stutzeri* present in the anodic chamber with pepper residues that would be involved in the transfer of electrons to the electrode, generating the maximum values of electric current of 6.04414 ± 0.2145 mA and electric potential of 0.77328 ± 0.213 V [74]. Recently, Yousef et al. (2024) demonstrated that the use of the species *R. marisflavi* strain Asu10 has a high potential in the renewable production of biohydrogen from agricultural lignocellulosic substrates without the need for pretreatment; the use of CaONP as a catalyst would increase the productivity of bio-H2 by said strain [75]. Bell pepper waste is reused for the benefit of the food and pharmaceutical industry due to the active ingredients it contains such as flavonoids, carotenoids, phenols, tocopherol, and polysaccharides that give them antioxidant, antibacterial, antifungal, immunosuppressive, and immunostimulant properties, including antidiabetic, antitumor, and neuroprotective properties, and also have the potential to act as functional food additives [76]. Finally, the microbial fuel cells were connected in series to observe the potential to generate bioelectricity. The MFCs managed to generate an electrical potential of 2.66 V that when placed with an LED bulb, turned it on successfully, Figure 6.

Table 1. Identification of molecules of microorganisms adhered to anodic electrode.

Code	Identified Species	Identity (%)	Accession Number
1	*Rossellomorea marisflavi*	99.57%	JCM 11544

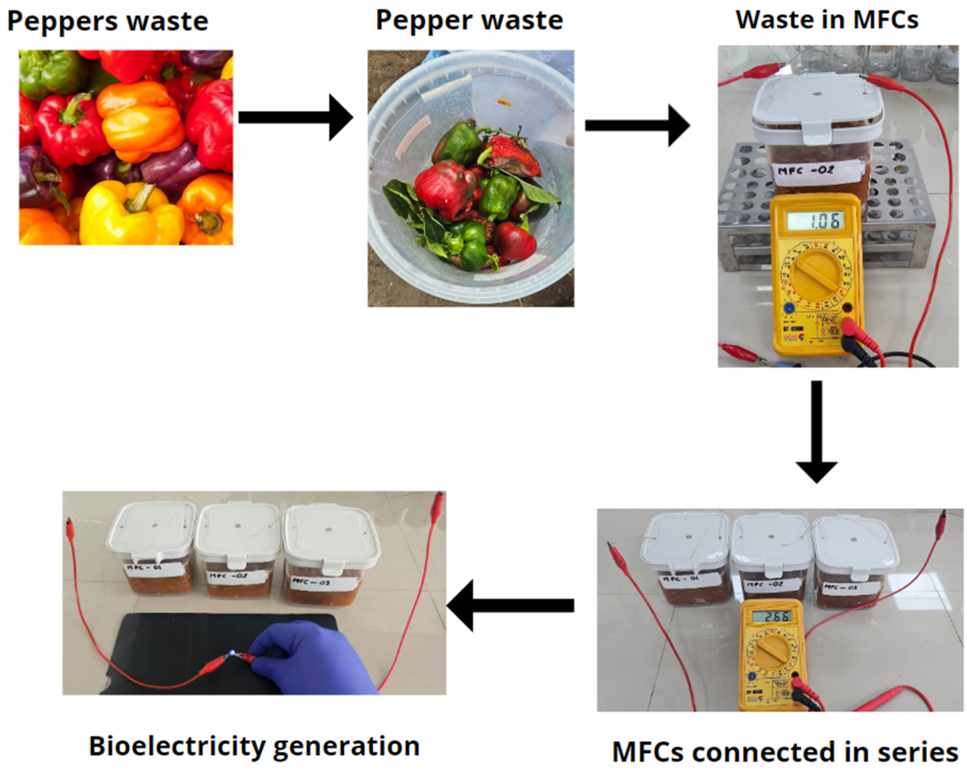

Figure 6. Design of bioelectric generation process.

4. Conclusions

Microbial single-chamber fuel cell (MFC-SC) technology is one of the most cost-effective and sustainable options for generating bioelectricity from organic waste. The MFCs-SC have proven in this research to be a biologically viable technique for reducing pepper waste and generating electrical energy. Furthermore, carbon and zinc electrodes are promising materials due to their electrical conductivity shown. The most relevant results are the generation of the voltage (1.018 ± 0.101 V) and electric current (5.118 ± 0.065 mA) with an electrical conductivity of 112.846 ± 4.888 mS/cm and an optimal pH of 7.141 ± 0.134 on the fourteenth day. Monitoring also observed a decrease in COD values by 85.4 ± 1.0%, while the maximum ORP observed was 426.995 ± 8.615 mV with an internal resistance of 33.541 ± 2.471 Ω. An important point is the reduction in COD values because the electrodes and organic waste used in this research will be proposed as an excellent prospect for reducing contaminated water with a high content of organic matter or heavy metals and a generator of electrical energy simultaneously. Also, the maximum power density observed was 154.142 ± 8.151 mW/cm^2 for a current density of 4.834 A/cm^2. It was possible to identify the *Rossellomorea marisflavi* strain on a molecular scale with 99.57% identity. Finally, the three microbial fuel cells manufactured were connected in series, producing an electrical potential of 2.66 V, necessary to light an LED light bulb. This research advances the use of waste as fuel in MFCs due to the high recorded values of electric potential, electric current, and power density for a long time.

Author Contributions: Conceptualization, R.-F.S.; methodology, C.-C.L.; validation, N.M.O. and N.S.-D.; formal analysis, R.-F.S. and D.L.C.-N.M.; investigation, R.-F.S. and D.L.C.-C.M.; data curation, D.L.C.-N.M.; writing—original draft preparation, N.T.-R. and C.-C.L.; writing—review and editing, R.-F.S.; project administration, R.-F.S. and D.L.C.-C.M. All authors have read and agreed to the published version of the manuscript.

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