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Potential Use of Coriander Waste as Fuel for the Generation of Electric Power

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Abstract: The increase in the population and its need to produce food has caused the level of contamination by organic waste to increase exponentially in recent years. Innovative methods have been proposed for the use of this waste and thus to mitigate its impact. One of these is to use it as fuel in microbial fuel cells to generate electricity. This research aims to generate bioelectricity using coriander waste in microbial fuel cells. The maximum voltage and current observed were 0.882 ± 0.154 V and 2.287 ± 0.072 mA on the seventh and tenth day, respectively, these values were obtained working at an optimum operating pH of 3.9 ± 0.16 and with an electrical conductivity of 160.42 ± 4.54 mS/cm. The internal resistance observed in the cells was 75.581 ± 5.892 Ω, with a power density of 304.325 ± 16.51 mW/cm^2 at 5.06 A/cm^2 current density. While the intensity of the final FTIR (Fourier transform infrared spectroscopy) spectrum peaks decreased compared to the initial one, likewise, with a percentage of identity, it was possible to attribute 98.97, 99.39, and 100% to the species *Alcaligenes faecalis*, *Alcaligenes faecali*, and *Pseudomonas aeruginosa*. Finally, the cells were connected in series, managing to turn on an LED light (red) with the 2.61 V generated. This research provides an innovative and environmentally friendly way that companies and farmers can use to reuse their waste.

Keywords: microbial fuel cell; bacteria; generation; bioelectricity; coriander waste

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1. Introduction

The increase in the population worldwide has generated great changes in the ecosystem; in 1960, there were less than 3100 million people and in 2020, there were more than 7800 million. This large increase has generated an exponential increase in different types of organic waste [1,2]. In addition, it has been reported that in the year 2020, the organic waste generated by people was approximately 54 to 64% of the total waste in developed countries, and approximately 715 million cubic meters of organic waste are generated daily worldwide [3,4]. On the other hand, the use of fuel from fossil sources has damaged the environment, but currently it continues to be one of the main sources of energy to keep society active, making the use of new technologies friendly to the environment a necessity to appease global warming [5,6].

Many countries are making efforts to stimulate the use of different types of waste, generating a circular economy in the process of reusing them, making the process sustainable [7,8]. In the search to reuse waste, creating benefit for society, microbial fuel cells (MFCs) technology has begun to be used because this technology is sufficiently capable of using different types of waste in the degradation process and generating bioelectricity at the same time [9–11]. There are different types of MFCs, among which it has been reported that single-chamber MFCs are the most versatile and economically viable for the future to be taken to larger scales. These types of cells are made up of two types of chambers (anodic and cathodic), Generally separated by a proton exchange membrane and an external circuit that joins the electrodes on the outside [12,13]. On the other hand, coriander (*C. sativum* L.) has increased its production and export, due to the fact that importing countries of this vegetable, such as the United States, Canada, Japan, and the European Union, have mainly increased the consumption of vegetables in general, and increased consumption of cilantro in the daily diet is mainly due to the fact that it has components that help alleviate inflammation problems and has been used for more than 2000 years because it is rich in minerals, vitamins, and iron but low in cholesterol; furthermore, not only is it used as food but also as traditional medicine to treat some diseases, for example, diabetes, insomnia, rheumatism, and intestinal gastroenteritis [14–16]. The increase in the consumption of this vegetable has generated an increase in waste, causing a problem for farmers and companies dedicated to the export and import of the fruit [17].

In this sense, works have been reported on the use of other wastes used as fuel for the generation of electrical energy in a MFC, for example, Rincón et al. (2022) fabricated single-chamber MFCs with graphite electrodes and anaerobic plantain debris as a substrate, managing to generate peaks of 0.35 V on the first day of operation and with a power density of 41.3 mW/m^2 and 0.287 mA/m^2 of current density [18]. Tomato waste has also been used as a substrate for the generation of electrical energy in single-chamber MFCs (with zinc and copper electrodes), managing to generate peaks of 1.1 V and 0.67 mA on day 15 of monitoring with a density of power and current of 224.77 mW/m^2 and 4.43 mA/cm^2, respectively; the high electrical parameters found are mainly due to the use of metallic electrodes, which facilitates the transport of electrodes [19–21]. The use of vegetable waste as a substrate has also been reported, managing to generate peaks of 0.804 V and 2.37 mA with an optimal power of 134 W whose registered power density was 211 mW/m^2 [22].

In this sense, the main objective of the research is the manufacture of single-chamber microbial fuel cells using zinc and copper as electrodes, and coriander waste as a substrate to observe their power for the generation of bioelectricity. For this, the parameters of electric current, voltage, pH, and conductivity were monitored for a period of 30 days; thus, the internal resistance, power density, and current density of the MFCs were also found. Finally, the microorganisms adhered to the anodic biofilm that generate electric current were molecularly identified. In this way, an innovative way of taking advantage of coriander residues will be given, generating bioelectricity and processing the waste of farmers and businessmen.

2. Materials and Methods

2.1. Fabrication of Microbial Fuel Cells

The anodic (copper, Cu) and cathodic (zinc, Zn) electrodes were fabricated both with an area of 200 cm^2; the rectangular-shaped anode electrode was placed inside the reactor and the rectangular-shaped cathode electrode was placed at the end of the MFC with one side of the electrode in contact with the environment; the separation distance between electrodes was 15 cm (see Figure 1). Both electrodes were joined by 8 mm copper wire on the outside, managing to form an external circuit with a resistance of $100 \pm 2\ \Omega$, the MFCs were performed in triplicate. The proton exchange membrane (PEM) was in contact with the cathode electrode and the substrate, whose membrane contained 10 mL of the concentration of 6 g of KCl plus 14 g of agar and 400 mL of H_2O.

2.2. Obtaining Coriander Waste

Coriander wastes correspond to the specimens not sold on the day by La Hermelinda market traders, located in Trujillo, Peru, who managed to collect a total of 4 kg. The collected residues were taken to the university laboratories in airtight bags and washed 5 times with distilled water to remove any type of impurities (for example, dirt obtained from the market) acquired from the environment, and then left to dry in an oven at room temperature, room at 35 ± 2 °C for 24 h. The coriander wastes were passed through an extractor (Labtron, LDO-B10-Camberley, Camberley, UK) to obtain juice from the waste. One liter of juice was obtained, which was placed in a beaker and stored until use.

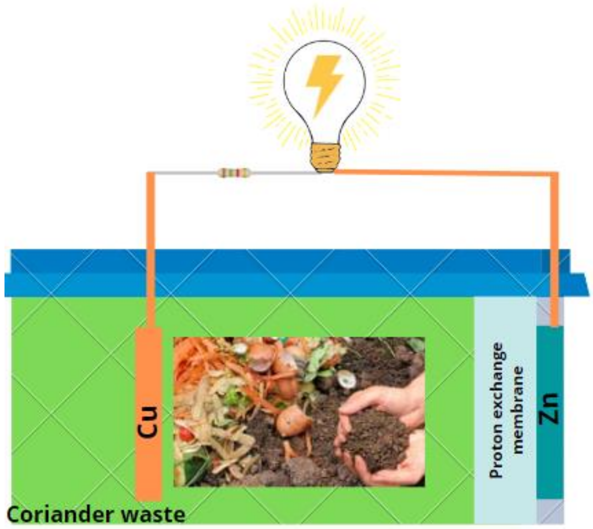

Figure 1. Schematic of the MFC.

2.3. Characterization of Microbial Fuel Cells

The values of electric current and voltage were obtained from a multimeter (Prasek Premium PR-85), whose monitoring was carried out for 30 days. The values of power density and current density were based on what was done by Segundo et al. (2022) [23]. The values of electrical conductivity (CD-4301 conductivity meter), pH (pH meter 110 Series Oakton), and degrees Brix (RHB-32 brix refractometer) were also monitored for 30 days, while for the resistance values of the MFCs, an energy sensor (Vernier-±30 V and ±1000 mA) was used.

2.4. Isolation of Microorganisms from the Anode

Anode plates were swabbed and inoculated in culture media such as Nutritive Agar, McConkey Agar for the isolation of bacteria, and Sabouraud Agar for the isolation of fungi and yeasts. The incubation time for the bacterial isolation media was 24 h at 35 °C, while the isolation of fungi and yeasts was 24 h at 30 °C.

2.5. Molecular Identification

Once isolated in the media, Gram staining was performed to identify the microscopic morphological characteristics. Finally, axenic cultures were carried out, which were sent to the BIODES laboratory (Laboratory of Integral Solutions Limited Liability Company, Royal Oak, MI, USA) for molecular identification.

3. Results and Analysis

Figure 2a shows the voltage values monitored at the MFCs for 30 days, from the first day the values increased from 0.731 ± 0.01 V to 0.882 ± 0.154 V on the seventh day and then decreased until the last day, Monitoring (0.321 ± 0.315 V). According to Torlaema et al. (2022), the high voltage values obtained in an initial state are mainly due to the formation of a mobile electron solution which initiates the transfer of electrons to the cathode [24], which is reaffirmed by Nosel et al. (2020) who also mentions that the fluctuations of the voltage values are due to the substrates used since some are more difficult to degrade than others, which also intervenes in the growth capacity of the microorganisms [25,26]. In Figure 2b, the values of the electrical current obtained from the monitoring carried out are observed. The current values increased from the first day, with its peak value being 2.287 ± 0.072 mA on the tenth day and then slowly decaying up to 1.337 ± 0.0828 mA on the last day of monitoring. The increase in the values of electric current is due to the process of adhesion of the microorganisms to the anode electrode in which the biofilm is formed, while the decrease in these values observed in the final stage of monitoring would be due to the fact that a large part of the substrate used as fuel begins to sediment (due to degradation) in microbial fuel cells [27–30]. These values found were higher than those shown by other authors. For example, Torlaema et al. (2022) using a single-chamber MFC managed to generate peaks of 18 mV on day 30, in which he used rice waste as a substrate [24]. Likewise, Parkash A. (2018) managed to generate 300 mV peaks in his single-chamber MFCs, using wastewater from the sugar process as a substrate [31].

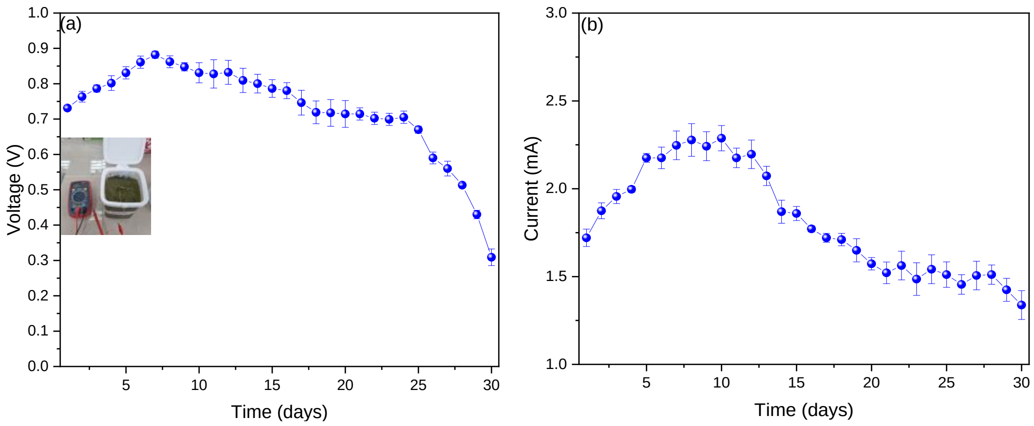

Figure 2. Monitoring values of (**a**) voltage and (**b**) electric current of microbial fuel cells.

Figure 3a shows the pH values obtained from the monitoring carried out, where it is observed that the values remain in the acidic and slightly neutral regime, with its optimum operating pH of 3.9 ± 0.16 on the seventh day. The pH values directly influence the generation of electrical energy, because microorganisms need environments at adequate pH for their growth and proliferation and the increase in microorganisms that generate electrical current these values will increase [32,33]. For example, Prasidha et al. (2020) in their research standardized their pH to 7.1 to the substrate used (food waste leachate) in their MFCs, managing to generate 410 mV voltage peaks in an anaerobic system, arguing that the values can be increased in aerated systems because oxygen is an electron acceptor [34]. Likewise, it has been reported that the optimal pH values for the performance of MFCs vary almost always depending on the substrate used [35]. For example, Li et al. (2021) demonstrated in their research the effect of pH on bacterial distribution in MFCs in which they used pH of 8.5, 9.5, and 10.5 for 700 h, managing to demonstrate that the pH of 10.5 was the one that obtained the best results compared to the other two, achieving peaks of 1221 ± 96 mW/m^2 of power density [36]. Figure 3b shows the values of electrical conductivity during the monitoring period, managing to observe that the values increase from the first day (130.98 ± 1.73 mS/cm) to the seventh day (160.42 ± 4.54 mS/ cm) to later decrease until the last day (76.740 ± 7.95 mS/cm). The research carried out by Stefanova et al. (2018) demonstrated that the values of electrical conductivity increase due to the decrease in the internal resistance of the substrate used, which could be due in the first days to the oxidation and reduction process that would occur without any problem, while the decrease in the values are due to sedimentation of substrate components over time [37,38].

In Figure 4a, the internal resistance ($R_{int.}$) of the fuel cells is shown, for which Ohm's Law (V = IR) was used where the voltage values were placed on the "Y" axis and those of electric current on the "X" axis. In this way, the slope of the linear adjustment is the internal resistance of the MFCs. The calculated internal resistance value was 75.581 ± 5.892 Ω, this value was calculated at the maximum peak of voltage and electric current generation (seventh day). According to Choudhury et al. (2021), the decrease in voltage values is due to the increase in the resistance of the MFCs, due to the energy requirement in chemical reactions (oxidation/reduction) [39]. Although it has been shown that any electronic device will better conduct electric current by having a low resistance, it has been reported that in the case of MFCs, low resistance values are due to a homogeneous formation of the biofilm on the anode electrode, while the formation of a porous biofilm with voids larger than the nanometer scale causes resistance values to increase due to leakage currents also increasing in the electrical system [40–42]. In Figure 4b, the power density (PD) values are shown as a function of the current density (CD), the DPmax found was 304.325 ± 16.51 mW/cm^2 at 5.06 A/cm^2 with a peak voltage of 689.48 ± 11.87 mV. These high PD values found are due to the content of carbon compounds, which are used as sources for the metabolism of the microorganism. For example, Adebule et al. (2018) used kitchen waste as fuel in their MFCs, managing to generate peaks of 803.71 mW/m^2 [43]. In contrast, if substances such as carvings or leaves of any kind of fruit or vegetable are used as fuel, the power densities are really low; for example, Rokhim et al. (2022) used banana plant stems as fuel and managed to generate a power density of 63.84 mW/cm^2 with voltage peaks of approximately 500 mV [44]. One of the works found with really high potential densities was the one carried out by Akatah et al. (2019) in which he took the MFCs to a large scale, managing to generate PD peaks of 10,009 mW/m^2 with a peak voltage of 1673 mV, which was enough to light a red LED light [45].

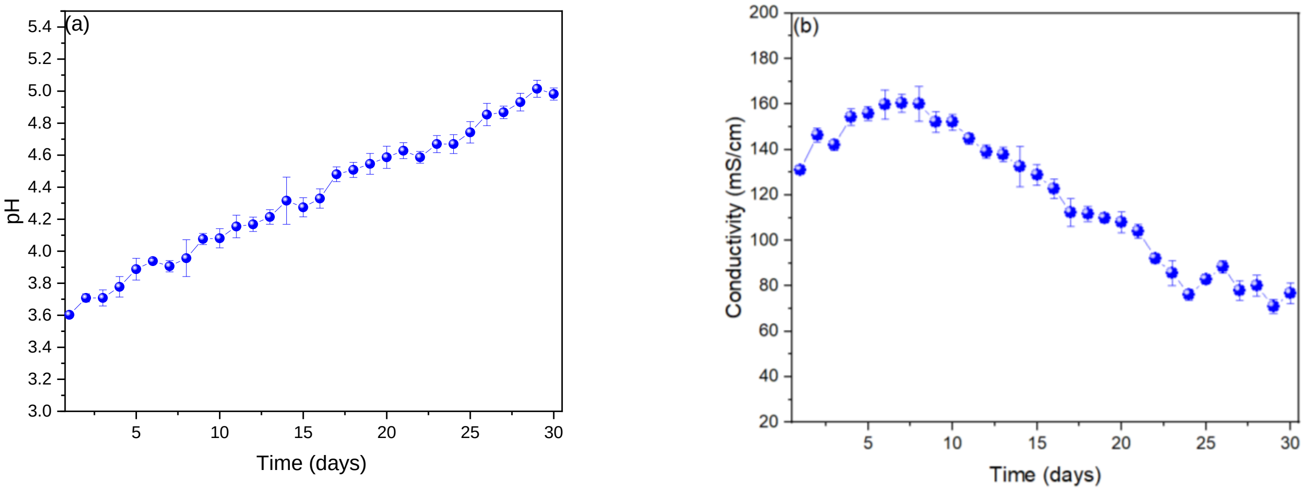

Figure 3. Monitoring of (**a**) pH and (**b**) conductivity values of microbial fuel cells.

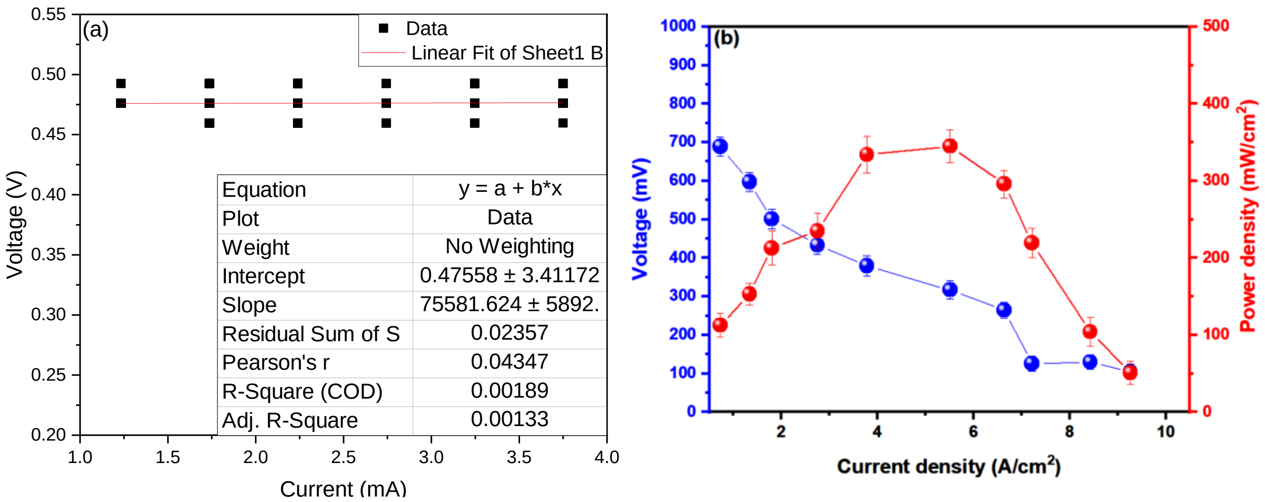

Figure 4. Values of (**a**) internal resistance and (**b**) power density as a function of current density.

The initial and final FTIR transmittance spectra of the used substrate are shown in Figure 5; making it possible to observe the most intense peak at 3331 cm^{-1} belonging to the O-H bonds, while the peak at 2969 and 2805 cm^{-1} belongs to the alkanes (C-H) bonds;

similarly, the 1686 cm^{-1} peak shows the presence of alkene compounds (C=C), and the 1496 and 968 cm^{-1} peaks show the presence of NO_2 and C-H bonds [46–48]. The decrease in the intensities of the peaks in the initial and final FTIR spectra is due to the fermentation of the substrate and the consumption of the components used as power sources for the microorganisms in the process of generating electrical energy of the MFCs. The same has been reported in other investigations [49,50]. Table 1 shows the bacteria that were identified by molecular biology techniques using the 16S rDNA gene, because it has a highly conserved sequence [51]. For the identification of the microorganisms present in the biofilm, they were analyzed by the BLAST program, which obtained a percentage of identity of 98.97% to the species *Alcaligenes faecalis*, 99.39% to the species *Alcaligenes faecalis*, and 100% to the species *Pseudomonas aeruginosa*. Bioelectrochemical systems such as MFCs use microbes as catalysts for the production of electrical current. In relation to this it has been investigated that only certain microbes are capable of carrying out an extracellular transfer of electrons both outward and inward (bidirectional electron transfer).

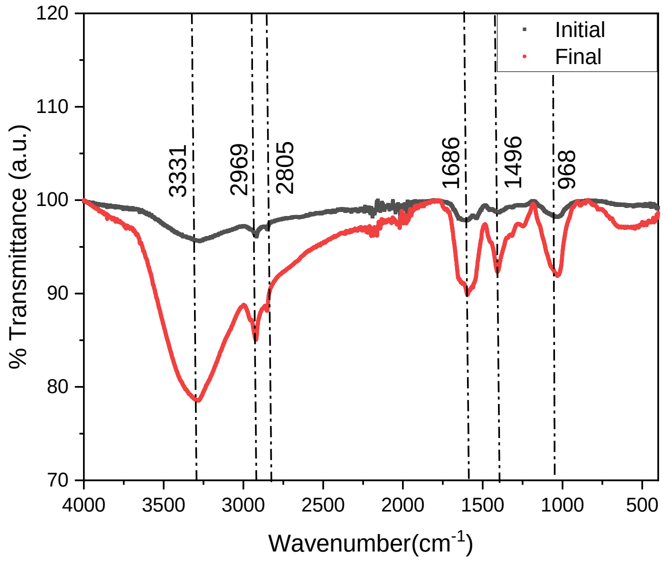

Figure 5. Initial and final transmittance spectrum of cilantro debris by FTIR.

Table 1. BLAST characterization of the rDNA sequence of bacteria isolated from the MFCs anode plate with coriander substrate.

BLAST Characterization	Length of Consensus Sequence (nt)	% Maximum Identidad	Accession Number
Alcaligenes faecalis	1390	98.97%	NR_113606.1
Alcaligenes faecalis	1348	99.52%	NR_113606.1
Pseudomonas aeruginosa	1384	100%	NR_117678.1

Thus, a study reported the catalyzation of an extracellular transfer of electrons by the action of the bacterium *Alcaligenes faecalis*, generating electricity with a potential of 0.3 V. Said result was attributed to the proteins of the pili and the outer membrane of the bacterium [52,53]. In this context, it is worth mentioning that the species *Alcaligenes faecalis* is a Gram-negative, facultative anaerobic bacterium with a bacillary shape and flagellar motility, which is commonly found in the environment in habitats such as soil and water, as well as in hospital settings [54]. While *Pseudomonas aeruginosa* is an environmentally persistent facultative aerobic bacterium [55], this species has been found to have the pigment pyocyanin responsible for its electrochemical activity along with cell permeability, increased electricity generation [56,57]. On the other hand, a study showed that *P. aeruginosa* produces a type IV conductive pili (PaT4P), which can function as a conductive nanomaterial [58].

Similarly, Rojas et al. (2022) reported strains of *Pseudomonas aeruginosa*, *Paenalcaligenes suwonensis*, *Klebisella oxytoca*, and *Raoultella terrigena* which obtained maximum voltages and currents of 1.01 ± 0.017 V and 3.71667 ± 0.05304 mA in the sixth and fourth day, respectively, which were studied in MFCs with banana residues [59]. In Figure 6, you can see the cycle of bioelectricity generation from the waste to its operation of the MFCs, as it can be seen that the MFCs were connected on the seventh day managing to generate 2.61 V. This value is much higher than those found in the literature, which is enough to turn on a red LED light.

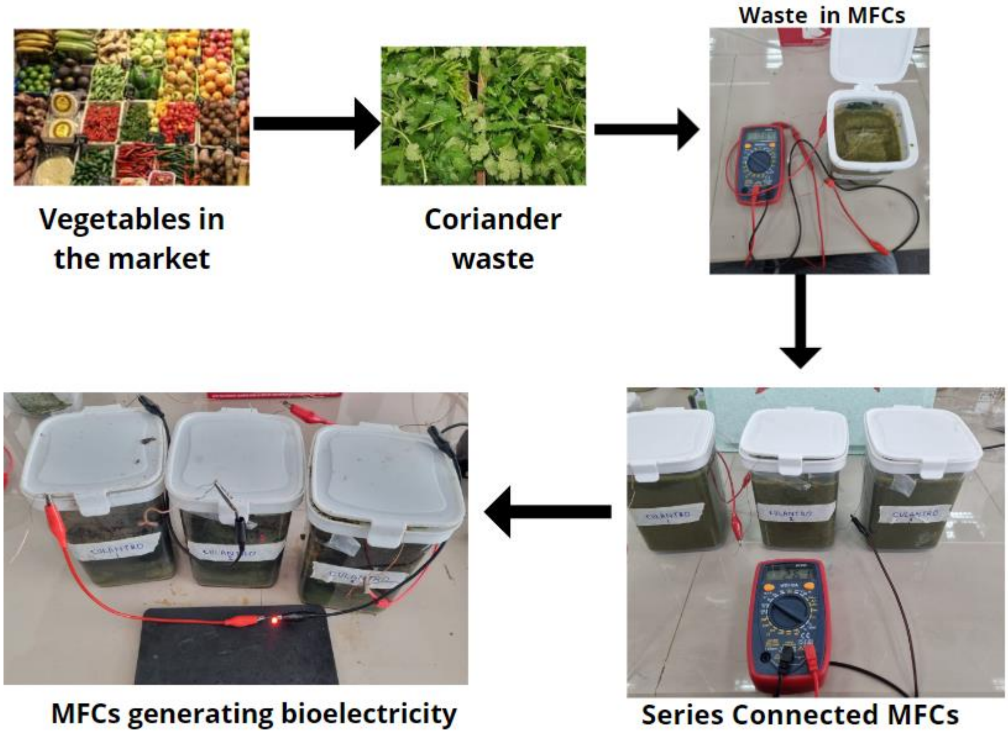

Figure 6. Diagram of the bioelectricity generation process through coriander waste.

4. Conclusions

This research successfully generated bioelectricity through laboratory-scale single-chamber microbial fuel cells using zinc and copper electrodes for 30 days. The values of electrical current and maximum voltage were 2.287 ± 0.072 mA and 0.882 ± 0.154 V on the tenth and seventh day, respectively. These values were obtained working at an optimum operating pH of 3.9 ± 0.16 on the seventh day, although the MFCs showed acid values in the first days. In addition, it was possible to observe that the electrical conductivity on the seventh day was 160.42 ± 4.54 mS/cm, the internal resistance of the MFCs was 75.581 ± 5.892 Ω, with a power density of 304.325 ± 16.51 mW/cm^2 in a density current of 5.06 A/cm^2 and a peak voltage of 689.48 ± 11.87 mV. The FTIR spectrum showed that the most intense peak belongs to the O-H and C-H bonds, whose intensities decreased on the last day of monitoring, mainly due to the fermentation and sedimentation of the substrate used. It was possible to molecularly identify the species *Alcaligenes faecalis*, *Alcaligenes faecali,* and *Pseudomonas aeruginosa* with an identity of 98.97, 99.39, and 100% respectively. The cells were connected in series, managing to generate 2.61 V, which was enough to turn on a red bulb, successfully generating electricity in an environmentally friendly way. This research provides a new and promising alternative to companies and farmers because they can use their own waste to generate electricity if this technology is taken to larger scales. For future investigations, it is recommended to investigate with stable pH values and to coat the electrodes with non-toxic components so that microorganisms are not affected and thus increase the efficiency of microbial fuel cells.

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