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Sustainable Electricity Production Using Avocado Waste

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Abstract: Agroindustry waste has exponentially increased in recent years, generating economic losses and environmental problems. In addition, new ways to generate sustainable alternative electrical energy are currently being sought to satisfy energy demand. This investigation proposes using avocado waste as fuel for electricity generation in single-chamber MFCs. The avocado waste initially operated with an ambient temperature (22.4 ± 0.01 °C), DO of 2.54 ± 0.01 mg/L, TDS of 1358 ± 1 mg/L and COD of 1487.25 ± 0.01 mg/L. This research managed to generate its maximum voltage (0.861 ± 0.241 V) and current (3.781 ± 0.667 mA) on the fourteenth day, operating at an optimal pH of 7.386 ± 0.147, all with 126.032 ± 8.888 mS/cm of electrical conductivity in the substrate. An internal resistance of 67.683 ± 2.456 Ω was found on day 14 with a PD of 365.16 ± 9.88 mW/cm^2 for a CD of 5.744 A/cm^2. Micrographs show the formation of porous biofilms on both the anodic and cathodic electrodes. This study gives preliminary results of using avocado waste as fuel, which can provide outstanding solutions to agro-industrial companies dedicated to selling this fruit.

Keywords: organic waste; microbial fuel cell; avocado; bioenergy

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1. Introduction

The increase in the worldwide population is exponential; it has been estimated that, by the year 2030, there will be 8.5 billion people and that, by the year 2100, this number will approach 10.9 billion [1,2]. Due to the great demand for food (fruits, vegetables, tubers and others) in the last decade, large amounts of waste have been generated worldwide [3]. The costs generated for the management and disposal of agricultural waste were reduced if they were used to generate another secondary good or if value was added to these types of waste [4,5]. Countries and companies dedicated to agribusiness have a significant problem due to the waste generated by producing different vegetables and fruits, contaminating and not taking advantage of these byproducts [6]. It is estimated that this production produces about 1.300 million tons of waste in one year, which has increased global pollution; it has been reported that 21% of greenhouse gases come from the agricultural sector [7,8]. Avocado has been one of the most consumed fruits in recent years; for 2033, it has been estimated that 12 thousand tons will be produced, three times more than in 2010 [9,10]. The Food and Agriculture Organization of the United Nations reported that, in 2021, 69 countries harvested avocados, generating interest and investment from entrepreneurs [11].

Due to the increase in this type of company, electrical energy consumption has also increased, becoming a large expense for entrepreneurs [12]. Furthermore, by providing a greater amount of electrical energy to businesses, rural places are left unattended [13]. It has been estimated that, by 2050, the increase in energy consumption will be 15–18% more than today [14]. The use of microbial fuel cell (MFC) technology is an up-and-coming technology because different types of waste are used as fuel for the generation of electrical current, where organisms oxidize the organic substrate, generating electrons, which are transferred through an electrochemical process to convert them into electrical energy [15]. Energy transfer can be achieved when electroactive microorganisms in a biofilm use electrons from an electrode for anabolism [16]. This technology contains different designs; theoretically, all cells must contain an anodic and a cathodic chamber typically separated by a PEM (proton exchange membrane) on the inside and joined on the outside by an external circuit [16–18]. Among the large quantities of designs are the single-chamber MFCs, which are the single-chamber ones due to their versatility and low manufacturing cost. The types of cells contain the cathode electrode exposed to O_2 for oxidation to occur [19].

Currently, the large scientific community has begun to use different types of waste as fuel, but in recent years, agricultural waste has become relevant for its use as fuel. Recently, Rojas-Villacorta et al. (2023) reported that using vegetable waste, for example lettuce, as a substrate in MFCs and Cu and Zn electrodes can generate current and voltage values of 5.697 ± 0.065 mA and 0.959 ± 0.026 V [20]. Likewise, Aleid et al. (2023) used fruit waste mixtures as fuel, generating peaks of 0.125 V on day 25 in their single-chamber MFCs with graphite electrodes [21]. Verma M. and Mishra V. (2023) used banana peels as fuel in their MFCs, managing to generate power density peaks of 2.2 ± 0.1 mW m^{-2} which, by using S. cerevisiae as a biocatalyst, was able to increase up to 86.9 ± 0.4 mW. m^{-2}, all with graphite electrodes and steel meshes [22]. The literature has observed that using metallic electrodes or those with metallic inlays considerably increases the power density and electric current values of the MFCs [23,24]. On the other hand, the FAO (Food and Agriculture Organization of the United Nations) reported that, in 2019, approximately 0.5 billion tons of waste (fruits and vegetables) were produced, generating losses not only in the agricultural stage but also in the settings of plant processing [25]. One of the most harvested and sold fruits is citrus, specifically orange and tangerine, because their use as a medicinal plant, and both its pulp and peel, have great antibacterial potential and other properties [26,27]. Fruit waste represents approximately 50 and 60% of their mass, and their yearly accumulation generates more than four tons of CO_2 for every ton of waste that rots and decomposes [28].

Avocado is produced mainly in Mexico (33%), the Dominican Republic (10.5%), Peru (7.8%), Indonesia (5.7%), and Colombia (5.1%) [29], where investment for planting and harvesting has increased in recent years [30]. In Europe, avocado consumption per capita increased by approximately 180% between 2018 and 2020, projecting these values to a more significant increase by 2025 [31]. Due to the fact that avocado provides a high energy and nutrient content, the National Health and Nutrition Survey (NHANES) in the United States reported that avocado provides, per 100 g,141 kcal, 1.5 g of protein, 12 g of total lipids, 16 mg of calcium, 0.7 mg of iron, 2 µg of iodine, 41 mg of magnesium, 400 mg of potassium and 28 mg of phosphorus [32]. The global surge in consumption, coupled with an escalating demand, results in a significant increase in waste generated at every stage, from harvest to consumption. Compared with other types of waste, avocado waste contains a higher content of organic matter which microorganisms use to generate electrical energy. Furthermore, the novelty of this research is the use of an MFC manufactured at low cost (zinc and carbon electrodes) and at a medium scale because one of the limitations to taking this technology to an industrial scale is the manufacturing costs of the electrodes [33].

The main objective of this research is to show the potential of avocado waste as a substrate in reverse microbial fuel cells. The parameters of electric current, voltage, pH, electrical conductivity, PD (power density), CD (current density) and Rint (internal resistance) were monitored for 28 days. Likewise, the micrographs of the electrodes in their initial and final state were also observed. Finally, the main microorganisms present on the anode electrode were molecularly identified. This research will be a futuristic, friendly and sustainable solution for companies when manufactured on a large scale.

2. Materials and Methods

2.1. Manufacturing of MFCs

A circular hole with a 10 cm radius was created on one side of the MFC cube to accommodate the cathodic zinc electrode. In contrast, the anodic carbon electrode was centrally positioned within the MFC, covering an area of 200 cm^2. The manufacturing process for the anodic electrode followed the method described by Agüero et al. (2023) [6], as illustrated in Figure 1a. Internally, the electrodes were connected using Nafion 117 (Wilmington, NC, USA), and externally, they were linked via a resistor with a resistance value of 50 ± 3.4 Ω. Figure 1b depicts the electrical energy generation process utilizing avocado waste as the fuel source in reverse microbial fuel cells.

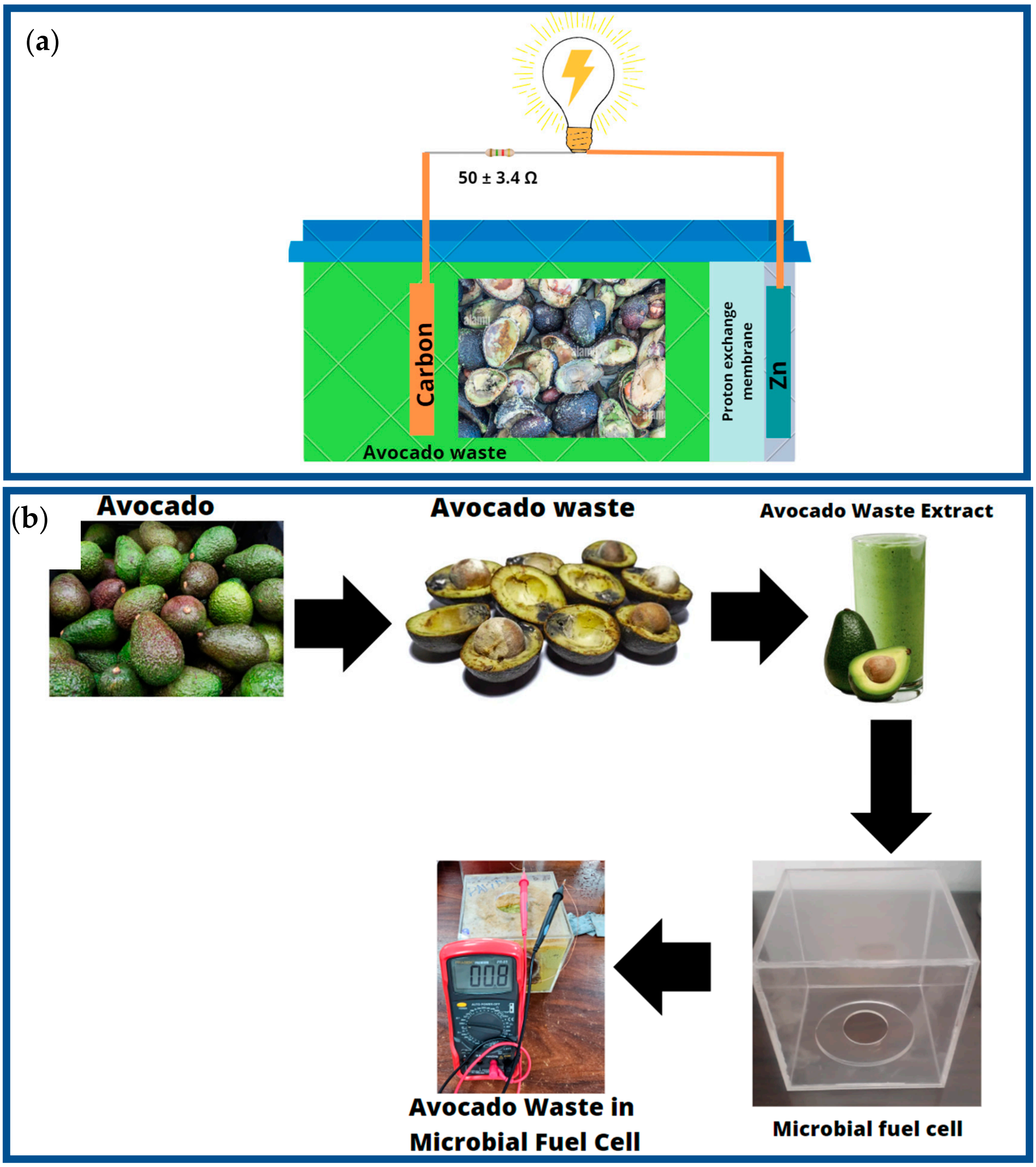

Figure 1. (**a**) Design of the MFCs-SC and (**b**) schematization of the bioelectricity generation process.

2.2. Determination of the Physical–Chemical–Biological Parameters of the MFCs

Electrical current and voltage were recorded using a digital multimeter (Waltham, MA, USA) set to an external resistance of 50 ± 3.4 Ω. pH levels and electrical conductivity was measured with a pH meter (110 Series, Oakton, MI, USA), while EC (electric conductivity), TDS (total dissolved solids) and DO (dissolved oxygen) were assessed using a CD-4301 conductivity meter (Lutron, Tamil Nadu, India). The Chemical Oxygen Demand (COD) was determined through the closed reflux colorimetric method, following the NTP 360.502:2016 standard [34]. Power density and current density measurements were conducted following the methodology of De La Cruz-Noriega, et al. (2023), using a range of $R_{ext.}$: 1.3 ± 0.15, 5 ± 0.25, 10 ± 0.27, 20 ± 2, 50 ± 4.2, 100 ± 8.2, 220 ± 19, 500 ± 21.5, 800 ± 24.5 and 1000 ± 29 Ω [35]. The internal resistance of the MFCs was gauged using a Vernier energy sensor capable of measuring up to ±30 V and ±1000 mA.

2.3. Collection of Avocado Waste

The avocado waste utilized as fuel in the MFCs was sourced from the La Hermelinda supply center in Trujillo, Peru. Merchants collected the waste and transported 10 kg of it to the laboratory for processing. In the lab, the waste underwent a thorough washing and drying process to remove impurities, after which it was crushed and stored in sterilized beakers. Each MFC was then loaded with 2.5 kg of the prepared avocado waste. In order to ensure consistency in the composition of the waste, it was filtered through a 4–5 µm mesh, and its chemical properties were analyzed, with the results detailed in Table 1.

Table 1. Chemical properties of the original avocado waste solution.

Parameters	Values
pH	5.64
Temperature (°C)	22.4 ± 0.01
Electrical conductivity (µS/cm)	43.08 ± 1.73
Dissolved Oxygen (mg/L)	2.54 ± 0.01
Total Dissolved Solids (mg/L)	1358 ± 1
Chemical Oxygen Demand (mg/L)	1487.25 ± 0.01

The information presented in Table 1 is vital because microorganisms grow at certain temperatures, pH and electrical conductivity; a slight variation in these parameters influences the metabolism of the microbes present in the substrates. At the same time, the values of chemical oxygen demand, dissolved oxygen and total dissolved solids are values of the organic components that microorganisms use to carry out their metabolisms and generate electrons, which influences the performance of the MFC.

2.4. Anodic Isolation of Microorganisms

The anode electrodes were thoroughly cleaned before being swabbed to inoculate them onto various culture media. Nutrient agar was utilized for general cultivation, whereas McConkey agar was specifically employed for bacterial isolation. Sabouraud agar was chosen to isolate fungi and yeasts. The bacterial cultures were incubated for 24 h at a temperature of 34 ± 1 °C, while the fungal and yeast cultures were similarly incubated for one day but at a lower temperature of 28 ± 1 °C.

The isolated medium was stained with Gram to obtain the identification of microorganisms present on the anode electrode. For this, the axenic cultures were sent to the BIODES laboratory for molecular identification [35].

3. Results and Analysis

The voltage increased from the first day of the investigation, generating peaks of 0.861 ± 0.241 V on day 14, then slowly decaying until the last day (0.531 ± 0.547 V), as shown in Figure 2a. The increase or decrease in voltage values is due to the oxidation–reduction reactions within the MFC. The reactions are due to the organic load present in the substrate; by decreasing the organic concentration because the microbes consume it, their voltage values decrease [36]. Behaviors similar to ours have been observed in the literature. Zafar H. (2023) generated voltage peaks of 0.22 V using apple waste as a substrate in his MFCs using graphite electrodes [37]. Yaqoob et al. (2023) generated voltage peaks of 1.390 V in their MFC-SC using synthetic wastewater waste as fuel but used two electrodes as anodes and one electrode as cathode (all graphite), thus creating a greater potential [38]. Likewise, Bhattacharya et al. (2023) generated 0.500 ± 0.015 V using sediment waste as a substrate in their single-chamber MFCs with graphite electrodes, showing that glucose inoculation into the cells manages to increase the voltage values [39]. The electric current values showed similar behavior to those of voltage; the electric current values increased from day 1 (0.904 ± 0.05 mA) until day 14 (3.781 ± 0.667 mA) and then decreased until day 28 (2.097 ± 0.871 mA), as seen in Figure 2b. According to Zhong et al. (2020), the high electrical energy values generated are due to a good electrode and its area because better bacterial growth can be obtained, thus generating a greater number of electrons [40]. The latter is reinforced by other researchers, who also mention that the decrease in electrical values in recent days is due to the decrease in the metabolism of the microbes located in the substrate due to the decrease in the carbon content used [41–43]. Bazina et al. (2023) mention that, in cases of biological energy, organic matter can be converted into electrical energy directly within the MFCs with the help of biocatalysts [44].

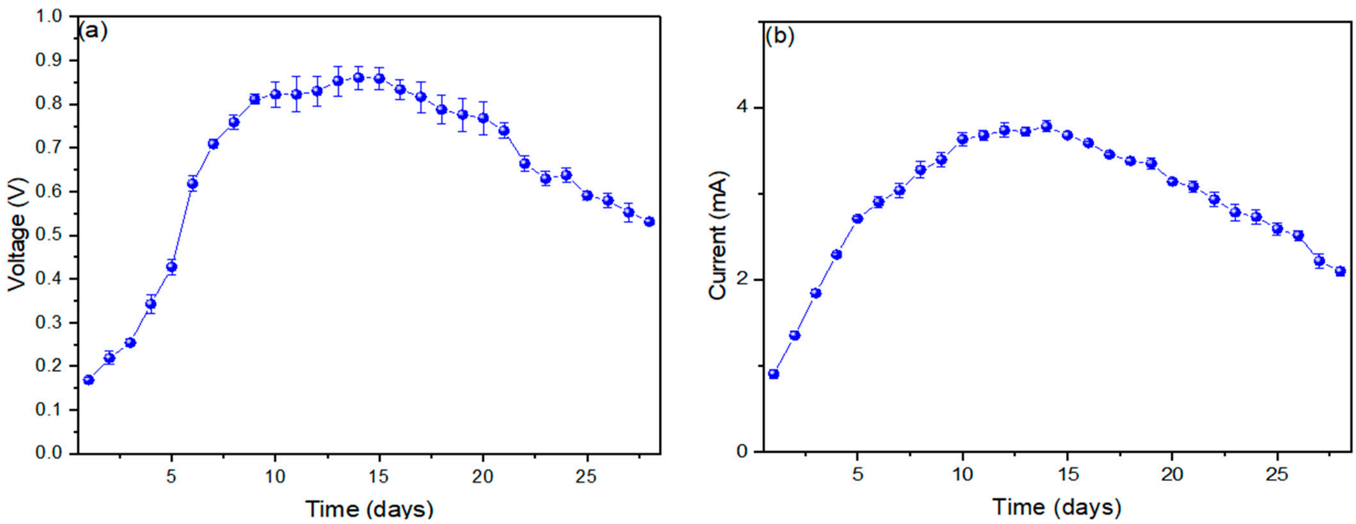

Figure 2. Electrical parameters of (**a**) potential and (**b**) electricity, obtained from monitoring.

Figure 3a shows the $R_{int.}$ found of the MFCs, for which Ohm's law was applied (V = RI), where x and y were placed as the current and voltage values, respectively, whose slope represents the resistance of the electronic device. The internal resistance found was 67.683 ± 2.456 Ω; this value is considerably lower than that reported in the literature. One of the important factors may be the high electrical conductivity shown above, due to the good adhesion of the biofilm to the anode electrode and the natural characteristics of the electrodes used [45]. Ullah Z. and Zeshan S. (2020) found an internal resistance of 370 Ω, managing to generate peaks of 0.780 V using carbon electrodes, and reported that carbon electrodes manufactured on metal meshes acquire metallic properties because they show better electrical conductivity [46]. The values calculated on day 14 of PD as a function of CD are shown in Figure 3b, achieving a peak PD of 365 ± 988 mW/cm^2 whose CD was 5.744 A/cm^2 for a maximum voltage of 683.036 ± 16.482 V. These PD results can be increased by studying different distances between the electrodes and improving the adhesion of biofilms [47,48].

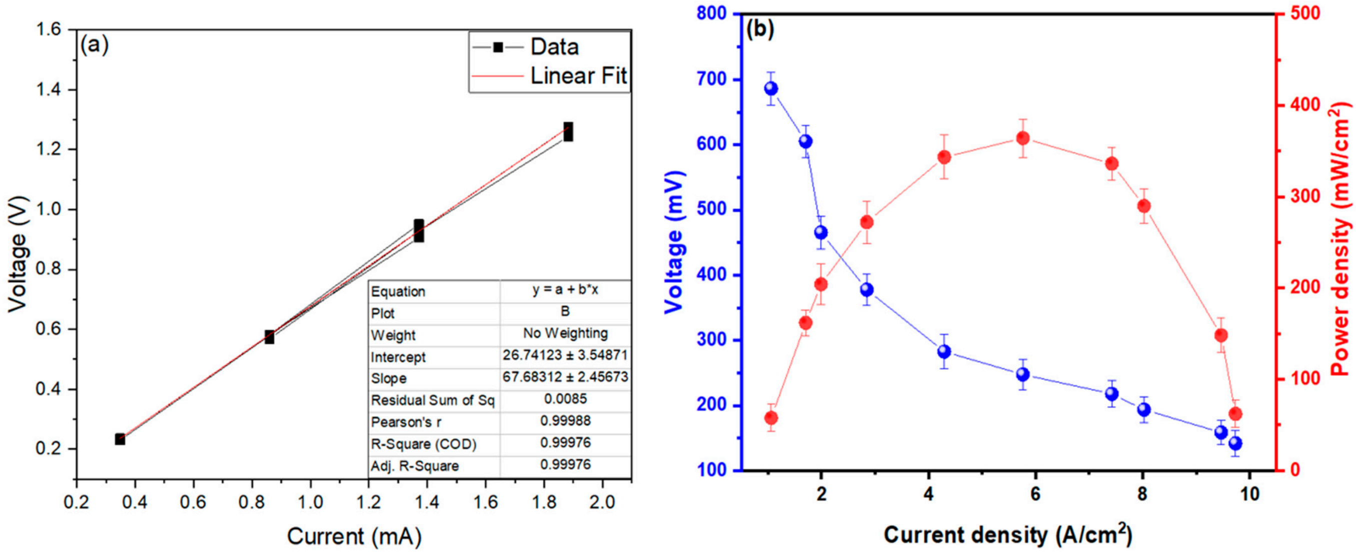

Figure 3. (**a**) $R_{int.}$ and (**b**) PD/CD calculated from the MFCs.

The degradation of electrodes over time significantly impacts the generation of electrical energy in microbial fuel cells (MFCs), primarily due to the wear and tear of metallic electrode surfaces. This effect is compounded by the internal resistance within MFCs, which comprises three main components: ohmic resistance, resistance to electrochemical reaction and resistance to mass transfer [49–51]. The study by Ma et al. (2018) provides insightful observations on the variability of microbial communities within MFCs, especially when processing certain organic wastes like food scraps. The researchers discovered that, while the same microbial species were present in both anodic and cathodic biofilms, their proportions varied significantly. Specifically, they identified *Proteobacteria* (61% at the anode, 42.9% at the cathode), *Bacteroidetes* (22.9% at the anode, 34.5% at the cathode) and *Firmicutes* (9% at the anode, 7.5% at the cathode), collectively constituting over 80% of the total bacterial population in these environments [52]. A crucial aspect of electrical energy generation in MFCs is the electron generation mechanism, whether through direct or indirect transfer, where microbial metabolism plays a vital role. In this context, monosaccharides present in the waste assume a critical function [53]. The monosaccharides, disaccharides and polysaccharides found in fruit waste are commonly utilized in the metabolic pathways of microorganisms for electricity production. However, they highlighted that plant-derived polysaccharides require more energy for degradation and subsequent integration into these metabolic pathways [54].

The records of the pH values can be seen in Figure 4a, with the optimal operating pH of these MFCs being 7.386 ± 0.147 on day 14. pH values tend to increase due to the fermentation that occurs by the substrate, as well as the oxidation–reduction process that occurs in the MFCs in energy generation [47]. The coffee waste has been used as substrate, and they adjusted the pH to 7 because previous works optimized the electrical values at that value [55]. Likewise, Babanova et al. (2020) generated electric current peaks of 0.600 V at a pH of 7.8 [56]. The records of the ECs are observed in Figure 4b, showing an increase in values from day 1 (43.089 ± 1.731 mS/cm) to day 14 (126.032 ± 8.888 mS/cm) and then a gradual decrease until the last day of monitoring. The electrical conductivity values tend to decrease due to the decrease in the organic load present in the substrate, which decreases due to the presence of microorganisms [57,58]. The increase in the values of electrical conductivity is mainly caused by the decrease in the $R_{int.}$ of the substrate used, which may be due to several factors (proliferation of microorganisms, the release of electrons in large amounts, etc.), while the decrease in these same values may be due to the sedimentation of organic matter in the final stage of monitoring or degradation of organic matter [59,60].

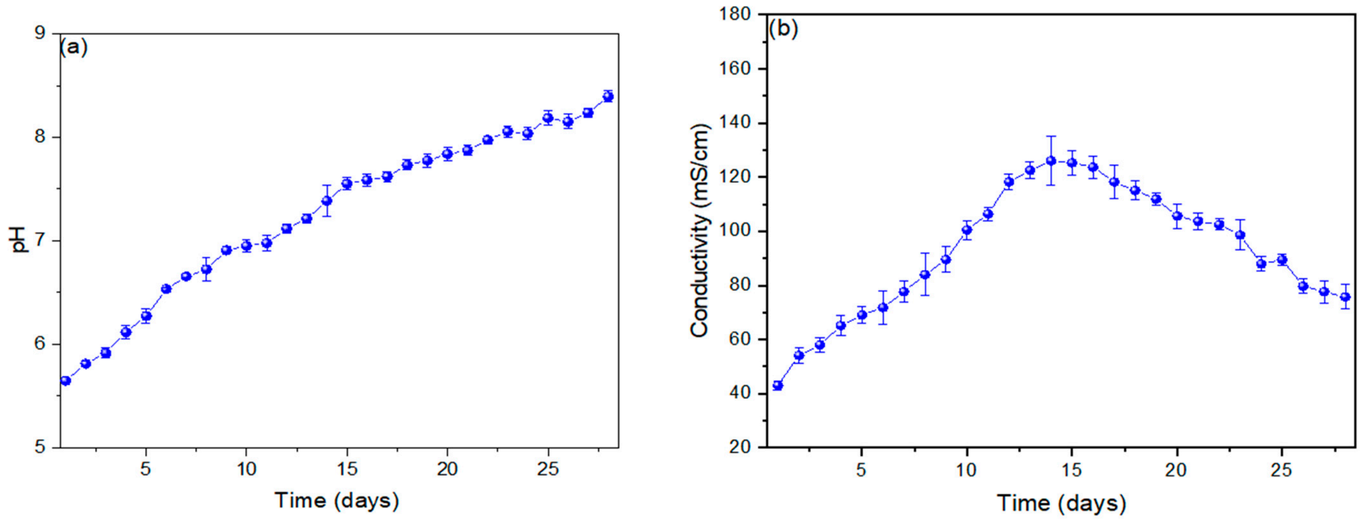

Figure 4. Electrochemical values obtained during monitoring of (**a**) pH and (**b**) conductivity.

Figure 5a,b present micrographs of the anode electrode at the beginning and end of the study, showing a smooth surface initially and the development of a biofilm by microorganisms in the final stage. Figure 5c,d depict the micrographs of the cathode electrode, revealing its initial smooth surface and the subsequent formation of porous structures due to reduction reactions during the electrical energy generation process. The successful biofilm adhesion can be attributed to the microorganisms on the substrates and the properties of the electrodes [61,62].

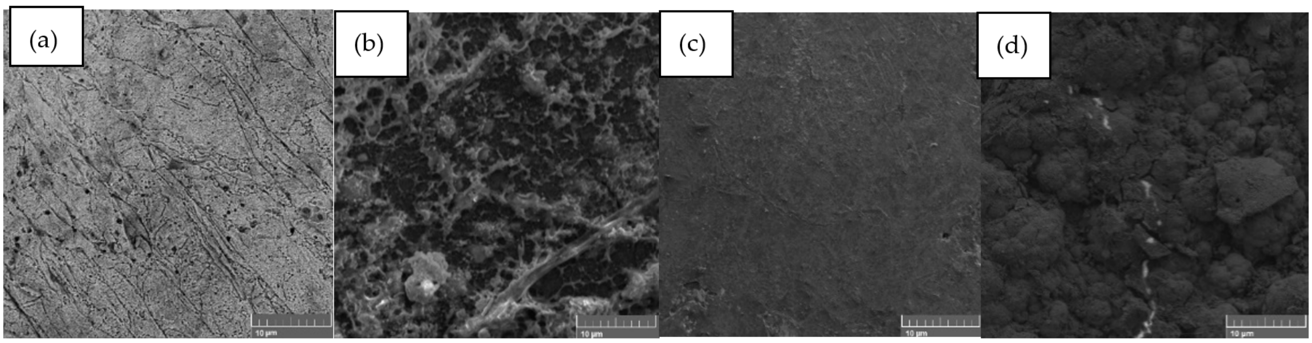

Figure 5. Micrographs of the surfaces of the anodic electrodes (**a**) initial and (**b**) final, as well as the cathode electrode (**c**) initial and (**d**) final of the MFCs.

The materials of the anodic and cathodic electrodes are chosen for their specific surface area and non-corrosive nature, making carbon-based electrodes like plain carbon and graphite in various forms (plate, sheet, felt, rod, etc.) popular choices due to their low cost and minimal maintenance requirements [63,64]. Metal-based electrodes, known for their excellent electrical conductivity, durability and ease of microbial adhesion, are also widely used [65]. Examples include copper, stainless steel, nickel and aluminum [66].

Microorganisms are crucial as they uptake various substrates (simple, complex, mixed substances) and catalyze them through redox reactions to produce clean energy. Electrochemically active microorganisms, characterized by their high electron generation and extracellular electron transfer capacities, are key players in this process [67]. Electrogenic microorganisms release electrons onto the surface of the anode, contributing to the measurable positive electric current, while electrographic microorganisms retrieve these electrons from the surface of the cathode [68]. Notably, some microorganisms can function as electron donors and acceptors depending on their environmental conditions [69].

Table 2 shows the bacteria identified through the molecular biology technique, for which the 16S rRNA gene was used because it contains a highly conserved sequence. The microorganisms present in the biofilm were identified using the BLAST program [70], which identified 100% of the species *Bacillus marisflavi*. In the literature, it has been found that bioelectrochemical systems, such as microbial fuel cells, use microorganisms found in substrates as biocatalysts for the production of electrons. For both the outside and the inside, this phenomenon is called bidirectional electron transfer [71,72]. The bacteria Alcaligenes faecalis have been reported as a biocatalyst that has the ability to transfer electrons, generating peaks of 0.3 V, attributing this phenomenon to the proteins of the pili and external membrane of the bacteria [73]. Likewise, there are species such as *Alcaligenes faecalis*, which is a Gram-negative bacterium with facultative anaerobic properties, which are most frequently found in the environment (soil, water or mud) and hospital environments [74]. On the other hand, *Pseudomonas aeruginosa* is a bacterium, and it has been discovered that this species has the pyocyanin pigment responsible for its electro-chemical activity along with cell permeability, which leads to an increase in the generation of electrons and, therefore, of electrical energy [75,76]. Furthermore, *P. aeruginosa* generates a type IV (PaT4P) pili capable of conducting electrons [77].

Table 2. Identification of microbes obtained from the microbial fuel cell.

Sample Identification	BLAST Characterization	Length of Consensus Sequence (nt)	% Maximum Identidad	Accession Number
M15	*Bacillus marisflavi*	1482	100.00	NR_025240.1

Use of organic waste in the last year has increased compared to previous years, becoming a vital topic in agribusiness due to the interest of many companies in reusing their organic waste as a profitable method for themselves. Table 3 shows the most relevant investigations on this topic this year, compared with our results. As can be seen, the authors who used metallic electrodes, either as meshes or plates, obtained higher voltage, power density and current density values than those who used carbon, graphite or other derivatives. As in our research, this would be due to the low opposition these types of materials offer to the flow of electrons; therefore, it has also been observed that using membranes with nanoparticles improves the transfer of protons and the reduction in the cathode chamber [78,79]. The anode electrodes of carbon, graphene, graphite and derivatives are the most used materials as anodes in MFCs due to their high biocompatibility for microbial growth owing to their surface characteristics (roughness) and electrical conductivity [80]. An immense amount of carbon research has been conducted in three ways: carbon felt, carbon cloth and carbon paper [81]. Currently, electrodes with metallic nanoparticles or metal plates are being researched because they offer a low cost in the market. Among the anodes of this type of material reported in the last four years are stainless steel meshes, which have been intensively investigated in their pure state owing to their excellent electrical conductivity, corrosion resistance and mechanical properties; thus, they also show great potential for large-scale manufacturing and long-term maintenance [82,83]. However, this research has observed that copper also has properties similar to steel, but zinc wears off rapidly in 30 days. Researchers have tried different types of compounds to search for conductive, chemically stable and biocompatible materials. An ideal anode would have to be suitable for microbial attachment and effortless transfer of electron flow because poor fixation would limit the performance of the MFC, generating low power density [84,85].

Table 3. Comparison of electrical parameters with other types of organic waste.

Substrate Type	Types of MFCs	Maximum Value of Voltage (V)	Maximum Power Density (mW/m^2)	Maximum Current Density (mA/m^2)	Electrodes	Ref.
Avocado waste	single chamber	0.861 ± 0.241 V	365.16 ± 9.88	5.744	Carbon/Zinc	this investigation
Oily kitchen waste	single chamber cubic	0.400	-	-	carbon	[78]
Sugarcane waste	single chamber	0.290	3.571	64.51	graphite	[79]
Yeast wastewater	single chamber	1.090	--	--	Cu-Ag cathode and	[80]
Sweet lemon peels	single chamber	0.792 ± 0.010	204.80 ± 1.28	640.0 ± 2.0	Anodo: stainless-steel mesh and cathode: cylindrical graphite rod	[81]
Fruit waste	single chamber	0.102	0.099	31.57	carbon	[82]
Banana peel waste	dual-chamber	0.307 ± 0.015	86.9 ± 0.4	129.4 ± 1	Anodo: carbon and cathode: graphite plate	[83]
Coriander waste	single chamber	0.882 ± 0.154	304.325 ± 16.51	506	Anodic: copper and cathodic: zinc	[84]
Tangerine waste	single chamber	1.191 ± 0.35	475.32 ± 24.56	553	Anodic: copper and cathodic: zinc	[85]

4. Conclusions

This study shows that avocado waste has excellent potential for generating bioelectricity through microbial fuel cells using carbon and zinc electrodes. Observing that the voltage and electric current values tend to increase rapidly in the first days until day 14, with maximum values of 3.781 ± 0.667 mA and 0.861 ± 0.241 V because the substrate concentration begins to decrease, leaving the microorganisms without nutrients for the generation of electrons. These electrical values were obtained with an optimal pH of 7.386 ± 0.147 and an electrical conductivity of 126.032 ± 8.888 mS/cm. The internal resistance value was calculated on day 14, finding a value of 67.683 ± 2.456 Ω with a power density of 365.16 ± 9.88 mW/cm^2 at a current density of 5.744 A/cm^2. The power density values can be increased by studying electrode distance variations and using a biocatalyst, as shown in previous studies with other substrates. At the same time, the micrographs showed good biofilm formation with a significant porosity on the surfaces. Finally, *Bacillus marisflavi* was identified with 100% certainty as the microorganism attached to the anode electrode.

This work gives the first advances in the use of avocado waste as fuel. For future work, it is recommended to manufacture cells on a larger scale, standardizing the pH value to the optimal value found in this research, as well as the use of nanoparticles for the coating of the electrodes, with some material that does not contaminate the substrate to prolong the power of the MFC.

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

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