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# Banana Waste-to-Energy Valorization by Microbial Fuel Cell Coupled with Anaerobic Digestion

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**Abstract:** Banana is the most cultivated fruit plant in the world. It is produced in Latin America, Asia and Africa. India and China are the world's largest banana producers, with almost 41% of the world's production. This fruit reaches a total world production of 158.3 million tons per year. However, during their production cycle, the banana agroindustry produces large volumes of solid waste derived from overripe fruit. It contributes between 8–20 percent of the waste (around 100 kg of banana waste for every ton of banana produced). Therefore, the use of overripe banana waste represents a huge opportunity for bioenergy production. This work demonstrates that banana waste can be further used for power generation using a microbial fuel cell (MFC) coupled with anaerobic digestion (AD). First, the maximum methane production (MMP), methane production rate (MPR) and biochemical methane potential (BMP) were measured using an anaerobic batch bioreactor for 64 days of monitoring. Finally, the digestate generated from AD was used in the MFC to determine the polarization curve, maximum voltage, maximum power density (MPD), resistance and current. As a result, the AD generated an MMP of 320.3 mL, BMP of 373.3 mL$CH_4$/gVS and MPR of 18.6 mL$CH_4$/Lb·day. The MFC generated 286 mV (maximum voltage), 41.3 mW/m$^2$ (MPD), 580.99 Ω (resistance) and 0.0002867 A (current). Both processes together produced a total bioenergy of 13.38 kJ/gVS. This coupled system showed a suitable and promising use of banana waste for ecofriendly bioenergy generation. Therefore, this feedstock could be taken advantage of for generating sustainable processes and developing a circular economy in the banana agroindustry.

**Keywords:** banana waste; ecofriendly bioenergy; biochemical methane potential; bioelectricity; sustainable processes

## 1. Introduction

The International Energy Agency [1] reports that in 2040, the total energy demand in the world will increase by 60%, and most of this consumption will come from developing countries. Likewise, it is predicted that due to greenhouse gas emissions generated from the consumption of fossil fuels [2,3], an increase in global warming between 1.4 and 5.8 °C will be reached by the end of the century if measures are not taken to mitigate this problem, all the economies and ecosystems of the world will suffer serious consequences [4,5]. These perspectives have forced humankind to generate clean energy from renewable sources to stop relying on fossil fuels. Therefore, the use of renewable energy sources is an effective measure that can be adopted to mitigate the growing energy demand, at the same time as improving the current and future global outlook. Hence, the importance of waste valorization by different biotechnological processes to allow the development of sustainability in full correspondence with the Sustainable Development Goals [6].

In this respect, the banana is the most cultivated fruit plant and is considered the fourth most crucial fruit plant in the world because it is a basic product for the family basket. It is produced in Asia, Latin America and Africa, each one contributes around 51, 33 and 14%, respectively, of the total production. The world's banana production reached 162.9 million tons per year in 2020: 119.8 million tons under the banana crop item (74%) and 43.1 million tons under the plantain crop item (26%) [7]. Conversely, it is common to see the 119.8 million tons figure erroneously being cited as representing the global production of bananas because it usually does not consider the plantains. Nonetheless, the banana agroindustry generates large volumes of solid waste derived from the maintenance and harvesting process, highlighting the pseudostems, leaves, rachis, fruit that do not meet the required quality standards and overripe fruit. This last one contributes between 8 and 20 percent of the waste [8], which happens to make a putrescible organic solid waste (POSW). The POSWs accumulated in sanitary landfills generate pollutants for aquifers and soil in the place where they are discarded, representing serious environmental and public health dangers [9]. Further, it is a resource loss if dumped directly without recovery.

On the other hand, considering that the amount of urban solid waste (USW) generated per capita in 2019 in Mexico was 0.944 kg/day, of which 46.42% corresponds to organic waste [10], it can be estimated that a person generates a contribution of organic waste of 159.94 kg/year. If one compares this value with the production of banana waste (76,480 tons/year), this agroindustry in Mexico generates pollution like that produced by 478,180 people. This shows that this waste's poor disposal and management can cause environmental problems. However, several researchers have reported that the use of this fruit waste represents additional sources of renewable biomass due to its high content of organic matter, is highly biodegradable and does not compete directly with food production. Therefore, it could be used as feedstock for the generation of bioenergy in the form of biogas [11], biomethane [12] or bioelectricity [13] by biotechnological bioprocesses.

Anaerobic digestion (AD) and microbial fuel cells (MFC) are biotechnological bioprocesses that have turned out to be novel alternatives since they have the advantage of coupling the treatment to produce bioenergy and/or electricity. AD has been an attractive, inexpensive technology whose products (biomethane) have a high added value, a very profitable and economically feasible alternative for developing countries. This technology constitutes a viable solution to reduce the volume and concentration of organic matter in the waste, improving its quality [14,15]. This biological degradative process is carried out by a series of a chain of interconnected biological reactions in which the biodegradable organic matter of a substrate is transformed into a mixture gas of methane (55–75%), $CO_2$ (25–45%), hydrogen, hydrogen sulfide and traces of other products under a joint effort of various microbial groups. A consortium of bacteria (i.e., hydrolytic, fermentative, obligate hydrogen-producing, homoacetogenic and syntrophic acetate oxidizing) and methanogenic archaea (i.e., acetoclastic and hydrogenotrophic) are involved in this process; the latter being very sensitive to oxygen. Hence, this process is strictly anaerobic. It is a complex multi-stage process with the presence of very different and closely dependent microbial populations [16]. Despite potential applications of this technology, very few works related to the use of banana overripe waste have been reported. Some researchers have reported the use of banana stems, peduncles, peels, bulbs, leaf sheaths and leaf blades [17–25]. However, the yields for biogas and methane production found in the literature are low, showing that these substrates are not fully biodegraded, even after many days.

The MFC is an emerging technology that could help solve two of the most critical problems facing today's society: the energy crisis and pollution generated by solid waste. MFC is a device that uses microorganisms to convert the chemical energy present in a substrate into electrical energy; this is possible when, under certain conditions, some microorganisms transfer the electrons produced in their metabolic activity to an electrode (anode) instead of to a natural acceptor electron (as oxygen) [26]. This technology comprises two cells, one anaerobic and the other aerobic, divided by a permeable proton exchange membrane. The anaerobic cell contains the organic substrate that, when oxidized by the action of microorganisms, generates electrons, protons and $CO_2$. Further, an electrode is placed in each of the cells. The anode in the anaerobic cell and the cathode in the aerobic cell; once the electrons are released in the anodic cell, they are captured by the anode and subsequently transferred to the cathode through an external circuit [26–28]. Simultaneously, protons are generated in the anodic cell that migrates to the cathodic cell through the permeable membrane, where they combine with oxygen from the air to be reduced to water with the electrons that they capture directly from the cathode, creating a current flow [27,29]. Despite potential applications of this technology, very few works have explored the use of banana waste, such as peel [30,31], and much fewer have explored overripe banana waste.

Both anaerobic technologies are distinguished from other power generation systems because they operate efficiently at room temperature and even at low temperatures; they degrade the organic matter present in the waste and can be used in the production of bioenergy simultaneously at a minimum cost; they produce less $CO_2$ than any other current technology that uses fossil fuels to generate energy. The few emissions of this gas do not require any type of treatment; therefore, the potential of these technologies is enormous. However, the processes proposed here are very different in terms of technology readiness level [32]. AD is a well-known process, and MFC is still in its beginning, and much more research is necessary. Even more, both technologies are operated in a coupled fashion. In addition, as only a few studies have examined the bioenergy potential of BW, a deeper and more investigation is necessary. Therefore, this research aimed to valorize the overripe banana waste-to-energy using an MFC coupled with AD.

## 2. Materials and Methods

### *2.1. Banana Waste (BW)*

The banana samples were collected in the market located in Tuxtla Gutiérrez, Chiapas, Mexico (latitude 16°44′39″ N and longitude 93°06′18″ W). Bananas in their last ripening phase (level 7 on the Von Loesecke scale) [33] were searched for to simulate the use of market waste about to be discarded. The banana peel and pulp were separated, then the pulp was ground in an industrial blender at a ratio of 1:1.25 banana/water. Later, it was stored in clear plastic bags with 20 mL of the sample at −20 °C until used.

### *2.2. Anaerobic Granular Sludge (AGS)*

The AGS was collected from a stabilized UASB type digester of the wastewater treatment plant (WWTP) from Chiapa de Corzo, Mexico (latitude 16°39′50″ N and latitude 93°01′01″ W). The average characteristics of AGS used were pH (7.2), TS (18.4 g/L), TVS (11.2 g/L), TVS/TS ratio (0.61), organic matter (61.4%), inorganic matter (38.5%) and SMA (0.22 gCOD/gVSS·day). Subsequently, to activate the AGS, it was fed with a synthetic solution [34].

### *2.3. Anaerobic Digestion (AD) Process*

The AD process was evaluated using the system shown in Figure 1. Glass batch bioreactors (400 mL working volume) on a laboratory scale coupled with a $CO_2$ trap were used. These bioreactors were inoculated with AGS from WWTP and fed with BW, a positive (synthetic solution) and negative control (distilled water) such as a substrate. The test unit contained 3 gCOD of the substrate (BW and positive control), 1 g TVS of AGS as inoculum, 40 mL of phosphate buffer solution, 2 mL of macronutrient solution, 1 mL of micronutrient solution and it was made up to 400 mL with distilled water. The pH was adjusted to 7.8 with (8 M) NaOH solution [32]. Each bioreactor was incubated at mesophilic conditions (35 °C) in a hot chamber over a 64-day duration. During the bioreactors' evaluation period, the methane production was measured with MilliGascounters (MGC) (RITTER, North Rhine-Westphalia, Germany) daily.

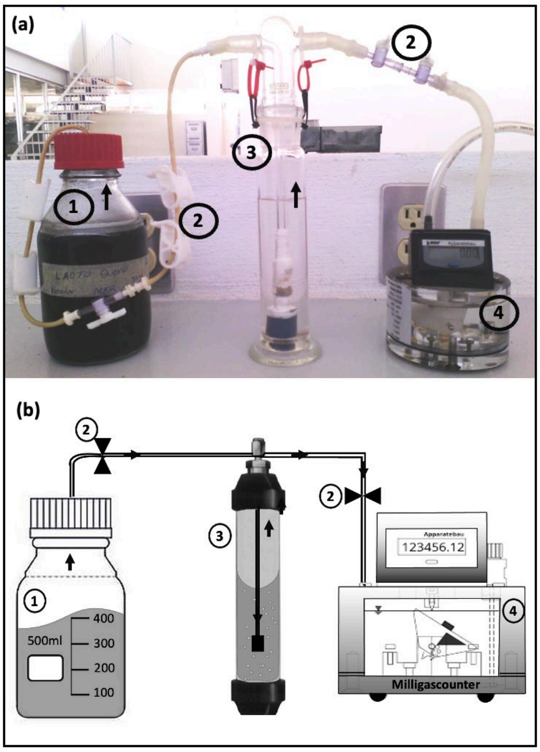


**Figure 1.** (**a**) Original experimental setup and (**b**) schematic diagram of the AD system. (1) Anaerobic batch bioreactor, (2) safety valves, (3) glass $CO_2$ trap, (4) RITTER MilliGascounters.

### *2.4. Microbial Fuel Cell (MFC)*

Figure 2 shows the microbial fuel cell used in the study, which has been used as a basis for the configuration presented by Rincon-Catalán et al. [32]. Two rectangular acrylic cells with a volume of 220 mL and 95% operating volume were made. Nafion N-117 (Sigma-Aldrich, Darmstadt, Germany) was used as the permeable proton exchange membrane between both cells. In the anaerobic cell, the hexagonal-shaped graphite (KOH-I-NOOR HARDTMUTH, České Budějovice, Czech Republic) anode was used, which was covered to maintain the anaerobic conditions. On the other hand, in the aerobic cell, the cathode of the same material and shape as that anode was used. Further, this cell was subjected to aeration. For the connection of the circuit, 0.30 mm copper wire (Unitech, Medley, FL, USA) was used.

The anode inoculation was carried out with anaerobic sludge from a natural wetland (latitude 16°37′5″ N and latitude 93°5′39″ W). For this process, the electrode was immersed in the anaerobic sludge for 10 days until the formation of a biofilm on the surface of the electrodes. Later, the colonization of the biofilm with a scanning electronic microscope (AXIO IMAGER A1, Carl Zeiss, Oberkochen, Germany) was observed. Finally, the MFC was fed with digestate generated from the AD of BW over a 21-day duration to determine the maximum voltage, polarization curve, power density, resistance and current according to that reported by Rincón-Catalán [34].

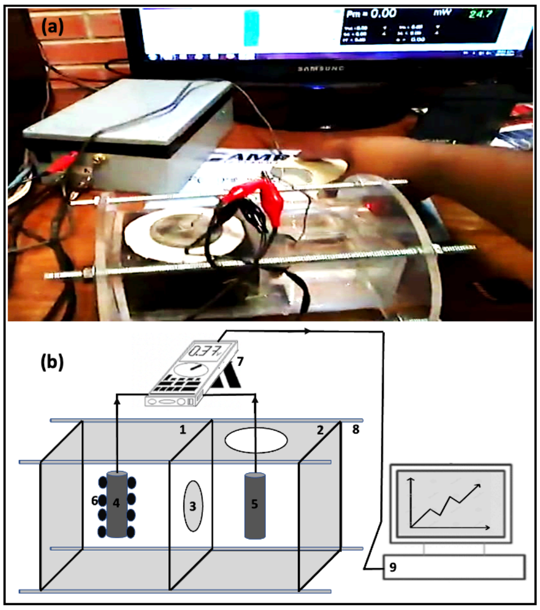


**Figure 2.** (**a**) Original experimental setup and (**b**) schematic diagram of the MFC system. (1) Anaerobic anode cell, (2) cathode cell, (3) Nafion membrane, (4) anodic graphite electrode, (5) cathodic graphite electrode, (6) biofilm (anaerobic sludge from a natural wetland), (7) multimeter, (8) bolt and nut set (cells connection), (9) computer for data analysis.

## 2.5. Analysis Methods

### 2.5.1. Characteristics Analysis

The characteristics of the banana waste, such as density, pH, chemical oxygen demand (COD), total solids (TS) and total volatile solids (TVS), were analyzed according to the Standard Methods for Examination of Water and Wastewater [35]. The percentage of moisture, organic and inorganic matter content was determined according to the Association of Official Analytical Chemists [36].

The COD was performed using the standard technique for the closed reflux, colorimetric analysis using a dry thermostat reactor (HACH DRB200, Ames, IA, USA) and Spectrophotometer UV-VIS (HACH DR5000, Ames, IA, USA). For the TS and moisture determination, 10 mL of sample were dried at 105 °C using a horizontal drying oven (ECOSHEL 9023A, Texas, USA). The samples were thereafter heated to 550 °C for 3 h to determine the TVS content using a muffle furnace (Felisa AR-340, Zapopan, Jalisco, Mexico). The organic matter content was estimated using the TVS/TS ratio, and the inorganic matter content was obtained by the difference of 100% minus the content of organic matter. The pH was determined using a portable pH meter (HACH sensION156, Ames, IA, USA). The density was calculated by measuring the water displacement of a 5 g of sample in a 250 mL graduated cylinder. Finally, the result was generated by the definition of absolute density.

### 2.5.2. Methane Analysis

The biochemical methane potential (BMP) [16], the biodegradability index [37], maximum methane production (MMP) [38] and methane production rate (MPR) [34] were determined according to the following modifications. Briefly, the BMP and percentage of biodegradability were obtained using Equations (1) and (2), respectively. The accumulated volume of methane was converted to standard conditions for temperature and pressure. The accumulated methane was plotted versus time kinetics until the speed was constant. At this last point of constant speed is where the value of BMP ($mLCH_4/gVS$) took place.

$$BMP = \frac{V_{CH_4}}{OM} \quad (1)$$

where BMP ($mLCH_4/gVS$) is the biochemical methane potential, $V_{CH_4}$ is the methane-accumulated volume ($mLCH_4$) during the experiment in standard conditions of temperature and pressure, and OM is the organic matter (gVS).

$$Biodegradability\ index\ (\%) = \frac{BMP}{490\ mLCH_4/gVS} \tag{2}$$

where 490 is the theoretical volume of methane per gram vs. removed at normal temperature and pressure (T = 273 °K; $p$ = 1 atm).

The MMP value was obtained when the kinetics of methane production ($CH_4$ accumulated vs. time) became asymptotic, and MPR was determined using Equation (3).

$$MPR = \frac{MMP}{V_B \cdot t} \tag{3}$$

where MPR ($mLCH_4$/Lb·day) is the methane production rate, MMP is the maximum methane production ($mLCH_4$), VR is the bioreactor volume (L) and t is the time (days).

2.5.3. Bioelectricity Analysis

The voltage was determined using a MUL-600 PC-interfaced multimeter (STEREN, Mexico City, Mexico). Voltage measurements were made at 15-min intervals for 5 days. Subsequently, the voltage values were converted to current units using the resistance value (1 kΩ). Later, the power of the MFC was calculated according to Equation (4).

$$P = I \cdot V \tag{4}$$

where P (W) is the power, I (A) is the current and V (mV) is the voltage.

Finally, the power density expressed as the power per unit area of the anode electrode is calculated using Equation (5).

$$PD = \frac{I \cdot V}{A} \tag{5}$$

where PD ($mW/m^2$) is the power density, and A ($m^2$) is the surface area of the anode electrode.

All the analyses and experiments in this study were performed in triplicate.

2.5.4. Organic Matter Removal Efficiency and Power Generation

In both processes, the following parameters, pH, COD, TS and TVS, were determined according to the Standard Methods for Examination of Water and Wastewater [35]. The COD, TS and TVS removal efficiency were determined according to Equation (6) [39].

$$E(\%) = \frac{C_{inf} - C_{eff}}{C_{inf}} \tag{6}$$

where E (%) is the removal efficiency, $C_{inf}$ is the influent concentration and $C_{eff}$ is the effluent concentration. This equation was used to calculate the efficiency of all monitored parameters.

## *2.6. Statistical Methods*

All the data obtained were expressed as the mean ± standard deviation (SD), and the statistical significance was determined using ANOVA (analysis of variance) followed by Tukey's test for multiple comparisons. The values were considered significantly different at $p < 0.05$, the statistical program Graphpad Prism version 6.0. was used (GraphPad Software Inc. La Jolla, CA, USA).

## 3. Results and Discussion

### 3.1. Physicochemical Characterization

The results of the average characteristics of BW are listed in Table 1. The results obtained show that this type of waste has a pH of 4.5 ± 0.1, which classifies it as acid waste. This low value is due to the maturity stage of the banana since the pH ranges between 5.0 and 5.8 for the pulp of the green fruit and between 4.2 and 4.8 for the ripe fruit derived from the presence of malic, citric and oxalic acid [40,41]. The moisture content of the pulp was 89.75 ± 0.2. Commonly, the range oscillates between 82 and 86%. Although the moisture content in this waste is high, it requires more water to be added to promote hydrolysis in AD.

**Table 1.** Physicochemical characterization of BW.

| Parameter | BW |
|---|---|
| Density (g/mL) | 0.997 ± 0.09 |
| pH | 4.5 ± 0.10 |
| COD (g/L) | 147.7 ± 0.50 |
| TS (g/L) | 102.5 ± 2 |
| TVS (g/L) | 95.3 ± 3 |
| TVS/TS ratio | 0.93 ± 0.03 |
| Moisture (%) | 89.75 ± 0.2 |
| Inorganic matter (%) | 6.9 ± 2.9 |
| Organic matter (%) | 93 ± 2.9 |

Each value represents the mean of three replicates ± SD.

According to the TVS/TS ratio, the BW has a high content of organic matter (93 ± 2.9%) that is suitable for an AD. A similar result was reported by Balat and Balat [42]. Conversely, Kalia et al. [43] and González-Sánchez et al. [44] reported a lower content (11 and 19%, respectively) of organic matter because they used waste banana stem and peel, which were not used in this study. It also presented a COD of 147.7 ± 0.5 g/L. A similar result was obtained by González-Sánchez et al. [44], who evaluated different agro-industrial wastes with the potential for methane production by AD. Although the BW has a high content of organic matter (TVS and COD), it does not indicate that it is 100% biodegradable. For this reason, anaerobic biodegradability tests were carried out through the calculation of the BMP to determine its value.

### 3.2. Anaerobic Digestion

The results of methane production from the AD of BW, positive and negative control, are shown in Figure 3a. As can be seen, methane production was higher in the positive control, since it is a 100% biodegradable substrate, it was easily assimilated by the microbial consortium present in the AGS; it reached an MMP of 968 ± 7.4 mL and MPR of 56.2 ± 1.12 $mLCH_4/Lb \cdot day$. Regarding the evaluation of the BW (Figure 3a), this showed an exponential phase (Log phase) that was almost immediate; therefore, this waste shows a high affinity with the inoculum. This is since waste has a high content of simple carbohydrates and the rest of the polymeric materials are easily hydrolyzable because of their high state of maturity. However, even when BW is easily hydrolyzed, the MMP and MPR were 320.3 ± 5.5 mL and 18.6 ± 0.4 $mLCH_4/Lb \cdot day$, respectively. The lower value of MPR is mainly due to the substrate type, particle size and low inoculum–substrate interaction (batch reactor without agitation) since, according to Angelidaki et al. [45], the size and substrate type can be very important parameters in the MPR rather than for the MMP from a given substrate, as well as the inoculum–substrate interaction. Because of these parameters, the decomposition rate in the hydrolysis stage is generally the limiting step of AD when solid organic matter is used as the substrate [46], causing a low value of MPR. However, despite the above, the microorganisms managed to adapt and reach the stationary phase on day 43. Finally, the negative control generated 8.9 ± 0.2 mL of methane; this low production was due to the absence of substrate and the catabolism of the same sludge.

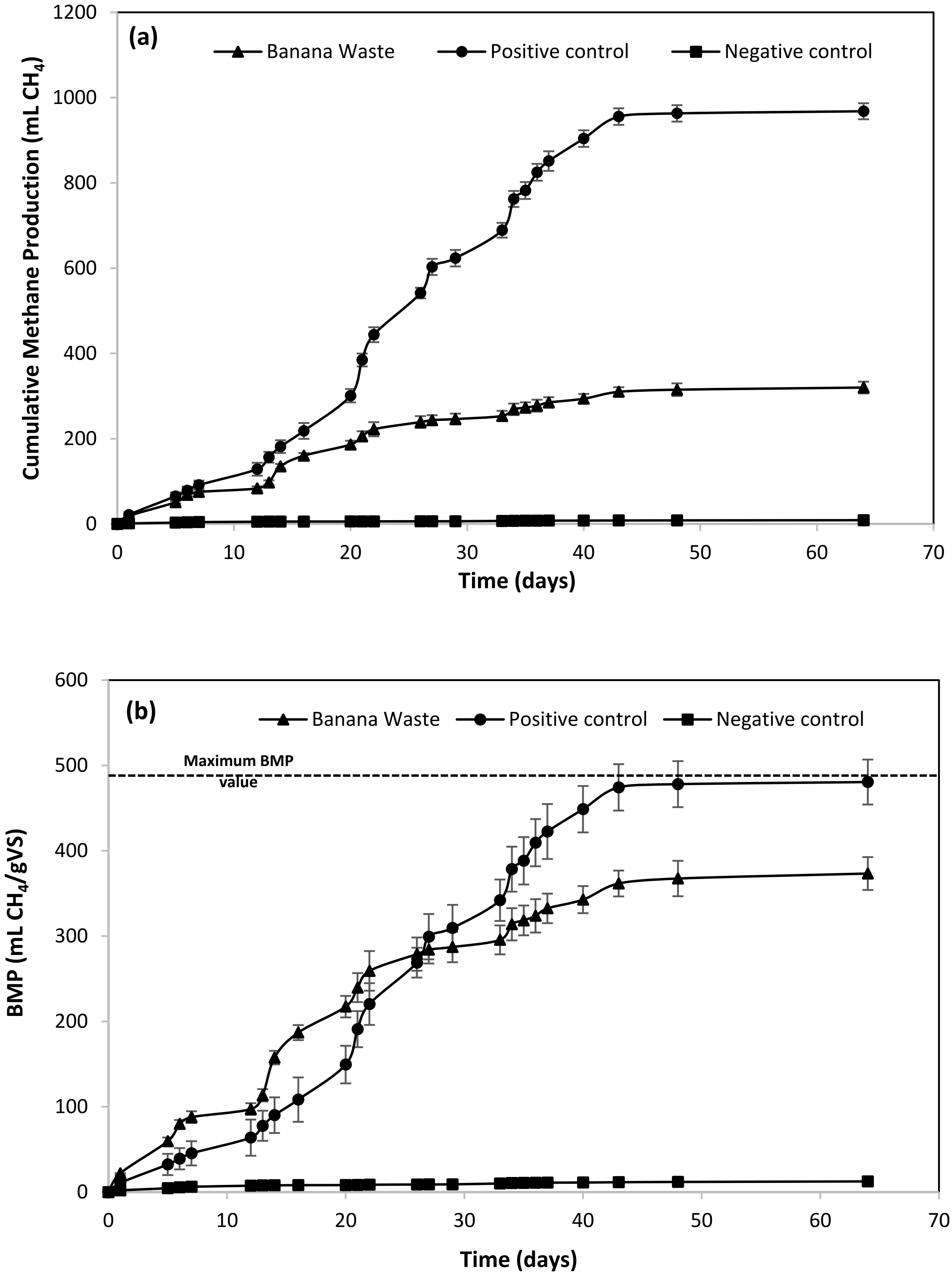


**Figure 3.** Cumulative methane production (**a**) and biochemical methane potential test (**b**). Each kinetics value represents the mean of three replicates ± SD.

On the other hand, once the amount of methane produced was obtained and knowing the concentration of COD added to the batch bioreactors of the experiments, the BMP test was determined (Figure 3b). This parameter is a respirometry test that indicates the anaerobic biodegradability of a substrate. Further, it quantitatively determines the potential of a substrate to be transformed into methane by the action of an anaerobic microbial consortium, so the theoretical MMP generated can be determined by the stoichiometry of mineralization of a mole of methane using reaction 1. Thus, the theoretical maximum methane production will be 490 $mLCH_4/gVS$ [47].

$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(l)}\ \Delta H = -802\ kJ\ \text{(Reaction 1)}$$

As expected, the positive control generated a BMP value (480.5 ± 11.6 $mLCH_4/gVS$) is very close to the theoretical MMP because the substrate used was 100% biodegradable. On the other hand, the BMP value of the BW was 373.3 ± 9.4 $mLCH_4/gVS$. Lower BMP values from BW were reported by several authors [18–24,48] since the banana waste (stem, bulbs, petioles-midribs, leaf blades, leaf sheaths, rachis stems, floral stalks, peels and peduncles) used by them had lower biodegradability, because the high lignin contents of their BW strongly affect their digestibility, and, consequently, affect their BMP performances compared to the pulp used in this work. BMP and biodegradability obtained from the present study were comparable to those in the previous studies (Table 2).

**Table 2.** BMP and biodegradability reported by previous studies.

| BW | Time (Days) | BMP ($mLCH_4/gVS$) | Biodegradability (%) | Ref. |
|---|---|---|---|---|
| Peels | 45 | 203-352 | 41.4–71.8 | [11] |
| Stem | 40 | 232 | 47.3 | [18] |
| Leaf blades | 188 | 98 | 20 | [20] |
| Petioles-midribs | | 127 | 25.9 | |
| Leaf sheaths | | 141 | 28.7 | |
| Floral stalks | | 144 | 29.3 | |
| Bulbs | | 150 | 30.6 | |
| Rachis stems | | 162 | 33 | |
| Peels | 12 | 251–284 | 51.2–57.9 | [21] |
| Peduncles | 132 | 162–257 | 33–52.4 | [22] |
| Green peels | | 208–303 | 42.4–61.8 | |
| Bulbs | | 228–304 | 46.5–62 | |
| BW | n.d. | 316 | 64.5 | [23] |
| Peduncles | 100 | 210–260 * | 60–74.2 | [24] |
| Peels | 30 | 268–331 | 54.6–67.5 | [48] |
| Pulp | 64 | 373.3 ± 9.4 | 76.2 ± 1.6 | This work |

BMP (Biochemical Methane Potential), BW (Banana Waste). * ($mLCH_4/gCOD$).

This value obtained is considered promising since it indicates that the anaerobic biodegradability of BW was 76.2 ± 1.6% (indicates the percentage of the organic matter present in the feedstock that can be converted to methane). The power generated in the AD process was calculated from the BMP, where the volume value was converted to mass in units of moles using the ideal gas equation ($PV = nRT$). Later, the moles were converted to energy (kJ), considering that 1 mole of methane produces 802 kJ using Equation (1). BW generated 13.37 kJ/gVS; this value is high compared to the theoretical power production (17.55 kJ/gVS) and other reported results [20,22,49]. Hence, 1 kg of banana overripe waste can generate 1568 kJ. Based on these values (BMP, biodegradability and power generation), this waste shows great potential for energy valorization in AD.

### *3.3. Microbial Fuel Cell*

The MFC was operated over a 21-day duration. The image generated by a scanning electron microscope (Figure 4) shows the presence of microorganisms after the electrode (anode) was immersed in the anaerobic sludge for 10 days; as it is evident, the electrode was colonized until the formation of a biofilm rich in anaerobic microorganisms (e.g., bacilli and coccobacilli). In addition, the presence of fungal filaments was observed; the latter can be due to traces of oxygen from the starting operations in the system.

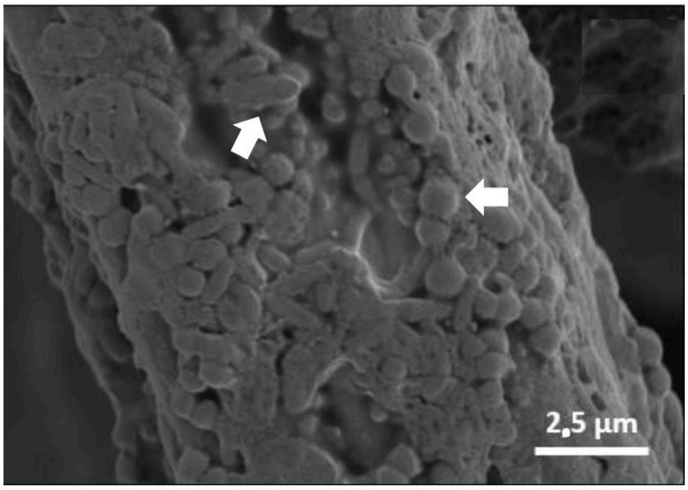


**Figure 4.** Microorganisms present in the anode biofilm from a scanning electron microscope.

As shown in Figure 5, the electricity is immediately generated in the MFC after anode inoculation. The maximum voltage generated was 286 mV due to the metabolic oxidation process of organic materials contained in the digestate and for the anaerobic microorganisms present in the biofilm generated on the graphite electrode. The salinity of the substrate improved the conductivity and, therefore, the internal resistance of the system, which allows a higher rate of electron transfer, observing that maximum potential.

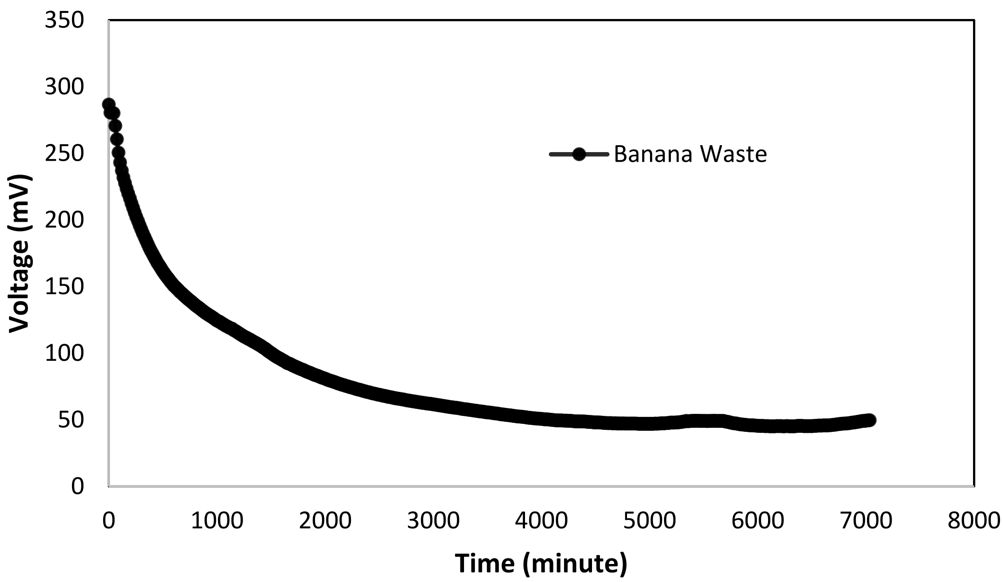


**Figure 5.** Voltage generation by MFC from BW digestate-feeding.

To know the behavior of the MFC, a polarization curve was made to determine the internal resistance of the cell. The highest point of the curve corresponds to the point where the internal and external resistances are equal. In this way, in Figure 6 a plateau area that encompasses four points can be observed. By superimposing this plateau on the current vs. potential graph, an area of the second graph is obtained to calculate the equation of the line; the slope of this equation is the internal resistance of the system, whose value is 580.99 Ω.

In the graph (Figure 6) of current vs. power, the power and current tend to increase up to a certain limit; after that, the power begins to decay concerning the increase in current density, which indicates a typical behavior of microbial fuel cells [50].

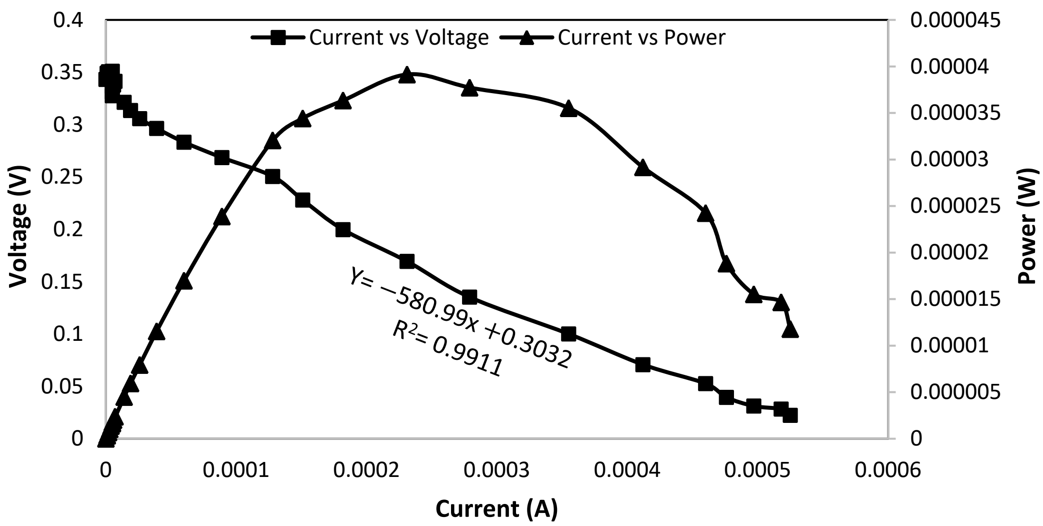


**Figure 6.** Polarization curve by MFC from BW digestate-feeding.

It can also be seen in Figure 6 that two regions of the three characteristic regions in the polarization curves correspond to a rapid drop in voltage concerning low current densities that are associated with activation overpotentials since they are energy losses in the initiation of oxidation-reduction reactions. Then, it is observed that the voltage drops linearly concerning the current, and it is in this region where the ohmic overpotentials are dominant, which suggests that one has a low activation loss but a higher ohmic loss, which means that the losses come from their electrodes rather than food and microbial activity [51]. The current and power as a function of the surface area of the exposed electrode are shown in Figure 7. The maximum values were 41.3 mW/m$^2$ for power density, and 0.0002867 A for current density generated in the MFC fed with BW digestate. Table 3 shows the comparison of MPD and maximum voltage from the present study with previous studies.

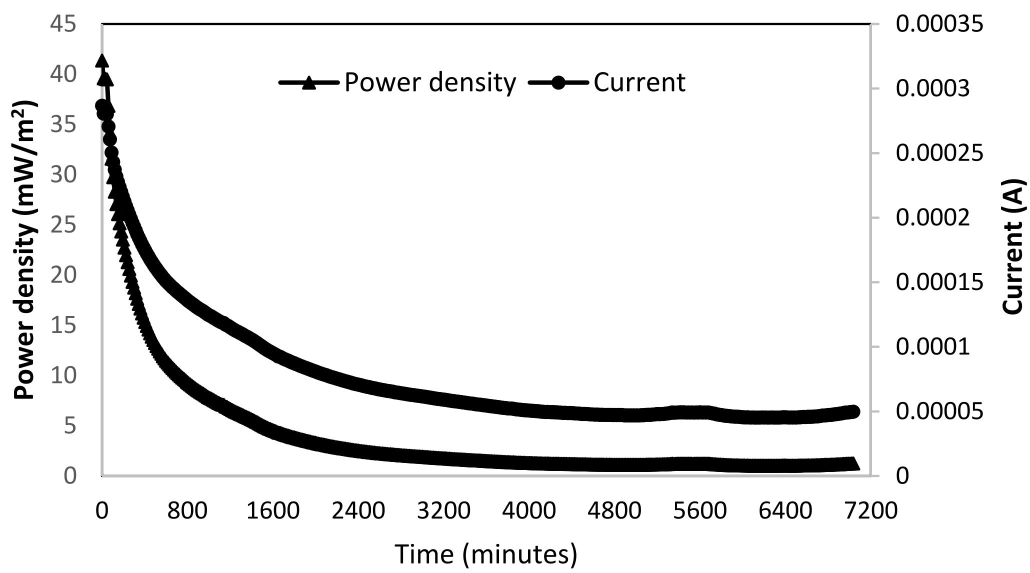


**Figure 7.** Power density and current generated by MFC from BW digestate-feeding.

**Table 3.** MPD, max voltage, and internal resistance reported by previous studies.

| BW | Max Voltage (mV) | MPD ($mW/m^2$) | Internal Resistance (Ω) | Ref. |
|---|---|---|---|---|
| Peels | 125–146 | 11.3–13.1 | 3500–4200 | [32] |
| Peels | 237.1 | 23.74 | n.d. | [33] |
| Peels | 760 | 160 | 32 | [34] |
| Pulp | 286 | 41.3 | 580.99 | This work |

MPD (Maximum Power Density), n.d. (not determined).

The MPD and maximum voltage obtained in this research are greater than the average range of peel banana waste (real substrates) [13,30] because the use of lignocellulosic waste is more difficult to biodegrade, even the crushed carbohydrates present in the overripe banana pulp. This research even exceeds some values obtained from molecules such as lactate [52] and acetate [53,54]. However, it showed lower values than reported by Abdallah et al. [32] since they evaluated two sets of four MFCs, each connected in series. The power generated in the MFC process was calculated from the average of watts ($8.33 \times 10^{-6}$ W) generated during the measurement; later it was multiplied by the monitoring time (7035 min) in seconds to obtain the value in Joules (W·s). The result was divided by the TVS (2.5 gVS/L) that entered the system and was multiplied by the volume of the anode cell (0.21 L) to obtain how much power was generated from one gram of VS. The digestate from BW in MFC generated $6.69 \times 10^{-3}$ kJ/gVS. The power generation in the MFC is mainly due to the degradation (catabolism of anaerobic microorganisms) of organic matter by electrogenic bacteria, which, in 5 days, oxidized a percentage (8–10%) of the organic matter contained in the digestate.

Table 4 shows the organic matter removal efficiency such as COD, TS and TVS for both processes. This system evaluated (AD-MFC) generated a removal efficiency concerning the COD of 85.4 ± 1.0%, TS of 43.5 ± 1.9% and TVS of 62.9 ± 1.8%. These high COD and TVS removal efficiency are attributed to the that the BW presents a high biodegradability (76.2 ± 1.6%), which allowed the microorganisms present in the AGS of the AD and the anaerobic sludge of the MFC to easily degrade the organic matter present. This high COD and TVS removal efficiency is attributed to the high biodegradability presented by the substrate used (BW). This value obtained is considered promising compared to the biodegradability results reported by other researchers [11,18,20–24,48] because they used other banana waste such as leaf blades, petioles-midribs, leaf sheaths, floral stalks, bulbs, rachis stems, peels, peduncles and green peels. However, TS removal efficiency was lower; this event is attributed to the presence of inorganic matter (salts) derived from substrate conditioning. Therefore, it was difficult for both microbial consortia to remove the corresponding inorganic part. Although, it has been reported that the presence of these inorganic salts in the MFC facilitates the transfer of electrons, improves the stable output voltage, shortens the treatment processing time and reduces the internal resistance [55]. This research is the first to report a coupled system (AD + MFC) for banana waste treatment. Thus far, there have been no reports about these coupled systems for banana waste treatment by domestic and international academic papers in professional journals.

The total power generation from both processes was 13.38 kJ/gVS. Therefore, this waste from being used by the banana agroindustry in Mexico would allow it to generate around $41.52 \times 10^6$ kWh/year. It is known that the average consumption of electrical energy registered in a home (developing country) is 3000 kWh/year. It concluded that this technology could satisfy the energy needs of 13,843 homes.

**Table 4.** Organic matter removal efficiency by AD and MFC.

| Parameter | AD | | | MFC | | | $E_T$ (%) |
|---|---|---|---|---|---|---|---|
| | Influent (g/L) | Digestate (g/L) | $E_1$ (%) | Digestate (g/L) | Effluent (g/L) | $E_2$ (%) | |
| COD | 3.337 ± 0.2 | 0.544 ± 0.05 | 83 ± 1.7 | 0.544 ± 0.05 | 0.485 ± 0.03 | 10 ± 1.7 | 85.4 ± 1.0 |
| TS | 27.81 ± 1.7 | 20.3 ± 0.8 | 27 ± 2.2 | 20.3 ± 0.8 | 15.7 ± 0.2 | 22 ± 1.7 | 43.5 ± 1.9 |
| TVS | 6.2 ± 0.4 | 2.5 ± 0.1 | 59 ± 1.8 | 2.5 ± 0.1 | 2.3 ± 0.07 | 8 ± 0.8 | 62.9 ± 1.8 |
| pH * | 7.8 ± 0.1 | 7.2 ± 0.3 | - | 7.2 ± 0.3 | 6.9 ± 0.2 | - | - |

* Dimensionless unit. $E_1$ is removal efficiency by AD; $E_2$ is removal efficiency by MFC; $E_T$ is total removal efficiency. Each value represents the mean of three replicates ± SD.

## 4. Conclusions

The BW has a biodegradability value of 76.2 ± 1.6% with 95.3 gVS/L; therefore, it has great potential as a feedstock for bioenergy production in the form of biomethane and bioelectricity if it is used as a substrate in the MFC coupled with AD. The AD generated an MMP of 320.3 mL, MPR of 18.6 $mLCH_4/Lb \cdot day$ and BMP of 373.3 $mLCH_4/gVS$. Further, the MFC generated a maximum voltage of 286 mV, a power density of 41.3 $mW/m^2$, a resistance of 580.99 Ω and a current of 0.0002867 A. These values showed the potential to produce extra energy to that already produced in the AD. This coupled system showed a high potential for COD removal (85.4 ± 1.0%) and at the same time, generated total energy up to 13.38 kJ/gVS from both treatment processes. With the use of these technologies, waste could be taken advantage of, such as BW, for generating sustainable processes and developing a circular economy in the banana agroindustry. Further, this study thus posits that this MFC-AD integrated system could be useful for energy recovery and waste treatment processes (e.g., livestock waste, municipal waste, fruit/vegetable waste, including wastewater of different origins).

In addition, it is recommended to evaluate the feasibility of co-digestion with other food residues (solid or liquid), implement a mixing system that allows increasing the contact time between the inoculum and substrate, carry out a previous adaptation of the inoculum, continuously operate both coupled systems, implement other types of electrodes (different shapes or materials) and large scale evaluation; all this with the aim of increasing performance in the production of bioenergy and minimizing pollution.

## 5. Statement of Novelty

Banana wastes (pulp, peel, etc.) are generally sent to open dumps or decompose on the spot without being used, becoming an environmental problem. These wastes have the potential to be treated and transformed into value-added by-products. Here it is demonstrated that both systems can operate coupled and fed with banana waste for methane and bioelectricity generation. At the same time, these coupled processes reduce the environmental impact caused by the banana agroindustry, in addition to the great potential for the valorization of banana waste as a feedstock for bioenergy production.

**Author Contributions:** N.I.R.-C. performed the experiments, literature review and compiled the data. S.P.-F. performed the conceptualization, validation, data curation and project administration. A.C.-S. performed the validation, formal analysis, data curation, writing—original draft preparation and writing—review and editing. P.J.S. performed the conceptualization, data curation and formal analysis. M.d.C.H.-C., R.M.S.-A., J.M.E.H.-M., M.E.D.-E. and H.A.E.-A. performed some of the remaining experiments. E.I.R.-V. and H.A.N.-A. performed validation and data curation. All authors have read and agreed to the published version of the manuscript.

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## Abbreviations

| | |
|---|---|
| $\Delta H$ | Change in Enthalpy |
| % | Percentage sign |
| A | Area |
| AD | Anaerobic digestion |
| AGS | Anaerobic granular sludge |
| BMP | Biochemical methane potential |
| BW | Banana waste |
| $C_{eff}$ | Effluent concentration |
| $C_{inf}$ | Influent concentration |
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| COD | Chemical oxygen demand |
| E | Removal efficiency |
| $E_1$ | Removal efficiency by AD |
| $E_2$ | Removal efficiency by MFC |
| EDTA | Ethylenediaminetetraacetic acid |
| EET | Extracellular electron transfer |
| $E_T$ | Total removal efficiency |
| g/L | Grams per liter |
| gCOD | Grams of chemical oxygen demand |
| gCOD/gVSS | Grams of chemical oxygen demand per gram of volatile suspended solids |
| gTVS | Grams of total volatile solids |
| gVSS | Grams of volatile suspended solids |
| $H_2O$ | Water |
| I | Current |
| kg/year | Kilogram per year |
| kJ | Kilojoule |
| kJ/gCOD | Kilojoule per gram of chemical oxygen demand |
| kWh/year | Kilowatt-hour per year |
| Lb | Liters of bioreactor (bioreactor volume) |
| $m^2$ | Square meter |
| MFC | Microbial fuel cell |
| mL | Milliliter |
| $mLCH_4/gCOD$ | Milliliters of methane per gram of chemical oxygen demand |
| mm | Millimeter |
| MMP | Maximum methane production |
| MPR | Methane production rate |
| mW | Milliwatts |
| $mW/m^2$ | Milliwatts per square meter |
| OM | Organic matter |
| $O_2$ | Molecular oxygen |
| °C | Degrees Celsius |
| P | Power |
| PD | Power density |

| | |
|---|---|
| pH | Potential of hydrogen |
| POSW | Putrescible organic solid waste |
| SMA | Specific methanogenic activity |
| ton | Tonne |
| ton/year | Tonne per year |
| TS | Total solids |
| TVS | Total volatile solids |
| TVS/TS ratio | Total volatile solids to total solids ratio |
| UASB | Upflow Anaerobic Sludge Blanket |
| USW | Urban solid waste |
| V | Voltage |
| VSS | Volatile suspended solids |
| W | Watts |
| W·s | Watts per second |
| WWTP | Wastewater treatment plant |
| Ω | Ohm |

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