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Potential Use of Mango Waste and Microalgae *Spirulina sp.* for Bioelectricity Generation

De La Cruz-Noriega M., R. Nazario-Naveda, Santiago M. Benites
Vicerrectorado de Investigación Universidad Autónoma del Perú, Lima 15842, Peru.

Rojas-Flores S.*
Universidad Señor de Sipan, Chiclayo-Perú.

D. Delfín-Narciso
Grupo de Investigación en Ciencias Aplicadas y Nuevas Tecnologías, Universidad Privada del Norte, Trujillo, 13007, Peru

Rojas-Villacorta W.
Escuela de Postgrado, Universidad Nacional de Trujillo, Trujillo 13001,Peru.

F. Díaz
Escuela Académico Profesional de Medicina Humana, Universidad Norbert Wiener, Lima, Peru.

***Corresponding author:** segundo.rojas.89@gmail.com

Potential use of organic waste and microalgae generates bioelectricity and thereby reduces harmful effects on the environment. These residues are used due to their high content of electron-generating microorganisms. However, so far, they have not been used simultaneously. Therefore, this research uses mango waste and microalgae *Spirulina sp.* in double-chamber microbial fuel cells to generate bioelectricity. The cells were made at a laboratory scale using zinc and copper electrodes, achieving a maximum current and voltage of 7.5948 ± 0.3109 mA and 0.84546 ± 0.314 V, with maximum electrical conductivity of the substrate being 157.712 ± 4.56 mS/cm and an optimum operating pH being 5.016 ± 0.086. The cells showed a low internal resistance of approximately 205.056 ± 25 Ω, and a maximum power density of 657.958 ± 21.114 mW/cm^2 at a current density of 4.484 A/cm^2. This research provides an excellent opportunity for mango farmers and exporting and importing companies because they can use their own waste to reduce their electricity costs when this prototype is brought to a large scale.

Keywords: organic waste, mango, microalgae Spirulina sp., bioelectricity, renewable energies.

Introduction

In the last centuries, two phenomena of global concern have been experienced, population growth and industrialization, which have led to an increase in energy demand (Hanif, 2018). Because of this, fossil fuels have been the main source of energy supply. However, it has led to generating serious problems in the climate, due to the increase of greenhouse gases in the atmosphere (Shindell and Smith, 2019) accelerating climate change and global warming, a major problem that humanity is facing (Milne et al.,2021), making dependence on these fuels unsustainable (Wang et al., 2021).

The two aforementioned phenomena have been one of the causes of waste generation. Often residues are inappropriately managed, which until now represents one of the main problems for the food industry (Fierascu et al., 2020). This leads to a problem of accumulation in the environment that through decomposition releases greenhouse gases (GHG) contributing to global warming. According to the Food and Agriculture Organization, it has been estimated that 8% of GHGs come from food waste (Matei et al., 2021). A portion of this food waste is fruit waste, and only in 2017 more than 1 billion tons of different fruits were produced worldwide (Fierascu et al., 2020), and it is estimated that more than 60 million tons of waste from these fruits are discarded globally (Castro-Vargas et al., 2019).

Mango (*Mangifera indica L.*) is one of the most consumed and cultivated tropical fruits around the world, and is the second most traded tropical fruit in the world and the seventh most produced, reaching an annual production of 46 million tons (Castro-Vargas et al., 2019; Lee et al., 2021; Lorenzo-Santiago et al., 2018; Marcos et al., 2020; Owino et al., 2021). However, waste inevitably generates from all this global production, for example, in some parts of the world, like in African and Asian countries, the post-harvest loss of mango fruit can reach up to 50% (Owino et al., 2021), which if not managed properly could lead to environmental pollution problems.

Different biotechnological alternatives have been proposed to reuse and add value to different mango residues (Ahmad Shahrim et al., 2022; Mandha et al., 2021; Manhongo et al., 2021; Tirado-Kulieva et al., 2021) because it is an important source of phenolic compounds (Tirado-Kulieva et al., 2021). A proposal that has gained more interest from scientists to address environmental problems is microbial fuel cell technology (MFCs), which was proposed by Michael Potter in 1911 (Gajda et al., 2018). These bio-electrochemical systems are an emerging technology that exploits microbial metabolism to use the chemical energy contained in organic substrates to generate electricity in an environmentally sustainable way (Gul et al., 2021; Hassan et al., 2021). Usually, an MFC consists of an anode and cathode chamber, a proton exchange bridge (PEB), and catalysts (microorganisms). In addition, there is a variety of models and materials according to their usefulness (Mohyudin et al., 2022; Suresh et al., 2022). On the other hand, MFCs can use organic substrates such as fruit residues to generate electricity (Rojas-Flores et al., 2020). Among the fruit residues, some components help to generate electricity, for example, mango pulp contains a variety of reducing sugars, amino acids, aromatic compounds, and functional compounds, such as pectin, vitamins, anthocyanins, and polyphenols (Lebaka et al., 2021), which are oxidized in the metabolism of microorganisms to obtain electrons that will be used to generate electricity. Therefore, some experiments have been tested where the electric current was generated by MFCs using mango waste (Rahman et al., 2021). Yaqoob et al. (2022) have succeeded in producing a maximum current density of 87.71 mA/m^2 from mango waste in an MFC, while Symonds et al. (2018) have generated a maximum voltage and a power density of 1.133 V and 276,078 mW/m^2, respectively, from wastewater from the mango pulp process using an MFC with an aerated cathode.

On the other hand, nowadays, the use of microalgae has intensified in different fields of science, MFCs being a technology to which these photosynthetic microorganisms can be coupled (Raja et al., 2022). They have proven to be very useful in reducing mechanical aeration costs since they release oxygen (O_2)

during photosynthesis (Kannan and Donnellan, 2021). Huarachi-Olivera et al. (2018) have managed to produce electrical energy in a double-chamber MFC by using the microalgae *Chlorella Vulgaris* and a microbial community where the bio-electrogenic activity and potential increased from 23.17 mW/m^2 to 327.67 mW/m^2 and 200 mV to 954 mV, respectively, over 32 days. Another research work belongs to Rojas-Flores et al. (2021), where they used *Chlorella sp.* to generate bioelectricity through a photobioreactor, which was provided with two copper and zinc electrodes, and obtained maximum values of 0.93179 ± 0.0323 V and 23.79 ± 0.9516 mA, as well as a maximum power density and current of 4.71441 ± 0.12861 W/cm^2 and 401.5873 mA/cm^2, respectively. Nookwam et al. (2022) have also used microalgae to generate bioelectricity and treat wastewater by using an MFC with a photosynthetic-cathode chamber connected in a vertical cascade contributing to self-sustainability due to its high efficiency in O_2 production as an electron acceptor, thereby improving the efficiency of the cathode. This evidence suggests that microalgae can be successfully coupled with the MFC technology to improve energy production.

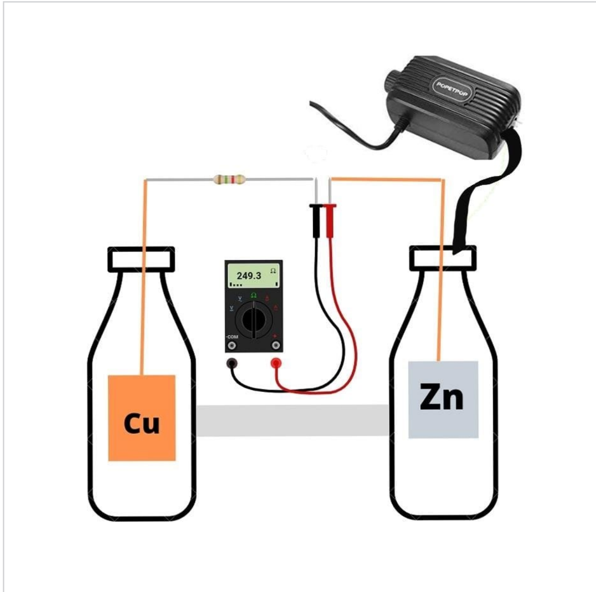
Therefore, the objective of this research was to generate electric current by means of double-chamber microbial fuel cells, using zinc and copper as electrodes, monitoring their voltage, current, pH, conductivity, power density, and current density values for 35 days, in order to develop an alternative eco-friendly solution to the various organic residues produced in the region.

Method and Materials

Construction of double-chamber microbial fuel cells

Two 1-L airtight polyethylene containers were used as anodic and cathodic chambers for each cell (3 MFCs in total), connected by a proton exchange membrane (10 mL of the concentration of 6 g of KCl plus 14 g of agar and 400 mL of H_2O) of a tubular shape with 10 cm and 2.5 cm in length and diameter, respectively. The electrodes used were zinc (anode) and copper (cathode) of 100 cm^2 area and 3.5 mm thick, which were placed inside each chamber connected by a circuit with a resistor of 100 Ω (see *Fig. 1*).

Fig. 1. *A microbial fuel cell prototype*



Collection and preparation of mango waste for the anode chamber

Mango (*Mangifera indica*) waste was collected from CUC SAC. Moche, Peru. It was washed four times with distilled water to remove any impurities (dust, insects, or other impurities). Then, using an extractor (Maqorito- 400 rpm), 500 mL (150 mL for each MFC) of mango extract was obtained.

Preparation of Spirulina sp. microalgae cultures for the cathode chamber

The microalga *Spirulina sp.* was cultured according to the methodology by Huarachi-Olivera et al. (2018), where a synthetic medium for algae was used based on salts such as: peptone (292 mg/L); $NaHCO_3$ (250 mg/L); $MgSO_4{\cdot}7H_2O$ (18 mg/L); $FeSO_4{\cdot}2H2O$ (4 mg/L); KCl (19 mg/L); $(NH_4)_2SO_4$ (382 mg/L); $K_2HPO_4{\cdot}3H_2O$ (346 mg/L); $CaC_{l2}{\cdot}2H_2O$ (13 mg/L). The volume ratio for the cathode was 1:1 (microalgae + synthetic medium).

Characterization of microbial fuel cells

Daily current and voltage monitoring was performed using a Prasek Premium PR-85 multimeter and an external resistor of 100 Ω. On the other hand, current density (CD) and power density (PD) values were obtained using external resistors 10 ± 0.2, 40 ± 2.3, 50 ± 2.7, 100 ± 3.2, 300 ± 6.2, 390 ± 7.2, 560 ± 10, 680 ± 12.3, 820 ± 14.5, 1000 ± 20.5 Ω; by the formula CD = I/A and PD = IV/A (Segundo et al., 2022), where I is the current with different external resistors, V is the voltage of open-circuit cells, and A is the area (144 ± 5.2 cm^2). Conductivity (conductivity meter CD-4301) and pH (pH meter 110 Series Oakton) changes were also measured, and the resistance values of MFCs were measured using an energy sensor (Vernier ± 30V and ± 1000 mA).

Results and Analysis

Voltage values increased from the first day (0.3162 ± 0.0037 V) to the twenty-first day (0.84546 ± 0. 314 V) and then slowly decayed until the last day (0.46335 ± 0.124 V; see *Fig. 2 (a)*. The increase in voltage is due to the increase in electrons and protons generated at the anode due to the increase in redox reactions (Cao et al., 2021), and to the aeration obtained by the cathode chamber with the algae due to the increase in O_2 reduction reactions (Kannan and Donnella, 2021). *Fig. 2 (b)* shows the values of the electric current generated, observing an increase from the first day (3.834 ± 0.035 mA) to the nineteenth day (7.5948 ± 0.3109 mA), and then decreasing until the last day (2.374 ± 0.312 mA). Compared with other investigations, the maximum values of voltage and electrical current obtained with mango residues were lower compared with the values obtained from blueberry residues (1.127 ± 0.096 V and 1.130 ± 0.018 mA) (Rojas-Flores et al ., 2021), while they were higher than the values obtained from papaya residues (0.736 ± 0.204 V and 5.57 ± 0.45 mA) and pineapple (0.3484 ± 0.003 V) (Flores et al., 2020). Waste fermentation plays an important role in generating the ideal conditions for the acclimatization of electron generating microorganisms, which flow from the anode to the cathode generating electric current. The increase of current values suggests an adhesion of these microorganisms, generating a biofilm to the anode electrode and good reception of the cathode electrode (Rojas-Flores et al., 2022; Saravanan et al., 2021). But substrate degradation in the final stage of monitoring generates an imbalance between oxidation and reduction at the anode and cathode, leading to a decrease in this parameter (Yu et al., 2021).

Fig. 2. *Values of (a) voltage and (b) electric current of the microbial fuel cells during monitoring*

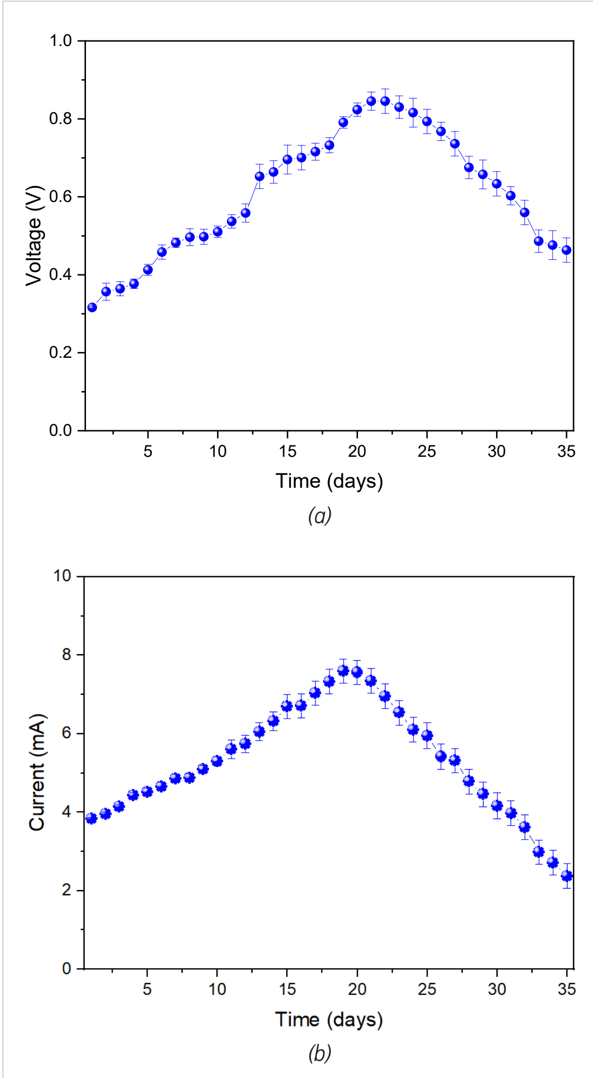
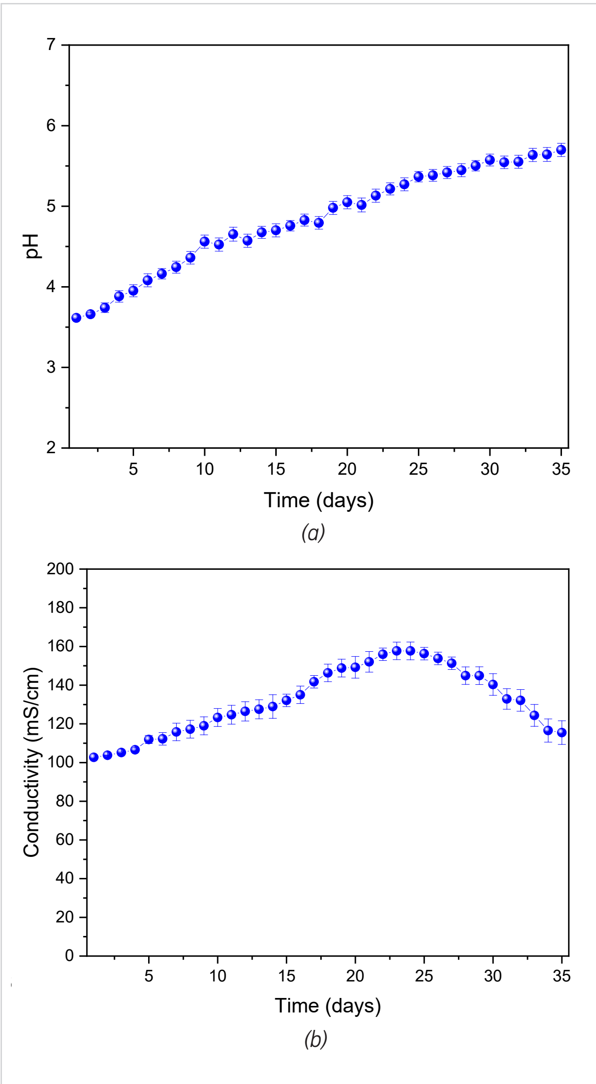


Fig. 3 (a) shows the pH values monitored during 35 days, observing that they vary from moderately to slightly acidic with an optimum operating pH of 5.016

± 0.086 on day 21. According to Kalagbor et al., (2020) pH variations are due to hydrolysis and acidification of fruit waste. Likewise, it is also observed that mango waste tends to neutral pH as the days go by (Azouma et al., 2018). *Fig. 3 (b)* shows the variations of the electrical conductivity values of mango waste, which increased from the first day (102.688 mS/cm) of monitoring until day 23 (157.712 ± 4.56 mS/cm), and, then, slowly decreased until the last day (115.4826 ± 6.124 mS/cm).

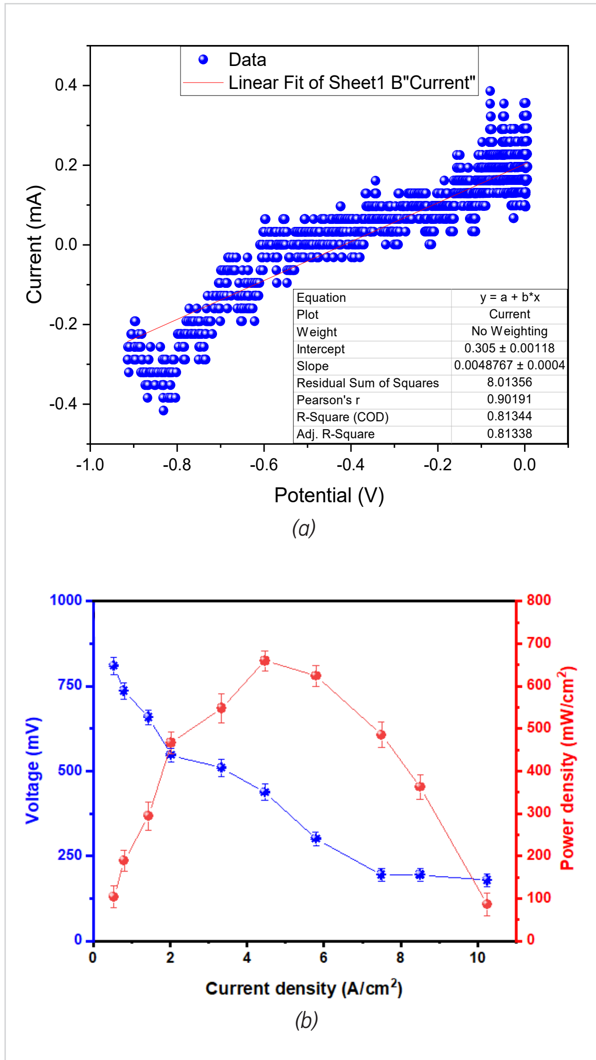
Fig. 3. *Values of (a) pH and (b) electrical conductivity of microbial fuel cells during monitoring*



The initial acidic conditions favored the high values found in this study, while the decrease in values is mainly due to substrate sedimentation in the final stage of monitoring (Gazali and Moqsud, 2019; Pandit et al., 2021).

Fig. 4 (a) shows the values of internal resistance of the microbial fuel cell, which were calculated using Ohm's Law modeling, multiplying resistance (R) by current (I) to obtain the voltage (V), i.e., V = RI, where the slope of the linear graph will be the inverse of the resistance. Since the x-axis was assigned to power values and

Fig. 4. *Values of (a) internal resistance and (b) power density and current density of microbial fuel cells*



the y-axis to current values, the experimental data fit the equation y = 0.0048767 x + 0.305, with R^2 = 0.8134. Hence, the internal resistance of the cell was 205.056 ± 25 Ω, which is low compared with other works, and this shows the good biofilm formation (Roy and Bharadvaja, 2020). The low resistance shown is due to the electrodes used (metallic materials), which have good electrical conductivity and low resistance to the passage of electrons (Flores et al., 2020). *Fig. 4 (b)* shows the values of voltage (V) and power density (PD) according to the current density (CD), obtaining a $PD_{max.}$ of 657.958 ± 21.114 mW/cm^2 at 4.484 A/cm^2 of CD and a peak voltage of 810.57 ± 15.47 V. This research surpasses that of Prasidha et al. (2020) who have shown a $DP_{MAX.}$ of 25.7 mW/m^2 in their double chamber cells in which they used fruit and vegetable waste leachates as substrate with an optimum pH of 6.9. Similarly, Latif et al. (2020) have managed to generate a $DP_{MAX.}$ of 62 mW/m^2 using Indian tropical fruit waste in double-chamber microbial fuel cells with a peak voltage of 700 mV. Wang et al. (2021) have used waste of Sprite, apple juice, and orange juice in their cells, managing to generate PD of 33.41 W/m^2, 20.63 W/m^2, and 12.75 W/m^2, respectively.

Conclusions

Bioelectricity was successfully generated in low-cost, laboratory-scale, double-chamber fuel cells, using zinc and copper as electrodes. Mango waste and Spirulina sp. microalgae residues can be used in both the anodic and cathodic chambers, respectively. Voltage and current peaks of 0.84546 ± 0.314 V and 7.5948 ± 0.3109 mA, respectively, were achieved; with an optimum operating pH of approximately 5.016 ± 0.086. The maximum electrical conductivity of mango waste was 157.712 ± 4.56 mS/cm, while the microbial fuel cells showed a low internal resistance of 205.056 ± 25 Ω. The maximum power density was 657.958 ± 21.114 mW/cm^2 at a current density of 4.484 A/cm^2. For future studies, it is recommended to coat the electrodes with chemical compounds to improve the efficiency of the cells and stabilize the pH of the substrate at its optimum operating value. Finally, this research seeks to provide an alternative to companies to generate their electricity, and in this way, they could improve the management of organic waste.

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