Journal of Experimental Biology and Agricultural Sciences, April - 2022; Volume – 10(2) page 387 – 395

Journal of Experimental Biology and Agricultural Sciences

http://www.jebas.org

ISSN No. 2320 – 8694

Performance of electrical energy monitoring data acquisition system for plant-based microbial fuel cell

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Received – January 16, 2022; Revision – March 22, 2022; Accepted – April 11, 2022
Available Online – April 30, 2022

DOI: http://dx.doi.org/10.18006/2022.10(2).387.395

KEYWORDS

Data acquisition system

Open circuit voltage

Polarization curve

Power density

Stevia rebaudiana

ABSTRACT

Plant microbial fuel cell (Plant-MFC) is an emerging technology that uses the metabolic activity of electrochemically active bacteria (EABs) to continue the production of bioelectricity. Since its invention and to date, great efforts have been made for its application both in real-time and large-scale. However, the construction of platforms or systems for automatic voltage monitoring has been insufficiently studied. Therefore, this study aimed to develop an automatic real-time voltage data acquisition system, which was coupled with an ATMEGA2560 connected to a personal computer. Before the system operation started it was calibrated to obtain accurate data. During this experiment, the power generation performance of two types of reactors i.e. (i) Plant-MFC and (ii) control microbial fuel cell (C-MFC), was evaluated for 15 days. The Plant-MFC was planted with an herbaceous perennial plant (*Stevia rebaudiana*), electrode system was placed close to the plant roots at the depth of 20 cm. The results of the study have indicated that the Plant-MFC, was more effective and achieved higher bioelectricity generation than C-MFC. The maximum voltage reached with Plant-MFC was 850 mV (0.85 V), whereas C-MFC achieved a maximum voltage of 762 mV (0.772 V). Furthermore, the same reactor demonstrated a

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Peer review under responsibility of Journal of Experimental Biology and Agricultural Sciences.

Production and Hosting by Horizon Publisher India [HPI]
(http://www.horizonpublisherindia.in/).

maximum power generation of 66 mW m^{-2} on 10 min of polarization, while a power density with C-MFC was equal to 13.64 mW m^{-2}. *S.rebaudiana* showed a great alternative for power generation. In addition, the monitoring acquisition system was suitable for obtaining data in real-time. However, more studies are recommended to enhance this type of system.

1 Introduction

The consumption of fossil fuels and the environmental problems caused by their excessive use has made it possible to find other alternatives for the production of clean energy, such as solar energy, which is a universal and reliable source; to respond to the high demand for electricity of the world population (Prabha et al. 2021; Maddalwara et al. 2021). It has been reported that the earth receives approximately 120,000 TW (traveling wave) of solar energy per year, with a power density of 170 W m^{-2} achieving the earth's surface, exceeding the current global demand of ~ 16 TW (Sekar and Ramasamy 2015).

On the other hand, other types of sustainable energy sources such as microbial fuels cells (MFCs) and plant-MFCs have been studied to produce bioelectricity (Rusyn et al. 2021; Apollon et al. 2022a). Since their implementation, these technologies have been studied from different angles. For example, MFC technology has been used in diverse fields of application such as (waste) water treatment (Choudhury et al. 2021; Saeed et al. 2022), nutrient recovery (Sharma et al. 2021; Sabin et al. 2022), and remediation of heavy metal (Wang et al. 2022; Lam et al. 2022) as reviewed by Apollon et al. (2022b). MFC uses both the metabolism of microorganisms adhering to the anode compartment, as well as the electrochemical process to transform chemical energy into electrical energy (Logan et al. 2006; Rusyn 2021). Unlike MFC, plant-MFC is a technology that uses the plant's photosynthetic activity to continuously generation of bioelectricity. The plant-MFC technology has been implemented in 2008 by Strik and co-workers using the *Glyceria maxima* (Reed manageress) plant to generate bioelectricity (Strik et al. 2008). During the experiment, a power density was reached up to 67 mW m^{-2}. Later, Wetser et al. (2015) managed to increase the yield of Plant-MFC using another plant species such as *Spartina anglica*. The maximum power density found in 10 min of polarization was 679 mW m^{-2}, which dropped to 240 mW m^{-2} in long-term operation (two weeks). In a Plant-MFC system embedded with *Caltha palustris*, the maximum voltage of 1454.1 mV and a current of 11.2 mA, were achieved respectively (Rusyn et al. 2019). Therefore, the performance of a bioelectrochemical system such as Plant-MFC is highly dependent on its type, design, and configuration. In addition, it also depends on the types of materials anodes and cathodes; and also plant species used (Rusyn 2021; Maddalwara et al. 2021).

Plant-MFC has been chosen as one of the safe sources of bioelectricity generation. The use of this technology has made it possible to largely reduce greenhouse gas emissions. The use of plants in MFCs allows for increasing the amount of biomass, as well as the power generation without the need to harvest the plants (Moqsud et al. 2015). Plant-MFCs can produce sustainable energy 18 times greater than the conventional sediment system. The increase in energy generation is due to the increase in the availability of organic matter (OM) in the anode chamber due to microbial oxidation (Ramadan et al. 2017).

Plant-MFC plays an important role in agricultural systems today. The implementation of this technology allows not only to produce of clean energy but also to evaluate the plant growth parameters such as plant height, number of shoots, stemming diameter, etc., (Apollon et al. 2020). In previous studies, researchers from different countries have developed Plant-MFC prototypes both to produce bioelectricity, as well as to evaluate plant growth through the system (Angelini et al. 2008; Luo 2009; Helder et al. 2010; Sudirjo et al. 2019a). The results of these investigations reported that the Plant-MFC systems influence both plant height, as well as the amount of biomass produced by the plant. In a study conducted by Apollon et al. (2020), it was found that the Plant-MFC had a positive effect on the plant height parameter. The same phenomenon was confirmed when the plants received doses of 150 mg L^{-1} of ammonium nitrate (NH_4NO_3), by using a prototype based Plant-MFC installed vertically in the soil (Apollon et al., 2022a). However, Plant MFCs also face great challenges concerning power generation in the long-term operation and their large-scale application in real-time. In a review done by Apollon et al. (2021), the most recent advances and trends in terms of Plant-MFC configurations were discussed, as well as the types of membrane, anode, and cathode materials used; the factors affecting the performance of Plant-MFC technologies, the challenges faced by bioelectrochemical systems and their possible real-time applications.

Hence, the main objectives of this study were (i) to build a Plant-MFC by choosing suitable and low-cost materials, as well as evaluating their performance; and (ii) to design an acquisition system to monitor the voltage in real-time in the Plant-MFC.

2 Materials and Methods

2.1 Design and Implementation of the Data Acquisition System

According to Maldonado-Ruelas et al. (2018), the voltage acquisition of BES technologies such as Plant-MFCs is generally very low power with high electrical impedance. To solve this problem, it is necessary to make schemes capable of coupling the impedances of the Plant-MFC systems. One of the schemes that must be implemented is the automatic data acquisition system (Arulmani et al. 2021; Zhang et al. 2021), which allows monitoring the voltages without problems through a digital platform system (Attia et al. 2022). The voltage acquisition system used in this study was divided into 6 steps or stages (Figure 1A). Figure 1B shows an ATMEGA2560 (Arduino) that was used in this study. Its main role was to facilitate the capture of the data as accurately as possible. Additionally, the system was linked with the ATMEGA2560 (Figure 2a), which was connected to a personal computer (Figure 2b).

One of the important features of this Arduino is the number of analog ports it has; in addition to being very easy to handle (Maldonado-Ruelas et al. 2018). The system comprised 32

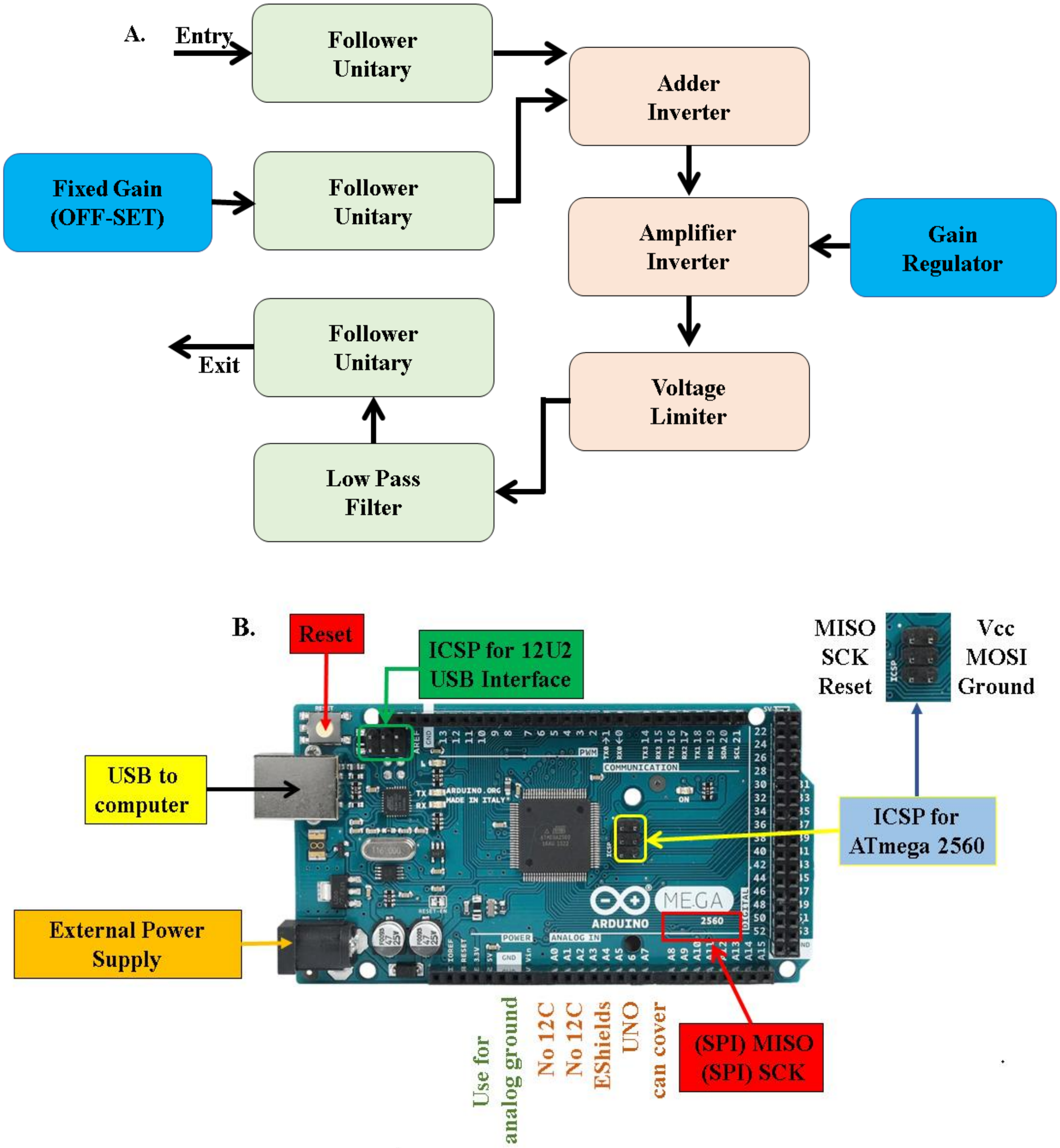

Figure 1 (A) General schematic presentation of the voltage automatic data acquisition system (adapted from Maldonado-Ruelas et al. 2018); and (B) characteristics of the Arduino used in this study.

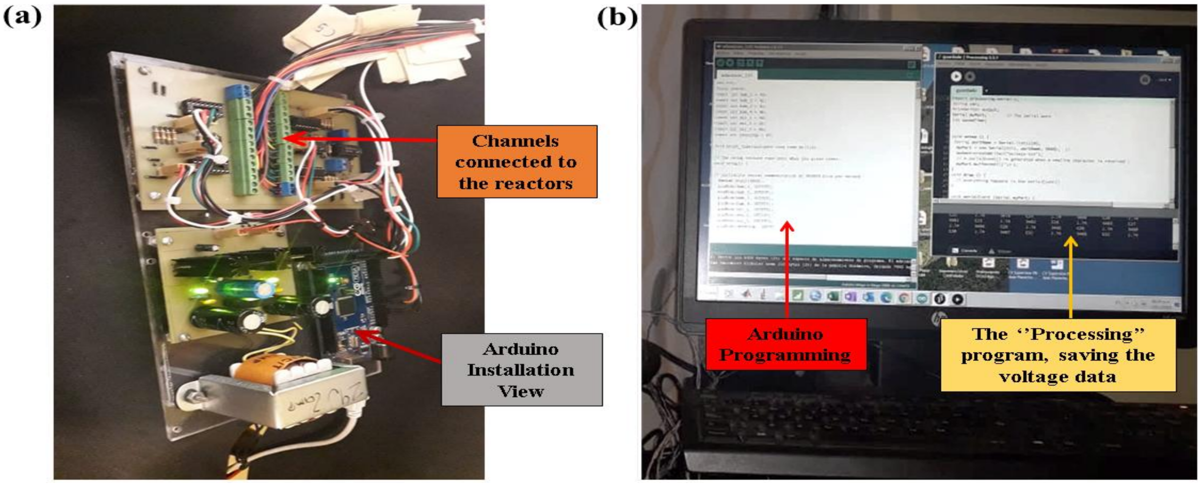

Figure 2 (a) Interface operation phase and (b) monitoring of voltage data by using a personal computer. Two windows are open on the screen. The window on the left shows the Arduino programming code and the window on the right indicates the program that saves the data by generating a .txt file.

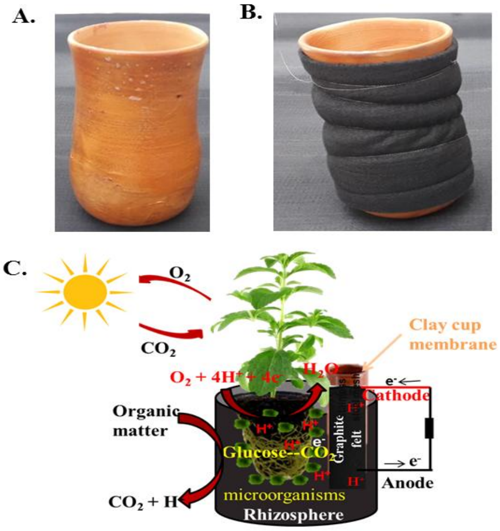

Figure 3 (A) Clay cup membrane, (B) constructed electrode and (C) schematic illustration of the evaluated Plant-MFC.

channels and 16 analog outputs. Before data monitoring, the digital platform was calibrated with the main objective of obtaining accurate data. Finally, the voltage data obtained in real time were automatically saved using the Processing platform (version 3.4) coupled to the interface. The data was updated by generating a ".txt" file with the exact information arranged for later analysis. This allowed avoiding data loss when there was a short circuit or other problems with the system.

2.2 Plant-MFC construction and operation

Two individual reactors i.e. (i) Plant-MFC and (ii) C-MFC were manufactured using a clay cup membrane (3 mm thick); the height of 20 cm and diameter of 9 cm (0.0693 m^2) (Figure 3A). For the anode electrode (Figure 3B), 648 cm^2 of graphite felt (ESGRAF, S.A de C.V., Mexico) of 6 mm diameter was used, placed around the entire surface of the pitcher. Graphite felt was previously reported as potential anode material (Kuleshova et al. 2021). 270 cm^2 of stainless-steel mesh (NYLOMAQ SL PLATE 9.5 mm 610 X 610 mm) was used as the cathode electrode, which was placed inside the clay cup. Subsequently, the Plant-MFC was embedded with the *S. rebaudiana* plant, as shown in Figure 3C. The electrode system of Plant-MFC was installed manually and placed about 20-30 cm below the soil. The experiment was carried out in the Faculty of Agronomy of the Autonomous University of Nuevo León, for 15 days. During this period, both the Plant-MFC and C-MFC were irrigated every two days with 2L of tap water.

2.3 Bioelectricity measurements

The open-circuit voltage (OCV) was recorded (in real time) in a time interval of 15 min/data, by using the constructed data acquisition system, for 15 days. Then, at the final stage of the experiment, 11 external resistances (between the ranges of 100 Ω to 1000 Ω) were manually applied in 10 min of polarization (Rusyn and Hamkalo 2020). Current and power were calculated using Ohm's law as reported by Apollon et al. (2022a). Then, current and power densities were normalized considering the area (0.0693 m^2) of the anode surface of the Plant-MFC reactor. Eq. (1) indicates ohm's law, and Eqs. (2) – (3) show the bioelectricity calculation process according to the ohm's law (Nasrabadi and Moghimi 2022). Finally, Eq. (4) shows the process of calculation of current density, according to the anode surface projected area (Rusyn et al. 2021; Apollon et al. 2020).

- Voltage (V): $V = I * R$ (1)
- Current intensity (A): $I = \frac{V}{R_{ext}}$ (2)
- Power (W): $P = V * I$ (3)
- Current density: $I = \frac{V}{A_{anode}\ R_{ext}}$ (4)

Where:

V: Voltage (Volts).

I: Intensity (A).

R_{ext}: External resistance (Ω).

A_{anode}: Anode Surface Projected Area.

V_{oc}: Open Circuit Voltage (Volts).

3 Results and discussion

3.1 Performance of the reactors in OCV

Results presented in Figure 4 show that the two evaluated reactors in this study had a different behavior for the OCV parameters. Plant-MFC turned out as a more effective reactor in this study, reaching a higher OCV with a value of 850 mV (0.85 V), whereas, C-MFC indicated an OCV of 762 mV (0.772 V). This behavior is because there was greater bacterial activity in the Plant-MFC than in the MFC (Apollon et al. 2022a); although, the reactors shared the same type of membrane. For instance, when the plant carries out the photosynthesis process, this allows a large number of exudates or organic compounds to be present in the anode compartment (Strik et al. 2008). The aforementioned results were in the ranges reported by Kumar et al. (2018), by using a dual-chambered Plant-MFC (DcPMFC) which was set up with an internal cathode chamber and external terracotta separator air-cathode electrode assembly. However, in another study conducted by Kumar et al. (2020), voltage performances of 292.1 mV (0.2991 V) and 321.7 mV (0.3217 V), were found in two types of reactors: Type-I (horizontal) and Type-II (vertical) of terracotta based ceramic Plant-MFCs (C-PMFC), respectively. These results were inferior to those reached in our study. In addition, a study done by Syed et al. (2021) showed an OCV of 650 mV (0.65 V), by using cattle manure (cow dung and buffalo dung) in MFCs for green energy generation, which was also inferior to that reported in this study. In a study conducted by Apollon et al. (2020), a maximum OCV of 1200 mV (1.2 V) was achieved in a novel vertically integrated plug-in ceramic stick-based Plant-MFCs embedded with two *Opuntia* species (*O. ficus-indica* and *O. joconostle*). During the experiment, the Plant-MFCs were irrigated with 1L /week of water, for 30 days while in the present study 2L of water was used every two days, for 15 days. Previously, the maximum voltage of

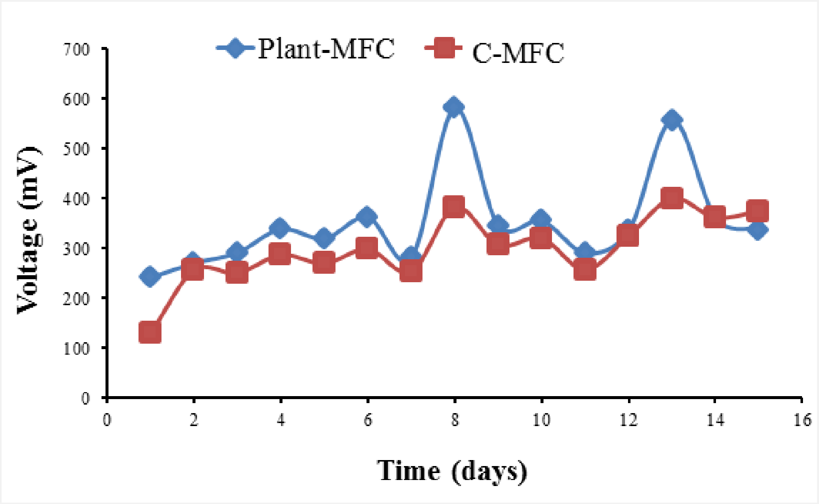

Figure 4 Voltage output performance in the two reactors for 15 days.

1454.1 mV (1.4541 V) was achieved in soil plant-MFC (Rusyn et al. 2019). These results are superior to those found in our study. Therefore, it can be argued that the system used in this study can drive Plant-MFC technology in saturation conditions. In addition, the data acquisition system developed to monitor data in real time was suitable.

3.2 Polarization experiment

Polarization was performed at the end of the study. The results have indicated different behavior between both reactors, which shared similar anode compartment (Figure 5a). Maximum voltage of 600 mV (0.6 V) was obtained in Plant-MFC, compared to the C-MFC that indicating a voltage of 448 mV (0.448 V), with a resistance of 1000 Ω. Plant-MFC showed higher energy efficiency of 186 mA m^{-2}, being the best reactor in this study. Subsequently, exhibited a maximum power density of 66 mW m^{-2}(Figure 5b), which was higher (86.21% and 74.54%) than that reported by Kumar et al. (2020). Besides, other studies indicated power densities inferior compared to that reached in this study (Sudirjo et al. 2019b; Syed et al. 2021; Apollon et al. 2022a). However, in a recent study, higher power densities of 1613.3 ± 155.5 (system with five branches) and 1185.1 ± 29.1 mW m^{-2} (system with one collector branch), respectively, were reported in microbial electrochemical systems (MES) by optimizing the “anode-collector” (Li et al. 2022). Hence, these researchers found that integrating a metal current collector into the anode electrode was an effective strategy to reduce the power loss of the system and these results were higher than those found in the two evaluated reactors. This difference is due to the types of systems used in both studies, as well as the operation time of the systems.

On the other hand, it is important to look for alternatives to improve Plant-MFC technology. For example, to increase the performance or efficiencies of the systems, it is necessary to apply adequate treatments. Treatment involves adding a catalyst to the electrode to facilitate the transfer of electrons from bacteria to the anode and cathode surfaces to acceptors, as well as structural alteration of the anode and cathode surfaces to accommodate more bacteria for transport electrons. Oxygen (O_2) is the most commonly used electron acceptor as cathode for the reduction reaction in most studies of Plant-MFCs. It is the most sustainable electron acceptor

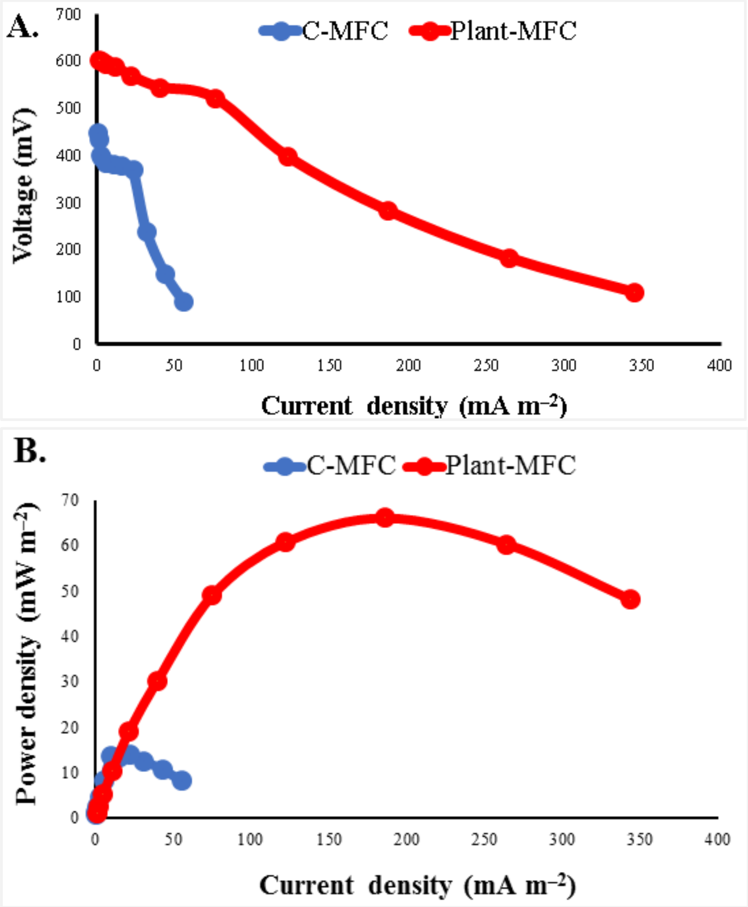

Figure 5 (A) Polarization curve and (B) power density curve of Plant-MFC and C-MFC at the final stage of study.

due to its inexhaustible availability. Biocatalysts, comprising bacteria grown on the cathode surface, lower the critical oxygen concentration from 5.5–6.6 to 0.1 mg L^{-1} and improve the oxygen affinity for the cathode (Schröder 2012). Therefore, plants play a crucial role in the production of O_2, increasing the yield of Plant-MFC. In addition, measuring the voltage of the Plant-MFC in real time allows knowing exactly its efficiency. With this, it can be argued that the implementation of a real-time voltage data acquisition system in BES, allows to save both more time, as well as to obtain real data from the systems. Extending the use of Plant-MFCs on a large scale is inevitable in the future.

4 Conclusions

In this study, the performance of an automatic voltage data acquisition system for Plant-MFC was evaluated. This system allowed to obtain data in real time and prolonged. The use of this system has advantages due to the number of channels, it's cost effective, and its easy handling. In addition, the clay cup membrane used for the reactor design made it possible to produce bioelectricity at a low cost. Finally, alternative electricity production technologies such as Plant-MFCs are needed to satisfy the future electricity demand.

Acknowledgment

WA extends his thanks for the Ph.D. grant from the National Council for Science and Technology (CONACYT, for its acronym in Spanish), as well as the Universidad Autónoma de Nuevo León (UANL, for its acronym in Spanish) through the Subdirectorate of Postgraduate Studies of the Faculty of Agronomy (FA-UANL, for its acronym in Spanish) for his acceptance in the Ph.D. Program. WA, also, thanks in a particular way his Doctoral Thesis Committee. In addition, AILM and WA thank PAICYT (Programa de Apoyo a la Investigación Científica y Tecnológica) – (CT1519-21) from Universidad Autónoma de Nuevo León for their support. KSK would like to acknowledge the Technological Development and Innovation projects 2021/Federal Technological Institutes and Centers (TecNM).

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