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VOLTAGE PRODUCTION IN A PLANT-MICROBIAL FUEL CELL USING *Agapanthus africanus*

PRODUCCIÓN DE VOLTAJE EN UNA CELDA DE COMBUSTIBLE MICROBIANA VEGETAL UTILIZANDO *Agapanthus africanus*

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Abstract

Due to the existing energetic demand worldwide the search for alternative energy sources is necessary. Bioenergy has been studied in the last decades as a promising energy source and the use of bioelectrochemical devices has become important. In this paper the plant *Agapanthus africanus L. Hoffman*'s was used to evaluate both growing and voltage generation in an electrochemical device adapted at the root system of the plant. For this, *Agapanthus* was planted either with or without compost and varying the position of the anode. Growth and voltage generation was monitored throughout all the experiments. All plants showed a satisfactory growth, and the carbon fiber anode position affect neither the vitality of the plant nor the system performance, moreover, the addition of compost (33%v) increased the generated voltage reaching a maximum value of 690 mV. Experimental data indicate a great potential of *Agapanthus africanus* to generate voltage in a green and sustainable way. Energy obtained from plant-microbial fuel cell can be used to power on low consumption electronics using an electronic device composed by 1.2 V batteries.

Keywords: bioenergy, bioelectrochemistry, carbon fiber, plant fuel cell, rhizomes.

Resumen

Debido a la demanda energética global se ha hecho necesario buscar fuentes energéticas alternativas. La bioenergía ha sido estudiada en las últimas décadas como un recurso energético prometedor, y el aprovechamiento de los sistemas bioelectroquímicos se ha hecho cada vez más importante. En la presente investigación se utilizó la planta *Agapanthus africanus L. Hoffman´*s para producir voltaje mediante un sistema electroquímico adaptado en las raíces de las plantas, para ello, los *Agapanthus* fueron sembrados con o sin composta variando la posición del ánodo con respecto al fondo de la maceta. El crecimiento de la planta y el voltaje generado fueron monitoreados durante todo el experimento. Todas las plantas mostraron un crecimiento adecuado, la posición del ánodo a base de fibra de carbono no afectó ni la vitalidad de las plantas ni el rendimiento del sistema, además, la adición de composta incrementó la generación de voltaje alcanzando un valor máximo de 690 mV. Los datos experimentales indican un gran potencial de la planta *Agapanthus africanus* para generar voltaje de una manera sustentable. La energía obtenida mediante la celda de combustible microbiana vegetal puede utilizarse para cargar dispositivos electrónicos de bajo consumo a través de un sistema de baterías de 1.2 V.

Palabras clave: bioenergía, bioelectroquímica, celda de combustible vegetal, fibra de carbono, rizomas.

1 Introduction

The use of conventional energy sources such as gas, coal and petroleum has not only increased the atmospheric pollution, global warming and respiratory diseases, but also has diminished the fossil fuels reserves and the energy security around the world (Mishra *et al*., 2017). The constant increase of energy demand requires the development and implementation of new technologies that provide non-conventional energy in a sustainable way (Chin-Tsan *et al*., 2018, Tellez-Méndez *et al*., 2018). Bioelectrochemical devices use the capability of microorganisms to produce energy; among all these systems, Microbial Fuel Cells (MFC) have been intensely studied in the last decades for their simultaneous production of electricity and organic waste removal (Zheng *et al*., 2017), the performance

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of this MFC mainly depends on substrate, electron transfer from bacteria to electrode, ions diffusion, temperature, pH and mass transfer (Peraza-Baeza *et al*., 2016). From conventional MFC some alternative bioelectrochemical systems have been developed such as: one chamber microbial fuel cell (Montpart *et al*., 2015), microbial desalination cell for sea water treatment (Al-Mamun *et al*., 2018), microbial electrolysis cell for hydrogen production (Kadier *et al*., 2014), and Plant Microbial Fuel Cell (PMFC) for sustainable energy production. The concept of PMFC was first proposed by Strik *et al*. (2008), who used a double chamber MFC coupling the roots of a plant in the anodic chamber in order to use the carbohydrates reserves at the rhizome as substrate for microorganisms. They constructed the first PMFC employing the plant it Glyceria maxima, graphite felt as electrodes and a Cation Exchange Membrane (CEM). The maximum voltage achieved by them was 256 mV after 72 days, while the maximum power density was 67 mW/m^2, this fact showed the potential of PMFC as starting point for future researchers. In agreement with Nitisoravut & Regmi (2017), PMFC can be divided in two main structures: Bio-control and bio-system. Bio-control is associated to external input to achieve an internal voltage and involves irradiation from sun to plant and photosynthetic routes. The second one refers to the transformation of roots carbohydrates into voltage by microbial metabolisms and electrochemical performance.

Voltage and clean energy generation by PMFC is a new research topic and is in constant development, however, nowadays only few papers have reported the potential of different genus of plants to produce voltage. Helder *et al*. (2010), reported the potential of different plants to produce voltage and green energy by PMFC using graphite rod and gold wire as anode and cathode respectively, the maximum voltage achieved by them was 400 mV from *Arundinella anomala*, some semi-arid plants were also evaluate to produce voltage and green energy (Tapia *et al*., 2017) then, the effect of salinity and growing media on *Puccinellia distans* were reported (Khudzari *et al*., 2018), and even the simultaneous production of electricity and pigments on direct photosynthetic microbial fuel cell haven been analyzed (Gouveia *et al*., 2014). The use of carbon fibre as electrodes in PMFC was firstly evaluated by Moqsud *et al*. (2015); they observed a maximum voltage of 700 mV from rice plants planted with soil and compost. Currently there are no previous reports about voltage generation from *Agapanthus africanus* in environmental conditions and employing carbon fibre and an air cathode. The aim of the present work was to evaluate the effect of compost addition and the position of anode on voltage generation in a PMFC adapted with *Agapanthus africanus L. Hoffman*'s. In each test the vitality of the plant was constantly monitored by measuring length and width of three leaves randomly selected. Voltage generation and plant growth are reported and discussed in present paper.

2 Materials and methods

2.1 *Agapanthus africanus*

Agapanthus africanus L. Hoffman's employed in this work was collected from Metepec, State of Mexico, and transported to Technological Institute of Toluca, where these plants were planted and conserved in environmental conditions. This plant was selected due to the abundance, high adaptability to regional climate and its capability to growth through the year, as well as the distinctive characteristic of *Agapanthus* to produce high amount of rhizomes (Olubunmi, 2017).

2.2 *Characterization of soil, compost and water*

Tap water used to irrigate the plants was characterized to determine pH, temperature and electrical conductivity, soil and compost were analyzed to determine their physicochemical characteristics and the amount of organic matter. For the latter, samples were taken, milled into powder and dried overnight at 45°C, then, the percentage of elemental carbon, nitrogen and hydrogen was determined in an Organic Elemental Analyzer *Flash 2000* coupled with a Thermal Conductivity Detector (TCD), while sulphur was quantified employing a Flame Photometric Detector (FPD). Physicochemical characterization of water, compost and soil was carried out according to standard methods (APHA, 2002).

2.3 *Construction of a PMFC*

The first experiment was performed to evaluate the effect of anode position on voltage generation, for this a PMFC was constructed in a bucket with the following dimensions: 24.5 cm height, 28 cm superior diameter and 20 cm inferior diameter (1 PMFC). The first anode was set at 6.5 cm from the bottom of

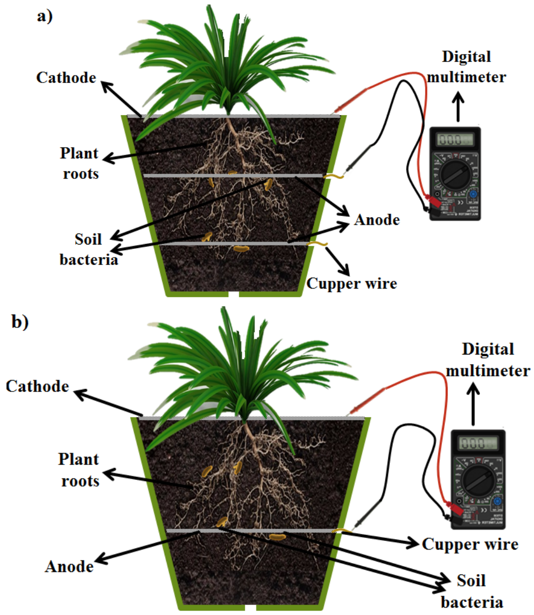

Fig. 1. Diagram of PMFC system arrangement with a) two anodes and b) one anode.

the bucket, while, the second one was placed at 13 cm from the bottom (figure 1a). The average area of electrodes was 812 cm^2. Three more PMFC's (2 PMFC) were constructed to compare the voltage generation from two different size prototypes using a small bucket (height, 16.5 cm; superior diameter, 21 cm; inferior diameter, 15 cm), only one anode with 306 cm^2 superficial area was adopted at 7 cm from the bottom (figure 1b). For this experiment *Agapanthus africanus* was planted on soil with no compost.

In order to evaluate the addition of compost on voltage generation, a second experiment was made. In this test, smaller buckets were employed. In two buckets *Agapanthus africanus* was planted with no compost, while in another two it was planted with addition of compost (33 %v). Electrodes were placed similarly to that described previously for 2 PMFC. Compost was collected from the Technological Institute of Toluca, which was mainly prepared from kitchen, garden and corn crop residues.

In all experiments carbon-fiber textile was used as anode and cathode; this material has been reported as bio-compatible and efficient candidate for conventional MFC (Dhar *et al*., 2015; Wang *et al*., 2011). Most recently this material was used to obtain green electricity by PMFC using rice plants (Moqsud *et al*., 2015), thus, the implementation of carbon fiber as electrode is a novel alternative for bioelectrochemical purposes. In each experiment, an air cathode was adapted at the surface of the soil and the electrodes were connected with cupper wires. In order to reduce the cost and the complexity of the system, as well as to improve the real applicability of PMFC this study eliminates the use of CEM. A control system consisting of PMFC with no plant was employed in each test to evaluate the contribution of organic matter in soil-compost mix on voltage generation.

2.4 Set up of the PMFC

The generated voltage was quantified using a digital multimeter and solar irradiance and environmental temperature was monitored throughout the experiments. All PMFC's were placed into laboratory at natural conditions of light and moisture of Toluca. Plant growth analysis was carried out by sizing every two weeks both length and middle width of three leaves randomly selected. Tap water was used to irrigate the plants once per week. Open circuit voltage was measured using a digital multimeter and current was calculated according to Ohm's law (Eq. 1) considering an external resistance of 100 Ohms.

$$I = \frac{V}{R} \tag{1}$$

Where I is the current given in mA, V the voltage in mV and R the external resistance in Ohms (100 Ohms). Power density (P) in mW/cm^2 can be calculated correlating the generated voltage, the external resistance and the surface area of electrode (A) according to Eq. 2.

$$P = \frac{V^2}{AR} \tag{2}$$

2.5 Energy capture by electronic device

To capture the energy obtained by PMFC, an electronic device was constructed. This device is composed by two different systems; the first consists in a parallel circuit which has the function of loading a set of four 1.2 V batteries using the energy obtained from plants; the second one is a serial circuit responsible to send the charge from batteries to low consumption electronic devices such as a mobile cell phone or a LED spotlight. A switch between serial and parallel circuit was coupled to change the functionality of the electronic device. The main idea of the electronic device is to reduce the loading time of the batteries using a parallel circuit and to use the stored energy for

Table 1. Characterization of soil, compost and water.

Parameter	Compost	Soil	Water
Temperature (°C)	21.5 ± 0.2	21.8 ± 0.05	21.9 ± 0.25
pH	5.15 ± 0.01	5.71 ± 0.02	7.68 ± 0.02
Electrical conductivity (mS cm^{-1})	1844 ± 2	379 ± 3.5	724 ± 5
Moisture (%)	6.74 ± 0.11	22.56 ± 0.52	ND

ND: Not determined

Table 2. Elemental analysis of soil and compost.

Element Agapanthus	Soil (%)	Compost (%)
Hydrogen	1.978 ± 0.001	1.503 ± 0.051
Nitrogen	1.368 ± 0.041	1.540 ± 0.137
Carbon	16.974 ± 0.065	9.381 ±0.854
Sulphur	0.149 ± 0.0002	0.076 ± 0.001
Total	20.469 ± 0.108	12.499 ± 1.042

some purposes by switching the device to a serial circuit. Among all the PMFC's studied, three were chosen and connected in series, and then they were coupled with the electronic device (parallel circuit activated) during 3 days in order to determine its charge capacity. Finally, the electronic device was switched to a serial circuit and connected by USB port to a mobile phone.

3 Results and discussion

3.1 *Characterization of soil, compost and water*

According to elemental analysis, compost showed a minor percentage of hydrogen, carbon and sulphur in comparison with soil. As can be seen in Table 2, the amount of carbon diminished from 16.97% for soil to 9.38% for compost, which suggests that soil possess a major amount of carbohydrates and organic matter, while, compost is mainly comprised by inorganic matter and minerals. In contrast, the percentage of nitrogen was major for compost reaching a value of 1.54%. The C:N ratio determined for both soil and compost was 12.40 and 6.01 respectively.

3.2 *Effect of anode position on voltage generation*

PMFC employed to evaluate the position of anode on voltage generation was denoted as 1 PMFC, these cells are shown in figure 2.

Voltage generation was measured in each anode of each 1 PMFC including the control system. The voltage obtained from the anode located at 6.5 cm from the bottom of the bucket resulted similar to that obtained with the anode placed at 13 cm from the bottom (figure 3); this behavior was observed for all 1 PMFC, suggesting that the position of the anode does not affect the performance of bioelectrochemical system to produce voltage. This fact can be attributed to that PMFC acts as only one system and the electrons produced by bacteria are in constant movement through the cell and fall into the final electron acceptor (anode), in this case carbon fiber.

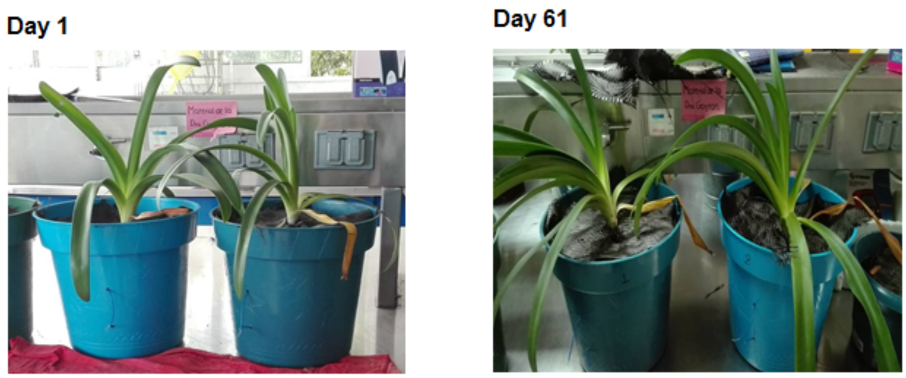

Fig. 2. Vitality of *Agapanthus africanus* in 1 PMFC.

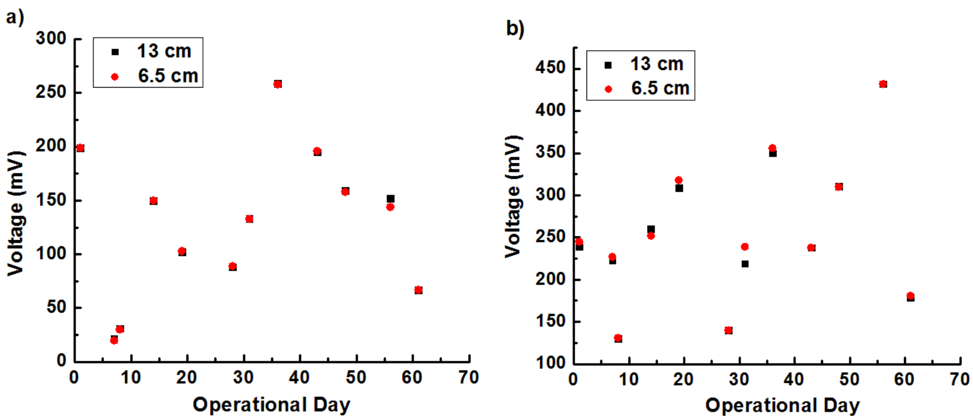

Fig. 3. Voltage generation from 1 PMFC using a) control system and b) *Agapanthus africanus*

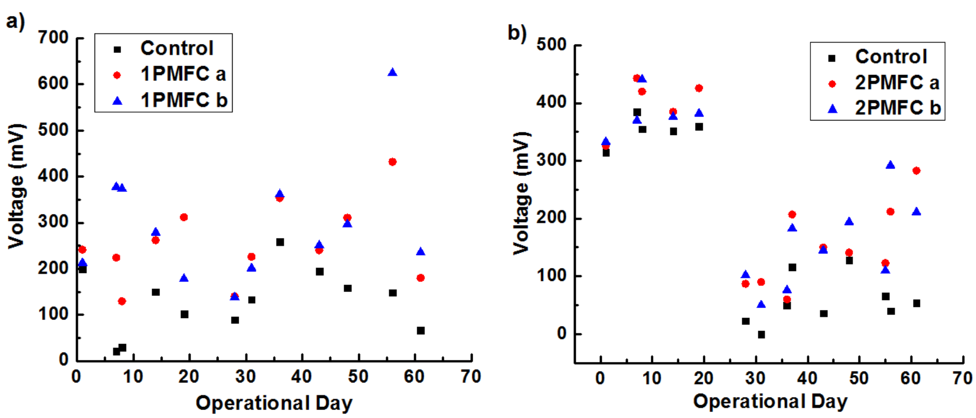

Fig. 4. Behaviour of voltage production from a) 1 PMFC and b) 2 PMFC.

As can be seen in figure 3, the difference in voltage obtained from the higher and the lower anode was not significant, thus, the position of anode is not an important parameter to take in account for voltage and green energy production. Buitrón & Pérez (2011), studied the effect of distance between anode and cathode in a dual chamber MFC; they concluded that there is not a significant effect of electrodes position on voltage generation, in agreement to the results in the present paper for PMFC with *Agapanthus africanus*.

The average voltage calculated from the higher and the lower anode was taken to compare the behavior of voltage production between 1 PMFC and 2 PMFC. For both tests, control systems showed the lowest voltage production through the experiment, this voltage can be due to the biological degradation of organic matter present in soil. The maximum voltage obtained from 1 PMFC was 624 mV after 56 days, while for 2 PMFC the highest voltages were observed at the start of the experiment, after 7 days the maximum voltage of 443 mV was reached (figure 4). Differences in voltage production between 1 PMFC and 2 PMFC can be attributed to the surface area of electrodes, the amount of organic matter in soil and the size and weight of *Agapanthus africanus* planted in each bucket.

The plants were watered with tap water every week and the production of voltage increased immediately after of water addition, so that can be associated to the water conductivity, which improved the electrons transportation through the system to the anode.

To evaluate *Agapanthus africanus* growth on soil in the presence of carbon fiber, three leaves of each test were monitored. The length of the leaves increased as a function of time, the maximum length was achieved after 56 days reaching a value of 45 and 36 cm for 1 PMFC and 2 PMFC respectively. The growth of leaves showed similar trend for all experiments and after 56 days they reached their maximum length (figure 5).

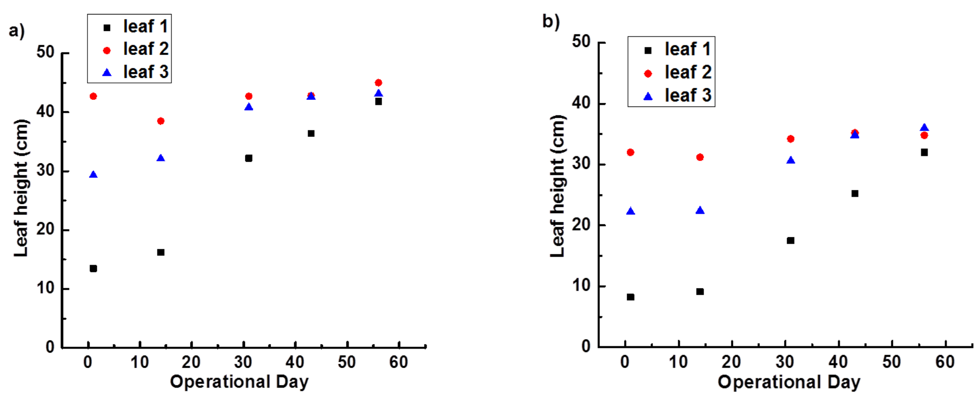

Fig. 5. Behaviour of leaves growth of a) 1 PMFC and b) 2 PMFC.

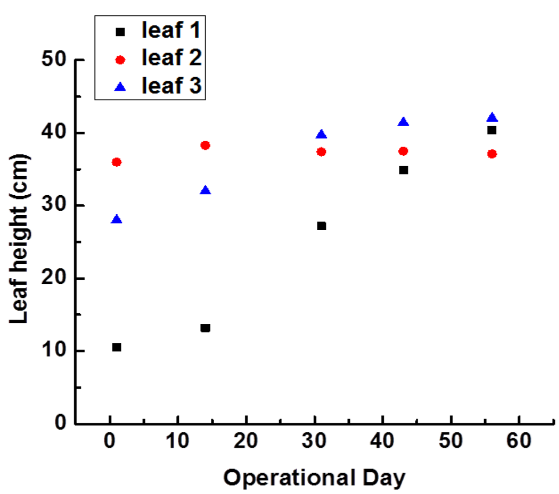

Fig. 6. Behaviour of leaves growth in *Agapanthus africanus* planted with no electrodes.

According to figure 5, leaves reached their maximum length after 56 days. All leaves converged at the same point, for 1 PMFC the maximum average length was 44 cm, while for 2 PMFC the average length of the leaves was 35 cm, this difference is associated to the size of the bucket and the free growing of plant roots inside the bucket. One more *Agapanthus africanus* was planted on soil without electrodes and copper wires in a small bucket, the profile of leaves growing (figure. 6) resulted similar in comparison to that showed in figure 5. This fact suggests that the presence of carbon fiber and the generation of voltage from plant roots did not affect the growth of *Agapanthus africanus*, thus, green energy production and cultivation of ornamental plant can be performed simultaneously in a sustainable way.

The average maximum width of the leaves was 3, 2.1 and 2.2 cm for 1 PMFC, 2 PMFC and *Agapanthus africanus* with no carbon fiber respectively. Both length and width of 1 PMFC and *Agapanthus africanus* planted without electrodes resulted similar to each other after 61 days. This fact can be due to the small bucket employed to plant *Agapanthus africanus*, An increase in operational time promotes an increase in the weight of the leaves in similar way to that observed for the length.

3.3 *Effect of compost addition on voltage generation*

To compare the voltage obtained from PMFC with or without compost a second test was performed in small buckets. The maximum voltage obtained from PMFC with no compost was 460 mV observed at 6 days; after this time the generated voltage diminished, reaching an average value of 300 mV that remained until the end of the experiment. In contrast, the voltage obtained from PMFC with compost increased as a function of time, showing a maximum of 690 mV after 31 days and an average voltage generation of 420 mV. PMFC with no compost showed the maximum voltage at the start of the experiment; this fact is associated to the presence of organic matter in soil and their degradation by microorganisms into low molecular weight compounds and electrons, which were captured by the anode to produce voltage. PMFC with no compost generated more voltage in comparison to the PMFC with compost in the first 13 days, after that, *Agapanthus africanus* planted with compost showed a major generation of voltage (figure 7), this behavior can be due to the presence of minerals in the compost, which can enhanced the absorption of nutrients by

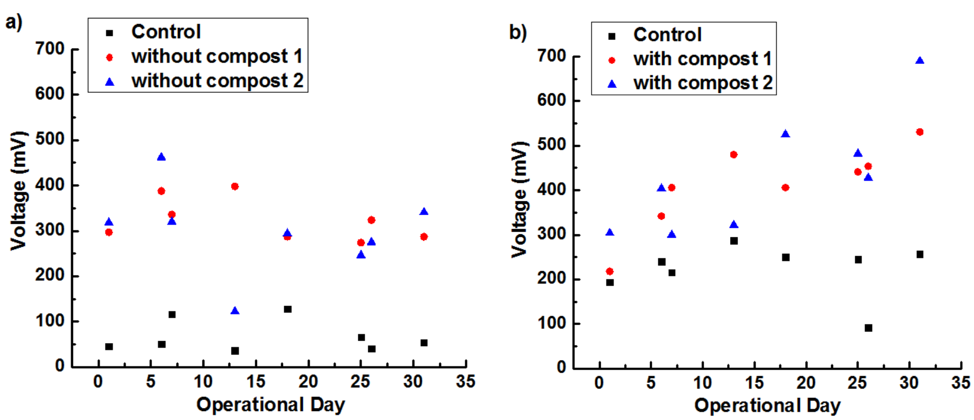

Fig. 7. Behaviour of voltage generation from PMFC with a) only soil and b) soil and compost.

Day 1 Day 31

Fig. 8. Vitality of *Agapanthus africanus* employed in PMFC with compost

Table 3. Voltage generation and power density from different PMFC with *Agapanthus africanus*.

Test	Maximum voltage (mV)	Current (mA)	Surface Area (cm2)	Power density (mW/cm^2)
1 PMFC	624	6.24	812	4.8
2 PMFC	443	4.43	306	6.41
PMFC without compost	460	4.6	306	6.92
PMFC with compost	690	6.9	306	15.55

Fig. 9. Interaction between carbon fibre and *Agapanthus africanus* roots.

the plant and increased the food reserves at the rhizome, thus these reserves were metabolized by bacteria, generating higher voltage. The positive effect of compost on voltage generation has been reported previously by Moqsud *et al*. (2015), working with rice plants and by Carmalin & Sreeja (2017), who studied the use of compost in a PMFC with *Canna Stuttgart* and *Trigonella foenumgraecum*.

In each test, *Agapanthus africanus* growth adequately, showing that carbon fiber does not affect the vitality of the plant. Figure 8 showed the plants after 1 and 31 days of operational time, and as can be seen in this picture the *Agapanthus* employed in experimentation look green, vital and beauty.

Once the experiment was finished, Agapanthus was transplanted into another bucket and the anode was recovered to observe the physical interaction between electrode and plant (figure 9). The roots were naturally intertwined within the carbon fiber structure and they were growing freely. This observation is in agreement to that reported by Moqsud *et al*. (2015), who observed the free growing of rice plants through carbon nanofibres.

3.4 Comparison of voltage generation and power density with some papers reported in literature

1 PMFC reached a maximum of 624 mV after 56 days; this value was similar to the maximum voltage reported in the present paper (690 mV) with *Agapanthus africanus* planted with soil and compost. Experiments carried out in small buckets (denote as 2 PMFC) with only soil showed similar voltages to each other; 443 and 460 mV. The highest voltage generation and power density were obtained for PMFC with compost reaching respective values of 690 mV and 15.55 mW/cm^2, while 1 PMFC showed a power density of 4.80 mW/cm^2 which was the lowest value among all experiments (Table 3). Despite to the similar voltages obtained with 1 PMFC and PMFC with compost, the calculated power densities were different to each other and this fact is associated to the total surface area of electrodes, since an anode of 812 cm^2 was adopted for 1PMFC while for small buckets only an anode of 306 cm^2 superficial area was used.

The maximum voltage obtained in this work resulted higher in comparison with other reports not only for PMFC (Carmalin & Sreeja, 2017; Hubenova & Mitov, 2012; Strik *et al*., 2008), but even for conventional MFC (Buitrón & Pérez, 2011; Tian-Shun *et al*., 2012; Pérez-Rodríguez *et al*., 2018). The maximum power density calculated in the present work resulted similar to that reported by Moqsud *et al*. (2015), who studied the potential of carbon fibre anode (125 cm^2) in a MFC coupled with rice plants, they determined 12.17 mW/cm^2 power density in a PMFC operated with only soil; however, they reached a maximum power density of 39.2 mW/cm^2 using a PMFC with 3%v compost. Perez-Rodríguez *et al*. (2018), reported a maximum voltage and density power of 97 mV and 0.39 mW/m^3 respectively in a MFC operated with domestic wastewater. In agreement with data obtained in this work, *Agapanthus africanus* has the capacity to

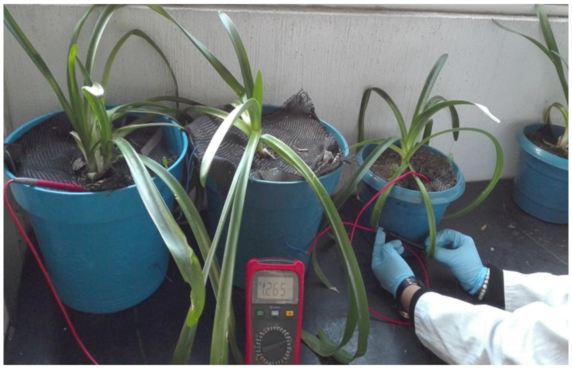

Fig. 10. PMFC's connected in series.

produce high amount of voltage in a PMFC, however, in order to improve the electrochemical performance, more studies are needed to evaluate the effect of some variable on voltage generation to deepen the knowledge about green electricity generation from this plant.

3.5 Electronic device employed to powering batteries

Among all the PMFC's employed in this work, three with the maximum generated voltage were chosen and connected in series to increase the potential to 1300 mV (figure 10), after that, they were connected to electronic device (switched in parallel circuit) for around three days. After this loading time, electronic device was separated from PMFC´s, switched to a serial circuit and connected by USB port to a mobile phone which had no energy for one day. Stored energy partially allowed charging the mobile phone. The energy obtained from PMFC's can be exploited employing capacitors as Yamasaki *et al*., (2018), made in previous research. They charged F10 capacitors from methane MFC and powered on a fan for over one minute using the stored energy.

Conclusions

The conformation of bioelectrochemical system allows producing voltage in an economical and feasible way, diminishing the complexity and the cost of the cell by eliminating the expensive membrane and improving the applicability in real environments. Carbon fibre allowed recovering energy and did not affect the growing of the plant, since this material was biocompatible. The position of the anode did not affect the performance of PMFC, suggesting that PMFC acts as an only one system and the electrons produced are in constant movement through the cell and fall into the final electron acceptor in the plant roots; however, the addition of compost increased the generated potential because it is mainly comprised by inorganic matter and minerals, beside a nitrogen content which was 1.54%. The maximum voltage obtained from PMFC without compost was 460 mV observed at 6 days, after this time, the generated voltage diminished until 300 mV and with compost increased as a function of time to 690 mV after 31 days. *Agapanthus africanus* showed a great potential to produce voltage in a PMFC, this voltage were satisfactory stored in an electronic device and then used for real application.

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