Comparison of the effect on electricity production in benthic microbial fuel cells using plasma-treated anodes

Comparación del efecto en la producción de electricidad en celdas de combustible microbianas bénticas empleando ánodos tratados con plasma

Flores-Martínez, Jordy Alexis[a], Fuentes-Albarrán, María del Carmen*[b], Alarcón-Hernández, Fidel Benjamín[c] and Gadea-Pacheco, José Luis[d]

[a] Universidad Autónoma del Estado de Morelos • LPP-8245-2024 • 0009-0009-8356-6328
[b] Universidad Autónoma del Estado de Morelos • LFS-3039-2024 • 0000-0003-1308-1332 • 171814
[c] Universidad Autónoma del Estado de Morelos • AEO-9146-2022 • 0000-0002-2465-0898 • 131028
[d] Universidad Autónoma del Estado de Morelos • LEM-8262-2024 • 0000-0001-9341-9289 • 160429

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Key Handbooks

The main contributions to the generation of science and technology in this research are based on the use of non-thermal plasma treatment technology on anodes that can be used in microbial fuel cells, with the purpose of improving their performance to produce electricity. Key aspects that must be understood to apply to the generation of universal knowledge consist of the changes that take place on the surface of plasma-treated electrodes and that can influence the optimization of the performance of a microbial fuel cell. In conclusion, in this research the effect of anodes treated with plasma was analyzed in comparison to an untreated anode, obtaining greater power production with the anode that had less exposure to plasma. The authors of this chapter do not have a CONAHCYT, PRODEP or external scholarship), they come from state public institutions (Autonomous University of the State of Morelos). The most used keywords are benthic microbial fuel cells, anodes, air plasma and power production.

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* ✉ [carmen.fuentes@uaem.mx]

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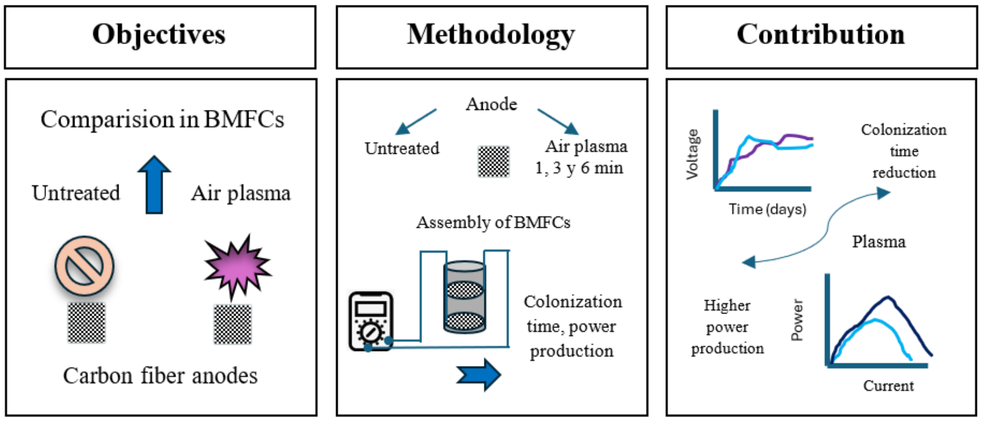
Abstract

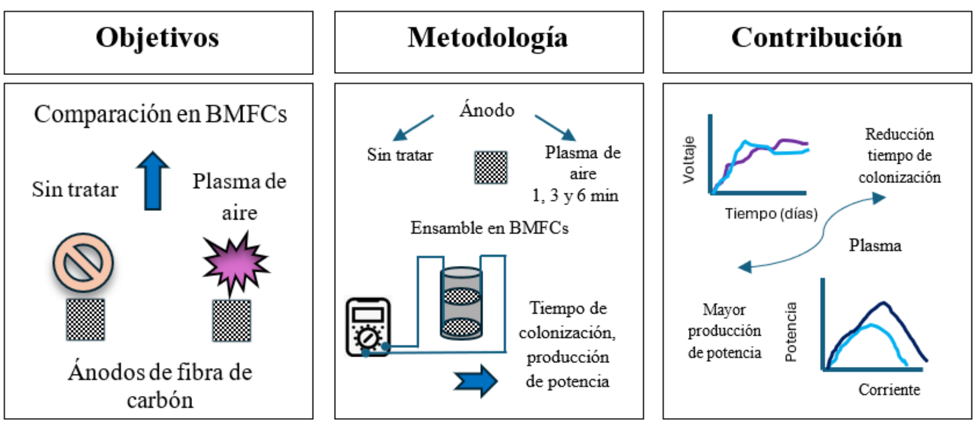
In this study, the effect on electricity production in four benthic microbial fuel cell (BCMB) devices was compared. The CCMBs used carbon fiber anodes subjected to different exposure times to a non-thermal plasma at low pressure, with exposure times of 1, 3 and 6 minutes respectively, in addition to a control (untreated anode). The lowest power production was obtained with the anode treated for 6 minutes, recording a power density of 1.33 mW/m^2 with a current density of 22.22 mA/m^2, while the highest power production was achieved with the CCMB using the anode treated for 1 minute, obtaining a maximum peak power of 2.02 mW/m^2 with a current density of 27.40 mA/m^2. The results showed that a shorter exposure time of the anode to plasma treatment has a favorable effect on power production.



Benthic microbial fuel cell, Anode, Air plasma

Resumen

En este estudio se comparó el efecto en la producción de electricidad en cuatro dispositivos de celdas de combustible microbianas bénticas (CCMBs). Las CCMBs emplearon ánodos de fibra de carbón sometidos a diferentes tiempos de exposición a un plasma no térmico a baja presión, con tiempos de exposición de 1, 3 y 6 minutos respectivamente, además de un testigo (ánodo sin tratar). La menor producción de potencia se obtuvo con el ánodo tratado 6 minutos, registrando una densidad de potencia de 1.33 mW/m^2 con una densidad de corriente de 22.22 mA/m^2, mientras que la mayor producción de potencia se alcanzó con la CCMB empleando el ánodo tratado 1 minuto, obteniendo un máximo pico de potencia de 2.02 mW/m^2 con una densidad de corriente de 27.40 mA/m^2. Los resultados mostraron que un menor tiempo de exposición del ánodo al tratamiento con plasma tiene un efecto favorable en la producción de potencia.



Celda de combustible microbiana béntica, Ánodo, Plasma de aire

Introduction

Benthic microbial fuel cells (BMFCs) are bioelectrochemical systems that use the metabolism of microorganisms to produce electricity (Tavakolian et al., 2020). BMFCs can use sediments from different aquatic bodies such as; rivers, lagoons and seas (Feregrino et al., 2023), also have the advantage of not requiring the use of a membrane for their operation. In a BMFC the anode is buried in the sediments, while the cathode remains floating or submerged in the overlying water. Electroactive bacteria (EAB) that colonize the anode oxidize the organic matter in the sediment using an electrode as an electron acceptor. Electrons and protons released by the oxidation of organic compounds at the anode are transferred to the cathode, where they react with oxygen (electron acceptor) to form water (Wang et al., 2023).

BMFCs constitute an alternative to generate bioelectricity while degrading pollutants. These systems can be used to power submersible ultrasound receivers, wireless temperature and oxygen sensors, as well as wireless telecommunications systems and low-power sensors for remote monitoring (Sun et al., 2024), in addition to being used in bioremediation processes, removing polychlorinated biphenyls (PBCs), polycyclic aromatic hydrocarbons (PAHs) and antibiotics and immobilizing heavy metals and phosphorus from sediments (Danhassan et al., 2023). However, its performance still faces several challenges for large-scale applications. Despite their advantages, the power output of BMFCs is low, several factors related to the configuration of these devices affect their performance, such as the electrode material, distance between the electrodes, depth of the anode, height of the anode embedded in the sediments, cathode configuration and type of aquatic body used (Gupta et al., 2023). Recent advances in BMFCs have focused on modifications of the anode as a key element to improve the performance of these systems, with the purpose of increasing the exposed surface, decreasing the internal resistance and having high electrochemical activity (Prakash et al., 2018).

These modification methods include surface treatments with physical or chemical methods, addition of highly conductive or electroactive coatings and the use of electrodes composed of metal and graphite (Wei et al., 2011). In this context, non-thermal plasma or cold plasma technology has attracted attention in many areas of study because it is environmentally sustainable. Non-thermal plasma is generated by subjecting a gas to an electric field in a low-temperature reactor, resulting in the production of an ionized gas. The free electrons of ionic species react with substances, oxidizing them (Abdalameer et al., 2024). This technology has various applications and has allowed the investigation of surface treatments of multiple types of materials, such as surfaces that will be coated with nanomaterials (Walden et al., 2024) and emerges as a highly efficient and controllable approach for the surface treatment of materials. of electrodes, which allows improving their electrochemical performance (Zhang et al., 2017).

From this perspective, in this study, carbon fiber electrodes were subjected to different exposure times to low-pressure non-thermal plasma (1, 3 and 6 minutes), to be used as anodes in three Benthic Microbial Fuel Cell devices. (BMFC-1, BMFC-3 and BMFC-6). Thus, the electricity production performance of fuel cells that used plasma-treated anodes was compared to a BMFC-U that used an untreated anode (control). It is suggested that plasma treatment modifies the surface of the anodes, improving their performance for electricity production in a BMFC.

This research was developed in the following stages: exposure of three anodes to a non-thermal plasma at low pressure, assembly of four BMFCs using the treated anodes and one BMFC-U with an untreated anode (control). Monitoring the microbial colonization time in the cells, and finally the performance of the cells was characterized using polarization and power curves.

Methodology

Microbial fuel cell benthics configuration

Four glass vessels were used to construct each of the BMFCs. The vessels had a lower diameter of 4.5 cm, an upper diameter of 8 cm and a height of 14 cm, having a total volume of 140.28 cm3. Sediments from a jagüey from a town in the state of Morelos, Mexico were used. The electrodes used were carbon fiber (Fibreglast®) with an area of 0.0009 m2. To build the BMFCs, an untreated anode (Control) was used, and three anodes subjected to different exposure times to a non-thermal plasma.

For plasma treatment, each electrode was placed in a reaction chamber at different exposure times (1, 3, and 6 minutes). To generate the plasma, a high voltage source (SPELLAN SL600) was used, applying a voltage of 5 kV with a current of 70 mA, a vacuum pump (LABCONCO 117) was used to generate vacuum in the reaction chamber (24 Torr).

Assembly of benthic microbial fuel cells

To assemble the cells, the anode was placed at the base of each cell, then a 3 cm layer of sediment, and then a layer of water was added at a height of 3 cm from the container. The cathode was placed on the surface of the water supported by a plastic base, and finally it was covered with water to a height of 3 cm. The electrodes were connected to the outside using copper wire to carry out the measurements. The cells were kept in operation for 18 days at room temperature. A schematic of the assembly is shown in Figure 2.1.

Box 1

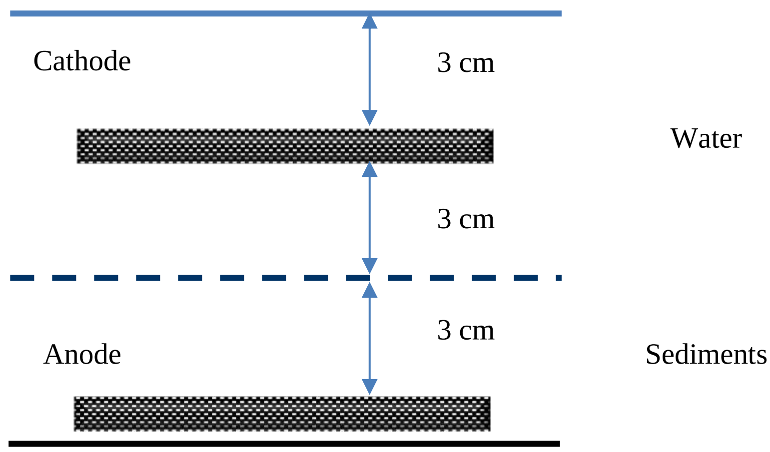


Figure 1
Scheme of the BMFCs

Source: Own Elaboration

Data acquisition and characterization of the BMFCs

During the startup stage of each of the BMFCs, the open circuit voltage (OCV) was monitored using a multimeter (Steren Professional Deluxe Multimeter with PC interface, Model: MUL-600). During this period microorganisms colonized the anode of each system. Once the BMFCs reached a stable voltage, the characterization of each cell was carried out using polarization curves and power curves, using a variable external resistance (R_{ext}) in a range of 500 Ω and 10 kΩ. For each resistance, the voltage obtained in each cell (E_{BMFC}) was recorded. For each pair of values (Ω-V) obtained experimentally, the current was determined using Ohm's law:

$$I = \frac{E_{BMFC}}{R_{ext}} \qquad [1]$$

To obtain the polarization curves, cell voltage was plotted against the current. The cell power (P_{BMFC}) was obtained using the following equation:

$$P_{BMFC} = \frac{E^2 BMFC}{R_{ext}} \qquad [2]$$

The obtained power density was normalized to the anode area (mW/m^2).

Results

Microbial colonization time

Figure 2 shows the microbial colonization time in the four BMFCs devices. In BMFC-U the voltage was slowly increasing during the first 4 days, while the voltage in BMFCs-1, 3 and 6 was slightly higher during the same period of time. The BMFC-U reached a maximum voltage of 0.35 V after 11 hours of operation, the BMFC-1 and the BMFCs-3 and 6 in a period of 7 and 9 days respectively, that is, the microbial colonization time was reduced by a in the cells that used the plasma-treated anodes by up to 36%. Finally, all systems maintained a relatively stable voltage during the last days of operation.

Box 2

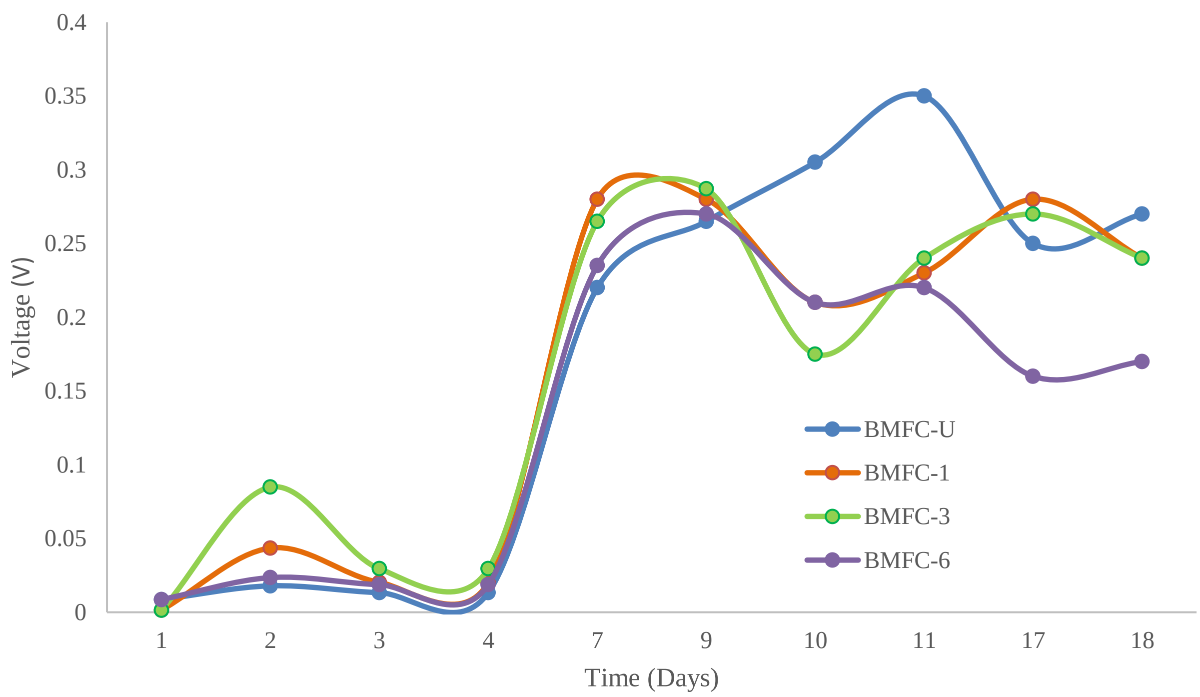


Figure 2
Microbial colonization time in CCMBs

Source: *Own Elaboration*

The reduction in microbial colonization time in BMFCs that used plasma-treated anodes suggests that changes occur on the anode surface when the treatment is applied, which allow greater microbial colonization in less time. In a study (Gholami et al., 2024) they used a nitrogen plasma modified nickel foam as an anode to improve the electrochemical performance in an MFC. They observed that the Ni foam exhibited an open cell structure and rough surface morphology, which provided a large contact area between bacteria and anodes in microbial fuel cells (MFCs) improving their performance.

Comparison of polarization curves

Figure 3 shows the polarization curves obtained for the four microbial fuel cell systems. BMFC-U reached the highest open circuit voltage (OCV) of 0.29 V, followed by BMFCs-1, 3 and 6 with an OCV of 0.27, 0.25 and 0.18 V respectively. Obtaining a lower OCV for the cell that used the anode treated with plasma for a longer time (6 minutes).

Box 3

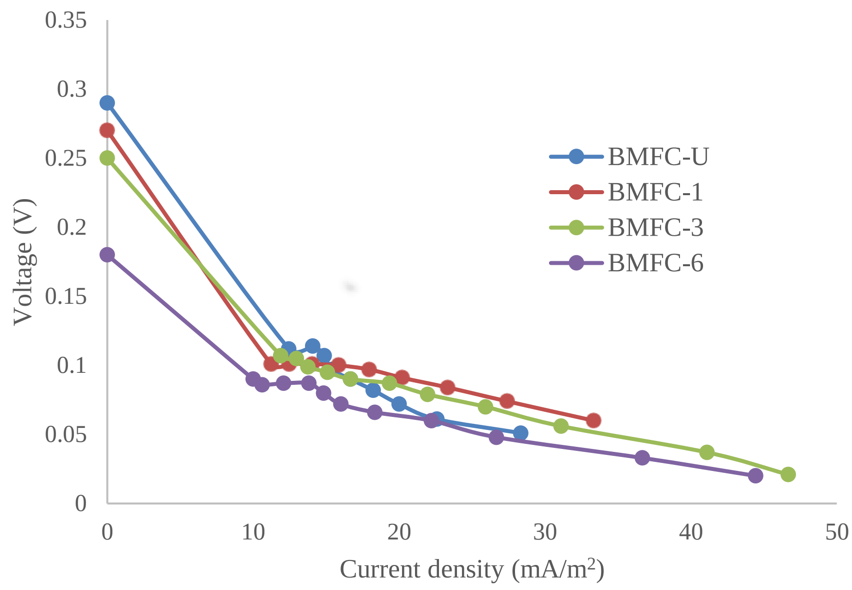


Figure 3
Polarization curves for BMFCs with different anodes

Source: *Own Elaboration*

In the four BMFCs devices, a rapid drop in potential is observed at low current densities, attributed to the activation losses of each system. As the current density increases, the BMFC-U shows a rapid loss of potential, while the BMFC-1 shows slower losses of potential.

Power production in benthic microbial fuel cells

The performance of the BMFCs in power production was examined, Figure 4 shows the results obtained. The BMFC-U achieved a maximum power density of 1.60 mW/m^2 with a current density of 14.07 mA/m^2. While the BMFC-1 reached the maximum peak power of 2.02 mW/m^2 with a current density of 27.40 mA/m^2, that is, in this system power production increased by 26% and the current density was reduced. doubled. However, with the BMFC-6 the lowest peak power was obtained, reaching 1.33 mW/m^2. Table 3.1 summarizes the results obtained for each BMFC.

Box 4

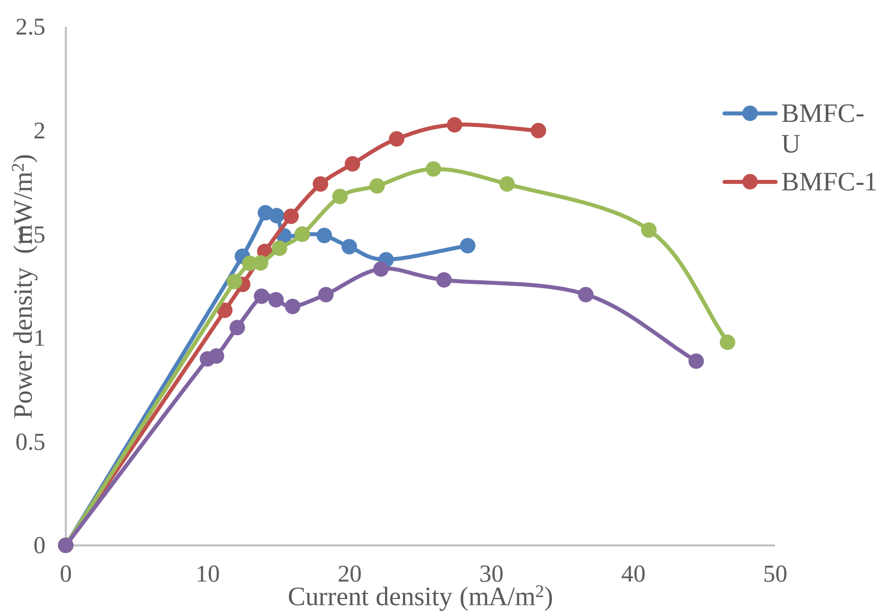


Figure 4
Power production in BMFCs

Source: *Own Elaboration*

It has been reported that pure carbon materials have a lower number of active sites, so they exhibit a lower electrochemical performance, which could be attributed to the lower power density obtained in the BMFC-U. Different levels of topological defects could be obtained by varying the duration of the plasma on the anode, which could improve the electrochemical performance of the material, influencing the power production, as observed in BMFC-1 (Ouyang et al, 2018).

Box 5

Table 2
OCV and power production for BMFCs

BMFC	OCV (V)	Maximum power density (mW/m^2)	Current density (mA/m^2)
BMFC-U	0.29	1.60	14.86
BMFC-1	0.27	2.02	27.40
BMFC-3	0.25	1.81	25.92
BMFC-4	0.18	1.28	26.66

Source: Own elaboration

Some studies have explored the use of plasma to treat electrodes for MFC applications. (Chang et al., 2016) used flow plasma at atmospheric pressure to treat carbon cloth electrodes for use in an MFC. They obtained a maximum power density of 7.56 mW/m^2, finding that the plasma treatment improved the electrochemical performance of the system by tripling the power density with respect to the MFC that used untreated electrodes. The plasma treatment allowed the carbon fabric to be highly hydrophilic, and the internal resistance of the MFC was significantly lower than the MFC with untreated electrodes, which influenced the increase in power. In another study, (Gholami et al., 2024), they used nickel foam modified with nitrogen plasma as an anode in an MFC, applying a treatment for 60 minutes, the MFC reached a maximum power density of 247.1 mW/m^2. In this work, a high hydrophilicity of the plasma-modified Ni foam electrodes was obtained, which facilitated the adhesion of bacteria and the formation of biofilms.

Conclusions

In this study, it was observed that plasma treatment reduces the microbial colonization time at the anode of BMFC-1 by up to 36%, compared to BMFC-U.

Greater power production was achieved in BMFC-1, obtaining a peak power of 2.01 mW/m^2, increasing up to 26% compared to the cell that used an untreated anode. This can be attributed to changes that occurred on the surface of the plasma-treated anode, which favored the adhesion of microorganisms and the transfer of electrons to the anode of the cell.

In this work, the morphology of the anode before and after plasma treatment was not examined, which can be done for future work.

Conflict of interest

The authors declare that they have no conflict of interest. They have no financial interests or personal relationships that could have influenced this book.

Authors' contribution

Flores Martínez, Jordy Alexis: Supported in carrying out the experiments and applying the research methods and techniques. Contributed to laboratory analysis.

Fuentes-Albarrán, María del Carmen: Design and implementation of the project idea, methods and applied research techniques. He supported the development of the experimentation, carried out the data analysis and wrote the work.

Alarcón-Hernández, Fidel Benjamín: Contributed to the research design, type of research, laboratory analysis, analysis of collected data and writing of the article.

Gadea-Pacheco, José Luis: Supported in the laboratory analysis. He worked on writing the article.

Availability of data and materials

All data used to support the findings of this study are included in the work.

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Abbreviations

BMFC	Benthic microbial fuel cell
MFC	Microbial fuel cell
OCV	Open circuit voltage

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