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Electricity generation with a microbial fuel cell fed cheese whey

Generación de electricidad en una celda de combustible microbiana alimentada con suero de leche

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Abstract

Energy production from renewable sources has become a strategy for exploiting other systems' waste reducing polluting gas emissions. Microbial Fuel Cell (MFC) technology is a sustainable alternative for electric power generation directly from waste without the need of mechanical parts. This study compared the electric power generation of two types of membranes (Nafion® and agar) and two types of electrodes (aluminum and graphite) in a double-chamber MFC. The system was fed with a sodium acetate and cheese whey solution; in the anode chamber sludges coming from a pork industry wastewater treatment plant were used. Results showed that the highest level of energy generation was obtained with a combination of Nafion® membrane and aluminum plate electrode (0.144 mW/h with 100 Ω and 0.497 mW/h with 300 Ω resitance) compared to other combinations. Therefore, MFC technology is an alternative for electric power generation from organic substrates.

MFC, Nafion, Cheese whey

Resumen

La producción de energía a partir de fuentes renovables se ha convertido en una estrategia para aprovechar los residuos de otros sistemas y reducir las emisiones de gases contaminantes. La tecnología de las celdas de combustible microbiana (CCM) es una alternativa sustentable para producir energía eléctrica directamente de los residuos sin necesidad de partes mecánicas. En el presente estudio se comparó la producción de energía eléctrica producida por una CCM de doble cámara, utilizando dos tipos de membranas (Nafion® y agar) y dos tipos de electrodos (aluminio y grafito). El sistema se alimentó con solución de acetato de sodio y suero de leche; en la cámara anódica se utilizaron lodos anaerobios provenientes de una empresa de tratamiento de aguas residuales porcícolas. Los resultados obtenidos mostraron que el nivel más alto de producción de electricidad se obtuvo cuando se usó una combinación de membrana de Nafion® y un electrodo de placa de aluminio (0.144 mW/h, para resistencia de 100 Ω y 0.497 mW/h, para resistencia de 300 Ω) en comparación con las otras pruebas realizadas. Por lo que la tecnología de las CCM es una alternativa de producir energía eléctrica a partir de sustratos orgánicos.

CCM, Nafión, Suero de leche

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Introduction

Electric power is essential to daily lives; however, high economic and environmental costs are associated with power generation from fossil fuels (Arun *et al*., 2020; Mohamed *et al*., 2020). Due to these costs, sustainable, environmentally friendly alternatives have been developed, such as wind and solar power, and bioenergy, produced through sustainable, carbon-neutral technologies (Arun *et al*., 2020; Toczylowska-Mamińskaa *et al*., 2020). Microbial Fuel Cells (MFCs) are a green alternative for power generation through organic matter oxidation (Arun *et al*., 2020; Mohamed *et al*., 2020; Toczylowska-Mamińskaa *et al* 2020; Xu *et al*., 2020); in MFCs a bioelectrochemical system converts chemical energy into electrical energy using electrogenic bacteria (Arun *et al*., 2020; Christwardana *et al*., 2020; Mohamed *et al*., 2020; Zhang and Liu, 2020). The principal substrates used in these systems for electricity generation are anaerobic and/or aerobic digestion sludges, organic waste, and residues from urban wastewater treatment, food industry, farming breweries, and other industrial sewages (Do *et al*., 2018; Mohamed *et al*., 2020; Toczylowska-Mamińskaa *et al*., 2020). MFCs generally have two independent chambers corresponding to the cathode and anode, respectively. Microorganisms responsible for decomposing organic matter present in the medium are placed in the anodic chamber; electrons flow from this chamber into the cathodic chamber, where protons pass through a semipermeable membrane and thus electrons and protons react to oxygen in the chamber, which contains water to close the circuit (Do *et al*., 2018; Xu *et al*., 2020). The main factors that influence MFCs function are electrode type and distance between electrodes, substrate type, pH, inoculum microbial load, reactor design, among others (Mohamed *et al*., 2020). Different materials have been studied for electrodes, including carbon and metallic materials, such as carbon paper, carbon fabric, carbon mesh, carbon foam, carbon brushes, graphite plates, graphite rods, stainless steel, copper, nickel, silver, gold, titanium, etc. (Do *et al*., 2018; Mohamed *et al*., 2020; Zhang and Liu, 2020); it has been determined that carbon-based anodes have lower electric conductivity than metallic anodes, and that metallic anodes may be toxic for the microbial community (Mohamed *et al*., 2020).

On the other hand, cathodes are generally made of graphite, graphite felt, carbon paper carbon fabric, and platinum (Do *et al*., 2018). However, a combination of materials in the anode and cathode has been found to increase power generation. for instance, a combination of carbon in the anode and platinum in the cathode produced three times more energy than single-material components (Do *et al*., 2018) Another important element in MFC chamber design is the proton-exchange membrane, which influences energy flow and the reduction of the anode´s substrate flow into the cathode, in addition to minimizing oxygen backscatter into the anode chamber, increasing coulombic efficiency and ensuring the system operation´s efficiency and sustainability (Do *et al*., 2018). The most widely used materials for proton-exchange membranes are Nafion, interpolymer bases for cation-exchange membranes and sulfonated polyether (Do *et al*., 2018). MFCs may generate up to 16 W/m², with a 50% reduction in total operation costs (Arun *et al*., 2020). For example, Toczylowska-Maminskaa *et al*. (2020) mention that a MFC is capable of generating 9 times the energy needed to operate a water treatment plant (283 W). This study compared power generation (measured in watts per second) of two proton-exchange membranes (Nafion and Agar) and two types of electrodes (aluminum plates and graphite rods) in a two-chamber MFC. The system was tested with sodium acetate as substrate, and it was compared with whey.

Materials and methods

Microbial fuel cell

A clear glass 1 L-capacity MFC with two identical chambers was used; chambers are joined by a semipermeable membrane ridge, which operates as described in the diagram in Figure 1.

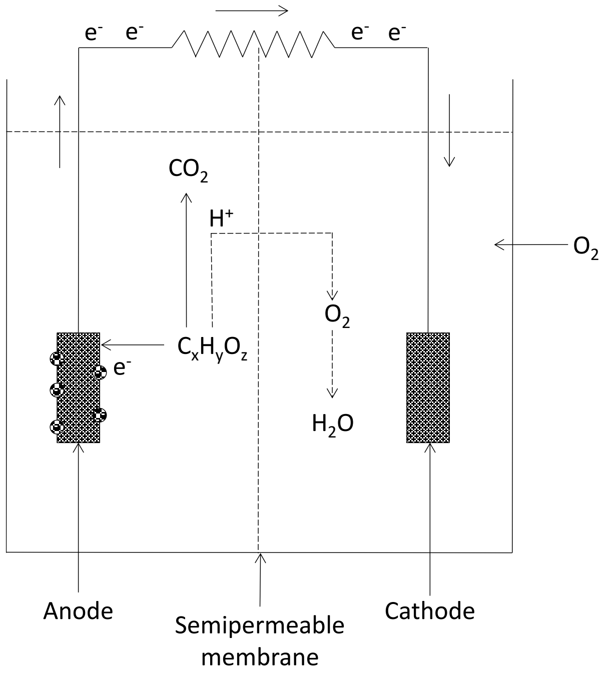

Figure 1 MFC operation diagram
Source: Own elaboration

Substrate

For evaluation of electrode and membrane type a sodium acetate-based, carbon enriched medium was prepared for the MFC cathode chamber. The medium contained 2.00 g/L CH3COONa, 0.31 g/L NH4Cl, 0.13 g/L KCl, 0.321 g/L NaH2PO4 and 10.317 g/L Na2HPO4. Once the membrane/electrode combination was selected, whey from cheesemaking was used as substrate.

Microorganism inoculum

The anode chamber was inoculated with 33 mL of anaerobic sludges obtained from a pork industry wastewater treatment plant. Sludges were triple washed through subculture in a 20 L anaerobic reactor, using synthetic waste as substrate.

Electrodes

Electrodes were made of two types of material: 10 mm x 100 mm graphite bars (99% pure) and 20 mm x 70 mm aluminum plates. The same types of electrodes were used in both chambers.

Membrane

Two membrane types were evaluated: Nafion® 117 (Thomas Scientific, 0.180 mm thick, 15x15 cm, with ion-exchange capacity of 0.90 milliequivalent weight/g) (Bioxon, 10 g/L). Nafion® membranes are composed of poly (vinylidene fluoride-co-hexafluoropropylene), lithium chloride, N, N-dimethylformamide and acetone, manufactured by electrospinning; its honeycomb structure allows the flow of protons adhered to ion water molecules (Guo et al., 2019; Yin et al., 2019); and potato dextrose agar (PDA) membranes. PDA membranes are composed of potato dextrose agar, agar concentration is taken by specifications of provide.

Voltage and power measurement

The connection between both chambers was made using a 12-gauge copper wire, to which 100 Ω and 300 Ω resistances were connected. Voltage was measured using a digital multimeter (Steren® model M-115). Measurements were made constantly every hour for the duration of the experiment. Power (W) was obtained with Ohm's Law equation from the voltage measurements.

MFCs operation

To evaluate MFCs operation, two types of substrates (acetates and whey) and two types of membranes (Nafion® and agar) were used. Two magnitudes of external resistances (100 Ω and 300 Ω) and two electrode types (aluminum and graphite) were used to quantify voltage measurements. Treatment combinations are shown in Table 1.

Treatment	Resistance (Ω)	Membrane	Electrode	Substrate
1	100-300	Agar	Aluminum	Acetate
2	100-300	Agar	Graphite	Acetate
3	100-300	Nafion	Aluminum	Acetate
4	100-300	Nafion	Graphite	Acetate
5	100-300	Nafion	Aluminum	Whey

Table 1 MFC operation combinations
Source: Own elaboration

Results and discussions

Treatments conducted with agar membranes show a maximum peak at 8 h of treatment, producing 22.9 mV with the 300 Ω resistance and using aluminum plate electrodes (Figure 2a). In the case of agar and graphite bar treatment, it was observed that the voltage produced remained constant (approx. 0.5 mV) throughout the duration of the experiment (Figure 2b). On the other hand, Nafion® membrane treatments show a maximum peak at 9 h with 36.6 mV (Figure 2c), using aluminum electrodes with 300 Ω resistance; for graphite bar electrodes, two peaks were observed, the first at 2 h with 40.1 mV and the second at 4 h with 38.7 mV (Figure 2d), both with 300 Ω resistances.

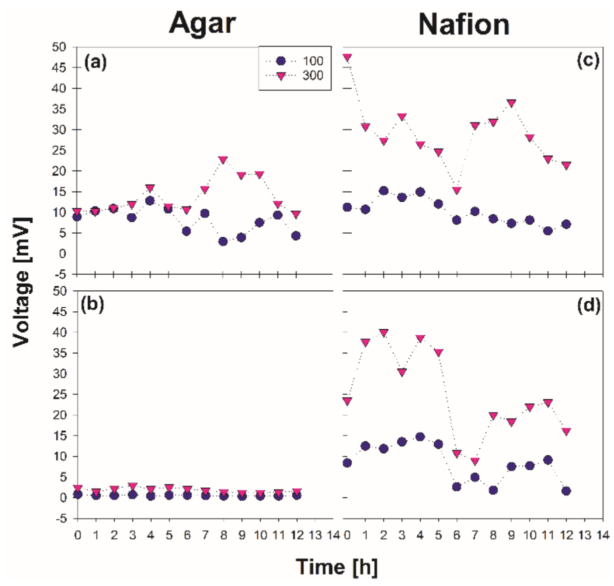

Figure 2 Voltage measurement in MFC operation; (a) Treatment 1; (b) Treatment 2; (c) Treatment 3 and (d) Treatment 4
Source: Own elaboration

Voltage measurements showed increases when Nafion® membranes were used in the system (Figure 2c and 2d) compared with measurements observed with agar membranes (Figure 2a and 2b). The same trend was observed with the two types of electrodes and resistances. These results suggest there is a better flow of energy when Nafion® membranes are used. As mentioned by Bose *et al.*, (2018) and Christwardana *et al.*, (2020), Nafion® membranes have high conductivity through sulfonates, showing high permeability in different MFC applications. These results are comparable to those reported by Guo *et al.*, (2019).

In the whey treatment it was observed that a higher amount of voltage was produced during the MFC operation (Figure 3) compared with treatments where anaerobic sludges were used (Figure 2); the highest peak was observed at 7 h of the experiment (45.6 mV), and the same voltage trend was maintained with the two types of resistance in treatments 3 and 4.

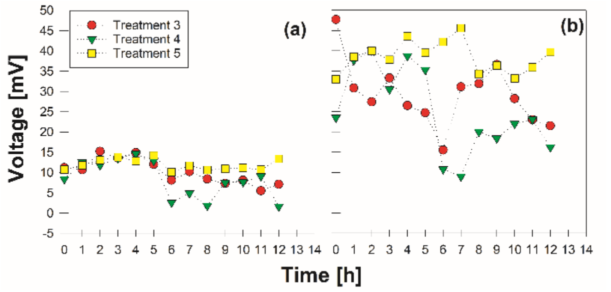

Figure 3 Voltage produced by the MFC with; (a) graphite electrode with 100 Ω resistance; (b) aluminum electrode with 300 Ω resistance
Source: Own elaboration

It was also observed that graphite electrodes had a higher point density as shown in Table 2; 147.00 mA/m^2 were obtained with 100 Ω resistance and 133.67 mA/m^2 with 300 Ω resistance for a 0.0014 m^2 area followed by aluminum electrodes (108.57 mA/m^2 with 100 Ω resistance and 113.57 mA/m^2 with 300 Ω resistance for a 0.0010 m^2 area). These results match the findings of Wang *et al.*, (2020), who mention that carbon-based electrodes have advantages over metal-based ones, increasing MFC efficiency; and Haavisto *et al.*, (2019), who studied different types of carbon-based electrodes (graphite, zeolite) and found that graphite fabrics (0.77 mA/m^2, 0.0056 m^2 area) and graphite plates (0.74 mA/m2, 0.0056 m^2 area) obtained a higher point density than other electrode types. Regarding the electric power generated by the system (Table 2), it was observed that treatment 5 which uses whey, Nafion® membrane and aluminum electrode obtained the best results both with 100 Ω (1.44 μW/h) and with 300 Ω resistance (4.97 μW/h), while treatment 2 had the least amount of power produced, 0.00 μW/h with 100 Ω and 0.01 μW/h with 300 Ω resistance.

On the other hand, the maximum power density obtained was 5,417.36 mW/m^2 for treatment 3, corresponding to 113.57 mA/m^2 (300 Ω resistance) point density at the beginning of the MFC operation, this same treatment with 300 Ω resistance (5,360.03 mW/m^2) also had one of the highest power densities, both results were obtained when the MFC was operated with Nafion® membrane and aluminum plate electrode (treatment 3) and graphite bar (treatment 4). Whey treatment had the third highest power density with 4,950.86 mW/m^2 for 300 Ω resistance and 1,440.29 mW/m^2 for 100 Ω resistance. However, it is outstanding of acetate treatments that the power density interval is still superior to those treatments; the minimum produced was 2,592.86 mW/m^2 and 728.64 mW/m^2 for 300 Ω and 100 Ω resistances, respectively, indicating power production remained constant throughout the duration of the study (Table 2).

Treatment	Resistance (Ω)	Power (μW/h)	Power density (mW/m^2)		Point density (mA/m^2)	
			Maximum	Minimum	Maximum	Minimum
1	100	0.74	1,170.29	60.07	91.43	20.71
	300	0.70	1,248.60	224.02	54.52	23.10
2	100	0.00	6.40	0.90	8.00	3.00
	300	0.01	28.03	4.80	9.67	4.00
3	100	1.12	1,650.29	216.07	108.57	39.29
	300	3.01	5,417.36	572.02	113.57	36.90
4	100	0.90	2,160.90	25.60	147.00	16.00
	300	2.43	5,360.03	270.00	133.67	30.00
5	100	1.44	1,440.29	728.64	101.43	72.14
	300	4.97	4,950.86	2,592.86	108.57	78.57

Table 2 Electric power produced in each MFC treatment
Source: Own elaboration

These results are comparable to those reported by Toczyłowska-Mamińska *et al.* (2020) who studied MFC energy production using preconditioned wastewater as substrate and carbon-based electrodes, and they quantified a maximum power density of 334 mW/m^2 equivalent to approximate to 1 A/m^2. In addition to this, Choudhury *et al.*, (2020) studied the energy produced by a MFC fed with stable wastewater, and they found that the greater amount of voltage was 0.352 V with a point density of 141 mA/m^2, going up to 0.666 V in the second feeding, while the greatest power density was 50 mW/m^2. Also, Liu *et al.*, (2019) reported a maximum power density of 0.198 mW/m^2 in a MFC operated with wastewater and carbon electrodes; they operated the MFC in similar conditions to the present study. Thus, it is suggested that it is possible using a MFC to generate electric power from organic waste, such as whey.

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Conclusions

In this study the use of microbial fuel cells and organic waste such as whey were evaluated as an alternative for electric power generation. An increase of point density (4,950.86 mW/m^2 with 300 Ω resistance and 1,440.29 mW/m^2 with 100 Ω resistance) and power generated (0.497 mW/h with 300 Ω resistance and 0.144 mW/h with 100 Ω resistance) was observed when using Nafion® membrane and graphite bars as electrodes in both chambers.

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