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Study of Performance and Operational Efficiency of Annular Single-Chamber Microbial Fuel Cell Using Chocolate Industry Wastewater

Abstract

The present research studies the performance and operational efficiency of a single annular chamber microbial fuel cells using wastewater from the chocolate industry. This research uses two air-cathode microbial fuel cells of 90 ml in volume. A graphite-coated stainless-steel mesh was used to reduce manufacturing costs as the anode in the spiral/annular geometry. The activated sludge of the Ghaem Shahr Treatment facility, containing various useful microorganisms, including bacteria, protozoa, and rotifers, was used as the mixed culture. To adapt the microorganisms in the mixed culture to the wastewater, 20 ml of a solution with a 1:1 ratio of wastewater and nutrient solution was added to the mixed culture every 48 hours, and this was repeated for 90 days. The operational efficiency of the microbial fuel cell, including potential efficiency, Coulombic efficiency, and energy conversion efficiency, was computed for the 100-ohm electrical resistance; also, to use the chocolate industry wastewater with chemical oxygen demand of 1400 mg/l, the microbial fuel cell with the optimal distance was calculated. The maximum voltage at a resistance of 100 ohms is used to compute the potential efficiency. The computed Coulombic efficiency for this system at the optimal distance of 0.7 cm using the chocolate wastewater is around 41.5%. The performance of the wastewater treatment of the chocolate industry and the cell structure in this research was compared to those of the previous ones. The power produced by the microbial fuel cell in this system is 3.6 times as much as the value reported by Mr. Patil.

Keywords: *Microbial fuel cell, Potential efficiency, Coulombic efficiency, Energy conversion efficiency, Chocolate industry wastewater*

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Introduction

The microbial fuel cell is a novel technology that reveals the latest methods to produce electricity and bio-electricity from biomass using bacteria. In other words, the microbial fuel cell is a type of technology to convert the energy stored in chemical bonds of organized compounds into electrical energy through microorganism-catalyzed reactions that have received much attention recently [1]. The theory of using microbial cells was consistent with attempts to produce electricity. M.C. Potter, a professor of Botany at Durham University, was the first to provide this theory in 1912 [2]. However, Potter managed electricity production from the E. coli microbe but failed to gain desirable results [3]. One reliable energy recovery method is using biomass from the stalk and leaves of corn or agricultural wastages. It is estimated that around 250 million tons of biomass are produced from agricultural activities [4]. Hydrogen is derived from the fermentation of sugars obtained from the hydrolysis process of lignocellulosic substances of corn, as the process efficiency of every single mole of glucose cannot yield over 4 moles of hydrogen, with only 2 moles of hydrogen being normally produced [5]. In a microbial fuel cell, electricity is produced from cellulose being fermented into hydrogen. This activity occurs when hydrogen reacts with the platinum catalyst [6]. Also, the use of sugar produced from the hydrolysis of the corn stalk could produce direct electricity in the microbial fuel cell [7].

Microbial fuel cell technology is a promising but different method for wastewater treatment. This technology can be used to extract energy in the form of electricity or hydrogen gas and treat wastewater. In late 1990, Kim et al. demonstrated that bacteria in microbial fuel cells could be applied to determine the concentration of lactic acid in water [8]. Microbial fuel cells can also be used in bio-sensors to measure the biological oxygen demand (BOD) in an organic material-contaminated environment. For this, it is required to establish an appropriate relationship between the cell's Coulombic efficiency and the environmental contaminant [9]. However, a microbial fuel cell has opened a promising window to replacing fossil fuels with new and green energies. Thus, this new technology is attracting the attention of researchers in industrial and market domains.

The main challenge in making microbial fuel cells is determining materials to maximize the produced power and Coulombic efficiency. The next challenge is the price and appropriate configuration for industrial usage. The main elements of a microbial fuel cell are the anode electrode, a cathode electrode, and a proton exchange membrane. Anode has now experienced the highest level of development with the introduction of graphite fiber brush electrodes. The membranes, or the materials which separate anodes from cathodes, are one of the biggest challenges to designing microbial fuel cells due to their high processes and considerable effects on the internal resistance of the fuel cells [10].

The voltage produced by microbial fuel cells is more complicated to be understood than by chemical fuel cells, which are predictable. In a microbial fuel cell, placing the bacteria in the electrode and processing the enzymes or structures required to transfer electrons to the outside of the cell need much time. In mixed microbial cultures, types of bacteria can grow and produce various potentials, as the potentials produced by a pure microbial culture cannot be predicted either. As for the electron donors (substrates) and electron acceptors (oxidizers), thermodynamic relations involve limits over the maximum produced voltages [11]. As stated, the goal of the present research was to study the performance and operational efficiency of the single annular chamber microbial fuel cells using chocolate industry wastewater.

Materials and Procedure

This research uses two air-cathode microbial fuel cells of 90 ml in volume. A graphite-coated stainless-steel mesh was used to reduce manufacturing costs as the anode in the spiral geometry. The graphite coating reduces resistance but increases the conductivity of the anode. To demonstrate the system's ability to generate electrical energy and treat wastewater, the chocolate industry wastewater with high oxygen demand load and containing large amounts of industrial detergents with high stability and hardness was selected as feeding to the single-chamber microbial fuel cells. The activated sludge of the Ghaem Shahr Treatment facility, containing various useful microorganisms, including bacteria, protozoa, and rotifers, was used as the mixed culture. To adapt the microorganisms in the mixed culture to the wastewater, 20 ml of a solution with a 1:1 ratio of wastewater and nutrient solution was added to the mixed culture every 48 hours, and this was repeated for 90 days. It is noteworthy that the nutrient solution included a combination of minerals, salts, and vitamin substances deemed necessary for the continued growth and activity of the microorganisms.

Designing, manufacturing, and operating biological fuel cells

The body of the single chamber microbial fuel cell includes a transparent plexiglass plate of 3 mm thick for the upper and lower caps, another transparent plexiglass plate of 3 cm thick for the cell's walls, and the other plexiglass plate of 6 mm thick for the holder of the cathode in the center of the cell.

The upper and lower caps of the single-chamber microbial fuel cell constitute two more parts of the cell's body, which are cut onto the plexiglass plates 3 mm thick. A circle of 3.5 cm in diameter was made on each of these caps to allow for air passage. Four holes with a diameter of 4 mm were created and bolted together to connect the caps to the main body. The general design of the cell's body with a 90-cm^3 volume and its dimensions are illustrated in figure 1.

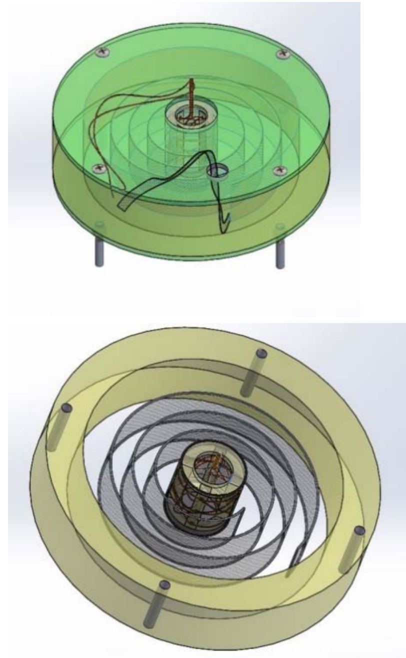


Figure 1: General design of the single microbial fuel cell with a spiral anode

The American-made carbon fabric (U.S. E-TEK) was used to make the cathode electrode. To make the anode electrode, it is best to use porous surfaces; thus, the 300 stainless steel mesh was used for this. The stainless steel dimension of 2*57 cm was separated and rinsed with deionized water. In the next stage, to remove organic contaminants on it, this mesh was immersed in the acetone solution. Consequently, the mesh was boiled in a solution with 0.1 M of hydrochloride acid and again boiled in deionized water to remove the bad smell of the hydrochloride acid.

Findings

Computation of Operational Efficiency of Single Chamber Microbial Fuel Cells

The operational efficiency of the microbial fuel cell, including potential efficiency, Coulombic efficiency, and energy conversion efficiency, was computed for the 100-Ohm electrical resistance; also, to use the chocolate industry wastewater with chemical oxygen demand of 1400 mg/l, the microbial fuel cell with the optimal distance was calculated.

1. **Potential Efficiency (PE)**

The microbial fuel cell voltage to the open-circuit voltage ratio reveals the potential efficiency. The maximum voltage at the resistance of 100 ohms is used to gain more potential efficiency.

$PE= V/OCV = (378)/(856) \times 100=44.15\%$

2. **Coulombic Efficiency (CE)**

Figure 2 illustrates the intensity of electrical current variations for the 100-ohm resistance, computed at 96 hours. Since the drop in oxygen chemical demand of the wastewater was examined within 96 hours, the Coulombic efficiency can be calculated from numerical integration of the intensity of the electrical current by time in this range (Figure 3).

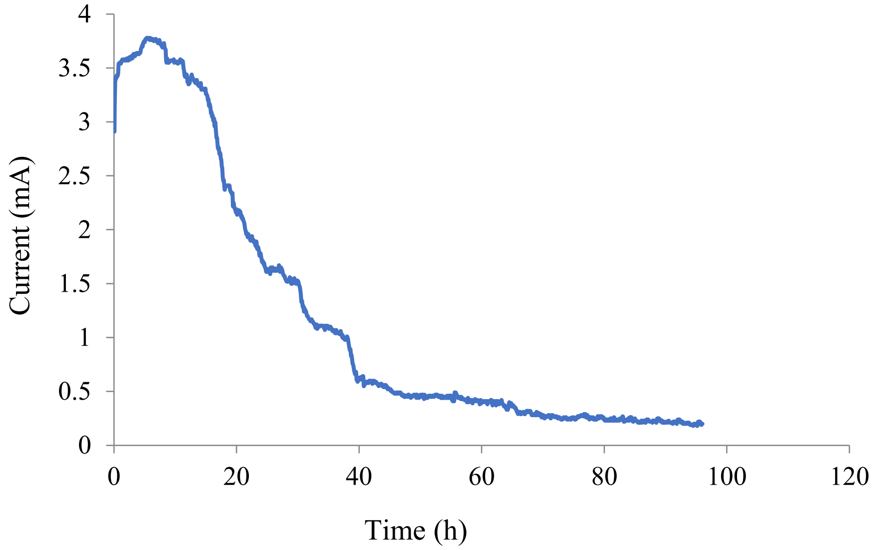


Figure 2: Intensity of current variations at the 100-ohm resistance for the microbial fuel cell at the electrode distance of 0.7 cm

Using the Origin software, the integral value of the intensity of the electrical current by time or area under the curve of the intensity of the current by time within 96 hours was 113.869 mAh. The chemical oxygen demand reduction rate within 96 hours was 91.2%. Thus, the Coulombic efficiency is:

$$C_E = \left(\frac{8\int I\,dt}{FV_{An}\Delta COD}\right) = \left[\frac{8\times113/869\times3600}{96485\times0/09\times0/91\times1000}\right] \times 100 = 41\%/5$$

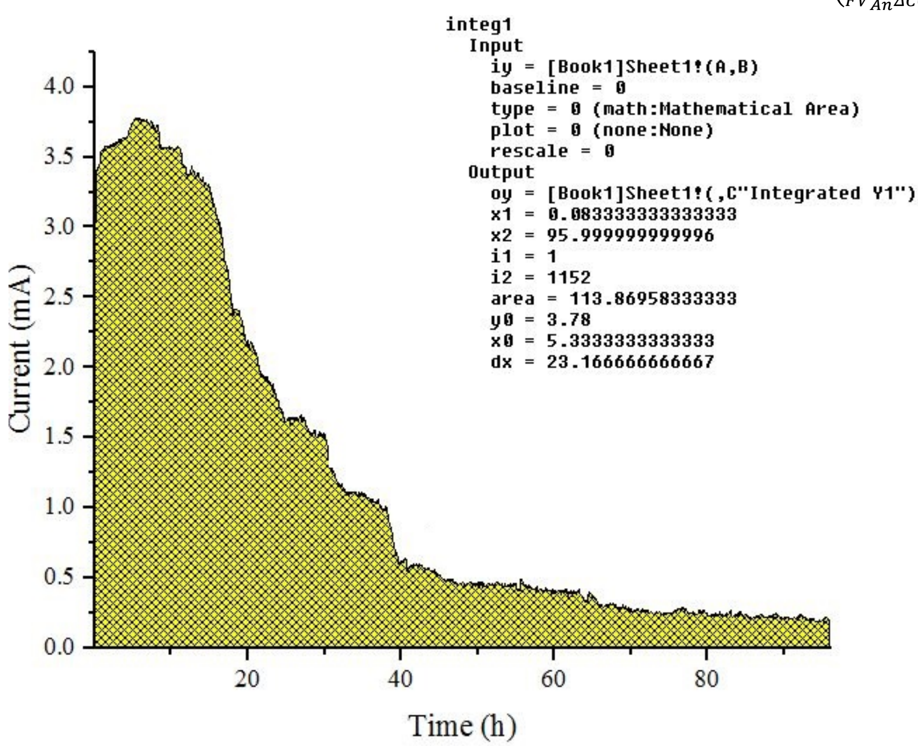


Figure 3: Integral computation of the current intensity by time at 96 hours using the Origin software

As stated, Coulombic efficiency describes the ratio of electrons recovered in the form of electrical currents from the oxidation of wastewater to the total accessible electrons. In Coulombic efficiency computation, the term integration of the current intensity by time changes by the changing of the external resistance in a way that the Coulombic efficiency remains almost constant; for example, when the electrical resistance decreases, the current intensity increases, and although the current intensity increases, the time needed to reach the maximum current intensity decreases; thus, the term integration of the current intensity by time remains almost constant. The greater the Coulombic efficiency, the more the microorganisms in the microbial fuel cells will be in an ideal condition, as a more desirable feeding condition will be met. The very design of the microbial fuel cell, which increases the annular anode level to provide a greater surface for microorganisms to grow, degrade more wastewater, and generate more electrons, is another factor that increases the Coulombic efficiency rates in this research.

3. Energy Conversion Efficiency (ECE)

Energy conversion efficiency is calculated from the multiplication of potential efficiency by the Coulombic efficiency:

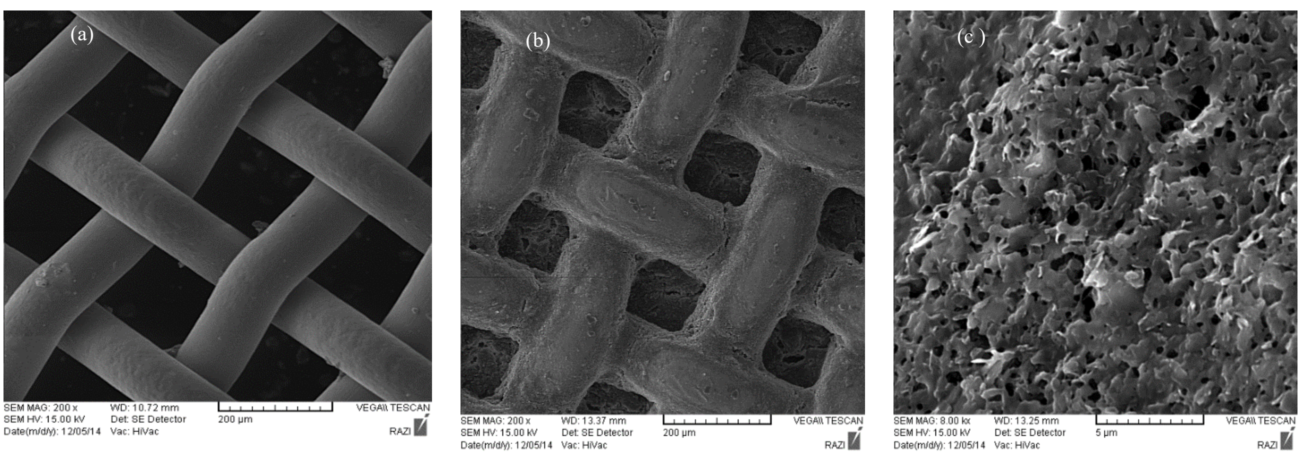
$$ECE\ (\mathcal{E}_E) = PE \times C_E = 32.18\%$$

Comparison of Microbial Fuel Cell Performance

Consistent with the latest attempts aimed at comparing the wastewater treatment of the chocolate industry in the microbial fuel cell and the wastewater used in the present research, the only academic contribution in this regard pertains to Patil et al.. They reported a dual-chamber structure, suggesting a maximum power of 6.19 W/m^3 [12]. Also, the only study on an annular single-chamber microbial fuel cell with annular anodes was carried out by Mardanpour et al. [13]. This fuel cell was first developed by Mardanpour, which generated a maximum power of 20.2 W/m^3 in dairy wastewater treatment. The present research optimized the electrode distance between the cathode and anode to successfully generate a maximum power of 22.898 W/m^3, which is better than the value reported by Patil.

Morphology of the biofilm formed on the surface of the anode electrode

The biofilm formed on the surface of the anode electrode plays a crucial role in achieving the maximum power and current. Consistent with the previous studies, increasing the anode area of contact and surface porosity can increase bacterial adhesion, electron transfer, and output power [14]. Scanning electron microscope images (a, b and c) indicate that the stainless-steel mesh, which was improved by graphite coating, can provide a porous and solid surface for the growth and bonding of the biofilm. Figure 4 (a) illustrates that the stainless steel has a smooth surface, which, after being coated with rough and porous graphite, has provided an appropriate substrate for the density and adhesion of the biofilm.



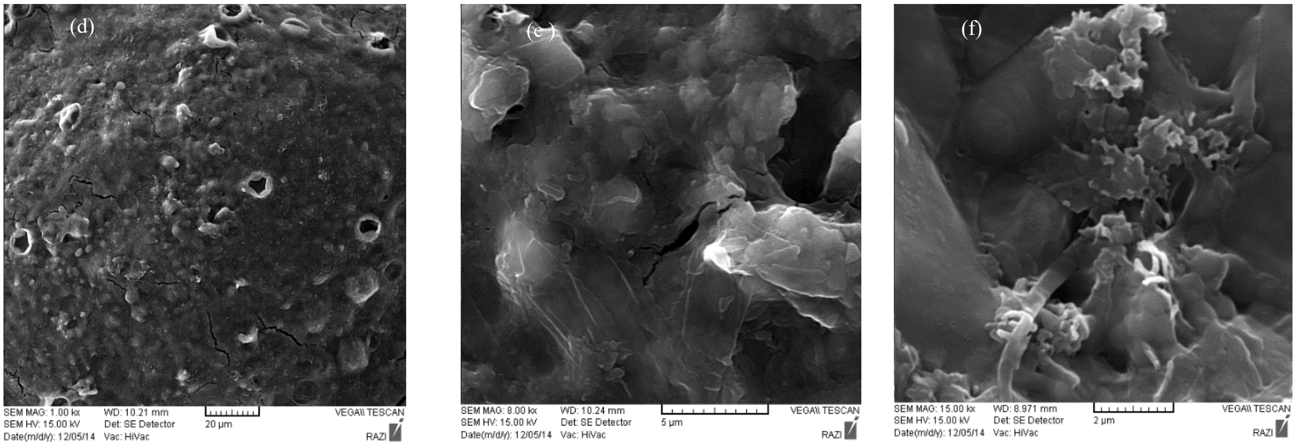


Figure 4: SEM images of the annular anode (a: stainless-steel mesh before being coated with graphite; b and c: the graphite-coated film on the surface of the stainless-steel mesh; d, e and f: biofilm formed on the electrode surface coated with graphite in different magnifications)

The high area of contact of the stainless-steel mesh caused the biofilm formed on its surface to have a uniform morphology and high density, thereby generating and transferring electrons on the biofilm more easily. In sum, it is concluded that the high porosity of the anode helps easier bacterial adhesion on its surface, thus, making the infiltration of the substrate into the biofilm faster.

Conclusion

Biotechnology of microbial fuel cells is a novel science by which microorganisms, as cheap catalysts, convert the chemical energy in the organic and inorganic compounds into electrical energy. One of the first laboratory stages to develop this technology into practical usage is to optimize the parameters affecting cell performance. The power generated is a concrete feature of the microbial fuel cell performance. This research reviewed the operational efficiency of the annular single-chamber microbial fuel cell using chocolate industry wastewater to simultaneously treat the wastewater and generate electrical power and current. For this, a graphite-coated stainless-steel mesh as the anode provided a porous surface for the proper growth and bonding of the biofilm. Second, using the anode in the annular geometry, the level of the anode electrode increased, and the time to get the substrate to reach the microorganism decreased. The chocolate industry wastewater contained hard, degradable, and stable compounds such as solvents, detergents, and oils as substrates. This research used two annular single-chamber microbial fuel cells of 90 cm^3 in volume, which enjoyed fully similar configurations, with the only difference being that they were tested non-continuously at an electrode distance. The results indicated that the voltage used to gain potential efficiency is the maximum voltage at a resistance of 100 ohms. The Coulombic efficiency calculated for this system at the optimal distance of 0.7 cm using the chocolate industry wastewater was around 41.5%. The performance of the system in this research was compared to that of other previous studies on chocolate wastewater treatment and the cell structure used. The power generated by the microbial fuel cells in this system was 3.6 times the value reported by Mr. Patil.

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Conflict of interest
None.
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Ethics statement
None.

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