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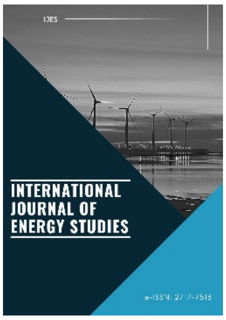

Research Article

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Investigation and modeling of wastewater treatment, electricity generation and coulombic efficiency by new design nested cylindrical dual chamber microbial fuel cell

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Highlights

- NDMFC can efficiently treat wastewater and obtained high COD removal efficiency.
- PTFE-based composite electrodes maximized power density and voltage value.
- Full factorial experimental modeling shows MFC as a competent technology for wastewater treatment.
- Maximizing MFC performance is possible by reducing the reactor internal resistance and electrode resistance.

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ABSTRACT

Microbial fuel cells (MFCs) have attracted significant attention in recent years due to their potential in the biological treatment of waste and wastewater, as well as in energy conversion technologies. In this study, a reactor was designed using polypropylene material. The design positioned the cathode chamber inside the anode chamber to reduce diffusion resistance by minimizing the distance between the two chambers. Additionally, composite anode/cathode electrodes were developed using PTFE (polytetrafluoroethylene). As a result of the study, values for maximum voltage, maximum power density, and COD (chemical oxygen demand) removal efficiency were determined. The coulombic efficiency was also calculated and found to be 11.49%. pH and temperature values were monitored and these parameters remained within a consistent range throughout the study. The findings showed that this reactor design achieved comparable electricity generation potential and effective COD removal efficiency. Finally, voltage and COD removal values were used in Dizayn Expert 7.0.0 (Stat-Ease Inc., Minneapolis, MN, USA) for full factorial experimental modeling to validate the experimental results. Overall, the study is expected to contribute significantly to the literature on reactor designs in microbial fuel cell research.

Keywords: Microbial fuel cell, Reactor design, Electrode design, Design expert

1. INTRODUCTION

Fossil fuels, formed from natural resources such as coal, natural gas, and oil, were created over millions of years through the compression and heating of dead plant and animal matter within sediment and rock layers. These fuels have long been used as primary energy sources to power electronic devices, motor vehicles, and support daily life. However, fossil fuels are considered unsustainable due to their finite nature and the threat of depletion. Consequently, there is a growing need for renewable and sustainable alternatives [1].

Microbial fuel cells represent an emerging technology capable of converting organic waste into electricity, offering a promising solution to both energy production and wastewater treatment challenges [2]. In MFCs, the chemical energy stored in biomass is transformed into electrical energy through redox (oxidation-reduction) reactions [3]. To generate electrical current, the system requires several key components, including a proton exchange membrane (PEM), anode and cathode electrodes, and a conductive wire [4].

Microbial fuel cell technology offers several advantages. These include efficient conversion of organic matter into energy, reduced sludge production compared to conventional wastewater treatment plants, and the recovery of valuable by-products. However, MFCs also have certain disadvantages, such as low power output and high costs. From an industrial perspective, it is therefore crucial to improve efficiency and develop new catalyst and electrode designs for MFC technology [5]. The effectiveness of MFCs in wastewater treatment and electricity generation largely depends on various factors, particularly the design and type of electrode materials used. As a result, researchers are actively exploring innovative designs to enhance the overall efficiency of MFC systems [6].

Various MFC designs are commonly used in laboratory settings, including cylindrical reactors, single-chamber cubes, dual-chamber cubes, plate-type reactors, tubular reactors, and dual-chamber H-type reactors [7]. In this study, a nested MFC was designed with the cathode chamber is placed inside the anode chamber. This configuration reduces the distance between the two chambers, ensuring lower internal resistance and higher voltage output. Additionally, both compartments were constructed with a cylindrical shape to prevent the formation of dead zones within the reactor.

2. MATERIAL AND METHODS

2.1. Reactor Design

The nested cylindrical dual chamber microbial fuel cell (NDMFC) is made of polypropylene material. The cathode chamber of the reactor is designed to be placed in the anode chamber and manufactured in Ankara Ostim Seymen Machine. The difference between the Tubular Microbial Fuel Cell and the reactor used in this study is not only the difference between geometry and location of the anode and cathode chambers but also the contact area between anolyte and catholyte, flow pattern and electron transfer path between anode and cathode chamber. The height of the anode chamber is 17 cm and its diameter is 11 cm. The effective working volume of the anode chamber is 700 mL. The height of the cathode chamber is 11 cm and its diameter is 5 cm. The effective working volume of the cathode chamber is 200 mL. Before using this reactor, a membrane was placed at the bottom of the cathode chamber and sealed. The technical drawing and image of the nested cylindrical dual chamber reactor are given in Figure 1.

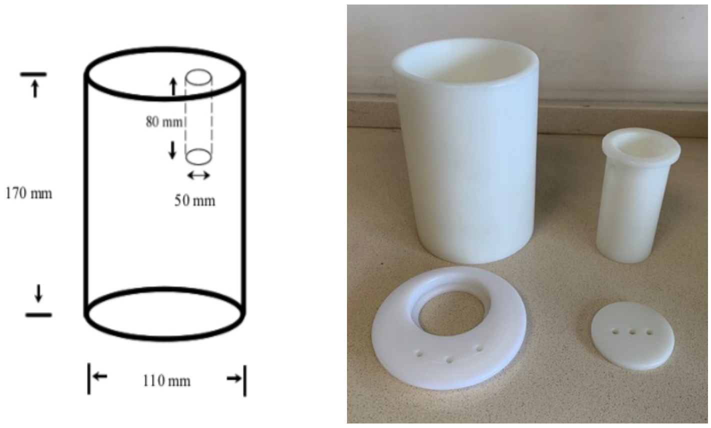

Figure 1. The technical drawing and figure of nested cylindrical dual chamber reactor.

2.2. Electrode Design

Stainless steel mesh (5 cm x 5 cm) with 0.25 mm wire diameter, 0.18 mm thickness and 385 µ pore size was used as current collector (Tek Metal, Ostim, Ankara). 0.25 g expandable graphite (Sigma-Aldrich) was poured into the beaker with 8.75 g active carbon (Merck) as carbon material. 1 g polytetrafluoroethylene (Sigma-Aldrich) was used as polymer and the prepared electrode paste was spread on both surfaces of the current collector. The electrodes pressed under 4 tons pressure for 1 min were dried at 65°C for 1 day and then the dried electrodes were pressed again under 4 tons pressure for 1 min. The electrodes are shown in Figure 2.

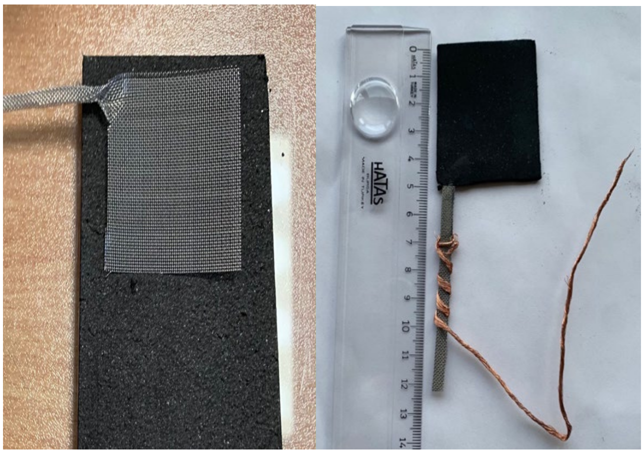

Figure 2. PTFE-based electrodes.

2.3. NDMFC Operation

In the study, Ankara Tatlar Wastewater Treatment Plant inlet water was used as domestic wastewater. Firstly, 2 L of wastewater was obtained and pH, conductivity, TSS (total suspended solids), COD and alkalinity analyses were performed. The analysis results of the domestic wastewater used in the studies are given in Table 1.

Table 1. Characterization of the sample taken from Tatlar Wastewater Treatment Plant.

pH	Conductivity (mS/cm)	Alkalinity (mg/L $CaCO_3$)	TSS (mg/L)	COD (mg/L)
7.52	1.71	320	453	485

The anode chamber was filled with 700 mL of domestic wastewater, while the cathode chamber was filled with 200 mL of deionized water and aerated. Nafion 117 membrane (Ion Power, 720 Governor Lea Rd, New Castle, DE 19720) was used to separate the reactor chambers. COD and pH measurements were conducted at specific intervals throughout the study.

Voltage data were collected by 1 kΩ external resistance. Copper wire is used between the electrodes to enable electron transfer. These measurements of the NDMFC were continuously recorded in 10 min intervals by using a digital multimeter FLUKE 8808A (USA). Power density of the NDMFC was calculated as follows (1):

$$Power\ Density = (I.V)/A \tag{1}$$

where, I is the current, V is the voltage, and A is the anode surface area [8].

The coulombic efficiency was calculated at an external resistance of 1 kΩ based on changes in chemical oxygen demand (COD) concentration as follows (2):

$$CE = \frac{M \int_0^{tb} I dt}{F\ b\ V\ \Delta COD} \tag{2}$$

where M is the molecular weight of substrate, ΔCOD is the change of substrate concentration over the time t, F is Faraday's constant, V is the volume of the NDMFC chamber, and b is the moles of electrons for the substrate [9].

3. RESULTS AND DISCUSSIONS

3.1. Voltage and Power Density

As shown in Figure 3, a rapid increase in voltage values was observed with the initial substrate concentration and the activity of electroactive microorganisms. Therefore, it can be stated that substrate concentration is a key factor affecting reactor performance in MFC studies [10].

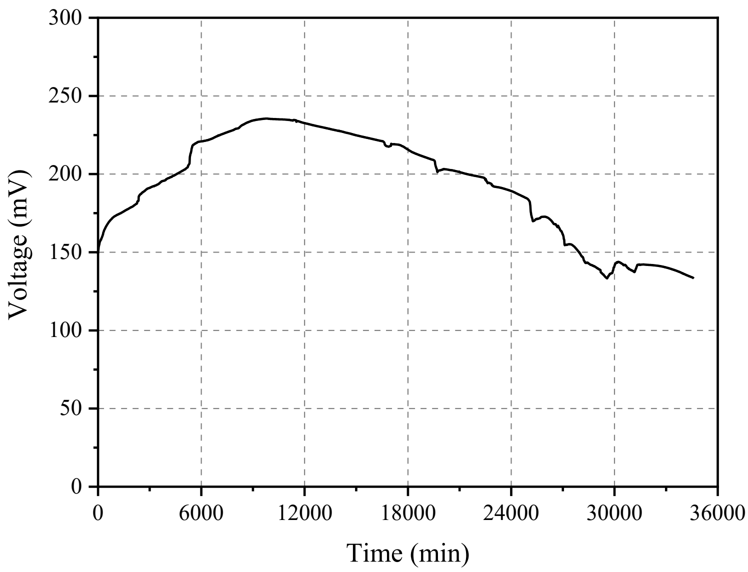

Figure 3. Voltage-Time Graph of NDMFC operation

In Figure 3, the voltage values initially increased slowly, likely due to the time required for the electroactive bacteria to adapt to the environment. As the bacteria acclimated, the rate of voltage increase accelerated, eventually reaching a peak of 236 mV. After this maximum was reached, the voltage began to gradually decrease, likely due to the depletion of available substrates in the environment. The power density values calculated with the voltage values are given in Figure 4.

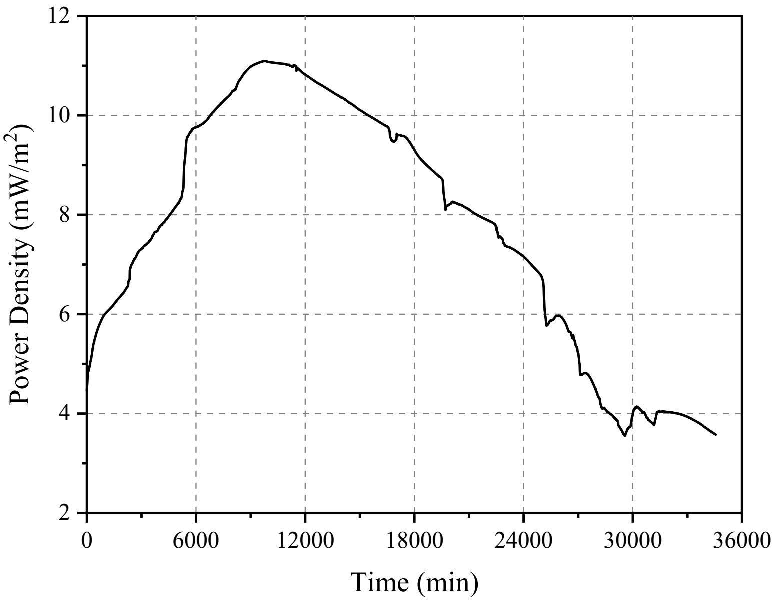

Figure 4. Power Density-Time Graph of NDMFC

The total power generated by the NDMFC increased during operation. The maximum power density was calculated considering the electrode surface area and was found to be 11.09 mW/m^2.

3.2. COD Removal and Coulombic Efficiency

In the study, COD and pH measurements were also performed daily and the findings are shown in Figure 5.

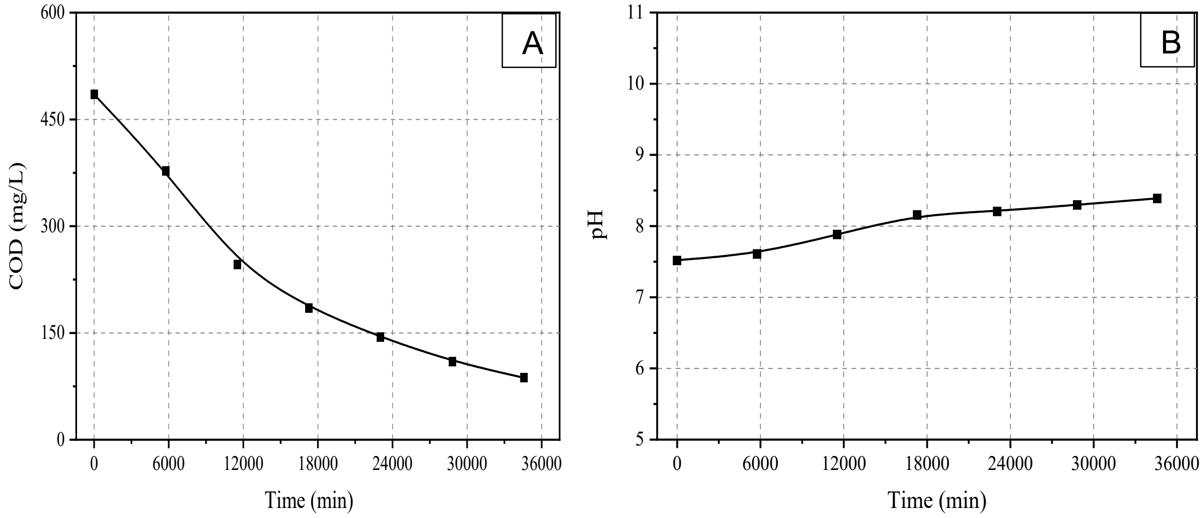

Figure 5. COD Removal Graph (A) and pH-Time Graph (B) of NDMFC

Figure 5 (A) is examined, after the domestic wastewater with an initial COD value of 485 mg/L was placed as substrate in the anode chamber of the NDMFC, the organic matter started to be rapidly consumed by the electroactive bacteria. COD was measured at certain intervals of the study and the COD removal efficiency was found as 82.6%. The pH value is an important parameter for the activation of electroactive bacteria. It can be said that pH value plays an important role in performance of electroactive bacteria and biofilm formation [11]. When Figure 5 (B) is examined, it is seen that the reactor and electrode configuration does not cause pH changes that would negatively affect the vital activities (corrosion, toxicity, etc.) of exoelectrogenic bacteria.

Finally, the coulombic efficiency (CE) was calculated using the current values and COD removal efficiency obtained from the study. As a result of the study, the coulombic efficiency was found to be 11.49%.

3.3. Modelling of Full Factorial Experimental Design

Full factorial experimental design, one of the modeling tools of the Design Expert 7.0.0 (Stat-Ease Inc., Minneapolis, MN, USA) was used for experimental verification and statistical analysis. Full factorial design is a modelling method that creates experimental points defined by the minimum and maximum values of each factor using all possible combinations in each full trial or repetition of experiments and performs modeling [12]. The factors in the modeling study were determined as voltage (mV), COD (mg/L) and time (min.). Temperature (°C) and pH measurements were also performed in the anode compartment at certain periods. Since these parameters need to be kept at certain intervals for the living conditions of microorganisms, they were not included in the modeling studies. The best 5 results of the full factorial design optimization performed for the study are shown in Figure 6.

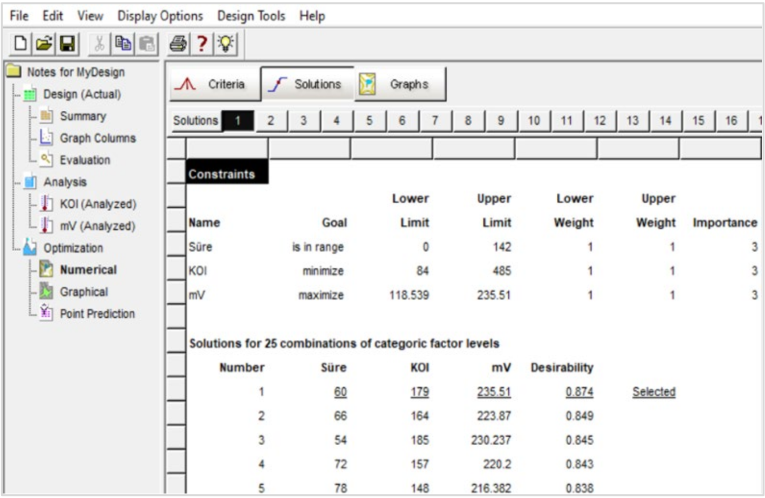

Figure 6. Full factorial design optimization results

In Figure 6, the desirability was obtained as 0.874. With the modeling study created based on the trial points where the voltage value was maximum, the highest voltage value of 235.51 mV was reached as a result of the process applied for 132 minutes. With the experimental verification studies carried out at the point obtained by modeling, the voltage value was found to be 236 mV. According to the obtained results, it is seen that the data obtained at the optimum point and the data obtained as a result of the experimental studies are compatible with each other.

The NDMFC is a promising technology when it is used to generate electricity. NDMFC has been shown to be an effective solution for high wastewater treatment capability and bioelectricity generation. The comparison performance of NDMFC under different operating conditions is presented in Table 2.

Table 2. Comparison of literature studies with the current study.

Substrate	Power Density	COD Removal (%)	CE (%)	Study
Synthetic wastewater	8.91 mW/m^2	86	0.22	[13]
Domestic wastewater	23.52 mW/m^3	93.52	3	[14]
Domestic wastewater	5.42±0.17 mW/m^2	94.00±0.05	-	[15]
Domestic wastewater	4.65 mW/m^2	93.13 ± 4.83	1.01	[16]
Domestic wastewater	11.09 mW/m^2	82.6	11.49	This study

The comparative analysis showed that the power density, COD removal efficiency and CE values obtained in NDMFC of the present study were significantly similar to the results obtained in the earlier studies (in Table 2).

4. CONCLUSIONS

The performance of NDMFCs (nested cylindrical dual chamber microbial fuel cell) depends on several factors, including substrate type and concentration, mode of operation, electrode materials and dimensions, ion exchange membrane, and reactor design. These factors play a crucial role in enhancing electrical efficiency. As a result of the study; maximum voltage and maximum power density values were found as 236 mV and 11.09 mW/m^2, respectively. Furthermore, COD removal and coulombic efficiency were also calculated as 82.6% and 11.49%, respectively. When the results are examined, NDMFCs can be used for both domestic wastewater treatment and electricity generation. PTFE-based electrodes have shown superior performance when used as both anode and cathode materials. This is due to their biocompatibility, high mechanical strength, enhanced microbial-electrode interactions, and the supportive micro-environmental conditions they provide, all of which contribute to improved NDMFC performance.

NOMENCLATURE

CE: Coulombic efficiency

COD: Chemical oxygen demand

NDMFC: Nested cylindrical dual chamber microbial fuel cell

PTFE: Polytetrafluoroethylene

TSS: Total Suspended Solids

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DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Gizem Hazan AKÇAY: The experimental studies, analysis, writing original draf, editing the whole manuscript.

İrfan AR: Supervising the whole process.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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