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Enhanced Pollutant Removal and Power Generation in Wastewater Using Microbial Fuel Cells: A Pathway to Sustainable Energy

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ABSTRACT

Microbial fuel cells (MFCs) demonstrate potential for wastewater treatment while concurrently generating renewable electricity. This investigation aimed to enhance current output by optimising the operational parameters of a dual-chamber MFC. The study utilized a household-constructed dual-chamber MFC with an agarose gel-based proton exchange membrane to enhance current generation in municipal wastewater treatment. The MFC effectively reduced the chemical oxygen demand (COD) from 291 mg/L to 134 mg/L, demonstrating substantial degradation of organic contaminants. An increase in total dissolved solids (TDS) and electrical conductivity (EC) was observed, indicating material decomposition and ionization. The pH level decreased slightly from 7.7 to 7.3, presumably due to hydrogen ion movement during electrochemical processes. Through optimisation of wastewater volume and operational conditions, a peak current production of 1124 μA was achieved. Future studies should focus on refining operational parameters and examining the catalytic properties of the cathodic microbial community to enhance MFC performance and scalability. These findings highlight the dual chamber MFC's potential as a sustainable solution for concurrent wastewater treatment and renewable energy production, establishing a foundation for scalable applications in environmental remediation and clean energy generation.

Keywords: *Microbial fuel cell, Wastewater treatment, Bioelectricity, Organic pollution reduction, Current production*

1. Introduction

The global population is experiencing rapid growth, leading to an increase in energy demands for both residential and commercial sectors. Consequently, it is imperative to identify novel, cost-effective, and environmentally sustainable energy alternatives. In Pakistan, the energy sector faces challenges in generating sufficient power to meet this growing demand [1]. Research indicates that Pakistan incurs substantial financial and energy losses annually. The United Nations has established two primary Sustainable Development Goals focused on water and energy resources [2]. Microbial fuel cells (MFCs) show potential for wastewater treatment and bioenergy generation, but optimizing design and operational parameters is crucial for real-world applications [20].

The application of principal component analysis (PCA) to the system can facilitate the identification of parameters that should be prioritised for performance enhancement. This is essential for ensuring future integration between Microbial Fuel Cell (MFC) performance and the monitoring and maintenance of large-scale applications [3]. The present study examined ampere current production. Microbial fuel cells can provide a low-cost, sustainable solution for wastewater treatment and nitrogen removal, with configuration selection depending on wastewater nature[21]. The novel system of stacked constructed microbial fuel cells effectively treats wastewater and generates electricity, offering a cost-effective and sustainable solution for pollution control [22].

This innovative approach enables the application of various treatments to a dual-chamber MFC, including the utilisation of wastewater, nutrient types, power generation, and the incorporation of specific substrates. These substrates may include artificial electron donors or real substrates such as wastewater containing or lacking urea from urine or meat processing plant-suspended particles [4]. An alternative method to enhance MFC performance involves optimising treatment conditions, such as pH, temperature, organic concentration, ionic strength, wastewater conductivity, media type, bacteria, electrode material, chamber configuration, or cell topography [5]. In this investigation, a two-chamber MFC was constructed using common household items, employing an Agarose gel-based proton exchange membrane. Furthermore, a voltmeter was utilised to measure current production and analyse physicochemical characteristics.

While studies on pure cultures demonstrate promising results, mixed community cultures present a more realistic selection of microorganisms for practical applications. However, limited research has been conducted on the robust performance of mixed consortium MFC systems. Although screws and wires can rapidly adjust connected weights, a more precise method for consistently regulating applied pressure is required [6]. In light of this, we are currently investigating the optimal operating parameters for a dual-chamber MFC utilising an electrode as the anode and a messaging cathode. Our present research examines the cathodic microbial consortium's kinetic reduction capacity and electrochemical reduction rates under various operating conditions, including different substrates, concentrations, and cycle operations. Chronoamperometric tests revealed reduced hydrogenase activity in the cathodic microbial community due to excess potential [7].

Microbial fuel cells (MFCs) can convert organic substrates into electrical energy using microorganisms as catalysts. Studies have been conducted to enhance MFC performance and identify power-limiting factors to improve its viability as a power source []. This research aims to optimise the operating parameters of a dual-chamber MFC system, focusing on various operational factors such as substrate type, concentrations, and operating cycle. By analysing the kinetic reduction capability of the cathodic microbial consortium, we demonstrated that dividing substrate feeding into distinct cycles benefits the cathodic oxygen reduction reaction process. Additionally, we observed significant enzyme "activation" in the cathodic microorganism, highlighting the catalytic properties of the cathodic tri-carboxylic acid (TCA) cycle [9]. Our examination of the cathodic microbial consortium's kinetic reduction capability showed that separating substrate feeding into distinct cycles enhances the cathodic oxygen reduction reaction process. Moreover, we noted substantial enzyme "activation" in the cathodic microorganism, emphasising the catalytic characteristics of the cathodic TCA cycle [10] .

2. Materials and Methods

2.1 Sample Collection

Approximately 8000 mL of municipal wastewater, serving as the substrate or feedstock for MFC, was collected from a sampling location at Margalla View Housing Society in Islamabad, Pakistan. For each experiment, the required quantity of substrate was isolated in a plastic container. Several physicochemical characteristics of the wastewater were examined, including pH, total dissolved solids, chemical oxygen demand, and electrical conductivity.

2.2 Dual Chamber MFC

A two-compartment microbial fuel cell (MFC) was constructed following the subsequent procedure. Two distinct chambers were fabricated using plastic containers for the anode and cathode. The anode chamber was designed to contain municipal wastewater as the microbial medium, while the cathode chamber held an electrolyte solution, specifically potassium ferricyanide, to support reduction reactions. A carbon electrode was inserted into each chamber, ensuring complete submersion in their respective solutions to promote efficient electron transfer.

To separate the chambers, a proton exchange membrane (PEM) composed of agarose gel was positioned between the anode and cathode compartments. This membrane facilitated the movement of protons generated in the anode chamber to the cathode chamber while preventing oxygen entry into the anode chamber, thus maintaining the anaerobic environment crucial for microbial activity.The electrodes were subsequently connected using copper wires to create a closed circuit, which was connected to a voltmeter and a 0.5 Ω external resistor. This configuration allowed for regular voltage measurements across the resistor, which were utilised to determine current production. Following the assembly of the system, municipal wastewater was introduced into the anode chamber, and the electrolyte solution was added to the cathode chamber. The compartments were securely sealed to prevent oxygen infiltration into the anode chamber, thereby fostering anaerobic conditions that enhance microbial electricity generation.

Upon activation, voltage readings were documented at set intervals to track the MFC's current production. This setup yielded valuable data for optimising MFC conditions, such as modifying the wastewater volume to improve microbial activity and electron transfer efficiency. The dual chamber MFC was engineered to maximise power output and pollutant removal efficiency, aligning with the study's objectives of sustainable wastewater treatment and renewable energy production.

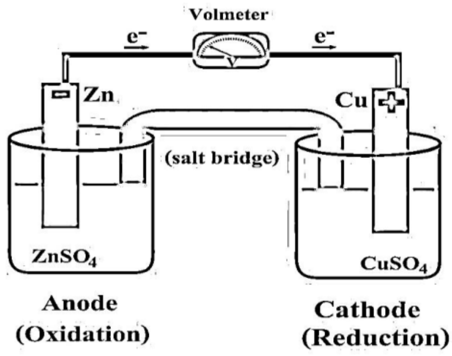

Fig 1. Schematic Diagram of Microbial Fuel Cell (MFC)

2.3 Current production and analysis

PH and electrical conductivity were measured through a pH meter (ATC pH meter) and an E.C. meter. TDS (total dissolved solids) were determined by the ATLAS TDS meter. The colorimetric method was used to measure the chemical oxygen demand (COD) [11, 12]. The output of the MFC was expressed using current (μA). The voltmeter (DT-830D) was used for this purpose. Voltmeter readings were noted only after a steady and constant value was obtained and later converted into current using Ohm law. While current production was measured through voltage external resistance, which was 0.5 Ω.

3. Results and Discussion

3.1. Before Experiment

Prior to the MFC experiments, four key physicochemical parameters of the collected wastewater were analysed: pH, total dissolved solids (TDS), chemical oxygen demand (COD), and electrical conductivity (EC). At the time of collection, the initial measurements were as follows: pH of 7.7, electrical conductivity of 1142 μS/cm, total dissolved solids of 560 mg/L, and COD of 291 mg/L. The initial COD value was elevated due to the presence of increased concentrations of organic and inorganic compounds in the wastewater, including residual food waste from bottles and cans as well as emulsified oil. The higher COD value indicates a greater degree of organic pollution in the water [13].

*3.2. After Experiment*The biological cycle means lag (initial phase), log (exponential phase), stationary, and decline phases, which were obtained by using current measurements for the next 24 hours. As in the first experiment of 3000 mL wastewater maximum current, the next 24 hours' current production showed that it took eight hours to yield maximum current production, which was 916 μA (Fig 2), and then after eight hours, it started to decline, and the last current reading was 412 μA after 24 hours. At the start, maybe there was no movement of ions, so after some time when microbes started decomposition of the organic or inorganic substrate, as a result energy was generated, and when microbes started mobility, it tends to increase the current output.

While in another experiment, maximum current production of 1124 µA was observed by increasing the solvent to 500 mL, and it took ten hours to yield maximum current production, then after 11 hours it started to decline, and the last current reading was 640 µA after 24 hours.

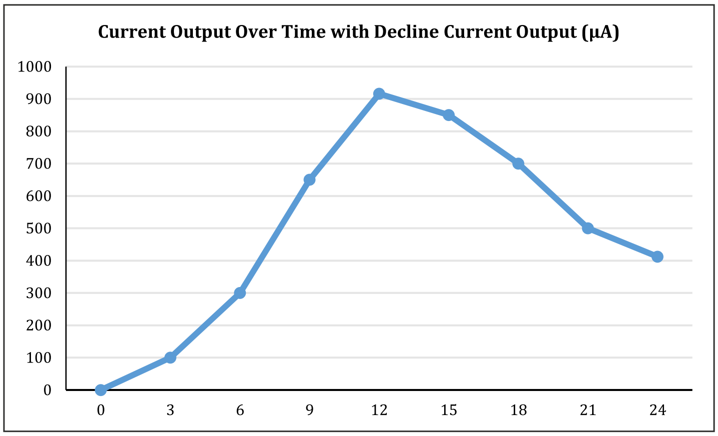

Figure 2: Current Output (µA) and Decline Pattern Over Time in Microbial Fuel Cell

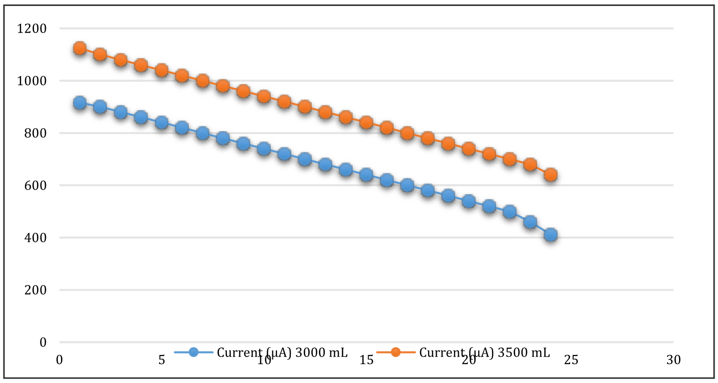

Figure 3: Current Production Growth curves of wastewater volumes

3.3. Physio-chemical parameters analysis

Before the MFC experiment, the pH of the collected wastewater was 7.7, but after the experiment, it reduced to 7.3 because the decrease in MFC-treated water pH was because of the movement of hydrogen ions to the cathode, which led to the decrease in pH of the wastewater that is present in the anode chamber [14]. TDS of the wastewater increased up to 1147 mg L^{-1} as its initial value was 790 mg/L. Similarly, EC increased up to 1304 µS/cm, and the EC value increased because TDS levels went up. This happened because microbes moved and decomposed organic and inorganic pollutants. At initial, COD of 291 mg/L was observed in municipal wastewater before the experiment, but after the experiment, it reduced to 134 mg/L because soluble compounds were degraded by microbes, which led to the decrease in COD [15]. MFCs can effectively degrade chemical oxygen demand (COD) and biological oxygen demand (BOD), with studies showing degradation rate constants of 0.048 and 0.069, respectively, when oxygen is supplied to the anode chamber [16].

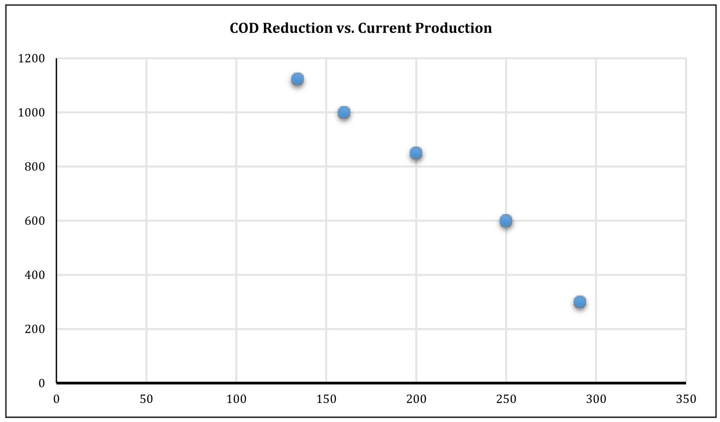

Figure 4: Impact of COD Reduction on Electricity Generation in MFCs

The findings from earlier research on dual-chamber microbial fuel cells (MFCs) are consistent with the observed decrease in COD and the expansion of TDS and EC. Wen-Wei et al. [15] showed significant COD decreases due to microbial degradation of organic matter, which is comparable to the 54% COD reduction in this study and suggests efficient pollutant breakdown within the MFC. Furthermore, Obileke et al. [14] found that the breakdown and ionisation of organic and inorganic components during the microbial metabolic process increased the wastewater's conductivity, which is compatible with the rise in TDS and EC.

MFCs can generate substantial power; for instance, a model projected a daily power generation of 50,515.16 kW from a municipal wastewater treatment plant, sufficient to support approximately 2,530 households [17]. The use of electrogenic microorganisms, including certain bacteria and fungi, has been shown to produce high power densities, enhancing the overall energy output of MFC systems[18].

According to Walter et al. [13], proton migration towards the cathode chamber during redox reactions has been demonstrated to contribute to a reduction in pH, which explains the pH drop from 7.7 to 7.3 caused by electrochemical processes within the MFC. The results of Ganjar et al. [7], who also noted higher current production by modifying substrate conditions in a dual-anode MFC, corroborate the current output of 1124 µA obtained in this work by optimising wastewater volume. These related results emphasise the MFC's potential as a renewable energy source and for treating wastewater, highlighting the importance of ideal operating conditions for improved MFC performance. While MFCs offer eco-friendly solutions, challenges such as high capital costs and energy density limitations must be addressed to improve scalability and cost-efficiency [19].

Overall, the findings show how well the microbial fuel cell (MFC) system works to produce a sustainable current output in addition to lowering wastewater contaminants. Along with variations in pH, TDS, and EC, the observed 54% decrease in COD demonstrates the MFC's potential as a wastewater treatment technique.

The current output further demonstrates MFCs' potential for producing renewable energy, peaking at 1124 μA under ideal circumstances. These results are in good agreement with earlier studies, confirming the optimisations used in this investigation and highlighting the significance of controlling the substrate and operational parameters. More sophisticated microbial consortiums and electrode materials may be investigated in future studies to improve the stability and efficiency of current output in MFCs.

Table Experiment Results before and after dual chamber experiment

Parameters	Before Experiment	After Experiment
pH	7.7	7.3
Total Dissolved Solids (TDS)	790 mg/L	1147 mg/L
Electrical Conductivity (EC)	820 μS/cm	1304 μS/cm
Chemical Oxygen Demand (COD)	291 mg/L	134 mg/L

4. Conclusions

This study demonstrates the efficacy of a two-chamber microbial fuel cell (MFC) in concurrently purifying municipal wastewater and producing electricity. The MFC, featuring an agarose gel-based proton exchange membrane, effectively reduced the chemical oxygen demand (COD) of the wastewater from 291 mg/L to 134 mg/L, indicating substantial decomposition of organic contaminants by the microbial community. Furthermore, the total dissolved solids (TDS) increased from 790 mg/L to 1147 mg/L, while the electrical conductivity (EC) rose from 790 μS/cm to 1304 μS/cm, suggesting the breakdown and subsequent ionisation of organic and inorganic substances. The wastewater's pH decreased from 7.7 to 7.3, presumably due to hydrogen ion migration towards the cathode during the MFC's electrochemical processes. The maximum current output recorded was 1124 μA, achieved through optimisation of wastewater volume and operational conditions. These results underscore the potential of MFCs as a viable technology for wastewater treatment and renewable energy production.Future studies should focus on enhancing various operational factors, including substrate types, concentrations, and cycle operations, to improve the performance and scalability of MFC systems. Investigating the catalytic properties of the cathodic microbial consortium and the role of the TCA cycle in the reduction process could further enhance MFC efficiency. This research establishes a foundation for the practical implementation of MFC technology in real-world wastewater treatment scenarios, contributing to the development of sustainable energy solutions.

Author Contributions

Z.E; writing—original draft preparation, experiments, and data analysis, T,& A; conceptualization, writing, review and editing,validation. All authors have read and agreed to the final version of the manuscript.

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