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Simultaneous Treatment of Catfish Pond Wastewater and Bioelectricity Generation Using a Double-Chamber Microbial Fuel Cell

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ABSTRACT

This study investigates the application of a double-chamber microbial fuel cell (MFC) for the simultaneous treatment of catfish pond wastewater and bioelectricity generation. Catfish pond effluent was used as the substrate and inoculated into the anodic chamber of the MFC, which was operated for a period of 120 hours under controlled pH conditions ranging from 5 to 9. Wastewater quality parameters, including chemical oxygen demand (COD), biochemical oxygen demand (BOD), dissolved oxygen (DO), and voltage output, were monitored at 24-hour intervals to evaluate treatment efficiency and electrical performance. The results demonstrated a progressive reduction in organic pollutant load with increasing operating time and pH. COD and BOD values decreased from initial concentrations of 296 mg/L and 270 mg/L to final values of 150 mg/L and 122 mg/L, respectively, indicating effective wastewater treatment within permissible discharge limits. Concurrently, bioelectricity generation was observed, with a maximum voltage output of 0.04 V recorded at near-neutral to slightly alkaline conditions (pH 8–9). The findings highlight the potential of microbial fuel cell technology as a low-cost, environmentally sustainable approach for treating fish pond wastewater while enabling energy recovery. This study supports the feasibility of integrating MFCs into decentralized wastewater treatment systems, particularly in developing regions where energy and environmental challenges coexist.

Keywords: Microbial fuel cell, Catfish Pond wastewater, Bioelectricity generation, Wastewater treatment, Organic matter removal, Renewable energy.

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1. INTRODUCTION

Global energy demand continues to rise as a result of rapid population growth, industrialization, and expanding urbanization, particularly in developing countries. At the same time, increasing environmental pollution and the depletion of fossil fuel reserves pose serious challenges to sustainable development [1–3]. Conventional energy sources remain dominant worldwide, yet their continued use is associated with greenhouse gas emissions, climate change, and ecological degradation [4,5]. Consequently, there is growing interest in renewable and sustainable energy technologies that can simultaneously address energy scarcity and environmental pollution.

Wastewater management represents one of the most energy-intensive sectors of modern infrastructure. It has been estimated that wastewater treatment accounts for approximately 3–4% of total electricity consumption in developed countries, with comparable trends emerging globally [6]. Paradoxically, wastewater itself contains a substantial amount of chemical energy stored in organic matter, which, if effectively recovered, could offset or even exceed the energy required for treatment [7,8]. This realization has driven research toward technologies capable of integrating wastewater treatment with energy recovery.

Among emerging bioelectrochemical technologies, microbial fuel cells (MFCs) have attracted significant attention due to their ability to convert chemical energy in organic substrates directly into electrical energy through the metabolic activities of microorganisms [9–11]. Unlike conventional bioenergy systems such as anaerobic digestion, MFCs generate electricity without intermediate energy conversion steps, making them attractive as low-temperature, low-emission systems [12]. In an MFC, electroactive microorganisms oxidize organic matter at the anode, releasing electrons and protons; the electrons flow through an external circuit to the cathode, generating electrical power, while protons migrate through a membrane or salt bridge to complete the electrochemical reaction [13–15]. Extensive studies have demonstrated the feasibility of MFCs for treating a wide range of waste streams, including domestic wastewater, industrial effluents, agricultural waste, and food-processing wastewater [16–19]. Reported benefits of MFC technology include reduction of chemical oxygen demand (COD) and biochemical oxygen demand (BOD), recovery of energy, reduced sludge production, and lower operational costs compared to conventional treatment systems [20–22]. However, despite these advantages, practical implementation of MFCs remains limited due to challenges such as low power density, high internal resistance, and sensitivity to operating conditions [23–25].

The performance of MFCs is strongly influenced by several operational parameters, including reactor configuration, electrode materials, microbial community structure, substrate type, pH, temperature, and ionic conductivity [26–28]. Among these factors, pH plays a critical role in microbial metabolism, proton transport, and overall electrochemical performance [29,30]. Deviations from optimal pH conditions can inhibit microbial activity, reduce electron transfer efficiency, and limit electricity generation [31]. Therefore, understanding the influence of pH and operational time on both wastewater treatment efficiency and bioelectricity generation is essential for optimizing MFC performance. Aquaculture wastewater, particularly fish pond effluent, represents a significant but underutilized waste stream with high organic content. Catfish pond effluent typically contains uneaten feed, fish excreta, suspended solids, and nutrients that can cause severe water pollution if discharged untreated into natural water bodies [32,33]. In Nigeria and other developing countries, inadequate wastewater management practices in aquaculture systems have contributed to eutrophication, depletion of dissolved oxygen, and deterioration of aquatic ecosystems [34,35]. Conventional treatment methods for fish pond wastewater are often costly and energy-intensive, limiting their adoption at small and medium scales.

Recent studies have explored the use of fishery and aquaculture wastewater as substrates for MFCs, demonstrating promising COD and BOD removal efficiencies alongside electricity generation [36–38]. These findings suggest that MFCs could serve as an environmentally friendly and economically viable solution for decentralized treatment of aquaculture effluents while enabling energy recovery. Nevertheless, research on the application of MFCs specifically for catfish pond wastewater, particularly under varying pH conditions and extended operational periods, remains limited.

Therefore, this study investigates the performance of a double-chamber microbial fuel cell for the simultaneous treatment of catfish pond wastewater and bioelectricity generation. The effects of operating time and pH variation on COD, BOD, dissolved oxygen, and voltage output were systematically evaluated over a 120-hour period. By integrating wastewater treatment with renewable energy recovery, this research aims to demonstrate the potential of microbial fuel cell technology as a low-cost, sustainable, and environmentally friendly solution for managing aquaculture effluents, particularly in resource-limited settings.

2. MATERIALS AND METHODS

2.1. Materials

Catfish pond wastewater (effluent) used as the substrate in this study was collected from a local fish farm located in Awka, Anambra State, Nigeria. The effluent primarily contained uneaten fish feed, fish excreta, fish scales, and suspended organic matter typically associated with intensive catfish aquaculture systems. The collected wastewater was transported to the laboratory in clean, airtight plastic containers and used without further pretreatment to preserve the indigenous microbial community. The major materials and reagents used in this study included a fabricated double-chamber microbial fuel cell (MFC), distilled water, potassium chloride (KCl), agar-agar powder, hydrochloric acid (HCl, 0.1 M), sodium hydroxide (NaOH, 0.1 M), and standard laboratory glassware. Analytical instruments included a calibrated pH meter, a digital multimeter for voltage measurement, and standard titration apparatus for wastewater characterization.

2.2. Microbial Fuel Cell Configuration

A laboratory-scale double-chamber microbial fuel cell was fabricated and used for this study. The MFC consisted of two separate chambers (anode and cathode compartments) connected by a salt bridge that served as the proton exchange medium. The anode chamber was designed to operate under anaerobic conditions, while the cathode chamber was exposed to atmospheric oxygen to serve as the terminal electron acceptor. No external microbial inoculum was introduced into the system, as the indigenous microorganisms present in the catfish pond wastewater served as the biocatalysts. The anode chamber was completely sealed after inoculation to prevent oxygen intrusion, thereby ensuring anaerobic conditions necessary for electrogenic microbial activity. The cathode chamber contained distilled water and was maintained under aerobic conditions throughout the experimental period. A schematic representation of the double-chamber microbial fuel cell used in this study is shown in **Figure 1** and the basic mechanism of electricity generation in microbial fuel cells is illustrated in **Figure 2.**

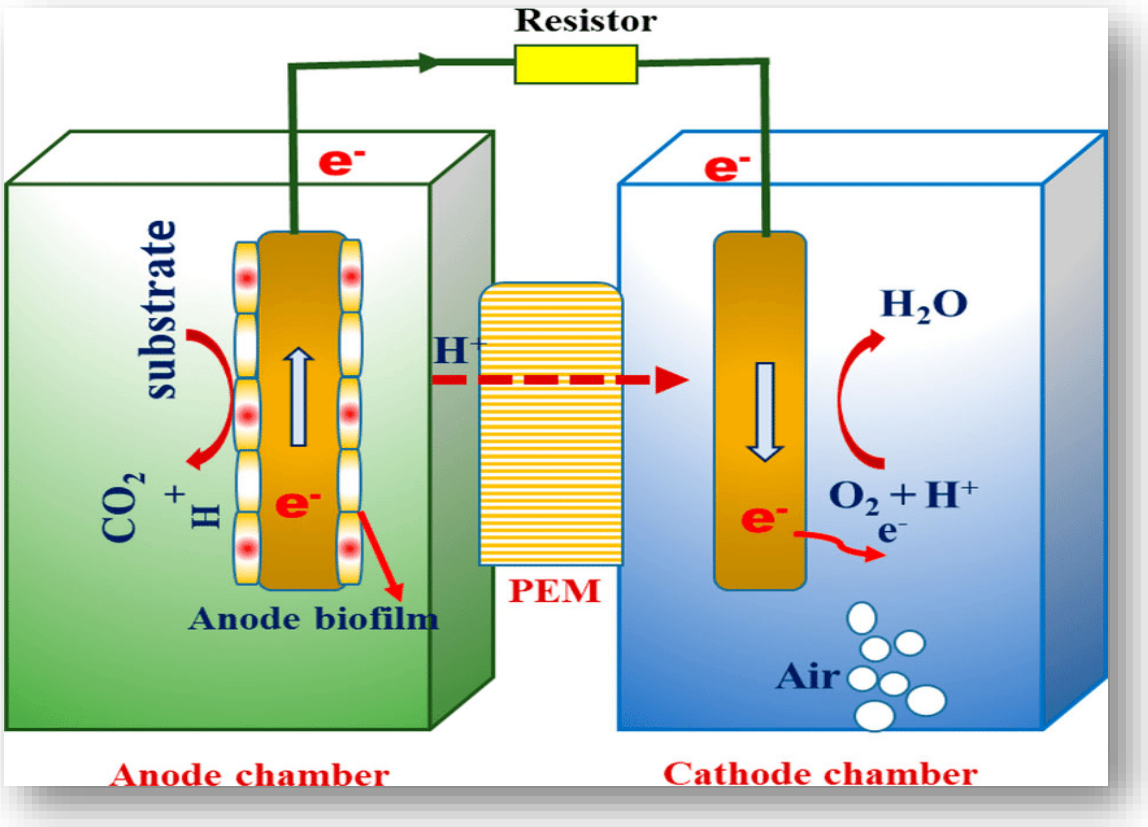


Figure 1. Schematic representation of the double-chamber microbial fuel cell used in this study, showing the anodic and cathodic compartments connected by a salt bridge. [39]

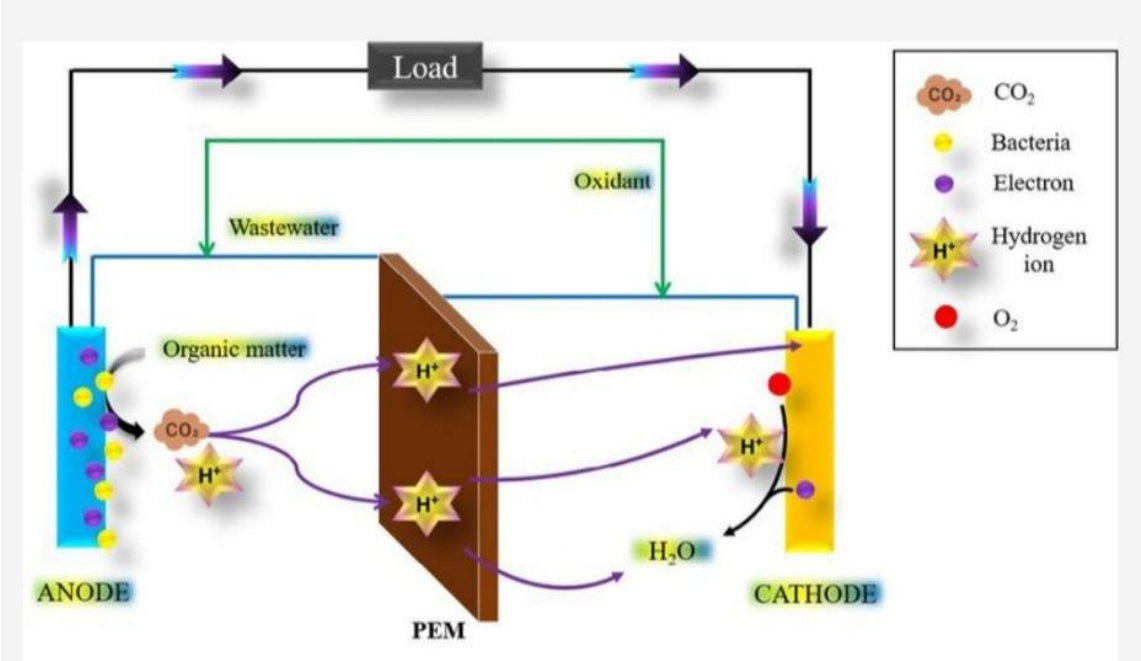


Figure 2. Schematic illustration of electron and proton transfer mechanisms responsible for electricity generation in a microbial fuel cell.

2.3. Preparation of the Salt Bridge

The salt bridge was prepared using a mixture of potassium chloride (KCl) and agar-agar as the gelling agent. Specifically, 50 g of KCl and 20 g of agar-agar were dissolved in 100 mL of distilled water. The mixture was heated to approximately 100 °C until complete dissolution was achieved and a homogeneous solution formed. The hot solution was immediately poured into a polyvinyl chloride (PVC) conduit of approximately 100 mm length and 50 mm internal diameter before cooling below 40 °C, at which point gelation occurs. The inner surface of the conduit was roughened to enhance adhesion between the gel and the pipe wall. The solidified salt bridge was used to connect the anode and cathode chambers, allowing proton transfer while preventing bulk fluid mixing between compartments.

2.4. Substrate Preparation and pH Adjustment

The collected catfish pond wastewater had an initial pH range of approximately 5–6. To evaluate the effect of pH on wastewater treatment efficiency and electricity generation, wastewater samples were adjusted to different pH values (5, 6, 7, 8, and 9) using standard solutions of 0.1 M HCl and 0.1 M NaOH. For each experimental run, 350 mL of the pH-adjusted wastewater sample was introduced into the anode chamber of the MFC. The cathode chamber was filled with distilled water. All experiments were conducted at ambient laboratory temperature.

2.5. MFC Operation and Experimental Procedure

The MFC was operated in batch mode for a total duration of 120 hours. Prior to formal data collection, the system was allowed to stabilize for approximately 24 hours to enable microbial acclimatization to the anode environment and substrate conditions. Samples were withdrawn from the anode chamber at 24-hour intervals (24, 48, 72, 96, and 120 hours). At each sampling interval, wastewater quality parameters, including pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD), and dissolved oxygen (DO) were analyzed. Simultaneously, electrical output in terms of voltage was measured across the external circuit using a digital multimeter.

2.6. Electrochemical Monitoring

Voltage generation from the microbial fuel cell was monitored using a calibrated digital multimeter connected across the anode and cathode electrodes through an external circuit. Voltage readings were recorded at each 24-hour sampling interval. The observed voltage output was used as an indicator of microbial electrochemical activity and electron transfer efficiency during substrate degradation. No external resistance optimization was applied, as the objective of this study was to evaluate baseline electricity generation during wastewater treatment rather than maximum power density.

2.7. Wastewater Characterization

2.7.1. Determination of Chemical Oxygen Demand (COD)

Chemical oxygen demand (COD) was determined using the standard dichromate reflux titration method. COD represents the amount of oxygen required to chemically oxidize organic matter present in the wastewater. The COD value was calculated using the expression:

$$\text{COD (mg/L)} = [(B-T) \times 0.025 \times 50{,}000] / 15 \qquad (1)$$

where B is the volume of titrant used for the blank and T is the volume of titrant used for the sample. COD values below 250 mg/L were considered acceptable for environmental discharge.

2.7.2. Determination of Dissolved Oxygen (DO)

Dissolved oxygen (DO) concentration was determined using the standard titrimetric method. DO indicates the amount of free oxygen available in the wastewater, which is essential for aerobic microbial processes and aquatic life. DO values greater than or equal to 5 mg/L were considered environmentally acceptable.

2.7.3. Determination of Biochemical Oxygen Demand (BOD)

Biochemical oxygen demand (BOD) was measured using the 5-day BOD test method. BOD represents the amount of oxygen consumed by microorganisms during the aerobic degradation of organic matter. The BOD value was calculated as:

$$BOD\ (mg/L) = (D_1 - D_5) / P \qquad (2)$$

where D_1 is the initial dissolved oxygen, D_5 is the dissolved oxygen after 5 days of incubation, and P is the dilution factor. BOD values below 150 mg/L were considered suitable for discharge.

2.7.4. Determination of pH

The pH of wastewater samples was measured using a calibrated digital pH meter. Measurements were taken by immersing the pH probe into a 250 mL aliquot of the wastewater sample after appropriate calibration using standard buffer solutions.

2.8. Data Analysis

Experimental results were recorded at each sampling interval and analyzed to assess trends in wastewater treatment efficiency and electricity generation over time. Graphical representations were used to illustrate the relationships between operating time, pH, COD, BOD, DO, and voltage output. All reported values correspond directly to the experimental data obtained from the MFC operation.

3. RESULTS AND DISCUSSION

3.1. Overall Performance of the Microbial Fuel Cell System

The performance of the double-chamber microbial fuel cell (MFC) was evaluated over a 120-hour operating period using catfish pond wastewater as the substrate. Key performance indicators included chemical oxygen demand (COD), biochemical oxygen demand (BOD), dissolved oxygen (DO), pH variation, and voltage output. These parameters collectively provide insight into the effectiveness of wastewater treatment and the associated bioelectrochemical energy recovery process. Overall, the results demonstrate a progressive improvement in wastewater quality accompanied by measurable electricity generation. This confirms the feasibility of integrating organic matter degradation and energy recovery within a single bioelectrochemical system, consistent with established microbial fuel cell theory [1–3].

Table 1. Summary of wastewater treatment and voltage generation performance of the microbial fuel cell over 120 hours.

Time (hr)	Chemical oxygen demand (COD) (mg/l)	Biological oxygen demand (BOD) (mg/l)	Dissolved oxygen (DO) (mg/l)	pH	Voltage
24	**296**	**270**	**45 -18**	**5**	**0.01**
48	**275**	**246**	**54 – 29.4**	**6**	**0.03**
72	**222**	**197**	**59.2 - 39.5**	**7**	**0.04**
96	**191**	**182**	**62 - 43.8**	**8**	**0.04**
120	**150**	**122**	**60 - 47.8**	**9**	**0.09**

3.2. Effect of Operating Time and pH on Wastewater Treatment Performance

3.2.1. pH Variation during MFC Operation

The variation of pH with operating time is shown in **Figure 3**. The pH increased steadily from an initial acidic condition (pH 5 at 24 h) to an alkaline condition (pH 9 at 120 h). This trend reflects the dynamic biochemical processes occurring within the anodic chamber. The gradual increase in pH can be attributed to the consumption of protons during microbial metabolism and electrochemical reactions at the cathode, as well as the degradation of organic acids present in the wastewater [4,5]. Similar pH shifts have been reported in MFC systems treating organic-rich wastewaters, where proton accumulation and transport limitations influence system performance [6]. Importantly, pH plays a critical role in microbial activity, enzyme stability, and electron transfer efficiency. Most electrogenic microorganisms exhibit optimal metabolic activity near neutral pH, while highly acidic or alkaline conditions may inhibit biofilm development and electron transport [7,8].

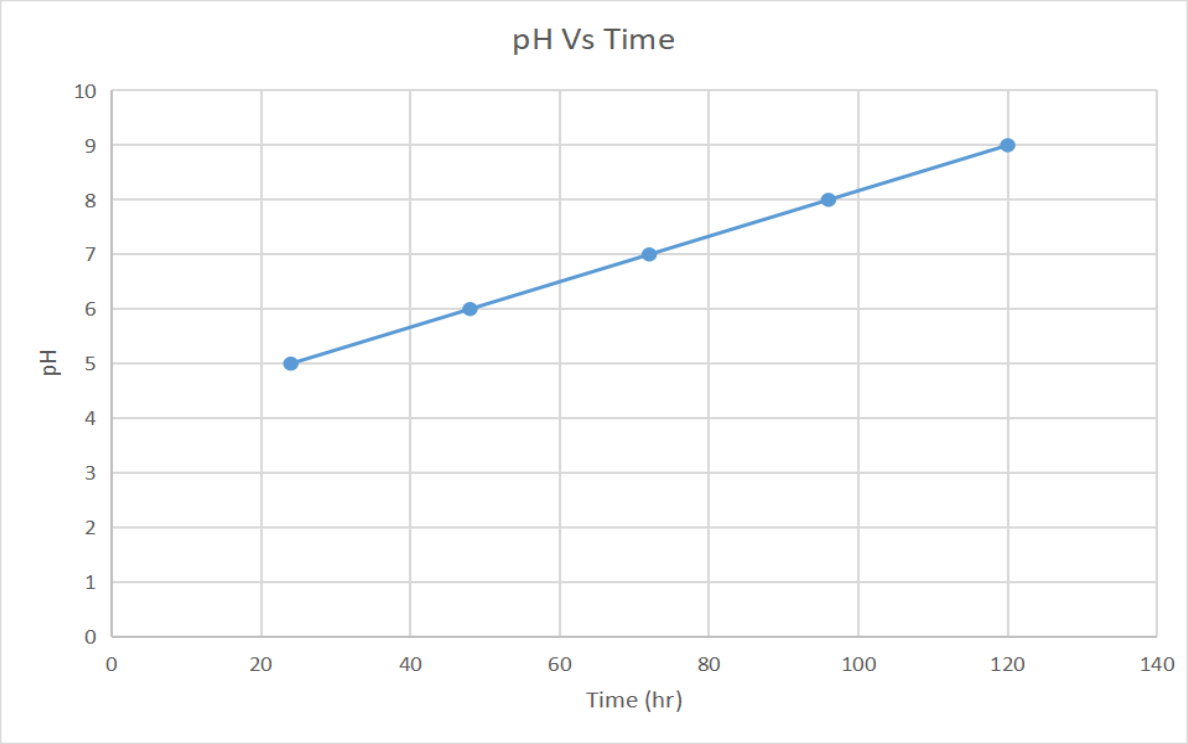


Figure 3. Variation of pH with operating time during microbial fuel cell operation.

3.3. Chemical Oxygen Demand (COD) Removal

The variation of COD with operating time is presented in **Figure 4**. COD values decreased from an initial concentration of 296 mg/L at 24 hours to 150 mg/L at 120 hours, representing a substantial reduction in organic pollutant load. The observed decrease in COD indicates effective oxidation of organic matter by electroactive microorganisms in the anode chamber. As microorganisms metabolize biodegradable compounds, electrons and protons are released, with electrons transferred to the anode and subsequently through the external circuit [9,10]. This simultaneous process of organic matter degradation and electron recovery is a defining feature of microbial fuel cell systems.

The highest COD removal efficiency was achieved at longer operating times and higher pH values, suggesting enhanced microbial adaptation and stabilization of the biofilm on the anode surface. Biofilm maturation improves electron transfer pathways, reduces internal resistance, and enhances substrate utilization efficiency [11,12]. The final COD value of 150 mg/L falls within acceptable discharge limits for wastewater, demonstrating the practical applicability of the MFC for catfish pond effluent treatment [13].

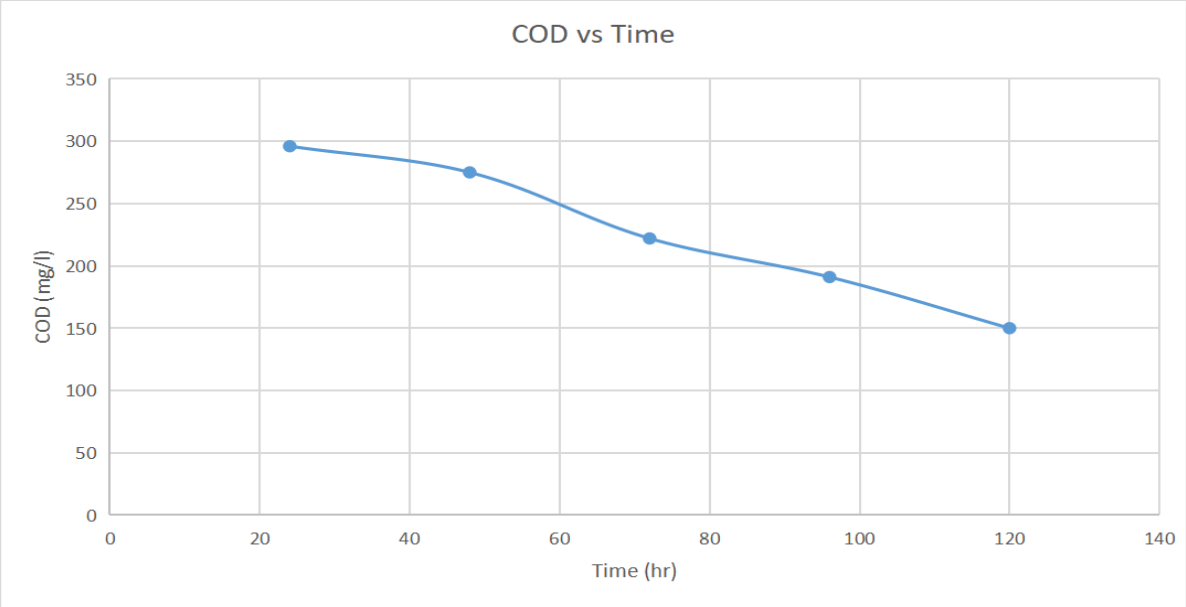


Figure 4. Variation of chemical oxygen demand (COD) with operating time.

3.4. Biochemical Oxygen Demand (BOD) Reduction

Figure 5 shows the comparison of initial and final COD and BOD concentration during microbial fuel cell treatment of catfish pond wastewater. **Figure 6** illustrates the variation of BOD with operating time. BOD values decreased from 270 mg/L at 24 hours to 122 mg/L at 120 hours, indicating effective biodegradation of organic matter. BOD reduction reflects the ability of microorganisms to aerobically and facultatively decompose biodegradable organic compounds. The decreasing trend observed confirms sustained microbial activity throughout the experimental period. Slight deviations observed between 72 and 96 hours may be attributed to microbial acclimatization to changing pH conditions and substrate composition [14]. The final BOD value of 122 mg/L meets environmental discharge standards, further confirming the effectiveness of the MFC as a wastewater treatment system. Comparable BOD removal efficiencies have been reported in MFC studies treating aquaculture and food-processing wastewater [15,16].

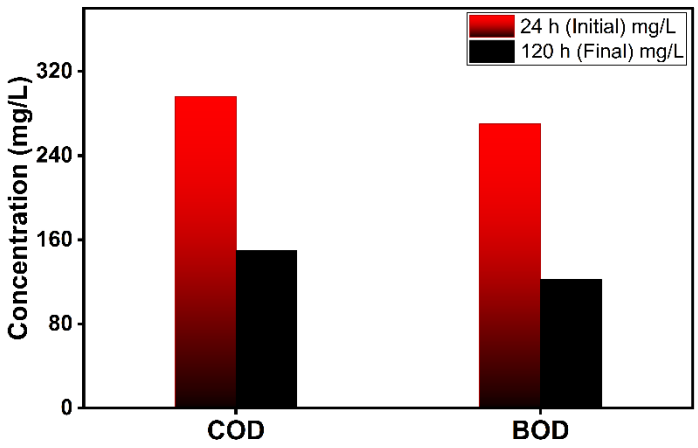


Figure 5. Comparison of initial (24 h) and final (120 h) COD and BOD concentrations during microbial fuel cell treatment of catfish pond wastewater.

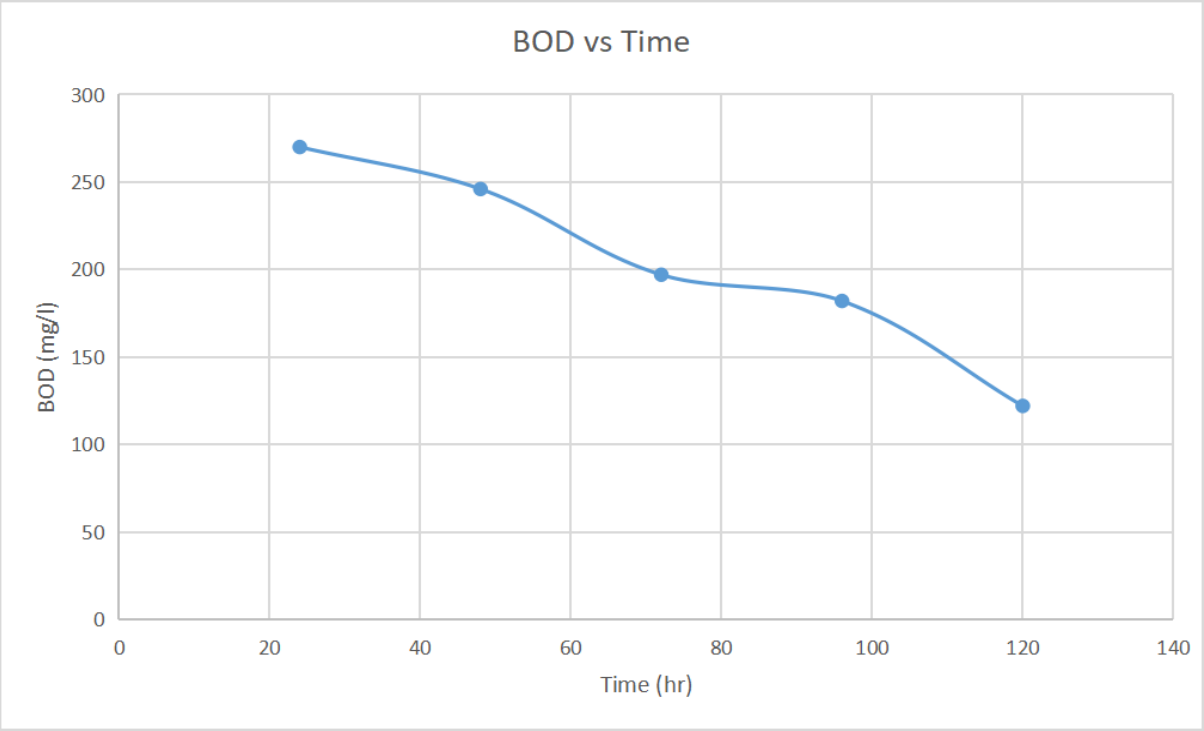
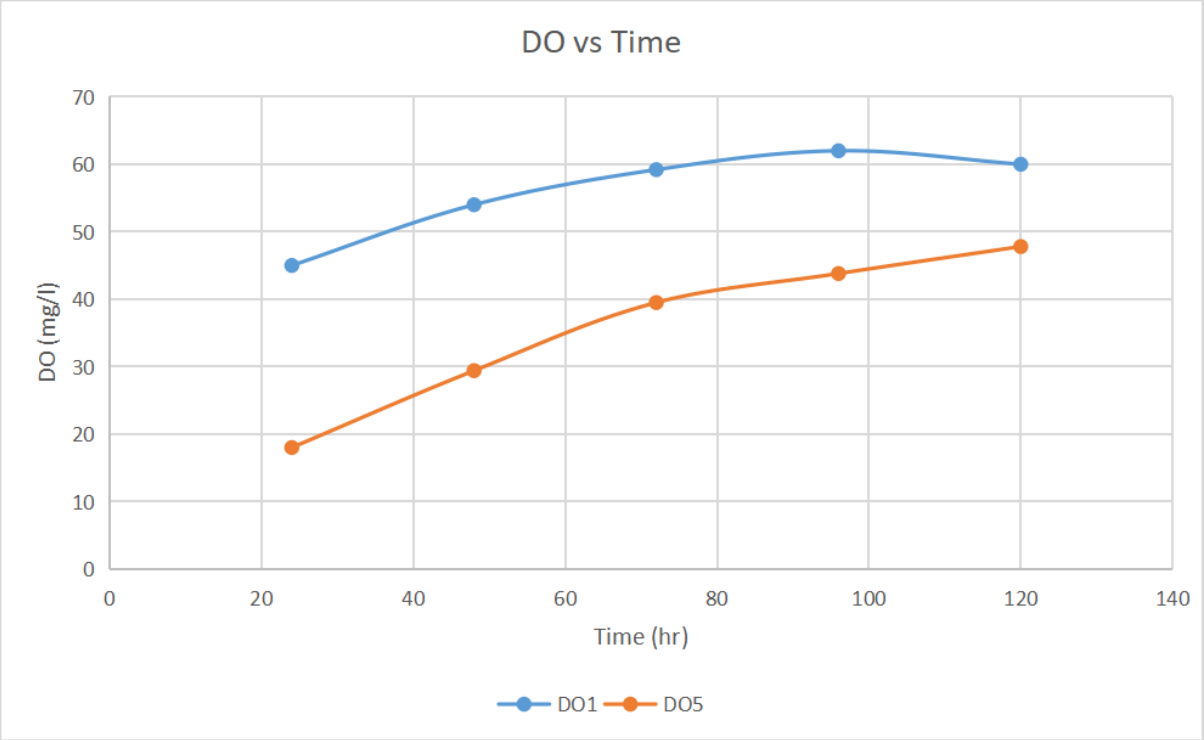


Figure 6. Variation of biochemical oxygen demand (BOD) with operating time.

3.5. Dissolved Oxygen (DO) Dynamics

The variation of dissolved oxygen (DO_1 and DO_5) with operating time is shown in **Figure 7**. DO_1 increased from 45 mg/L to approximately 60 mg/L over the course of the experiment, while DO_5 increased from 18 mg/L to 47.8 mg/L.

The increase in DO_1 suggests improved oxygen availability and system stabilization over time. This trend may be attributed to reduced oxygen demand as organic matter concentrations declined and microbial metabolism became more efficient [17]. The increase in DO_5 indicates improved oxygen balance during incubation, reflecting reduced biodegradable organic load. Dissolved oxygen is inversely related to BOD, and the observed DO increase corresponds with the declining BOD values reported in this study. Similar relationships between DO and BOD have been documented in previous wastewater treatment studies involving microbial fuel cells [18].



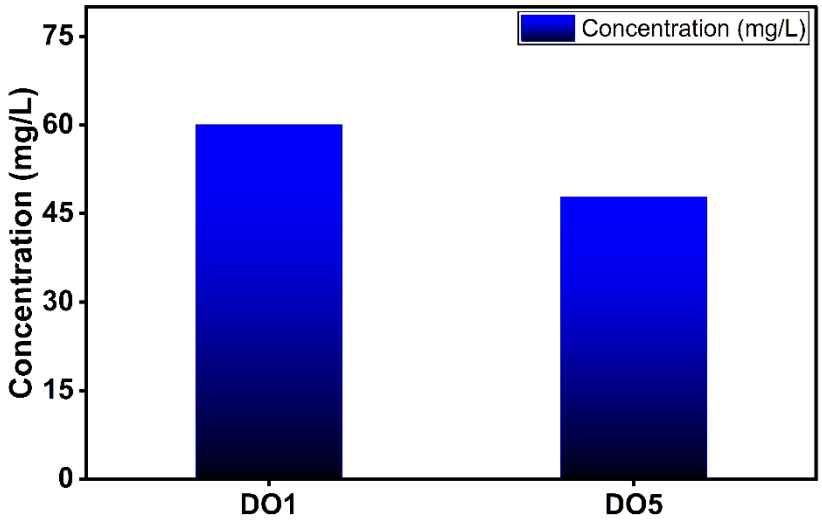


Figure 7. Variation of dissolved oxygen (DO) with operating time and comparison of initial (DO_1) and 5-day (DO_5) dissolved oxygen concentrations during microbial fuel cell operation.

3.6. Electricity Generation and Voltage Output

Figure 8 shows the variation of voltage output with operating time. The voltage increased from 0.01 V at 24 hours to a maximum of 0.04 V between 72 and 96 hours, followed by a decline to approximately 0.009 V at 120 hours.

The initial increase in voltage output can be attributed to microbial growth, biofilm formation, and enhanced electron transfer as microorganisms adapted to the anodic environment [19,20]. The stabilization of voltage between 72 and 96 hours suggests a balance between substrate availability and microbial population density. The subsequent decline in voltage at longer operating times is likely due to substrate depletion and reduced availability of biodegradable organic matter, leading to decreased electron production [21]. This behavior is characteristic of batch-operated MFC systems and has been widely reported in literature [22].

Although the voltage output recorded in this study is relatively low, it is important to emphasize that the primary objective of the system was wastewater treatment rather than power maximization. Low voltage output is common in laboratory-scale MFCs without external resistance optimization or advanced electrode materials [23].

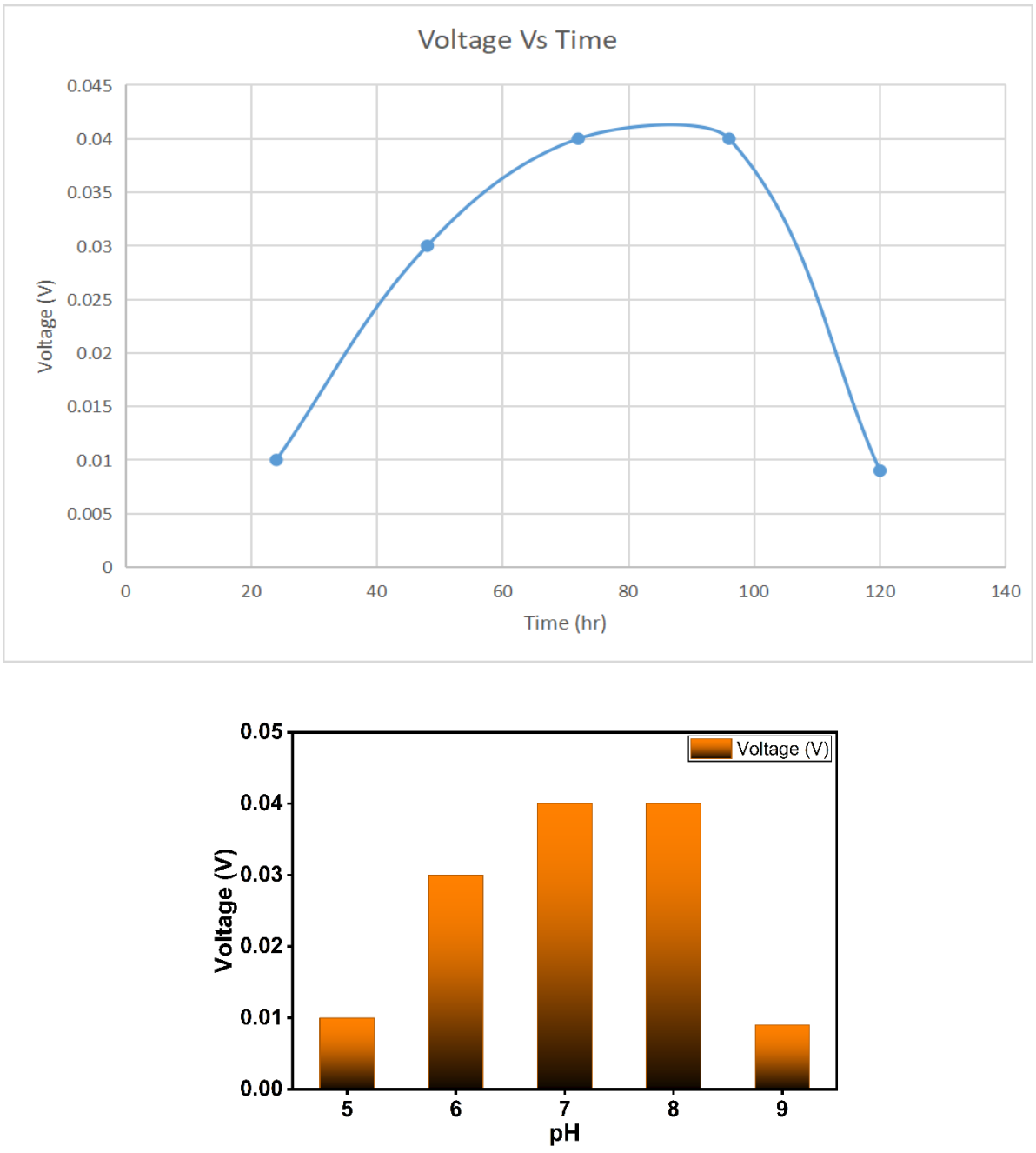


Figure 8. Variation of voltage output with operating time and Effect of pH on voltage generation in the microbial fuel cell.

3.7. Relationship between Wastewater Treatment and Electricity Generation

The simultaneous reduction of COD and BOD alongside measurable voltage generation confirms the direct link between organic matter degradation and electron recovery in the microbial fuel cell. As organic compounds are oxidized, electrons released during microbial metabolism are captured by the anode, generating electrical potential. The results of this study align with established bioelectrochemical principles, where electricity generation is proportional to the rate of substrate oxidation and microbial electron transfer efficiency [24,25]. The observed trends demonstrate that even low-strength aquaculture wastewater can serve as a viable substrate for MFC-based treatment systems.

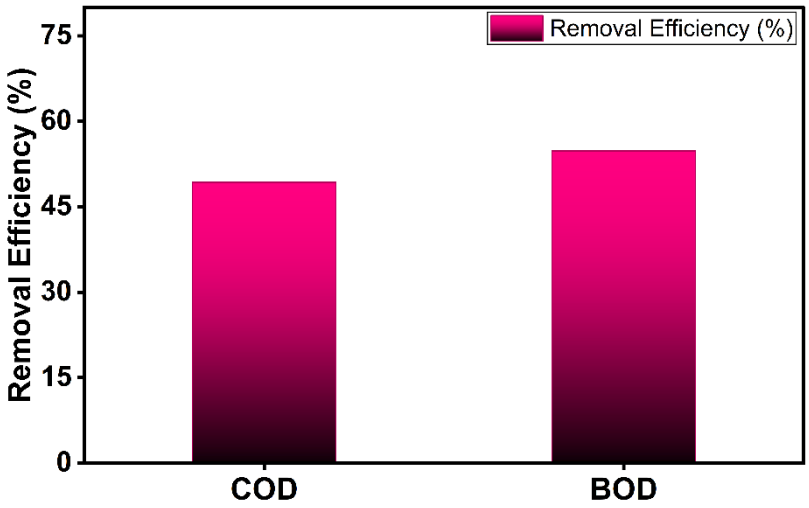


Figure 9. Percentage removal efficiency of COD and BOD during microbial fuel cell operation.

3.8. Scientific Significance and Practical Implications

The findings of this study demonstrate that microbial fuel cell technology can effectively treat catfish pond wastewater while simultaneously generating electricity. The system achieved acceptable COD and BOD reduction within a relatively short operating period, highlighting its potential for decentralized wastewater treatment in aquaculture settings. While the power output remains low, the primary advantage of the MFC lies in energy recovery rather than energy production. By offsetting part of the energy demand required for wastewater treatment, MFCs offer a sustainable and environmentally friendly alternative to conventional treatment technologies [26,27].

4. CONCLUSION AND RECOMMENDATIONS

4.1. Conclusion

This study investigated the performance of a double-chamber microbial fuel cell (MFC) for the simultaneous treatment of catfish pond wastewater and bioelectricity generation. The results demonstrate that microbial fuel cell technology is capable of effectively reducing organic pollutant load while recovering electrical energy from aquaculture effluent.

A progressive decrease in chemical oxygen demand (COD) and biochemical oxygen demand (BOD) was observed over the 120-hour operating period, with final values of 150 mg/L and 122 mg/L, respectively. These values fall within acceptable environmental discharge limits, confirming the treatment efficiency of the system. The variation of pH during operation significantly influenced microbial activity and system performance. Improved wastewater treatment and voltage generation were observed under near-neutral to slightly alkaline conditions, indicating favorable metabolic activity of electroactive microorganisms. The maximum voltage output of 0.04 V recorded during the study confirms the feasibility of energy recovery from catfish pond wastewater, although the power output remained relatively low due to the laboratory-scale configuration and absence of performance optimization measures.

Overall, the findings highlight the dual functionality of microbial fuel cells as both wastewater treatment units and energy recovery systems. While the electrical energy generated is modest, the primary benefit of the MFC lies in offsetting part of the energy demand required for wastewater treatment, thereby contributing to sustainable and environmentally friendly waste management practices. This technology presents a viable option for decentralized treatment of aquaculture effluents, particularly in developing regions where conventional treatment systems are often costly and energy-intensive.

4.2. Recommendations

Based on the outcomes of this study, further research is recommended to enhance MFC performance through optimization of electrode materials, external resistance, and reactor configuration. Long-term operation studies and scaling-up investigations are also necessary to evaluate the practical applicability of MFCs in real aquaculture systems. Additionally, future studies should explore power density, coulombic efficiency, and economic feasibility to strengthen the potential for commercial implementation of microbial fuel cell technology in wastewater treatment and renewable energy recovery.

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