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Mine Wastewater Bioremediation and Bioelectricity Generation Potential of a Microbial Fuel Cell Utilizing Bacillus licheniformis

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Abstract: *This study explores the feasibility of a low-cost Microbial Fuel Cell (MFC) system employing Bacillus licheniformis for simultaneous bioremediation of cadmium (Cd) from mine wastewater and bioelectricity generation. The investigation focuses on the influence of various operational parameters (temperature, pH, contact time) on MFC performance and Cd removal efficiency. B. licheniformis achieved a maximum Cd reduction of 50% under optimized conditions (27°C, pH 6.55) at week 4, as quantified by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Dissolved oxygen (DO) levels exhibited a temporal decrease, indicative of bacterial consumption for metabolic activity. Bioremediation efficiency demonstrated a positive correlation with contact time. While bioelectricity generation increased over time, the maximum open-circuit voltage attained was 982.33 mV. This research demonstrates the potential and offers a cost-effective solution by simultaneously removing Cd and generating bioelectricity, promoting waste treatment with renewable energy production. Further optimization is required to enhance bioelectricity output.*

Keywords: Microbial Fuel Cell; Bioelectricity; Cadmium Bioremediation; Bacillus licheniformis; Mine Wastewater

1. INTRODUCTION

The escalating global demand for mine products has led to an increase in mine wastewater generation, presenting a critical environmental challenge [1]. Cadmium (Cd) contamination in mine wastewater poses a significant environmental and human health threat due to its high toxicity, persistence, and bioaccumulation potential [2]. Traditional remediation methods, such as precipitation, adsorption, and ion exchange, are often expensive and generate secondary waste streams [3]. Developing efficient, sustainable, and cost-effective technologies for Cd bioremediation in mine wastewater is critical [4]. Microbial fuel cells (MFCs) have emerged as a promising technology for addressing environmental challenges associated with wastewater treatment [5]. These bioelectrochemical systems harness the metabolic activity of electroactive bacteria to convert organic pollutants in wastewater into bioelectricity through anaerobic respiration [6]. Recent advancements in MFC design and operational strategies aim to reduce construction and maintenance costs while enhancing power production efficiency [7]. Optimizing MFCs holds significant potential for the development of a sustainable and cost-effective solution for wastewater treatment, bioremediation, and bio-electricity generation [4].

MFCs represent a bioelectrochemical technology that harnesses the metabolic activity of microorganisms to convert organic matter in wastewater into bioelectricity through a process known as anaerobic respiration [8]. A crucial component of an MFC is the electroactive bacteria, often referred to as exoelectrogens. These bacteria act as biocatalysts within the anode chamber, degrading organic matter and releasing electrons and protons through the oxidation process [4].

A key feature of MFCs is the phenomenon of extracellular electron transfer (EET) [9]. Electrons produced by exoelectrogens are transferred from the biofilm on the anode to the anode surface itself. These electrons then travel through the external circuit to the cathode chamber. Meanwhile, protons generated during the oxidation process migrate through a selective

membrane separator towards the cathode chamber, completing the electrical circuit within the MFC system [10]. The half-cell reactions occurring at the anode and cathode can be summarized by the following equations:

Anode (Oxidation) [10]:

$$\text{Organic matter} + H_2O \rightarrow CO_2 + H^+ + e^- \quad (1)$$

Cathode (Reduction):

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (2)$$

The successful transfer of electrons and protons across the MFC components generates a measurable electrical current. This bioelectrochemical process holds significant potential for wastewater treatment, as it allows for the simultaneous conversion of pollutants into bioelectricity while achieving bioremediation objectives [11].

Bacillus licheniformis, a metal-tolerant bacterium commonly found in soil environments [12], exhibits potential for Cd bioremediation due to its cell wall properties and ability to biosorb heavy metals [11].

The general objective of this study is to design, develop, and characterize a low-cost MFC system employing B. licheniformis for the simultaneous and efficient removal of Cd from mine wastewater while generating bioelectricity. Specifically, the study aims to: design and develop an MFC system optimized for Cd bioremediation and bioelectricity production from mine wastewater; evaluate the system's efficacy in reducing Cd from mine wastewater by monitoring Cd concentration changes over time; and measure and analyze the electrical output and power generation of the MFC component.

This research presents a promising approach to address two pressing environmental issues: heavy metal contamination and energy generation. While the

individual components of the study - MFCs for bioelectricity generation and microbial bioremediation of heavy metals - are well-established, the combination of these technologies in a single system for the specific application of mine wastewater treatment is a novel approach. The integration of Cd bioremediation and bioelectricity production within a single MFC system is innovative and offers potential synergies between the two processes. While MFCs have been employed for heavy metal removal, the use of B. licheniformis for Cd bioremediation in an MFC context is relatively unexplored. If the bacterium exhibits high efficiency in Cd removal and bioelectricity generation, this could be a significant contribution to the field. Mine wastewater is a challenging environment due to its complex composition and high metal concentrations. Applying the MFC system to this specific wastewater type adds to the research's novelty.

This research is expected to contribute to the development of sustainable and cost-effective MFC systems for Cd bioremediation in mine wastewater treatment. Successful implementation of this technology can promote resource recovery (bioelectricity) while mitigating environmental pollution and protecting ecosystems and human health.

2. METHODOLOGY

2.1 Materials

This research employed a two-chambered MFC system for investigating cadmium (Cd) bioremediation in mine wastewater while generating bioelectricity. The MFC design incorporated two identical 5-liter polycarbonate containers as the anode and cathode chambers. A Nafion 117 proton exchange membrane (PEM) separated these chambers, enabling selective proton transfer while maintaining solution separation [13]. Stainless steel mesh electrodes were chosen for both the anode and cathode due to their high electrical conductivity and inoxidizability, crucial properties for efficient electron transfer in the MFC [14]. The electrodes were connected to an external circuit using copper wires with a predetermined resistance of 2000 Ω to complete the electrical pathway and facilitate current flow for power generation. For the biological component of the system, Bacillus licheniformis, obtained from the Biology Laboratory of Caraga State University, was used to drive bioremediation within the MFC. Standard microbiological media and culturing equipment were employed to maintain the culture and prepare an inoculum for MFC inoculation.

2.2 Microbial Fuel Cell Design

A two-chambered MFC system was designed for this study (Fig. 1). The anode chamber housed a stainless-steel mesh working electrode and 5 liters of pre-characterized mine wastewater. For the experimental setup, the wastewater was inoculated with 10 grams of Bacillus licheniformis to promote biodegradation. A nutrient solution (25 g sucrose, 10 g corn starch) was added to support bacterial growth. The cathode chamber contained a stainless-steel mesh counter electrode and a 5-liter $KMnO_4$ solution (catholyte) for electron acceptance. A Nafion 117 PEM separated the chambers, while the PEM bridge solution (500 mL distilled water, 14 g NaCl, 33.3 g nutrient agar) facilitated proton transfer and minimized solution mixing.

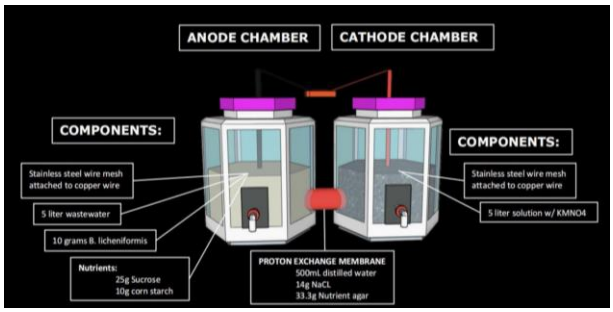

Fig. 1. MFC Design for Experimental Setup

The control MFC setup (Fig. 2) was identical, except for the absence of Bacillus licheniformis in the anode chamber. This allowed for comparison of bioremediation efficiency between the experimental and control conditions. Both setups maintained the same configuration of stainless-steel mesh electrodes, $KMnO_4$ catholyte, and PEM bridge solution.

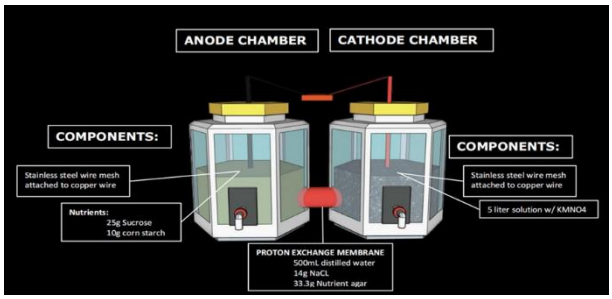

Fig. 2. MFC Design for Control Setup

2.3 Isolation and Purification of Putative Bacillus licheniformis Strains

A three-way streaking method was employed on two selective media: de Man, Rogosa and Sharpe (MRS) agar and Calcium Carbonate Agar (CCA). Additionally, a sterile control plate was included to monitor for potential contamination. Prior to inoculation, all materials were sterilized in an autoclave at 121°C and 15 psi for 30 minutes. After cooling, the sterilized materials were transferred to a biosafety cabinet disinfected with 70% ethanol and Lysol, followed by UV irradiation for 20 minutes to maintain a sterile environment. Approximately 25 mL of each media (MRS and CCA) were poured into separate petri dishes to create solidified plates for streaking. A loopful of the inoculum was then streaked onto each plate using the three-way streaking method to isolate colonies. The inoculated plates were incubated anaerobically within a sealed candle jar for 48-72 hours to promote the growth of acid-producing bacteria. Eighteen isolated colonies from each plate were selected for further purification through repeated streaking. Single colonies were aseptically transferred using an inoculating loop. The isolated strains were then purified and characterized based on their morphological, biochemical, and molecular characteristics. This process ensured the development of pure cultures of Bacillus licheniformis strains suitable for further experimentation [15].

2.4 Culture Preparation for Bacillus licheniformis

B. licheniformis cultures were then prepared. 5 mL of MRS broth were added to a test tube and sterilized in an autoclave at 121°C for 15 minutes. Bacteria were then inoculated from either a previously stored glycerol stock at 80°C or a slant culture. The inoculated tubes were incubated at 37°C for 24 hours. After incubation, a 2% (v/v) aliquot of the culture was transferred to fresh MRS broth and incubated again at 37°C for 24 hours. This step was repeated once more. Finally, another 2% (v/v) aliquot of the culture was inoculated into fresh broth and incubated at 37°C for 18 hours. This procedure ensured a healthy and active bacterial culture for further use.

2.5 Mine Wastewater Sample Collection

Grab sampling was employed as the initial method for water collection. Sterilized containers with a capacity of 40 liters were used to collect mine wastewater samples directly from the sampling site. The containers were submerged below the water surface and allowed to fill completely, minimizing air entrapment to maintain sample integrity. To account for potential spatial variations within the water body and ensure representativeness, multiple grab samples were collected from various locations. Following collection, the samples were stored at low temperatures to minimize changes in their chemical and microbial composition until subsequent analyses.

2.6 MFC Construction and Operation

Two clear polycarbonate plastic containers served as the anode and cathode chambers. Sterilized holes were drilled in the lids of both containers to accommodate copper wires, electrodes, and a PEM for gas exchange.

Within the anode chamber, a stainless-steel mesh electrode was connected to an external copper wire using soldering. The cathode chamber was similarly equipped with a stainless-steel mesh cathode and a copper wire connection. The cathode chamber solution consisted of 5L water containing 1.5 grams per liter of $KMnO_4$.

To separate the chambers while allowing for proton transfer, a PEM was inserted. A pre-cooled agar solution (14 g nutrient agar and 33.3 g NaCl dissolved in 500 mL distilled water) was solidified within a 6-inch long and 4-inch diameter PVC pipe to create this barrier [16]. The MFC was then sealed by firmly closing the lids with the electrodes, wires, and PEM in place. The external circuit was completed by connecting the free ends of the anode and cathode wires, enabling the measurement of the MFC's electrical output.

The anode chamber served as the site for microbial degradation of organic matter. It contained 5L of mine wastewater inoculated with 10 g of Licheniformis bacteria. Additionally, a nutrient solution (25 g sucrose and 10 g cornstarch) was added to support bacterial growth and organic matter breakdown. The cathode chamber, where oxygen reduction occurs, contained 5 L of distilled water and 7.5 g of $KMnO_4$.

This design facilitates the transfer of electrons from the degrading organic matter in the anode to the cathode compartment through the external circuit. Protons generated during the anode reaction are transported through the PEM to the cathode, while carbon dioxide, a byproduct of microbial respiration, is released to the environment. The PEM also prevents oxygen diffusion into the anode chamber, maintaining anaerobic conditions for optimal bacterial activity.

2.7 MFC Performance Monitoring

The performance of the MFC was monitored by measuring the voltage and current generated over time. A multimeter was connected to the external circuit of the MFC, and readings were recorded at regular intervals. Typically, six measurements were taken every 24 hours to capture the temporal dynamics of the MFC's electrical output.

According to Ohm's law, the current (I=V/R) and the power output (P=VI) were calculated using the external resistance R and the measured voltage V. The power density P_{an} (mW/m^2) was normalized to the anodic surface area following the equation below:

$$P_{an} = \frac{V^2}{A_{an}R} \quad (3)$$

Where, V is the measured voltage (mV), A_{an} is the anode surface area (cm^2), and R is the external resistance (Ω) [10]. This continuous monitoring allowed for the assessment of the low-cost MFC's effectiveness in generating electricity.

2.8 Wastewater Characterization

Physicochemical parameters of the wastewater samples were analyzed using a HANA HI-9819 Multi Water Quality Meter. This analysis included measurements of pH, dissolved oxygen (DO), and temperature. The measured values were then compared to the regulatory effluent thresholds established in DAO 2016-08 to assess the wastewater's compliance with environmental regulations [17].

2.9 Heavy Metal Analysis and Treatment Efficiency Evaluation

Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) was employed to quantify the concentration of heavy metals, particularly cadmium (Cd), in the collected mine wastewater samples [18].

Treatment effectiveness in removing Cd was assessed by comparing the initial and final wastewater concentrations. The reduction efficiency (RE) was calculated using the following equation [19]:

$$RE\ (\%) = [(C_{initial} - C_{final}) / C_{initial}] \times 100 \quad (4)$$

where: $C_{initial}$ and C_{final} represent the initial and final Cd concentrations in the wastewater, respectively. This formula calculates the percentage reduction in Cd concentration achieved through the treatment process.

3. RESULTS AND DISCUSSION

This study evaluated the efficacy of a Bacillus licheniformis-based MFC system for the bioremediation of Cd from mine wastewater, while concurrently generating bioelectricity. Key parameters monitored throughout the experiment included pH, temperature, dissolved oxygen (DO), contact time, turbidity, and bioelectric output (voltage).

Table 1 summarizes the changes in key operational parameters (pH, temperature, DO), along with their corresponding effects on Cd concentration and reduction efficiency over a four-week experiment using a B.

licheniformis-based MFC for Cd bioremediation from mine wastewater.

Table 1. Influence of Operational Parameters on Cadmium (Cd) Bioremediation in Bacillus licheniformis-based MFC System

Contact Time (Week)	0	1	2	3	4
pH	8.39	8.19	7.96	7.56	6.55
Temperature (°C)	26.94	26.82	27.18	27.22	28.27
DO (%)	38.77	37.75	35.96	36.70	30.73
DO (ppm)	5.36	5.06	4.85	3.42	1.69
Cd Concentration (ppm)	0.02	0.019	0.018	0.015	0.01
Cd Reduction Efficiency (%)	-	5.0	10.0	25.0	50.0

3.1 Influence of pH on Cd Reduction

Monitoring throughout the experiment revealed fluctuations in pH, as shown in Fig. 3, likely due to microbial activity and the release of organic acids. The ANOVA test indicates a significant effect of the group on pH ($F(371.090) = 1.184$, $p < 0.000$). The pH values decreased over time since Week 1, Week 2, Week 3, and Week 4 all have significantly higher pH values compared to Week Initial, with p-values of 0.010, 0.000, 0.000, and 0.000 respectively. Week 3 and Week 4 have a significantly higher pH value compared to Week 2, with p-values of 0.000. The differences between weeks are not significant, as all the p-values are above 0.05. The maximum reduction efficiency was in Week 4 at pH 6.55 with 50% Cd reduction. These findings suggest that near-neutral pH conditions might be more favorable for Cd bioremediation, potentially due to enhanced biosorption by Bacillus licheniformis [12]. At near-neutral pH, both the bacterial cell wall and Cd ions may have a net negative charge. Opposite charges create electrostatic attraction, facilitating the binding of Cd to the bacteria [20].

3.2 Influence of Temperature on Cd Reduction

The results revealed an optimal temperature range for Cd reduction, with peak efficiencies of 25% and 50% achieved at 28.27°C in Weeks 3 and 4, respectively (Table 1, Fig. 4). This aligns with the established principle that moderate temperature increases enhance microbial growth, metabolism, and enzyme activity, leading to faster bioremediation [21]. Within a moderate temperature range (generally between 25-40°C), increasing temperature can stimulate bacterial growth of B. licheniformis. This translates to a larger population of bacteria available for Cd removal through biosorption and potentially enzymatic mechanisms [22]. Some enzymes involved in Cd bioremediation by B. licheniformis might exhibit increased activity within a specific moderate temperature range. These enzymes could play a role in Cd detoxification or efflux (removal from cells), potentially enhancing overall bioremediation efficiency [23].

3.3 Influence of Dissolved Oxygen on Cd Reduction

This study monitored DO levels to assess the impact of oxygen availability on the performance of the Bacillus licheniformis-based MFC system. Statistical analysis (ANOVA) revealed a significant effect of treatment groups on DO ($F(4,143.244) = 21.394$, $p < 0.001$). Notably, DO concentrations decreased over time (Fig. 5), suggesting microbial consumption for metabolic processes and organic matter decomposition [24]. These findings necessitate further investigation to elucidate the interplay between DO levels, bacterial activity, Cd removal efficiency, and MFC electricity generation.

3.4 Influence of Contact Time on Cd Reduction

The findings demonstrate that a longer contact time significantly enhanced Cd removal (Fig. 6). Week 4 exhibited a significantly lower Cd concentration compared to Weeks 1, 2, and 3 ($p < 0.001$), indicating increased Cd uptake over time. In contrast, no significant differences were observed between Weeks 1, 2, and 3 ($p > 0.05$). These results align with established principles in biosorption, where extended contact time allows for improved interaction and binding between the biosorbent and the target metal [25]. This suggests that optimizing contact time within the MFC system could be a strategy to improve Cd bioremediation efficiency.

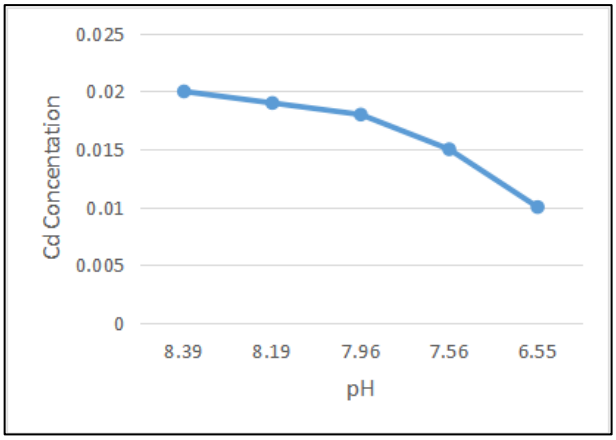

Fig. 3. The influence of pH in Cd reduction in mine wastewater

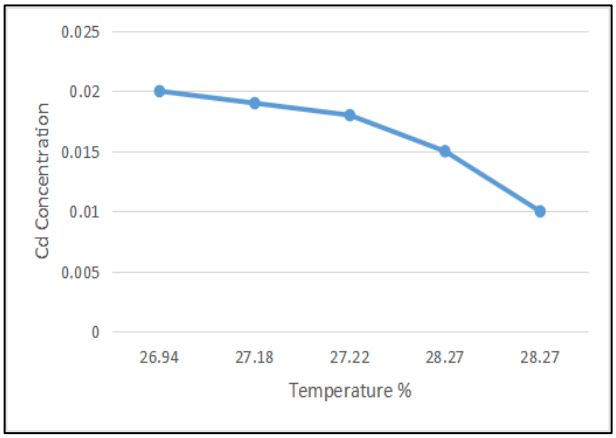

Fig. 4. The influence of temperature in Cd reduction in mine wastewater

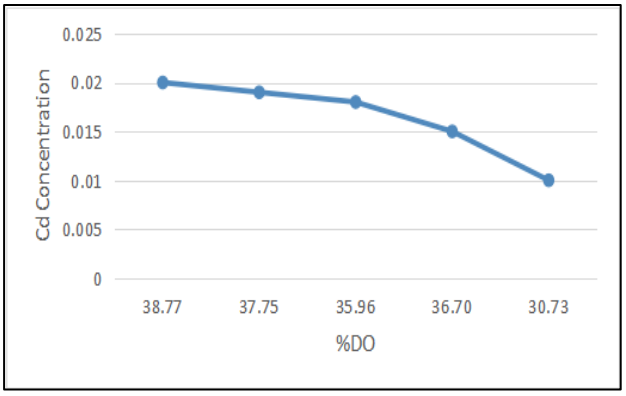

Fig. 5. Influence of dissolved oxygen (DO) in Cd bioremediation in mine wastewater

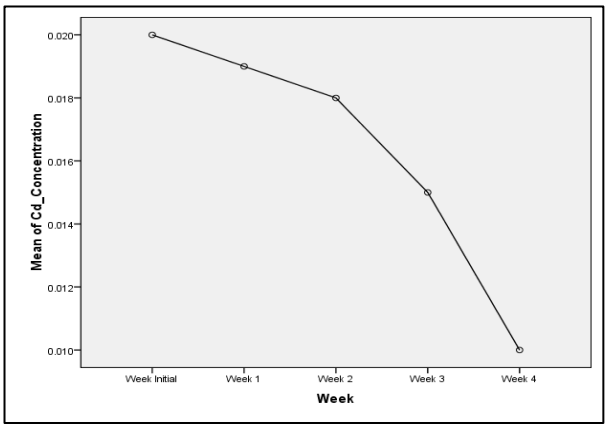

Fig. 5. The influence of contact time in Cd bioremediation of mine wastewater

3.5 Bacterial Growth Monitoring using Turbidity

Table 2. Turbidity/Absorbance Level (A) Measured Over Four Weeks in Bacillus licheniformis Cultures

Week	Turbidity /Absorbance Level (A)	
	Experimental Setup	Control Setup
0	0.750	1.260
1	0.885	1.356
2	1.105	1.534
3	1.301	1.69
4	1.918	3.156

Table 3. Statistical comparison of the Turbidity Level for Control and Experimental Group

	Turbidity	
	Control Setup	Experimental Setup
N	15	15
Mean	1.7684	1.1686
t-value	3.093	
p-value	0.004	
Interpretation	There is significant difference	

Turbidity measurements using the UV-Vis spectrophotometer were employed to monitor the growth of Bacillus licheniformis within the MFC system. This non-invasive technique offers a rapid means to assess bacterial populations [26]. Table 2 presents the turbidity/absorbance level (A) measured in both the experimental and control setups over a four-week period. The data allows for a comparison of bacterial growth patterns in the presence and absence of cadmium bioremediation processes in the MFC system.

The observed increase in turbidity over time indicates a progressive growth of the bacterial culture. Statistical analysis (independent samples t-test) revealed a significant difference in turbidity between the control and experimental groups ($t(28) = 3.093$, $p = 0.004$), with the control group exhibiting higher turbidity (mean = 1.77) compared to the experimental group (mean = 1.17). This suggests that the presence of heavy metals in the untreated control group might have contributed to the higher turbidity, while the experimental group potentially experienced a reduction in heavy metals due to bioremediation processes.

3.6 Bioelectricity Generation in the MFC System

This study investigated the potential of B. licheniformis for bioelectricity generation within the MFC system for Cd bioremediation from mine wastewater. Based on the data in Table 4, both the control and experimental setups exhibited an increase in average voltage generation (mV) over the four weeks. This suggests an improvement in the overall performance of the MFC systems over time, possibly due to several factors. As Bacillus licheniformis grows and colonizes the MFC electrodes, a denser biofilm can form, facilitating more efficient electron transfer and thus, higher electricity generation [6] [11]. The bacteria might be undergoing acclimation to the MFC environment, potentially optimizing their metabolic processes for improved power generation [27]. While the statistical analysis (t-test) in Table 5, did not reveal a significant difference in bioelectricity between the experimental and control groups ($p > 0.05$), the findings highlight the potential of the MFC system for sustainable wastewater treatment with bioremediation and electricity generation as co-benefits [28]. Further research is warranted to optimize MFC performance and enhance bio-electricity generation.

Table 4. Voltage Generation (mV) in the MFC System (Experimental and Control Setups) over Four Weeks

Week	Average Voltage Generated (mV)	
	Control Setup	Experimental Setup
1	752	747.5
2	814.1666667	825.6666667
3	866.1666667	862.8333333
4	944.1666667	982.3333333

Table 5. Statistical comparison of the Voltage Generation (mV) in the MFC System (Experimental and Control Setups)

	Bioelectricity Generation	
	Control Setup	Experimental Setup
N	180	180
Mean	816.1000	825.0722
t-value	-1.314	
p-value	0.190	
Interpretation	No significant difference	

4. CONCLUSION

This study explored the potential of a low-cost B. licheniformis-based MFC system for the concurrent bioremediation of Cd from mine wastewater and bio-electricity generation. The research methodology encompassed various aspects of MFC design, bacterial isolation, wastewater analysis, and treatment effectiveness evaluation.

The results revealed that several parameters influenced MFC performance and Cd removal efficiency. Notably, pH fluctuations and temperature variations impacted Cd reduction rates, highlighting the importance of optimized operating conditions. Beyond the influence of pH on Cd removal, it's crucial to consider its impact on microbial community structure and metabolism. Studies have shown that specific pH ranges can favor the growth of certain microbial species, which may have implications for both Cd bioremediation and electricity generation [29]. Temperature can affect not only microbial growth but also the solubility of Cd and the kinetics of biogeochemical reactions. A broader temperature range could be explored in future studies to optimize system performance [30]. Dissolved oxygen levels decreased throughout the experiment, indicating its consumption by bacteria for metabolic processes. The role of DO in the MFC system is complex. While it's essential for aerobic respiration, it can also influence the formation of biofilm and the distribution of microbial species within the system. A more detailed analysis of DO profiles and their correlation with microbial community dynamics could provide valuable insights [31]. Turbidity measurements confirmed bacterial growth, with significant differences between control and experimental groups, suggesting a link between bacterial activity and Cd bioremediation. Additionally, contact time emerged as a crucial factor, with longer durations enhancing Cd removal efficiency. Interestingly, bioelectricity generation increased over time, demonstrating the capability of Bacillus licheniformis to facilitate electron transfer reactions. However, statistical analysis did not reveal a significant difference in bioelectricity between experimental and control groups, suggesting potential limitations in the current MFC design. To improve bioelectricity generation, factors such as electrode materials, biofilm formation, and external resistance should be investigated in more detail. Optimizing these parameters can lead to higher power output [32].

5. FUTURE WORKS

This study demonstrates the potential of a low-cost MFC system utilizing B. licheniformis for Cd bioremediation from mine wastewater with concurrent bio-electricity generation. However, several recommendations can be further improved MFC performance and enhance its real-world applicability.

5.1 Substrate Supplementation

Continuously feeding the bacterial culture with essential nutrients, such as cornstarch or glucose, is crucial to sustain their growth and metabolic activity. These organic substrates provide energy sources that promote efficient electron transfer and enhance biodegradation of Cd in the wastewater [33]. Future research should explore the optimal concentrations and feeding strategies of these substrates to maximize Cd removal efficiency.

5.2 Operational Parameter Optimization

Further optimization of key operational parameters, including pH, temperature, and contact time, is recommended. Systematic studies investigating the individual and interactive effects of these parameters on Cd bioremediation and bio-electricity generation can lead to the development of a robust and efficient MFC design [34].

5.3 Microbial Community Analysis and Electrochemical Characterization

A deeper understanding of the microbial community composition and dynamics within the MFC system can be achieved through advanced techniques like metagenomic sequencing. This knowledge can be used to optimize bacterial selection and consortia development for improved MFC performance [27]. Additionally, electrochemical characterization techniques, such as cyclic voltammetry and electrochemical impedance spectroscopy, can provide valuable insights into the electron transfer processes and electrode kinetics within the MFC [35].

5.4 Scale-up and Real-world Application

Scaling up the MFC design for practical mine wastewater treatment applications is essential. Pilot-scale studies [36]recommended to evaluate the system's efficacy and techno-economic feasibility in real-world settings.

5.5 Long-term Performance Evaluation

Conducting long-term studies with the MFC system is crucial to assess its stability and sustained performance over extended operational periods. This will provide valuable data for the design and implementation of reliable bioremediation technologies [37].

5.6 Material Selection

While the current low-cost approach is valuable, future research can explore the use of advanced materials, such as high-conductivity membranes or biocompatible electrodes, to potentially enhance MFC efficiency and durability [38]. Safety considerations should also be addressed, with the exploration of alternative materials like aquarium glass for a safer and more robust MFC design.

5.7 Integration with Wastewater Treatment Processes and Environmental Impact Assessment

Investigating the potential for integrating the MFC system with existing wastewater treatment processes is essential. This would promote resource recovery and enhance overall treatment efficiency. Additionally, conducting a comprehensive environmental impact assessment of the MFC technology is crucial to ensure its sustainability and environmental benefits.

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