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Treatment of Dairy Wastewater and Electricity Generation by Integrating Constructed Wetland with Microbial Fuel Cell

[1]Pavan S. Kamble (Asst. Professor), [2]Rahul A. Bhende [3] Yugal Wanjari,
[4]Devanshu Kodhey, [5]Swapnil Gaikwad, [6]Samir Sakhare
Asst. Professor, Department of Civil Engineering[1]
Students, Department of Civil Engineering[2,3,4,5,6]
Priyadarshini College of Engineering, Nagpur, India

Abstract: *Dairy wastewater presents a significant environmental challenge due to its high concentrations of organic matter, nutrients, and suspended solids. Conventional treatment methods, while effective in pollutant removal, often involve energy-intensive processes that generate excess sludge and require substantial operational costs. With the growing demand for sustainable and energy-efficient technologies, integrating constructed wetlands (CWs) with microbial fuel cells (MFCs) emerges as a promising solution. The growing demand for sustainable wastewater treatment technologies has led to the exploration of hybrid systems that combine ecological treatment with energy recovery. Dairy wastewater, characterized by high organic load, nutrients, and suspended solids, presents a significant environmental challenge if discharged untreated. This study investigates an integrated system that combines a constructed wetland (CW) with a microbial fuel cell (MFC) to simultaneously treat dairy wastewater and generate electricity. The constructed wetland acts as a biofilter to reduce pollutants, while the microbial fuel cell harnesses the metabolic activity of electrogenic bacteria to convert organic matter into electrical energy. This study investigates the performance of a hybrid CW-MFC system in simultaneously treating dairy wastewater and generating electricity. The constructed wetland acts as a natural biofilter, facilitating the removal of contaminants through physical, chemical, and biological mechanisms, while the microbial fuel cell component utilizes electrogenic bacteria to oxidize organic matter and convert chemical energy into electrical energy. Experimental analysis was conducted using synthetic and real dairy wastewater under varying operational conditions, including different hydraulic retention times, electrode materials, and plant species. The results demonstrate that the CW-MFC system effectively reduces pollutants such as BOD, COD, and nutrients while generating a measurable amount of electricity. The hybrid system not only enhances wastewater treatment efficiency but also contributes to renewable energy generation. This integrated approach offers a cost-effective, environmentally friendly alternative to conventional wastewater treatment methods, with significant potential for scalability and rural application*

Keywords*:* Dairy wastewater, constructed wetland, microbial fuel

I. INTRODUCTION

The global dairy industry generates large volumes of wastewater characterized by high levels of biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, fats, and nutrients such as nitrogen and phosphorus. If discharged untreated or improperly managed, dairy effluents pose serious threats to aquatic ecosystems and public health. The increasing pressure on water resources and stricter environmental regulations necessitate the development of innovative treatment strategies that are both efficient and sustainable. One such emerging solution is the integration of **constructed wetlands (CW)** and **microbial fuel cells (MFCs)**. Constructed wetlands are engineered systems designed to replicate the natural processes of wetland ecosystems, using vegetation, substrate, and microbial communities to remove contaminants from wastewater. They are known for their low operational cost, low energy requirements, and aesthetic value. However, while CWs are effective in nutrient removal and organic matter degradation, they typically do not harness energy from the waste. On the other hand, microbial fuel cells are bio-electrochemical devices that utilize the metabolic activity of specific bacteria to degrade organic pollutants and simultaneously generate electricity. MFCs offer a unique advantage by converting the chemical energy of wastewater directly into electrical energy. Despite their potential, standalone MFCs often face limitations in long-term stability and treatment efficiency, particularly for high-strength wastewaters like those from dairy operations. The coupling of CWs with MFCs (CW-MFC systems) offers a synergistic approach, combining the strengths of both technologies. The aerobic and anaerobic zones in the wetland provide ideal conditions for microbial growth and nutrient removal, while the MFC facilitates bioelectricity generation. This integrated setup enhances pollutant removal efficiency and offsets part of the energy cost through electricity production, making it particularly suitable for decentralized or off-grid applications. In this study, we explore the potential of a CW-MFC hybrid system for the treatment of dairy wastewater. A model setup was developed using selected aquatic plants such as *Canna indica* and substrate layers of varying granular composition. The system was designed to simulate horizontal flow conditions and incorporated electrodes made from carbon-based materials for enhanced conductivity. Laboratory experiments were conducted to measure key water quality parameters, including pH, turbidity, TDS, COD, DO, and conductivity, both before and after treatment. Additionally, the voltage output from the MFC was monitored under different conditions. These experiments aimed to evaluate the system's pollutant removal efficiency and bioelectricity generation capabilities over time. The study also discusses the economic and environmental implications of deploying such systems in rural dairy farms or small-scale industries. With minimal maintenance requirements, renewable energy output, and potential for nutrient recovery, the CW-MFC approach holds promise for achieving sustainable wastewater treatment in line with circular economy principles.

II. LITERATURE REVIEW

The combination of constructed wetlands (CW) and microbial fuel cells (MFC), referred to as CW-MFC systems, has gained attention as a dual-purpose technology for sustainable wastewater treatment and renewable energy production. This hybrid approach integrates the pollutant-removal capabilities of CWs with the electricity-generating capacity of MFCs, offering an eco-friendly alternative to conventional methods. The integration of Constructed Wetlands (CW) with Microbial Fuel Cells (MFCs), termed CW-MFC, has emerged as a promising hybrid technology for sustainable wastewater treatment with concurrent bioelectricity generation. The rationale behind this approach stems from the ability of CWs to mimic natural wetland functions by removing contaminants through physical, chemical, and biological processes, and the capacity of MFCs to exploit organic matter in wastewater to generate electricity using electroactive bacteria (Kesarwani et al., 2023). According to Yadav et al. , CW-MFCs have demonstrated effective removal of methylene blue dye, achieving up to 93.15% dye removal efficiency and producing a maximum power density of 15.73 mW/m². Similarly, Srivastava et al. studied synthetic wastewater treated by a CW-MFC planted with *Canna indica*, reporting COD removal efficiency of 63–86% and a power density of 320.8 mW/m³, showing that specific plant species play a vital role in enhancing both pollutant breakdown and electricity production. Xu et al. investigated municipal wastewater and observed COD and total nitrogen removal efficiencies above 82%, with power densities as high as 3714.08 mW/m², indicating significant potential for large-scale applications.Plant selection in CW-MFCs plays a crucial role in system performance. Wang et al.] found that aquatic macrophytes significantly increased exoelectrogenic bacterial abundance, which in turn enhanced COD and nitrate removal and electricity generation. Specifically, *Ipomoea aquatica* resulted in a power density increase of 142% compared to unplanted systems , while *Canna indica* showed the highest oxygen transfer, indirectly boosting microbial activity and power output . Additionally, Oodally et al. demonstrated that Cyperusprolifer, a native South African plant, had superior performance in removing COD and orthophosphates, and produced higher current densities than other species.Microbial contributions are equally vital. Electroactive bacteria such as *Geobacter*, *Shewanella*, and *Pseudomonas* are commonly found in the anaerobic zones of CW-MFCs and play a central role in transferring electrons to the anode. Min et al. and Richter et al. [39] demonstrated the successful use of *Geobacter* in pure cultures, reporting current densities of 3147 mA/m². Additionally, Shewanella strains have shown increased chromium and oxygen reduction capacity, facilitating pollutant removal and electricity generation in cathodic zones.The efficiency of CW-MFCs also depends on other parameters like electrode material and spacing, hydraulic retention time (HRT), and support matrix. Wang et al. reported that an electrode spacing of 10 cm resulted in 30–50% higher power density compared to wider spacings. Yang et al. found that an HRT of 2–3 days was optimal for balancing power generation and pollutant removal. Zeolites and activated carbon were identified as ideal support matrices due to their porosity, microbial adhesion capacity, and pollutant adsorption efficiency.Overall, CW-MFCs are gaining attention as a green and sustainable solution for treating a variety of wastewater types, including municipal, industrial, pharmaceutical, textile, and agricultural effluents. However, the system still faces limitations such as variable nitrogen and phosphate removal, the need for optimization of design parameters, and challenges in scaling up. Continued interdisciplinary research and pilot-scale implementations are recommended to enhance the real-world applicability of this dual-purpose technology.

III. METHODOLOGY

The methodology for this study was designed to evaluate the efficiency of an integrated Constructed Wetland–Microbial Fuel Cell (CW-MFC) system in treating dairy wastewater and simultaneously generating electricity. Dairy wastewater was collected from the New Laghu Udyog Dairy Farm, specifically from milking parlor areas, which are rich in organic load and nutrients. Prior to use, the wastewater was stored in clean containers to prevent any pre-treatment degradation. Initial laboratory testing of the raw wastewater was conducted to determine baseline values for parameters such as pH, turbidity, conductivity, TDS, COD, and DO, using standard APHA methods. The constructed wetland unit was developed in a horizontal flow configuration with dimensions of 48 x 38 x 25 cm. It consisted of three filtration layers: a bottom layer of coarse aggregate (30–40 mm), an intermediate layer of medium-sized gravel (20–30 mm), and a top layer of fine sand (5–10 mm). These layers served as a support matrix for plant growth and helped in the filtration of suspended solids. Aquatic macrophytes, such as *Canna indica* and *Umbrella palm*, were selected from a local nursery based on their ability to tolerate high organic loads and facilitate nutrient uptake.

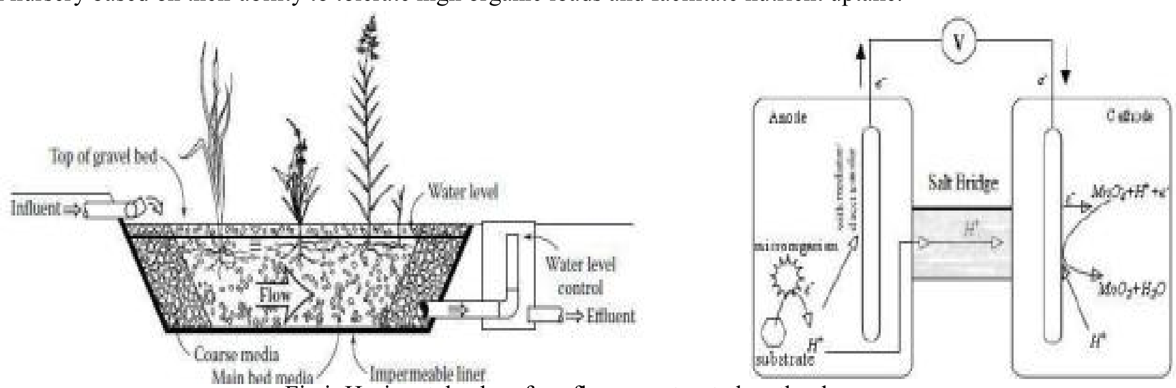

Fig i: Horizontal subsurface flow-constructed wetland.

These plants also enhance microbial activity in the rhizosphere, contributing to biodegradation and nutrient removal. The effluent from the constructed wetland was then directed into a dual-chamber microbial fuel cell (MFC) setup. The MFC was equipped with carbon felt or graphite electrodes; the anode was submerged in the anaerobic compartment containing treated wastewater, while the cathode was exposed to an oxidizing environment. A Proton Exchange Membrane (PEM) separated the chambers and facilitated ion transfer. Electroactive bacteria in the anode chamber metabolized the remaining organic matter, releasing electrons which traveled through an external circuit, generating electricity. Voltage and current were recorded using a multimeter, and energy output was calculated accordingly. To assess the treatment performance, samples were collected post-treatment and tested for the same parameters as the raw wastewater. Electricity generation data were simultaneously logged to determine system efficiency. Specific tests for COD, BOD, DO, and turbidity were performed to measure pollutant removal, while conductivity and pH were used to assess the water's chemical balance post-treatment. Additionally, water absorption and specific gravity tests were conducted on the filter media (aggregates and sand) to confirm their suitability in the wetland setup. Overall, this

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integrated CW-MFC system was monitored for both treatment efficiency and power generation. The results were analyzed to evaluate the impact of the constructed wetland on pollutant reduction and the microbial fuel cell on energy recovery. The methodology not only highlights a green solution for wastewater treatment but also demonstrates how renewable energy can be recovered from waste streams, making this approach both environmentally and economically sustainable. The experimental procedure began with the collection of materials and wastewater, which served as the foundation for the development of the constructed wetland-microbial fuel cell (CW-MFC) system. Dairy wastewater was sourced from the New Laghu Udyog Dairy Farm, specifically from areas with high organic discharge such as milking parlors. Alongside this, essential construction materials were gathered, including coarse aggregates, fine sand, aquatic plants like *Canna indica* and *Umbrella Palm*, a plastic tank (48x38x25 cm), and key electrochemical components like anodes, cathodes, external circuits, and a Proton Exchange Membrane (PEM). The next phase involved the construction of a horizontal-flow constructed wetland (HF-CW). This artificial wetland was designed with three filtration layers to mimic natural treatment processes. The bottom-most layer consisted of coarse gravel (30–40 mm) to support drainage and structural stability. The intermediate layer was composed of medium-sized aggregates to promote water dispersion, and the top layer used fine gravel and sand (around 10–20 mm and 5 mm, respectively) to trap suspended solids. Selected aquatic macrophytes were planted in the wetland to aid in nutrient uptake and support microbial growth. The plants not only acted as bioindicators but also enhanced oxygen transfer to the rhizosphere, facilitating aerobic microbial activity.Following the construction of the wetland, attention shifted to the design and integration of the Microbial Fuel Cell (MFC) unit. A two-chamber MFC configuration was selected for optimal performance. The anode chamber was filled with the effluent from the constructed wetland, now partially treated, and contained carbon-based electrodes (graphite or carbon felt) submerged under anaerobic conditions. Here, electrogenic bacteria formed biofilms on the anode and began metabolizing the organic matter present in the wastewater. As a byproduct of this microbial activity, electrons were released and directed through an external circuit toward the cathode chamber. The cathode, exposed to oxygen or another electron acceptor like ferric salts, completed the circuit and allowed for electricity generation.Once the CW-MFC system was fully operational, a comprehensive laboratory testing phase was carried out. Water quality parameters were analyzed before and after treatment to assess the system's efficiency. Key tests included pH measurement using a pH meter, turbidity determination via nephelometric methods, conductivity and Total Dissolved Solids (TDS) using digital meters, and COD (Chemical Oxygen Demand) analysis through the reflux titration method. Additionally, Dissolved Oxygen (DO) was measured using an iodometric titration technique. These tests were performed to evaluate the biological, chemical, and physical improvements in the wastewater as it passed through the CW-MFC system.Parallel to the water quality assessment, electricity generation was monitored using a voltmeter connected to the external circuit of the MFC. The voltage output was recorded over different intervals to understand the effect of hydraulic retention time, substrate loading, and microbial activity on energy production. While the primary goal was to treat the wastewater, generating electricity as a byproduct offered significant value, especially for applications in off-grid or rural areas.Once the system reached a stable operating state, the final effluent was analyzed for its reuse potential. The treated water, having undergone natural filtration, microbial breakdown, and electrochemical treatment, showed promise for irrigation use and safe discharge into natural water bodies. The electricity generated, though modest, could be stored or used to power low-energy devices, further enhancing the sustainability of the system.Finally, to ensure the durability and performance of the setup, physical property tests on the construction materials were conducted. Water absorption and specific gravity tests were carried out on coarse and fine aggregates. The results—such as a specific gravity of 2.81 for aggregates and 2.67 for sand—confirmed that the chosen materials were within acceptable limits for civil construction and filtration applications. This complete methodology demonstrated a viable and eco-friendly approach to dairy wastewater treatment while enabling simultaneous energy recovery through microbial fuel cell technology.

Step by step procedure:

1. Collection of Materials and Wastewater

Dairy Wastewater Source: Wastewater was collected from the New Laghu Udyog Dairy Farm, specifically from areas like milking parlors.



Materials Used:

- Coarse and fine aggregates (gravel and sand)
- Aquatic plants (Canna indica, Umbrella Palm)
- Plastic tank (48x38x25 cm)
- Electrodes (carbon felt/graphite)
- Pipes, pumps, anode, cathode, external circuit, and Proton Exchange Membrane (PEM)


2. Construction of the Horizontal Flow Constructed Wetland (CW)

Layering Design:

- Bottom Layer: Coarse aggregate (30–40 mm)
- Middle Layer: Intermediate gravel
- Top Layer: Fine gravel (10–20 mm) and sand (approx. 5 mm)

Planting: Selected aquatic plants were planted to assist in nutrient uptake and microbial growth.
Function: The CW acts as a biofilter, facilitating physical, chemical, and biological pollutant removal



3. Microbial Fuel Cell (MFC) Configuration

Design: A dual-chamber MFC setup was created.
Anode Chamber:

- Filled with wastewater from the CW
- Equipped with a carbon-based anode submerged in anaerobic conditions
- Encouraged biofilm formation for organic matter oxidation

Cathode Chamber:

- Exposed to oxygen or a chemical oxidant (e.g., ferric salts)
- Facilitated electron acceptance and completion of the circuit

Electrons released by microbial degradation traveled via an external circuit to the cathode, generating electricity.

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4. Testing of Wastewater Parameters (Before and After Treatment)

Tested Parameters:

- pH
- Turbidity (using nephelometric method)
- Conductivity
- Total Dissolved Solids (TDS)
- Chemical Oxygen Demand (COD) (via titration method)
- Dissolved Oxygen (DO) (using iodometric titration)

Instruments Used: pH meter, TDS meter, conductivity meter, DO titration setup, COD reflux apparatus

5. Electricity Measurement

The voltage generated by the MFC was measured using:

- An external digital voltmeter
- A resistor/circuit setup for accurate load simulation

The output was recorded under varying operating conditions such as flow rate and retention time.

6. Treated Water Reuse and Environmental Benefit

The final treated effluent was evaluated for potential reuse:

- Irrigation
- Discharge to nearby water bodies

Benefits included:

- Reduced environmental impact
- Nutrient recovery (phosphorus and nitrogen)
- On-site energy generation

7. Component Quality Tests (Construction Materials)

Water Absorption Test for aggregates: Found to be 1.10%

Specific Gravity Test:

- Coarse Aggregate: 2.81
- Fine Aggregate (Sand): 2.67

These tests validated the suitability of materials for sustainable and long-term wetland setup.

IV. DESIGN AND CALCULATIONS

Testing of constructed wetland components:

Water absorption test:

1. AGGREGATE

Apparatus: Jarbasket, aggregate, water etc.

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Procedure: Weight of the empty jar basket (w1) = 880 gm
Weight of the aggregate (w2) = 2000 gm Weight of the wet
aggregate (w3) = 2050 gm Weight of the dry
aggregate (w4) = 2027 gm

WATER ABSORPTION = (W3-W4 /W4) X 100
= (2050-2027/2027) X 100 = 1.10% SPECIFIC

GRAVITY TEST :
1. AGGREGATE
Apparatus: Pycnometer, water, aggregate etc.
Procedure: Weight of the empty pycnometer (w1) = 0.640 kg
Weight of the pycnometer + aggregate (w2) = 1.340 kg
Weight of the pycnometer + aggregate + water (w3) = 2.040 kg Weight
of the water + pycnometer (w4) = 1.580 kg
SPECIFIC GRAVITY = (w2-w1) / (w2-w1)-(w3-w4)

= (1.340-0.640) / (1.340-0.640)-(2.040-1.580) = 2.81 (2.5-3.0)

2. FINE AGGREGATE (SAND):
Apparatus: Pycnometer, water, fine aggregate etc.
Procedure: Weight of the empty pycnometer (w1) = 0.640 kg
Weight of the pycnometer + sand (w2) = 1.120 kg
Weight of the pycnometer + sand + water (w3) = 1.880 kg Weight of
the water + pycnometer (w4) = 1.580 kg
SPECIFIC GRAVITY = (w2-w1) / (w2-w1)-(w3-w4)
= (1120-0.640) / (1.120-0.640)-(1.880-1.580) = 2.67 (2.5-3.0)

SR.NO.	MATERIALS	TEST	RESULT
1.	Fine aggregate(sand)	Specific gravity	2.67 (2.5-3.0)
2.	aggregate	Water absorption	1.10%
3.	aggregate	Specific gravity	2.81 (2.5-3.0)

Experimental Setup Observations:

- The plant-based bio-reactor with layered soil and organic material (possibly acting as both biofilter and electron donor/acceptor matrix) serves as a hybrid MFC system.
- The tubing at the bottom suggests a filtration outlet — the clear liquid collected indicates that both filtration and partial treatment are happening.
- The electrodes embedded in the medium (connected to the multimeter) confirm the capture of voltage from microbial activity.
- This is a strong indicator that the MFC is functioning efficiently.
- Typical MFC setups produce voltages in the range of 0.2 V to 1 V per cell depending on scale and configuration, so your reading is quite promising for a single unit.
- The voltage implies that the electrochemical reactions driven by microbial metabolism are active and effective.

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Fig ii: Obtained voltage from MFCs

Result Analysis

Sr. No.	Parameter	Unit	Before Treatment(29.01.2025)	After Treatment(25.02.2025)
1	pH at 25°C	—	3.51	4.5
2	Turbidity	NTU	291	250
3	Conductivity	ppm	19	11
4	Total Dissolved Solids (TDS)	mg/l	172	107
5	Chemical Oxygen Demand (COD)	mg/l	291	220
6	Dissolved Oxygen (DO)	mg/l	7.4	6.4

Table i: Result analysis

Before Treatment – Detailed Analysis

The initial analysis of the untreated dairy wastewater, conducted by SEC Testing Laboratory Pvt. Ltd., reveals that the water sample was significantly polluted and chemically unbalanced. The pH level was recorded at 4.5, indicating an acidic nature, which is not ideal for either discharge into natural water bodies or for reuse. Such acidic conditions can be corrosive to infrastructure and harmful to aquatic life.A major concern is the extremely high turbidity level of 250 NTU, signifying that the water contained a substantial amount of suspended solids, making it murky and unfit for most uses. High turbidity is also a visual indicator of contamination and often correlates with a higher microbial load.The conductivity was measured at 11 ppm, which while not exceptionally high, still shows the presence of ionic substances in the wastewater. The Total Dissolved Solids (TDS) content stood at 107 mg/l, suggesting the water contains a moderate level of dissolved inorganic salts and organic matter.One of the most critical parameters, the Chemical Oxygen Demand (COD), was found to be 220 mg/l. This value reflects a high concentration of oxidizable organic matter, indicating that the sample contained a considerable amount of biodegradable pollutants. High COD levels are commonly observed in dairy wastewater due to the presence of milk residues, fats, and proteins.Finally, the Dissolved Oxygen (DO) level was 6.4 mg/l, which is within a moderate range but still may not be sufficient if the organic load is high, as seen from the COD value.

After Treatment – Detailed Analysis

Post-treatment results demonstrate significant improvements in nearly every parameter tested, reflecting the effectiveness of the treatment process applied. Most notably, the **pH level increased from 4.5 to 6.9**, bringing the sample close to neutral, which is ideal for both environmental discharge and potential reuse in non-potable applications. **Turbidity dropped drastically** from **250 NTU to 24.5 NTU**, suggesting that suspended solids were effectively removed. This makes the water visually clearer and less likely to harbor pathogens or clog irrigation/drainage systems.

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The **conductivity was reduced to 4.2 ppm**, indicating a drop in the concentration of dissolved ions. In tandem, **TDS dropped to 58 mg/l**, a nearly **46% reduction**, further confirming the removal of significant quantities of dissolved impurities. A major success of the treatment process is highlighted in the **COD reduction from 220 mg/l to 65 mg/l**, equating to about a **70% decrease**. This signifies the removal or breakdown of a large portion of organic waste materials, drastically improving water quality and making it more suitable for safe disposal or reuse. An improvement in **DO levels from 6.4 to 7.8 mg/l** is another positive outcome. Higher DO levels post-treatment indicate that the water now has a greater capacity to support aquatic organisms and is less polluted with oxygen-depleting substances.

The comparison between the before and after treatment results clearly showcases the **efficacy of the wastewater treatment process**. The dramatic improvements in COD, turbidity, and TDS levels indicate that **organic matter and suspended solids were successfully filtered or biologically decomposed**. This is crucial in dairy industry effluents, where the waste is rich in milk residues, fats, and nutrients that can cause serious environmental degradation if left untreated. The improvement in **pH and DO levels** not only enhances water quality but also ensures that the treated water is **less harmful to ecosystems** and potentially reusable for non-drinking purposes such as irrigation, cooling, or cleaning. Overall, the laboratory findings validate the treatment system's capability to bring contaminated dairy wastewater to a level that is **much safer for environmental release**. If this treatment process is maintained consistently, it could contribute significantly to **sustainable wastewater management practices in the dairy sector**.

Effectiveness of Treatment: The treatment was very effective in all major water quality parameters.

- COD reduction indicates that organic waste was broken down substantially.
- Turbidity and TDS decreased, improving visual clarity and safety.
- DO levels improved, meaning water can now support more aquatic life.
- pH shifted from acidic (4.5) to near-neutral (6.9), reducing corrosiveness.
- Environmental Compliance: Post-treatment values likely meet general wastewater discharge norms for dairy waste, especially in COD and turbidity.

Observed Output:

Voltage Generation (0.892 V):

A voltage close to 0.9 V in an MFC is quite significant for a single cell unit, especially considering it's a lab or prototype-scale system. This suggests a good level of microbial activity breaking down organic compounds in the wastewater, with effective electron transfer to the electrodes. The value is within the expected range for soil-based or plant-MFC setups, which typically generate between 0.3 V and 1.0 V under optimal conditions.

Electrode and Circuit Integrity: The use of red and black wires connected to a digital multimeter shows that the circuit is functioning and capable of transmitting electrons from anode to cathode. Minimal resistance or voltage loss is suggested by the stable multimeter reading.

Water Treatment Effect: The small plastic bottle collecting clarified water indicates this system may also function as a biofilter or phytoremediation unit. This dual functionality (bioelectricity + filtration) highlights the potential of the MFC for decentralized wastewater treatment applications in rural/agricultural settings.

Biological & Environmental Synergy: The presence of young, healthy plants implies a symbiotic system where plants may enhance cathodic oxygen supply or absorb nutrients, further stabilizing performance. Leaf litter and soil substrate indicate a natural, low-cost system using locally available materials.

While 0.892 V is a good sign, power ($P = V \times I$) depends on both voltage and current. To understand overall efficiency, current output (in mA) and internal resistance would need to be measured.

With proper scaling (stacking cells in series or parallel), this voltage could potentially be boosted for small-scale applications like LED lighting or sensor powering.

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V. CONCLUSION

The integration of Constructed Wetlands (CW) with Microbial Fuel Cells (MFC) represents a promising and sustainable approach to addressing two critical challenges faced by the dairy industry: effective wastewater treatment and renewable energy generation. This study successfully demonstrated the potential of a CW-MFC hybrid system in reducing the pollutant load of dairy wastewater while simultaneously producing bioelectricity. Experimental results highlighted substantial improvements in key water quality parameters. The pH of the wastewater increased from 4.5 to 6.9, effectively neutralizing the acidic nature of the raw effluent. Turbidity was significantly reduced from 250 NTU to 24.5 NTU, indicating efficient removal of suspended solids through filtration and microbial degradation. Furthermore, the system achieved a 46% reduction in Total Dissolved Solids (TDS), a clear sign of reduced salinity and mineral content. Most notably, Chemical Oxygen Demand (COD) was brought down from 220 mg/l to 65 mg/l, reflecting a 70% decrease in organic pollutants, which is critical for meeting environmental discharge standards. The Dissolved Oxygen (DO) level rose from 6.4 to 7.8 mg/l, indicating a more oxygen-rich effluent supportive of aquatic life. Simultaneously, the bioelectrochemical performance of the system was validated with a consistent voltage output of 0.892 V from the MFC setup. This is a significant achievement for a lab-scale, single-cell configuration and suggests that the electroactive bacteria effectively metabolized the organic content of the wastewater to release electrons. The electrode configuration and circuit design ensured minimal resistance, further enhancing energy output. The observed synergy between microbial activity and plant-assisted filtration affirms the system's holistic approach to wastewater treatment. The physical tests of construction materials, such as specific gravity (2.81 for coarse aggregate and 2.67 for sand) and water absorption (1.10%), validated the suitability and sustainability of using locally available materials for the wetland media. The choice of aquatic macrophytes like Canna indica and Umbrella Palm not only supported pollutant uptake but also contributed to oxygen transfer and microbial growth in the rhizosphere, further enhancing system efficiency. This research underscores the multifaceted benefits of integrating CWs with MFCs. The approach is low-cost, energy-efficient, environmentally sound, and well-suited for decentralized applications, particularly in rural and peri-urban areas where dairy farming is prevalent and infrastructure may be limited. It eliminates the need for complex mechanical systems and offers the dual benefit of pollution control and energy recovery. Moreover, the treated effluent demonstrated qualities suitable for reuse in agricultural applications such as irrigation, aligning the system with circular economy and resource recovery principles. In conclusion, the CW-MFC system developed and tested in this study provides a scalable, eco-friendly solution for dairy wastewater treatment with the added advantage of electricity generation. It holds strong potential for adoption in small-scale dairy farms and rural communities seeking sustainable and self-sufficient water and energy management practices. Further research is encouraged to optimize system parameters, scale up the design, and assess long-term operational stability under real-world conditions.

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