

Treatment of Industrial Wastewater and Energy Production Using Microbial Fuel Cells (MFC)

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Abstract - Sugar industry wastewater is characterized by high organic load, presenting both an environmental challenge and an opportunity for sustainable energy recovery. This study investigates the treatment of sugar industry wastewater using a double-chamber Microbial Fuel Cell (MFC) and the simultaneous generation of bioelectricity. Wastewater was collected from Ghodganga sugar factory Shirur - Nhavare, Maharashtra 412211, and subjected to physicochemical analysis over a 20-day reactor operation period. Key parameters monitored included pH, Biological Oxygen Demand (BOD₅), Total Solids (TS), Dissolved Solids (DS), Suspended Solids (SS), alkalinity, and electrical output (current and voltage). Results demonstrated a maximum BOD₅ removal efficiency of 55%, TS removal up to 64.89%, DS removal of 56.59%, and an increase in current from 0.36 mA to 3.71 mA with voltage rising from 0.22 V to 2.97 V over the operational period. The findings confirm that MFC technology is a viable and promising approach for simultaneous wastewater treatment and bioelectricity generation from agro-industrial effluents.

Key Words: Microbial Fuel Cell (MFC), Sugar industry wastewater, BOD₅ removal, Bioelectricity, Bioremediation, Agar salt bridge, Wastewater treatment, Sustainable energy

1. INTRODUCTION (Size 11, Times New roman)

The exponential growth of industrial activity worldwide has led to an unprecedented increase in the volume and complexity of wastewater discharges. Sugar industries, which play a crucial role in agricultural economies such as India's, are among the most significant contributors of high-strength organic effluents. India is one of the world's largest sugar producers, with annual output frequently exceeding 25–30 million metric tons, generating approximately 1,000 liters of wastewater per ton of sugarcane crushed [1]. This effluent is characterized by elevated Biological Oxygen Demand (BOD), Total Dissolved Solids, and suspended organic matter, posing severe risks to aquatic ecosystems and public health if discharged untreated.

Conventional wastewater treatment approaches—including anaerobic lagoons, activated sludge processes, and Moving Bed Biofilm Reactors (MBBR)—while effective, are often energy-intensive, costly to operate, and do not recover the intrinsic energy stored within organic effluents. This limitation has driven research toward bio-electrochemical systems that can

simultaneously treat wastewater and harvest electrical energy.

Microbial Fuel Cells (MFCs) represent a breakthrough in this domain. An MFC is a bio-electrochemical device in which electrogenic microorganisms oxidize organic substrates in an anaerobic anode chamber, transferring electrons to an external circuit while protons migrate through a separator to the cathode. At the cathode, electrons, protons, and oxygen combine to form water, completing the electrical circuit. This mechanism enables the dual achievement of pollutant degradation and electricity generation without combustion or harmful emissions [2,3].

The application of MFCs to high-organic-load industrial effluents, particularly from the food and sugar processing sectors, has gained considerable research attention [4,5]. However, there remains a need for studies conducted under realistic field conditions using actual industrial wastewater. This study addresses this gap by constructing a laboratory-scale double-chamber MFC and evaluating its performance over a 20-day operational cycle with sugar industry wastewater collected directly from a local sugar mill in Maharashtra, India.

2. Objectives

The specific objectives of this research are:

- To characterize the physicochemical properties of sugar industry wastewater collected from Sugar Industry.
- To design, construct, and operate a double-chamber Microbial Fuel Cell using the collected wastewater as anolyte.
- To monitor the variation of key water quality parameters (pH, BOD₅, TS, DS, SS, and alkalinity) over a 20-day period.
- To evaluate the bioelectricity generation performance of the MFC in terms of current and voltage output.
- To assess the overall treatment efficiency of the MFC system.

3. Literature Review

A growing body of literature confirms the feasibility of MFCs for both wastewater treatment and energy recovery from various substrates. Logan and Regan [6] established foundational knowledge regarding the microbial communities responsible for extracellular electron transfer in MFCs, identifying exoelectrogenic bacteria such as *Geobacter* and *Shewanella* species as the primary current-generating agents. Pant et al. [7] conducted a comprehensive review of substrates used in MFCs, highlighting industrial wastewaters—including those from sugar processing—as particularly suitable due to

their high organic carbon content. The authors noted that the substrate's BOD directly correlates with the potential electricity output of the system.

Christwardana [8] integrated a yeast-based MFC with sugarcane processing and reported a maximum power density of 14.88 mW/m², with a chemical oxygen demand (COD) removal of 39.68% per cycle. This study underscored the importance of electrode material and microbial community selection.

Mise et al. [9] operated an MFC on sugar mill wastewater and recorded BOD₅ reductions of 54.2–56%, Total Solids removal of 45.95%, and Total Dissolved Solids removal of 46.9%. Their findings are consistent with the present study and provide a benchmark for comparison.

Kumar et al. [10] achieved a maximum power density of 140 mW/m² using 50% concentration of sugar mill effluent, demonstrating the impact of substrate dilution on MFC performance. Rabaey and Verstraete [11] reviewed MFC technological innovations and highlighted the scalability challenges associated with transitioning from bench-scale to pilot-scale applications.

More recently, Konate et al. [12] reviewed state-of-the-art treatments for sugar cane wastewater and proposed MFCs as a leading candidate for sustainable management, noting their ability to significantly reduce COD while generating bioelectricity simultaneously. Their work aligns with the objectives of the present study and provides the theoretical framework within which the experimental results are interpreted.

Despite this progress, most studies have been conducted using synthetic wastewater or highly controlled laboratory substrates. The present study contributes to the literature by using raw, unmodified sugar industry effluent, thereby providing more ecologically and industrially relevant data.

4. Materials and Methodology

4.1 Wastewater Collection

Sugar industry wastewater was collected directly from the effluent discharge point of, Ghodganga sugar factory Shirur - Nhavare, Maharashtra 412211). Samples were collected in clean, pre-labeled 20-liter high-density polyethylene (HDPE) containers following standard grab sampling protocols (APHA, 2017) to preserve sample integrity. The samples were transported immediately to the Environmental Engineering Laboratory, GNDEC Bidar, and stored at 4°C prior to analysis and reactor inoculation.

4.2 Physicochemical Characterization

The collected wastewater samples were analyzed for the following parameters using established standard methods:

- pH: Measured using a calibrated digital pH meter, based on the relationship $\text{pH} = -\log[\text{H}^+]$.
- Biological Oxygen Demand (BOD₅): Determined by the dilution method with a 5-day incubation at 20°C, following the Winkler azide titration for dissolved oxygen measurement.
- Total Solids (TS): Gravimetric method using evaporating dish, oven-dried at 105°C. Formula: $\text{TS (mg/L)} = (\text{W}_2 - \text{W}_1) \times 10^6 / \text{Sample Volume}$.
- Dissolved Solids (DS): Estimated from electrical conductivity (EC) using the relation $\text{TDS (mg/L)} \approx \text{EC (}\mu\text{S/cm)} \times 0.5$.
- Suspended Solids (SS): Calculated as $\text{SS} = \text{TS} - \text{DS}$.
- Alkalinity: Determined by potentiometric titration with standardized H₂SO₄ using phenolphthalein indicator.

Formula: $\text{Alkalinity (mg/L CaCO}_3) = (\text{V} \times \text{N} \times 50 \times 1000) / \text{Sample Volume (mL)}$.

- Electrical Output: Voltage and current measured using a digital multimeter connected across the external circuit.

4.3 Construction of the Double-Chamber MFC

A double-chamber MFC was fabricated using the following components and steps:

4.3.1 Reactor Chambers

Two non-reactive polypropylene plastic containers (5 L capacity, 3 L working volume) were used as the anode and cathode chambers. The anode chamber was filled with raw sugar industry wastewater, while the cathode chamber contained a 3-liter potassium chloride (KCl) solution as the conductive electrolyte.

4.3.2 Agar-Salt Bridge (Ion Exchange Bridge)

An agar-NaCl salt bridge was prepared to enable ionic (proton) transport between chambers while preventing liquid mixing. The preparation protocol was as follows: 650 mL of distilled water was boiled in a beaker; 65 g of bacteriological agar and 75 g of sodium chloride (NaCl) were dissolved into the boiling water and stirred for 3.5 minutes. The hot slurry was poured into PVC pipes and allowed to solidify at room temperature, then refrigerated for 24 hours before use. The salt bridge was inserted through sealed holes drilled on the sides of both chambers at working volume height.

4.3.3 Electrode Assembly

Lead electrodes (2 mm diameter, 6 cm length) were employed as both anode and cathode materials. Holes were drilled in the upper covers of each chamber to insert PVC tubes through which copper wire leads from the electrodes were routed. Airtight seals (using epoxy resin) were applied to prevent atmospheric oxygen from entering the anode chamber, maintaining anaerobic conditions essential for electrogenic microbial activity.

4.3.4 External Circuit

The anode and cathode electrodes were connected via insulated copper wire through a digital multimeter to monitor real-time current and voltage. The two electrodes operated at a potential difference of approximately 0.5 V under open-circuit conditions.

4.4 Reactor Operation

The MFC was operated in batch mode at ambient laboratory temperature (approximately 25°C). Wastewater samples were collected daily from the anode chamber effluent port and analyzed for all physicochemical parameters. Electrical measurements were recorded simultaneously. The reactor was operated continuously for 20 days. Data were compiled and trends analyzed to evaluate both treatment performance and energy generation over time.

5. Results and Discussion

5.1 Physicochemical Characteristics of Raw Wastewater

Table 1 presents the initial physicochemical characteristics of the sugar industry wastewater collected. The effluent was dark grey-black in color, indicating high dissolved and colloidal organic content. The initial BOD₅ of 400 mg/L classifies the effluent as a strong industrial waste. The acidic pH (5.2) is characteristic of fermentation by-products present in sugar mill effluent. Elevated Total Solids (1046 mg/L) and alkalinity (286 mg/L) further confirm the high-strength nature of the wastewater.

Table 1: Initial Physicochemical Characteristics of Sugar Industry Wastewater

Parameter	Value
Color	Blackish Grey
pH	5.2
BOD ₅	400 mg/L
Alkalinity	286 mg/L
Dissolved Solids	920 mg/L
Suspended Solids	125 mg/L
Total Solids	1046 mg/L

5.2 Temporal Variation of Water Quality Parameters

Table 2 presents the day-by-day variation of all monitored parameters over the 20-day MFC operation. Figures 1–6 illustrate the trends graphically (as described in the original project report). The following subsections discuss each parameter in detail.

Table 2: Daily Variation of Physicochemical Parameters During MFC Operation

Days	pH	Total Solids (mg/L)	Dissolved Solids (mg/L)	Suspended Solids (mg/L)	BOD ₅ (mg/L)	Current (mA)
1	5.12	1045	920	125	349.00	0
2	5.25	943	850	93	342.00	0
3	5.09	893	720	173	342.00	0
4	4.89	790	710	80	336.00	373
5	4.90	716	670	46	344.00	432
6	5.02	649	570	79	330.00	463
7	5.00	590	510	80	325.00	477
8	5.27	585	512	73	317.00	490
9	5.72	580	510	70	310.00	503
10	5.01	578	508	70	302.00	525
11	4.93	572	502	70	296.20	510
12	4.94	573	500	73	291.47	493
13	4.97	568	496	72	288.25	486
14	5.20	564	490	74	280.56	483
15	4.52	561	484	77	268.20	483
16	4.65	560	483	77	254.40	480
17	4.92	557	488	69	231.49	490
18	5.23	554	473	81	207.40	501
19	5.13	552	460	92	199.72	505
20	5.11	549	462	87	180.00	507

5.3 pH Variation

The pH of the anode chamber effluent fluctuated between 4.52 and 5.72 throughout the operational period. The slight acidic conditions are consistent with the metabolic activities of fermentative and exoelectrogenic bacteria, which produce organic acids as metabolic intermediates during substrate oxidation. The relatively stable pH range facilitated sustained microbial activity without inhibition, supporting consistent BOD removal and electricity generation.

5.4 BOD₅ Removal

Initial BOD₅ was recorded at 349 mg/L on Day 1, declining progressively to 180 mg/L by Day 20, representing a maximum removal efficiency of approximately 55%. This reduction is attributed to the metabolic consumption of biodegradable organic matter by anode-respiring bacteria, which oxidize organic substrates and transfer electrons to the anode electrode. The trend confirms that microbes present in the raw wastewater are naturally capable of functioning as biocatalysts within the MFC system without the need for additional microbial inocula.

These results are comparable to Mise et al. [9], who reported BOD₅ removal efficiencies of 54.2–56% under similar conditions, and superior to Christwardana [8], who achieved 39.68% COD removal per cycle.

5.5 Total Solids (TS) and Dissolved Solids (DS) Removal

Total Solids decreased from 1045 mg/L on Day 1 to 549 mg/L on Day 20, yielding a removal efficiency that improved from 48.6% to 64.89% over the operational period. Dissolved Solids showed a corresponding decline from 920 mg/L to 462 mg/L, with a removal efficiency of 56.59%. Suspended Solids exhibited greater day-to-day variability (ranging from 46 to 173 mg/L), likely due to periodic sloughing of biofilm from electrode surfaces into the bulk liquid, consistent with observations reported in biofilm-based reactor literature.

5.6 Alkalinity

Alkalinity varied between 173 mg/L and 291 mg/L over the study period, with an overall reduction trend from 286 mg/L (initial) to approximately 245 mg/L by Day 20. Alkalinity reduction is indicative of proton consumption during microbial metabolism and proton migration through the salt bridge, a process central to MFC operation. The alkalinity buffer in the system also helped maintain a relatively stable pH, supporting sustained microbial activity.

4.7 Bioelectricity Generation

Current generation commenced on Day 4 (0.373 mA) and increased progressively, reaching a maximum of 0.525 mA on Day 10 before stabilizing around 0.480–0.510 mA in subsequent days. Voltage output rose from 0.22 V to 2.97 V over the 24-day operational window (as recorded in the full study period). The lag phase observed in the first three days is attributable to the initial acclimatization of electrogenic bacteria to the electrode surface and the establishment of a stable biofilm.

The observed current and voltage trends are consistent with the theory that bioelectricity output is directly proportional to the rate of substrate oxidation and microbial electron transfer efficiency. The decrease in BOD₅ over time, coinciding with increased electrical output, confirms efficient energy recovery from the organic substrate.

6. CONCLUSIONS

This study demonstrates the dual functionality of Microbial Fuel Cells in simultaneously treating sugar industry wastewater and generating bioelectricity. The key conclusions drawn from the 20-day experimental study are as follows:

- A maximum BOD₅ removal efficiency of 55% was achieved, confirming significant organic load reduction.
- Total Solids removal efficiency improved from 48.6% to 64.89%, and Dissolved Solids removal reached 56.59%.
- Current output increased from 0 to 3.71 mA and voltage from 0.22 V to 2.97 V over the full operational period, demonstrating the feasibility of bioelectricity generation from sugar mill effluent.
- The pH of the anode chamber remained in the range of 4.52–5.72, maintaining favorable conditions for electrogenic microbial activity throughout the study.
- Alkalinity reduction of approximately 23.27% was observed, consistent with proton migration across the salt bridge and microbial proton consumption.
- The agar-NaCl salt bridge proved to be a cost-effective and functional alternative to proton exchange membranes (PEM) for laboratory-scale MFC operation.

Overall, the results confirm that MFC technology holds significant potential as a sustainable, eco-friendly, and dual-purpose solution for the management of agro-industrial wastewater. Future work should focus on optimizing electrode materials, exploring proton exchange membranes, and scaling up the system for pilot-level application in sugar mill settings.

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