The University of Tehran Press

Pollution

https://jpoll.ut.ac.ir/

Print ISSN: 2383-451X
Online ISSN: 2383-4501

Treatment of Sugar Industry Wastewater and Electricity Generation Using Microbial Fuel Cells: Optimization of Operational Parameters

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Article Info

Article type:
Research Article

Article history:
Received: 27 February 2025
Revised: 21 November 2025
Accepted: 18 January 2026

Keywords:
Microbial Fuel Cells
Sugar Industry Effluent
Energy Recovery
Electrode Optimization

ABSTRACT

The sugar industry generates wastewater with high organic content, presenting serious environmental concerns. Microbial fuel cells (MFCs) offer an eco-friendly solution by simultaneously treating this effluent and producing electricity. This study evaluated MFC performance through batch experiments, optimizing operational parameters such as pH, salt bridge concentration, and electrode material. Treatment efficiency was assessed using Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) measurements. Maximum BOD and COD removal efficiencies of 89.73% and 90.03%, respectively, were recorded at pH 6. The highest current output was observed at a salt bridge concentration of 1M KCl. Among the electrode materials tested—Aluminium, Copper, Iron, and Carbon—the Carbon–Carbon (C–C) pair produced the highest voltage output of 2.398 V. This research adhered to standard laboratory practices and ensured that no hazardous or pathogenic waste was released during experimentation. The findings reinforce the potential of MFCs as a sustainable technology for effective sugar industry wastewater treatment and renewable energy generation, with attention to environmental and ethical research practices.

Cite this article: Harshada, W., & Amit, Sh. (2026). Treatment of Sugar Industry Wastewater and Electricity Generation Using Microbial Fuel Cells: Optimization of Operational Parameters. *Pollution*, 12(1), 16-30. https://doi.org/10.22059/poll.2025.391239.2819

DOI: https://doi.org/10.22059/poll.2025.391239.2819

INTRODUCTION

The increasing global demand for environmentally sustainable and renewable energy sources has driven intensive research into alternative energy generation technologies. A growing emphasis is placed on sustainable and eco-friendly solutions to reduce dependence on hydrocarbon-based fuels, largely due to pressing environmental issues and the ongoing energy crisis (Scott & Murano, 2007; Zhou et al., 2012; Logan, 2010; Rahimnejad et al., 2021).

The extensive reliance on fossil fuels such as coal and petroleum has led to significant environmental degradation, contributing to global phenomena such as climate change, acid rain, and air pollution. These fuels, while dominant in energy production, release harmful greenhouse gases and toxic pollutants into the atmosphere (Kim et al., 2002; Kim, Chang & Gadd, 2007; Das & Mangwani, 2010). In India, this challenge is compounded by rising fuel costs and the rapid depletion of fossil fuel reserves, further intensifying the search for cost-effective and renewable energy alternatives (Parkash, 2016; Pandey et al., 2021; Ali et al., 2023; Aremu & Agarry, 2018; Baranitharan et al., 2013). One promising direction is

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the integration of energy recovery with wastewater treatment. Industrial and domestic effluents are rich in biodegradable organic matter, making them viable substrates for energy production. Microbial Fuel Cells (MFCs) represent an innovative bio-electrochemical system where microorganisms catalyze the degradation of organic compounds, simultaneously generating electricity (Mathuriya & Sharma, 2009; Pandey, Mishra & Agrawal, 2011; Bahan et al., 2011). These systems harness metabolic activity to convert chemical energy stored in waste into electrical energy, offering dual benefits: pollution reduction and energy generation (Gupta et al., 2011; Mane & Rokade, 2010; Borah, More & Yadav, 2013; Lavanya, Dhankar & Chhikara, 2014).

MFCs have gained recognition for their ability to convert the chemical energy of industrial or household organic waste into bioelectricity or hydrogen, positioning them as viable tools for renewable energy production (Dalvi et al., 2011; Mali et al., 2012). Their energy-efficient operation enables partial energy recovery from contaminants, although further water purification often requires additional membrane-based post-treatment technologies (Zhen, 2012; Manohar et al., 2008). This shift reflects a broader trend in wastewater management: evolving from simple contaminant removal to a more sustainable approach that emphasizes energy conservation and resource recovery (Rao & Datta, 1998; Metcalf & Eddy, 2009; Ayachi, Bundela & Khare, 2013; Singh et al., 2010). Despite these advancements, no single treatment technology can currently address wastewater treatment, bioenergy generation, and water reuse in an integrated manner. Among the emerging approaches, MFCs stand out for their ability to support simultaneous wastewater purification and electricity generation. In these systems, electrochemically active bacteria in the anode compartment oxidize organic or inorganic substrates, releasing electrons and protons. The electrons travel through an external circuit to the cathode, generating an electric current, while the protons migrate internally to participate in oxygen reduction (Pham et al., 2006; Aelterman et al., 2006; Oji, Opara & Oduola, 2012). When connected to an external load, this electron flow produces usable electrical energy (Jayendrakishore, Vignesh & Gopalakrishnan, 2012; Patil et al., 2013; Asodariya & Patel, 2011; Deval, Bhagwat & Dikshit, 2014).

In this study, we aim to optimize the operational parameters of Microbial Fuel Cells (MFCs) specifically pH, salt bridge concentration, and electrode materials—to enhance both wastewater treatment efficiency and electricity generation. The innovation of this work lies in its integrated approach to energy recovery from high-strength sugar industry effluents, an area that remains underexplored. By tailoring MFC design to handle the unique chemical profile of sugar wastewater, this research contributes to the development of scalable, cost-effective, and dual-purpose systems for clean energy production and industrial wastewater management. Sugar industry wastewater, in particular, presents a unique challenge due to its high organic load, low pH, high chemical oxygen demand (COD), and the presence of suspended solids. Conventional treatment methods often fall short in energy efficiency and may produce secondary pollutants. MFCs are well-suited to handle such effluents because of their ability to operate under high-strength organic conditions while simultaneously recovering energy. The high sugar and nutrient content of this wastewater makes it an ideal substrate for microbial metabolism, enhancing electricity production and treatment efficiency (Pandey, Shukla & Singh, 2021; Rahimnejad et al., 2021; Ali et al., 2023).

The selection of sugar industry effluent in this investigation is based on its real-world relevance and high potential for bioelectricity generation. Unlike synthetic substrates or laboratory-prepared solutions, actual sugar mill wastewater offers a complex mixture of fermentable organics, making it an excellent test case for assessing MFC feasibility under industrial conditions. This choice reflects the practical goal of evaluating the MFC system's performance in treating a commonly encountered, high-strength agro-industrial effluent. Furthermore, the method aligns with the need for decentralized, energy-positive wastewater treatment systems in rural or semi-urban areas where sugar mills are predominantly located. By focusing on this specific type of effluent, the study addresses a critical gap in sustainable wastewater treatment technologies while highlighting the broader environmental and economic benefits of resource recovery. This study focuses on optimizing critical operational parameters, pH, salt bridge concentration, and electrode materials to improve the dual performance of MFCs in treating sugar industry wastewater and generating electricity. The findings aim to contribute to the development of sustainable and economically viable wastewater treatment technologies that align with current environmental goals.

MATERIALS AND METHODOLOGY

The discharge of waste materials from sugar businesses contributes to the degradation of the environment. India, being a prominent global producer of sugar, is susceptible to generating a substantial quantity of trash from its sugar businesses. The sugar industry generates several unpleasant wastes, including bagasse, ash, molasses, distillery wastes, press mud, and different chemicals (33). The emission of effluent gases, such as sulphur oxides (SOx) and nitrogen oxides (NOx), from industrial stacks can contribute to air pollution, particularly when coal, wood, or bagasse are utilized as fuel sources, particularly within the boiler section. Additional types of trash that can be found in the context of this study are mill house waste and filter cloth washing waste. These waste streams are characterized by elevated levels of biochemical oxygen demand (BOD) and suspended particles. The condenser washings consist of various chemicals employed for the purpose of washing, such as hydrochloric acid, caustic soda, sodium carbonate, and so on. The wastewater treatment process employing a microbial fuel cell involves the use of the following ingredients.

This research holds the potential to address and mitigate the adverse environmental impacts associated with sugar production, contributing to the broader adoption of renewable energy sources. The study is of significant importance due to its potential to offer a sustainable and cost-effective solution for treating sugar wastewater while concurrently generating power. The anticipated benefits extend to various sectors, including the sugar industry, wastewater treatment facilities, and the overall advancement of renewable energy. Additionally, the study has the capacity to provide valuable insights into the potential applications of microbial fuel cells (MFCs) for the treatment of diverse industrial wastewater.

The surface area of the electrode emerges as a crucial factor, with an enlarged surface area facilitating microbial attachment, ultimately leading to increased power production. The utilization of porous materials, such as carbon felt, allows the creation of electrodes with a substantial surface area. Surface treatment plays a pivotal role in enhancing electrode performance by modifying its hydrophilic or hydrophobic properties. This phenomenon can influence the presence of microorganisms on the electrode surface, subsequently impacting their attachment and growth. The geometry of the electrode is another influential factor affecting the performance of the microbial fuel cell (MFC). Various electrode shapes, including flat or tubular configurations, can influence the flow of electrolyte and the adhesion of microbes.

Microbial adhesion and performance can also be affected by the pore size and dispersion of the electrode material. The utilization of materials with consistent pore sizes and distributions holds the potential to enhance the power output of microbial fuel cells (MFCs). In summary, the meticulous selection of electrode materials and the incorporation of design modifications can significantly enhance the operational efficiency of microbial fuel cells.

Wastewater Sampling from Sugar Industry

Wastewater samples were collected from Sanjivani Sahakari Sakhar Kharkhana Ltd., located at Shahajanandanagar, Sanjivani, Kopargaon. Sampling was carried out from the final discharge outlets of the factory. A grab sampling technique was used, with samples collected at regular intervals over three consecutive days to ensure representative characteristics. A total of five samples were taken during operational hours and stored immediately at 4°C to preserve their integrity before analysis. The samples were analyzed on the same day to determine their initial physico-chemical properties, which included pH, BOD, COD, and various solids content. Waste generation in sugar mills also results from operational mishandling such as spillages, leakages, and handling losses of juice, syrup, and molasses. Although the volume from such sources is comparatively low, it contributes significantly to the waste water's high Biochemical Oxygen Demand (BOD) due to the presence of readily biodegradable organic material.

Table 1. Characteristics of the Sugar Industrial wastewater (Yarguddi and Dharme, 2014)

Sr.No.	Parameter	Unit	Value
1	pH	-	4.6 - 7.1
2	BOD (5 days at 20^{0}C)	mg/lit	300 - 2000
3	COD	mg/lit	600 - 4380
4	Total solids	mg/lit	870 - 3500
5	Total volatile solids	mg/lit	400 - 2200
6	Total suspended solids	mg/lit	220 - 800
7	Total nitrogen	mg/lit	10 - 40
8	COD/BOD ratio	-	1.3 - 2.0

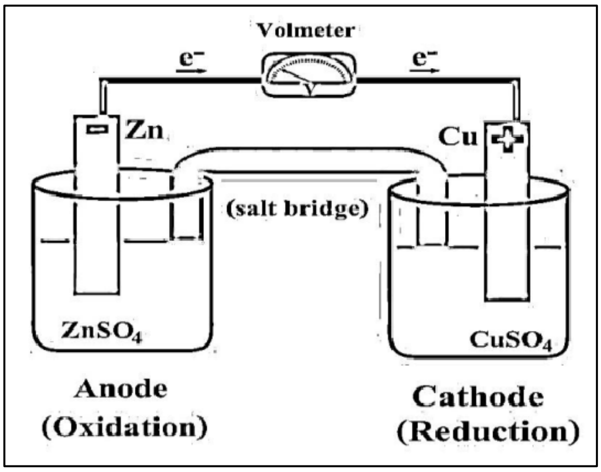

Fig. 1. Schematic diagram of the dual-chamber MFC system

Table 1 presents the characteristics of the combined sugar industry effluent, reflecting high organic loading and variability in composition.

A dual-chamber microbial fuel cell (MFC) was constructed with an anode and cathode connected by an agar–KCl salt bridge and an external circuit (Figure 1). The anode chamber, purged with nitrogen to maintain anaerobic conditions, was filled with inoculated sugar industry wastewater and contained a pre-treated graphite electrode (5 × 5 cm) for biofilm development and substrate oxidation. The cathode chamber, open to air, held a graphite electrode in aerated solution where oxygen served as the terminal electron acceptor. The salt bridge (3% agar with 1M KCl) enabled proton transfer while restricting oxygen diffusion, providing a cost-effective alternative to proton exchange membranes. Electrical output was measured across an external resistor using a digital multimeter for 72 h at room temperature. Analytical-grade reagents were used throughout: KCl and agar for salt bridges; graphite, aluminium, iron, and copper rods as electrodes; distilled water for solution preparation; and fresh sugar industry wastewater as substrate. Oxygen gas was used for chamber purging, while standard APHA methods employing $K_2Cr_2O_7$, FAS, H_2SO_4, and $HgSO_4$ were applied for BOD and COD analyses.

RESULTS AND DISCUSSION

Table 2 displays the recorded values for the initial concentrations of Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). These concentrations are notably higher when compared to the acceptable limits established by the Central Pollution Control Board (CPCB) in India.

The wastewater underwent treatment using a batch mode operation, employing both isolated and mixed adsorbent carbon. The amounts of BOD and COD were determined prior to and during treatment with the adsorbent. The study focused on several key operating factors, including adsorbent dosage, pH

Table 2. Initial characteristics of Sugar industry wastewater

Sr. No.	Parameters	Values	Unit
1	Physical Colour	Greenish grey	-
2	Odour	Unobjectionable	-
3	pH	10.2	-
4	Temperature	24	0C
5	BOD5,	2515	mg/lit
6	COD	6820	mg/lit
7	DO	Absent	mg/lit
8	Alkalinity	930	mg/lit
9	Chlorides	580	mg/lit
10	Total Solids	1520	mg/lit
11	Total Nitrogen	18	mg/lit

of the medium, treatment duration of the adsorbent, and agitation speed

Sugar Industry

A study is done on the effect of pH, treatment time and agitation speed on percentage reduction of BOD and COD, different types of electrodes leading to variable output of current, the molar concentration of salt bridge leading to different current variables in MFC for sugar industry wastewater sample, respectively. The results obtained for different parameters are as follows.

Effect of pH for Sugar wastewater

1. The effect of pH (1–12, step 1) on BOD and COD reduction was evaluated at a fixed treatment time of 180 min. Maximum removal efficiencies of 92.26% (BOD) and 94.08% (COD) occurred at pH 4, where abundant H^+ ions enhanced proton transfer and microbial metabolism. Above pH 6, excess OH^- suppressed proton availability and inhibited electroactive bacteria, lowering performance. Unlike domestic-waste MFCs that function optimally near neutral pH (6.5–7.5), sugar industry effluents favor acidic conditions due to their inherent low pH and high sugar load. Consistent with earlier reports (Yarguddi and Dharme, 2014). Fuel cell technology: A review. *International Journal of Innovative Research in Science, Engineering and Technology, 3*(7), 14668–14673.

, acidophilic exoelectrogens dominate in this environment, yielding peak efficiencies at pH 3–5. Thus, maintaining slightly acidic conditions is critical for maximizing both pollutant removal and bioelectricity generation in sugar-wastewater MFCs.

The Figure. 2. Illustrates how varying pH levels from 1 to 12 influence the efficiency of BOD and COD reduction using a microbial fuel cell (MFC). Maximum removal was achieved at pH 4, with BOD reduction of 92.26% and COD reduction of 94.08%, indicating that slightly acidic conditions favor microbial activity and electron transfer in sugar wastewater treatment. As the pH increased beyond 6, the efficiency declined gradually. For example, at pH 7, BOD and COD reduction dropped to 81.01% and 86.24%, respectively, while at pH 12, the reductions further decreased to 62.12% (BOD) and 71.46% (COD). This trend confirms that mildly acidic conditions (pH 3–5) are optimal for effective pollutant removal in MFCs treating high-organic sugar industry effluent.

Effect of Salt Bridge Molar Concentration on Current Output for Sugar Wastewater

The performance of a microbial fuel cell (MFC) is significantly influenced by the molar concentration of the salt bridge, which plays a crucial role in facilitating ion migration between the anode and cathode chambers. Table 4 presents the current output values over 21 days for different concentrations of KCl in the salt bridge (1 mM to 9 mM), and Table 4 presents the data pertaining to the impact of the molar

Table 3. Effect of pH on BOD and COD Reduction by MFC for Sugar Industry Wastewater.

Sr no	pH	Initial BOD (mg/l)	Initial COD (mg/l)	Final BOD (mg/l)	Final COD (mg/l)	BOD Reduction (%)	COD Reduction (%)
1	1	2610	6960	201.84	489	82.64	88.24
2	2	2610	6960	180.51	500	86.24	90.46
3	3	2610	6960	370.90	486	90.24	93.01
4	4	2610	6960	308.25	412	92.26	94.08
5	5	2610	6960	234.71	495	91.00	92.97
6	6	2610	6960	236.82	708	84.19	89.82
7	7	2610	6960	495.56	986	81.01	86.24
8	8	2610	6960	700.88	1213	73.14	82.57
9	9	2610	6960	752.62	1324	71.63	80.97
10	10	2610	6960	680.87	1445	69.34	79.23
11	11	2610	6960	900.00	1854	65.51	73.36
12	12	2610	6960	986.86	1986	62.12	71.46

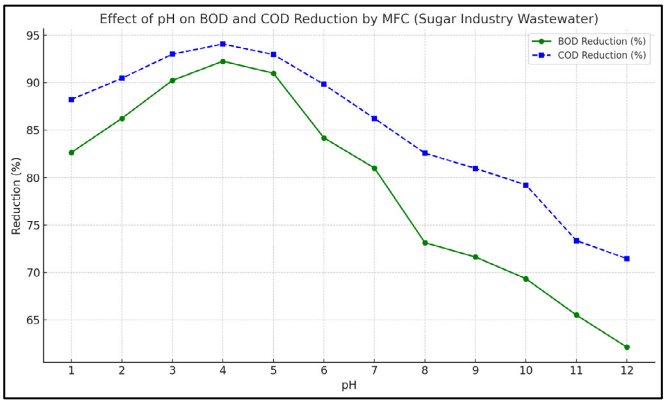

Fig. 2. Effect of pH on BOD and COD Reduction by MFC for Sugar Industry Wastewater.

concentration of the salt bridge in microbial fuel cells (MFCs) within the context of the sugar sector.

As shown in Figure 3, the MFC with a 1 mM KCl salt bridge consistently achieved the highest current output, peaking at 255 mA between days 8–11 and remaining superior to all other concentrations throughout the cycle. Moderate outputs were obtained with 3 mM (182 mA) and 5 mM (165 mA), while 7 mM and 9 mM bridges produced markedly lower currents, with 9 mM declining to 10 mA by day 21. The results confirm that moderate ionic strength improves proton transfer and lowers internal resistance, but higher concentrations reduce efficiency due to ion competition, osmotic stress on microbes, and salt precipitation or fouling. Thus, 1 mM KCl is identified as the optimal salt bridge concentration for sugar wastewater MFCs, balancing ionic conductivity and microbial activity.

Electrode variation studies further revealed that electrode material strongly influences electrochemical performance. Among the four anode materials tested against a graphite cathode, the carbon–carbon (C–C) configuration delivered the highest voltage (2.398 V on day 9), followed by Al–C (2.228 V), while Cu–C (1.795 V) and Fe–C (1.805 V) performed poorly. These findings align with prior reports highlighting the superior stability and biofilm affinity of carbon-based electrodes (Ali et al., 2023). Post-operation weight analysis confirmed this trend: aluminium and graphite remained stable, whereas copper and iron lost 7 g and 13 g, respectively, due to microbial or chemical corrosion. Such corrosion not only decreases electron recovery but also releases inhibitory metal ions into the anolyte (Pandey et al., 2021). Collectively, the results underscore the superior performance of carbon electrodes for sustained operation, while also pointing to the need for further studies on current generation from corrosion-driven

Table 4. Effect of Molar concentration of Salt Bridge on current output in volts across 10 ohms external resistance in Microbial Fuel Cell for sugar industry

Sr. no.	Days	1mM	3mM	5mM	7mM	9mM
		Current in mA across 10-ohm ext resistance				
1	1	148	110	95	55	40
2	2	150	116	110	62	45
3	3	165	128	123	70	47
4	4	175	140	130	80	49
5	5	200	152	137	95	52
6	6	210	170	145	97	52
7	7	250	173	155	100	52
8	8	255	182	165	105	52
9	9	255	182	165	105	52
10	10	255	182	165	105	52
11	11	255	182	165	105	52
12	12	245	182	158	105	52
13	13	230	182	153	100	52
14	14	220	182	148	92	45
15	15	200	176	130	87	40
16	16	190	170	128	73	40
17	17	182	165	122	71	35
18	18	177	160	119	70	30
19	19	169	154	108	63	22
20	20	153	145	98	59	11
21	21	151	130	90	40	10

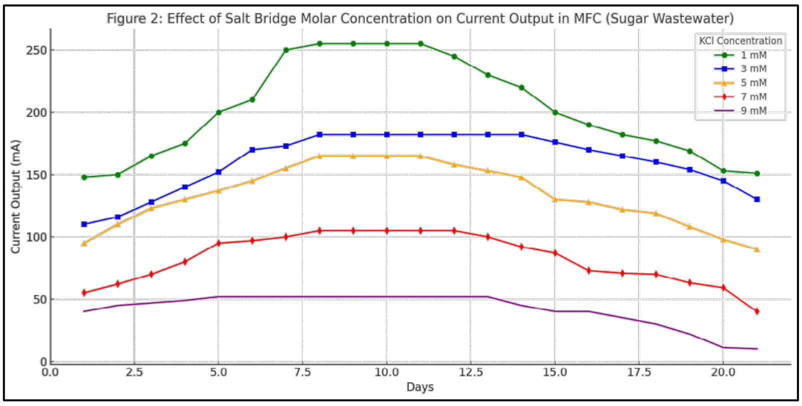

Fig. 3. Effect of the molar concentration of KCl in salt bridge on current output

processes in metal electrodes. The findings imply the need for further research to explore potential current generation resulting from chemical and/or microbial corrosion in metal electrodes. It's noteworthy that the aluminium and graphite electrodes exhibited minimal corrosion, evidenced by consistent weights before and after the operation, as detailed in Table 5.

Table 5 presents the electrode weights before and after operation in the microbial fuel cell (MFC), providing insight into the corrosion resistance and stability of the tested materials. Among the four materials Aluminium (Al), Carbon (C), Iron (Fe), and Copper (Cu), aluminium exhibited no weight loss, indicating excellent corrosion resistance during the MFC process. Carbon showed minimal weight loss of 1 g, confirming its high stability and suitability as an electrode material. In contrast, iron and copper showed significant degradation, with weight losses of 13 g and 7 g, respectively, suggesting

Table 5. Electrode Weights Before and After MFC Operation

Sr No.	Material	Initial Weight (g)	Final Weight (g)	Weight Loss (g)
1	Al	100	100	0
2	C	89	88	1
3	Fe	120	107	13
4	Cu	110	103	7

Table 6. The Potential Difference across the Carbon and Carbon Electrodes

Anode and Cathode	Time(Days)	Voltage (V)
C-C	0	1.655
	1	1.750
	2	1.795
	3	1.830
	4	1.920
	5	1.985
	6	2.220
	7	2.325
	8	2.380
	9	2.398
	10	2.375

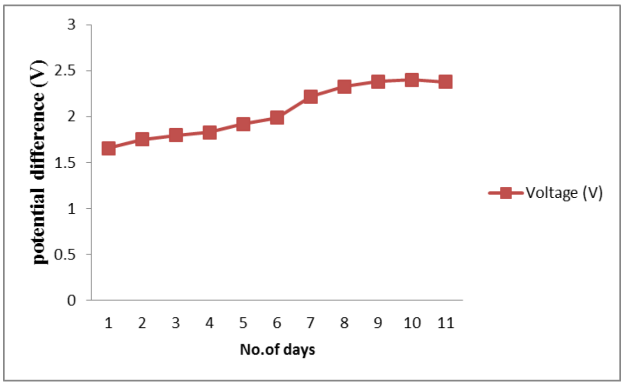

Fig. 4. The impact of Aluminium and carbon electrodes on the current output in the Microbial Fuel Cell (MFC).

higher susceptibility to corrosion and potential leaching of metal ions into the system. These results reinforce the suitability of carbon and aluminium as durable electrodes for long-term MFC applications and highlight the need for corrosion-resistant strategies when using metal electrodes like iron or copper. The performance of the fuel cell is evaluated by measuring voltage and power output.

Table 6 displays the potential difference generated across the Carbon–Carbon (C–C) electrode pair in a microbial fuel cell (MFC) over a 10-day experimental period. The voltage output shows a consistent upward trend from 1.655 V on day 0 to a maximum of 2.398 V on day 9, followed by a slight decline to 2.375 V on day 10. This steady increase indicates strong electrochemical performance, highlighting carbon electrodes' excellent conductivity, large surface area, and biocompatibility that support sustained microbial activity and efficient electron transfer. The minimal voltage drop after peak output suggests stability and low susceptibility to fouling or degradation, making the C–C electrode combination the most effective among those tested for continuous power generation in MFCs treating sugar industry wastewater.

Figure 4. Illustrates the variation in potential difference (voltage) across the Aluminium–Carbon

(Al–C) electrode pair in a microbial fuel cell (MFC) over 11 days. The voltage output shows a steady increase from around 1.6 V on day 1 to a peak of approximately 2.398V on day 9, followed by a slight plateau. This trend indicates that the Al–C combination effectively supports microbial activity and electron transfer, particularly during the initial operational period. However, the voltage stabilization after day 9 may suggest a saturation point in microbial performance or minor surface passivation of the electrodes. The graph demonstrates that Aluminium–Carbon electrodes offer good electrical output and corrosion resistance, making them a viable alternative in MFCs treating sugar industry wastewater, though further optimization for long-term use is warranted.

Table 7 presents the variation in potential difference (in volts) across the Copper–Carbon (Cu–C) electrode pair in a microbial fuel cell (MFC) over a period of 10 days. The voltage steadily increased from 1.200 V on day 0 to a peak of 1.795 V on day 9, followed by a slight decline to 1.760 V on day 10. This trend indicates that copper electrodes can support microbial activity and electron transfer reasonably well in the early stages. However, the decline after day 9 may be attributed to surface passivation, corrosion, or the toxic effect of copper ions on the microbial consortia. While Cu–C electrodes show moderate performance, the results suggest limitations in long-term stability, making them less suitable for prolonged MFC applications without protective treatment or modification.

From Figure 5 depicts the trend in potential difference (voltage) generated across the Carbon–Carbon (C–C) electrode pair in a microbial fuel cell (MFC) over a 10-day operational period. The voltage output increased consistently from 1.0 V on day 1 to a maximum of approximately 2.55 V on day 10, indicating a strong and sustained electron transfer process. This continuous upward trend reflects the superior conductivity and biocompatibility of carbon electrodes, which promote effective microbial colonization and electrochemical activity. The results confirm that the C–C combination provides the most efficient

Table 7. The Potential Difference across the Copper and Carbon Electrodes

anode and cathode	Time (Days)	Voltage (V)
Cu-C	0	1.200
	1	1.285
	2	1.320
	3	1.400
	4	1.470
	5	1.550
	6	1.610
	7	1.695
	8	1.775
	9	1.795
	10	1.760

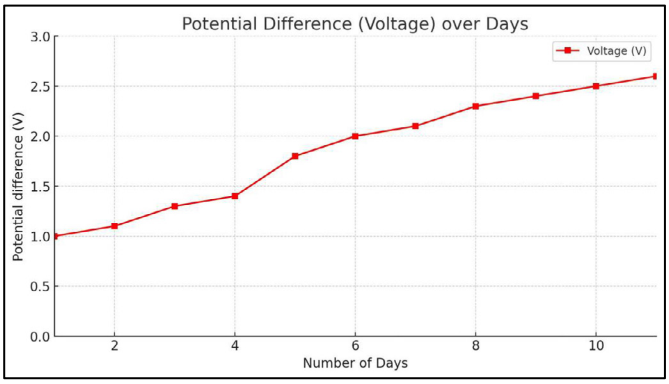

Fig. 5. The Impact of Copper and carbon electrodes on the current output in the Microbial Fuel Cell (MFC).

Table 8. The Potential Difference across the Iron and Carbon Electrodes

anode and cathode	Time(Days)	Voltage (V)
Fe-C	0	1.400
	1	1.475
	2	1.510
	3	1.570
	4	1.560
	5	1.595
	6	1.655
	7	1.705
	8	1.775
	9	1.805
	10	1.780

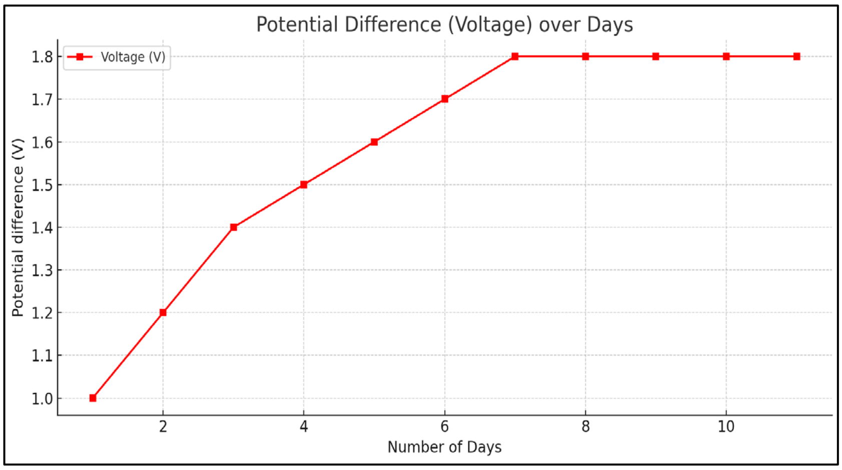

Fig. 6. The Impact of Iron and carbon electrode on current output by MFC

performance among tested electrode materials for electricity generation in MFCs treating sugar industry wastewater. This makes it a highly favorable choice for long-term and large-scale bio-electrochemical applications.

Table 8 presents the potential difference generated across the Iron–Carbon (Fe–C) electrode pair in a microbial fuel cell (MFC) over a 10-day period. The voltage increased gradually from 1.400 V on day 0 to a maximum of 1.805 V on day 9, followed by a slight decrease to 1.780 V on day 10. This trend reflects moderate and stable performance, suggesting that iron can support microbial activity and electron transfer, albeit less efficiently than carbon-based electrodes. The voltage plateau and eventual decline may indicate early signs of electrode surface fouling or corrosion, which could inhibit long term stability. These findings emphasize the need for further assessment of Fe–C electrode durability and its suitability for prolonged use in MFC applications.

Figure 6 illustrates the variation in potential difference (voltage) over time across the Iron–Carbon (Fe–C) electrode pair in a microbial fuel cell (MFC). The voltage steadily increased from 1.0 V on day 1 to a peak of 1.8 V by day 7, after which it plateaued and remained stable through day 10. This trend suggests that the Fe–C combination supports microbial activity and electron transfer effectively during the initial operational period. However, the leveling off indicates that the system may have reached a saturation point in microbial growth or electrode efficiency. The stable voltage after day 7 implies good short-term performance, though potential long-term issues such as electrode passivation

Table 9. The Potential Difference across the Aluminium and Carbon Electrodes

Anode and Cathode	Time (Days)	Voltage (V)
Al-C	0	1.586
	1	1.610
	2	1.685
	3	1.710
	4	1.808
	5	1.887
	6	1.973
	7	2.023
	8	2.185
	9	2.228
	10	2.160

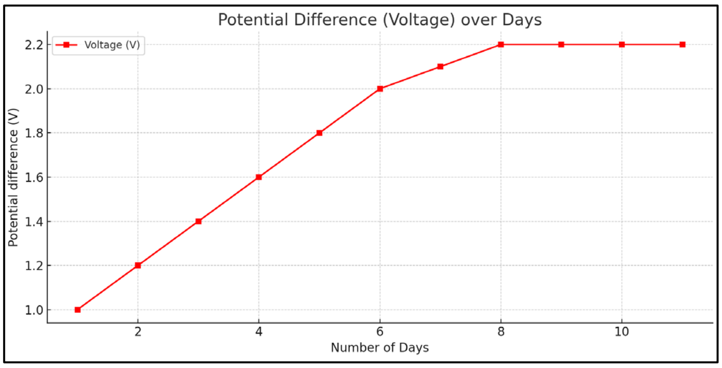

Fig. 7. The Impact of Aluminum and Carbon Electrode on Current Output by MFC

or microbial equilibrium may limit further gains in output. The graph underscores the importance of continuous monitoring and optimization of electrode materials in MFC applications for wastewater treatment.

Table 9 shows the potential difference across the Aluminium–Carbon (Al–C) electrode pair in a microbial fuel cell (MFC) over a 10-day experimental period. The voltage output increased steadily from 1.586 V on day 0 to a peak of 2.228 V on day 9, before slightly declining to 2.160 V on day 10. This trend indicates the effective electron transfer capability of the Al–C configuration during the early and middle stages of operation. However, the gradual decline after day 9 suggests possible limitations due to electrode surface passivation or microbial activity stabilization. Overall, the Al–C pair demonstrated good performance and potential as a cost-effective electrode combination in MFCs for sugar industry wastewater treatment.

Figure 7 shows the graphical representation of the Effect of Aluminum and carbon electrodes on current output by MFC. As a result, it can be deduced that no background current was present throughout the operation. Two significant observations are noted in this study. Firstly, the emergence of a background current is detected. Secondly, the impact of dissolved metal ions on the bacterial consortia, responsible for electron production, is demonstrated, particularly in the cases of copper and iron. It is essential to approach these findings with caution due to the extended duration of the experiment, necessitating further investigation into the modification of electrode materials.

During this operational phase, the measured potential difference across a 10-ohm resistance varied between 135mV and 239.5mV. The weights of the electrodes were measured both before and after the operation.

Comparative Study of Different Electrodes used in the above Studies

The collected data is systematically gathered and employed to construct a graph, illustrating the efficacy with the primary objective of identifying the electrode pair that produces the highest output. Based on the insights derived from Figure 7, it is evident that the C-C configuration results in the highest voltage. To conduct a comparative analysis of the potential difference across various electrodes, it is crucial to establish a comprehensive understanding of the fundamental concept of electrode potential. Electrode potential signifies the inherent tendency of an electrode to undergo either electron gain or loss when connected to another electrode within an electrochemical cell. The voltage across two electrodes in an electrochemical cell acts as the driving force for the movement of electrons, a phenomenon that can be quantified through the use of a voltmeter.

Table 10. presents a comparative analysis of the potential difference (in volts) across various electrode combinations—Carbon–Carbon (C–C), Iron–Carbon (Fe–C), Aluminium–Carbon (Al–C), and Copper–Carbon (Cu–C)—over a 10-day period. The data highlight the superior performance of the C–C electrode pair, which consistently generated the highest voltage, peaking at 2.398 V on day 9. This was followed by the Al–C pair (2.228 V), Cu–C (2.185 V), and Fe–C (1.795 V). The trend illustrates that carbon electrodes not only provide better electrical conductivity but also maintain more stable voltage outputs over time. The results underscore the critical role of electrode material in optimizing microbial fuel cell (MFC) performance for sugar industry wastewater treatment.

Figure.8 shows the comparison of potential differences across different electrode pairs, namely C-C, Cu-C, Fe-C, and Al-C. In each case, a metal electrode is paired with a carbon electrode within

Table 10. The comparative study of the Potential Difference across different electrodes

Days	**C-C**	**Fe-C**	**Al-C**	**Cu-C**
	Current in volts			
0	1.655	1.200	1.400	1.586
1	1.750	1.285	1.475	1.610
2	1.795	1.320	1.510	1.685
3	1.830	1.400	1.570	1.710
4	1.920	1.470	1.560	1.808
5	1.985	1.550	1.595	1.887
6	2.220	1.610	1.655	1.973
7	2.325	1.695	1.705	2.023
8	2.380	1.775	1.775	2.185
9	2.398	1.795	1.805	2.228
10	2.375	1.760	1.780	2.160

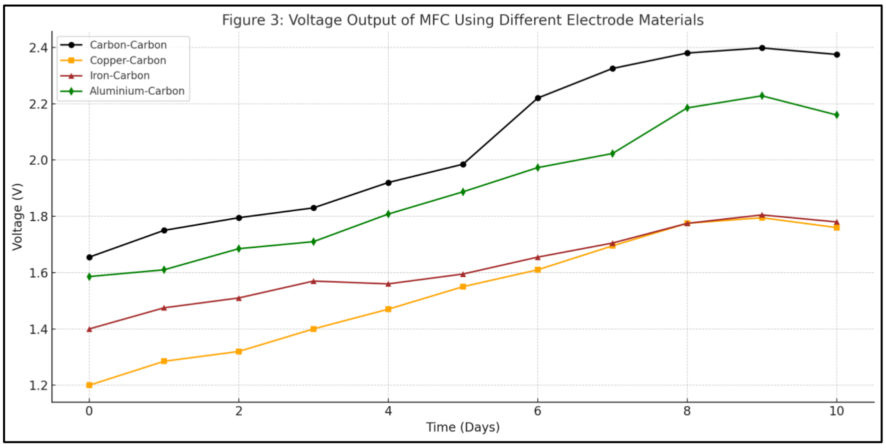

Fig. 8. Comparative study of different electrodes producing current output by MFC for the sugar industry

the electrochemical cell. Carbon, categorized as a non-metal, lacks the capacity to undergo oxidation or reduction processes. Therefore, it can be inferred that there is no potential difference between two carbon electrodes. The values thus obtained are listed below,

C–C: Peak 2.398 V
Al–C: Peak 2.228 V
Fe–C: Peak 1.805 V
Cu–C: Peak 1.795 V

In summary, the observed potential difference among the various electrode combinations can be ranked in the following order based on experimental findings: C-C > Al-C > Fe-C >Cu-C.These findings underscore the long-term advantages of carbon-based electrodes in MFC systems, particularly for acidic, high-COD wastewaters like those from the sugar industry. While metals may offer initial cost or conductivity benefits, their susceptibility to corrosion, ion leaching, and biofilm disruption limits their sustainability.

CONCLUSION

Microbial fuel cells (MFCs) demonstrate strong potential as sustainable systems capable of simultaneously treating high-strength industrial effluents and generating renewable electricity. Their integration into conventional wastewater treatment frameworks can transform energy-intensive processes into energy-positive operations.

In this study, several critical findings were established:

- Pollutant removal efficiency: BOD and COD reductions reached 92.26% and 94.08%, respectively, under optimized acidic conditions (pH 4), highlighting the role of proton availability in enhancing microbial activity and electron transfer.
- Salt bridge concentration: A 1 mM KCl bridge produced the highest current output (2.55 V), whereas higher concentrations impaired performance due to ion competition, osmotic imbalance, and fouling.
- Electrode material influence: The carbon–carbon (C–C) configuration achieved the maximum voltage (2.398 V) and long-term stability, outperforming Al–C, Fe–C, and Cu–C pairs.
- Corrosion assessment: Minimal degradation was observed for carbon and aluminium electrodes, while copper and iron exhibited significant weight loss (up to 13 g), suggesting corrosion-driven inhibition and reduced durability.

Overall, the results confirm the viability of MFCs for sugar industry wastewater treatment, with optimal performance achieved under acidic pH, low KCl concentration, and carbon-based electrodes. These conditions maximize pollutant removal, electricity generation, and system stability, providing a foundation for future upscaling and industrial deployment.

Limitations

While the study demonstrates the promising application of microbial fuel cells (MFCs) for treating sugar industry wastewater and generating electricity, several limitations exist. The experiments were conducted at a laboratory scale with batch operations, limiting the direct scalability to industrial settings. The study duration was relatively short (up to 21 days), restricting insights into long-term stability, electrode fouling, and microbial community dynamics. Additionally, the influence of fluctuating wastewater characteristics typical in real-world sugar mills was not evaluated. Future research must address these constraints through pilot-scale studies, continuous flow systems, and extended monitoring to validate real-time applicability and economic feasibility.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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