Larhyss Journal, ISSN 1112-3680, n°64, Dec 2025, pp. 135-156

PROCESS OPTIMIZATION OF MICROBIAL FUEL CELL FOR STARCH INDUSTRIAL WASTEWATER TREATMENT

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Research Article – Available at http://larhyss.net/ojs/index.php/larhyss/index
Received January 28, 2025, Received in revised form November 24, 2025, Accepted November 26, 2025

ABSTRACT

A microbial fuel cell (MFC) is a bio electrochemical process that utilizes the metabolic activity of microorganisms to treat wastewater and generating electricity at the same time. The starch industry generate wastewater with a significant amount of organic load, creating environmental concerns. This study explores the application of a MFC for starch industrial wastewater treatment and electricity generation. A mediator-free MFC was created with graphite electrodes, active anaerobic sludge as the microbial culture, and a salt bridge containing agar-KCl solution. The system was optimized by varying microbial culture dose (7.5%, 10%), KCl concentration (1M, 2M, 4M), and seasonal temperature (14 ^{0}C,16 ^{0}C, 28 ^{0}C). The MFC process optimization results showed that the highest COD reduction (87%) was noted with 200 mg/L (10%) microbial culture dose and 2M KCl at 28°C. In contrast, the highest electricity generation (0.6 V) was noted at 150 mg/L (7.5%) microbial culture dose and 4M KCl at 16°C. Increasing KCl concentration in the salt bridge gives improved electricity generation as well as higher microbial dose also gives enhanced COD reduction efficiency and reduced optimization period. This study offers dual benefits of MFCs for electricity generation and sustainable wastewater treatment.

Keywords: Microbial Fuel Cell, Anaerobic Culture, Salt Bridge, Electricity Generation, COD Reduction.

INTRODUCTION

Wastewater treatment is a cornerstone of sustainable water management (Bahir et al., 2015; Pandey et al., 2022; Qureshi et al., 2024), public health protection (Baba Hamed, 2021), and environmental preservation. As global populations increase and urbanization accelerates (Jelisavka et al., 2019; Remini, 2020a; 2020b; 2020c), the generation of domestic, industrial, and agricultural effluents has reached unprecedented levels, placing enormous pressure on natural aquatic systems. The effective treatment and valorization of these effluents are therefore vital to prevent surface- and groundwater pollution (Saadi et al., 2014; Bouchemal and Achour, 2015; Belhadj et al., 2017; Zegait et al., 2021; Lachache et al., 2023), preserve ecosystems, and promote the reuse of treated water in irrigation (Jelisavka and Goran, 2018), agriculture, and industry (Chauhan and Dikshit, 2023).

Society is increasingly shifting toward sustainable and renewable energy technologies in response to critical environmental challenges such as climate change and its impact on water resources (Nakou et al., 2023; Chadee et al., 2023; Mah et al., 2024), air pollution, and the depletion of fossil fuel resources (Nichane and Khelil, 2015; Pang and Tan, 2023; Remini, 2020d; Remini, 2024). Microbial Fuel Cells (MFCs) represent an innovative bio-electrochemical technology that combines principles from microbiology, electrochemistry (Sbai and Loukli, 2015), and environmental engineering. This approach offers a dual benefit: effective wastewater treatment and the generation of clean, sustainable energy. MFCs have attracted considerable attention for their ability to simultaneously degrade organic pollutants (Aw et al., 2016) and produce electricity (Long et al., 2023), positioning them as a promising alternative to traditional treatment methods (Logan et al., 2008; Rabaey and Verstraete, 2005; Pant et al., 2010; Gaouar and Gaouar, 2016).

MFC utilizes the electrochemically active bacteria, which oxidize organic matter at the anode, releasing electrons and protons. Then the generated electrons are transferred to the cathode through an external circuit, generating electricity, while protons pass through salt bridge to the cathode where they react with oxygen (or other electron acceptors) to form treated water (Logan, 2008; Du et al., 2007). The electron transfer mechanisms incorporate mediated transport, direct transfer by cytochromes, and wire-based conduction, depending on the microbes involved (Lovley, 2006; Rabaey et al., 2007).

Unlike anaerobic digesters that produce methane, MFCs primarily generate carbon dioxide and electricity, offering a cleaner and safer option for gas emissions (Franks and Nevin, 2010; Ieropoulos et al., 2013). MFCs have demonstrated versatility in treating a broad spectrum of substrates, ranging from simple compounds like glucose and acetate to complex industrial wastewaters. This capability has been validated in various MFC configurations, including both single-chamber and dual-chamber systems (Min et al., 2005; Wang et al., 2015).

MFC can be categorized into various types based on their design and operational approaches, like single-chamber, dual-chamber, mediator-based, and mediator-free systems. Dual-chamber MFCs, which feature separate anodic and cathodic compartments connected by a proton exchange membrane or salt bridge, are usually used in laboratory research due to their ability to maintain controlled environmental conditions (Min et al., 2005). In contrast, single chamber MFCs offering a simpler and cost-effective approach by eliminating the cathodic chamber, making it more suitable for practical, scalable solutions for real world application (Liu et al., 2004). Furthermore, mediator-free MFCs utilize electroactive bacteria capable of directly transferring electrons to the electrode surface, thereby eliminating the need for synthetic electron mediators, which are costly as well as environmentally hazardous (Lovley, 2006).

Mediator MFC technology uses artificial electron shuttles (i.e. mediators) to transfer electrons from microbial cells to the anode, improving the electron flow and energy generation. The previous studies assessed mediator MFCs for improving power densities and wastewater treatment efficiency, especially when coupled with innovative electrode and reactor designs (Mahmoud et al., 2022; Wang et al., 2022; Ambaliya Sanjay et al., 2024). The recent study demonstrated the biomass driven MFCs have improved applicability with mediators, enabling the utilization of varied organic feedstocks while maintaining consistent electron transfer rates (Moradian et al., 2021).

The starch processing industry, one of the largest contributors to industrial wastewater (Randika et al., 2022; Aroua-Berkat and Aroua, 2022; Zaidi et al., 2023; Swarnakar et al., 2023; Mumthaj et al., 2023). It is expected to generate 10-20 m^3 of wastewater per ton of starch production. The COD values usually from 5,000 to 50,000 mg/L in the generated wastewater (Zhang et al., 2019). The energy consumption for the treatment of 10 m^3 starch wastewater with conventional methods is around 8,500 kWh/day, which is quite costly and unsustainable (Mohan et al., 2008).

According to the Water Prevention and Control of Pollution Act of 1974 - India's principal legislation regulating water pollution - industries are required to treat their wastewater before discharging it into any environmental sink. MFCs offer a cost effective, sustainable, and viable option to meet legal discharge norms, contributing to circular economy (Cheng et al., 2006). Moreover, MFC is also suitable option for decentralized wastewater treatment in rural and peri-urban areas (Zhou et al., 2011; Zhang et al., 2020).

This study assesses the process optimization of a lab-scale mediator free MFC for starch industry wastewater treatment. The research aims to investigate the varied concentration of KCl in the salt bridge preparation, microbial culture, and temperature on the COD reduction and electricity generation. The outcomes are expected to contribute to the low-cost, energy-efficient treatment process for starch industry wastewater treatment.

The adopted approach of mediator-free MFC system addresses key societal needs by combining efficient wastewater treatment with clean energy generation, without relying on synthetic electron mediators. This approach is economic, environmentally friendly and eliminates the chemical handling and operational complexity. This wastewater treatment approach can be more suitable in rural and peri-urban areas, which leads to enhanced resource recovery and public health, while supporting a circular economy. This study's approach aligns with the broader concept of streamlining existing systems and improving their overall efficiency (Chadee et al., 2021). The mediator-free design also supports this idea by offering a reliable and scalable technology that does not depend on fragile or costly components, making it easier to apply in real-world situations.

The selection of parameters for analysis or optimization was based on their direct and significant impact on both starch wastewater treatment efficiency and energy generation in mediator-free MFCs. Microbial culture dose, salt bridge concentration, and operating temperature were chosen as they strongly affect microbial activity, internal resistance, and proton conductivity, three critical parameters affecting COD removal and energy generation. In mediator-free MFC, where no artificial electron mediators are used, these parameters become even more critical to enhance natural electron transfer mechanisms. Optimizing these parameters not only improves system performance but also supports scalability, making the technology more adaptable for industrial wastewater treatment and decentralized applications.

This study presents a novel approach to utilize the of active anaerobic sludge in a mediator-free MFC process for the treatment of starch industry wastewater while simultaneously generating electricity. By optimizing key operational parameters i.e. microbial culture dose (7.5%, 10%), salt bridge conc. (KCl -1M, 2M, 4M), and ambient temperature (14 ^{0}C,16 ^{0}C, 28 ^{0}C), his work contributes to the development of low-cost, energy-efficient, and sustainable wastewater treatment technologies. The approach aligns with the United Nations Sustainable Development Goals by promoting clean water and sanitation (SDG 6) and enabling affordable and clean energy (SDG 7) through renewable bio electrochemical processes.

MATERIAL AND METHODS

Microbial Fuel Cell lab set up

A laboratory-scale, mediator-free MFC was designed and fabricated to evaluate the treatment efficiency of starch industry wastewater and electricity generation. The MFC consisted of two compartments, anodic and cathodic chambers, constructed using locally available 2.5 L plastic containers. Each chamber was connected via a salt bridge for proton exchange and an external circuit for electron transfer. Table 1 gives the salient features of the lab scale MFC set up. Fig. 1a highlights the MFC set up and Fig. 1b gives the actual photo of the experimental work.

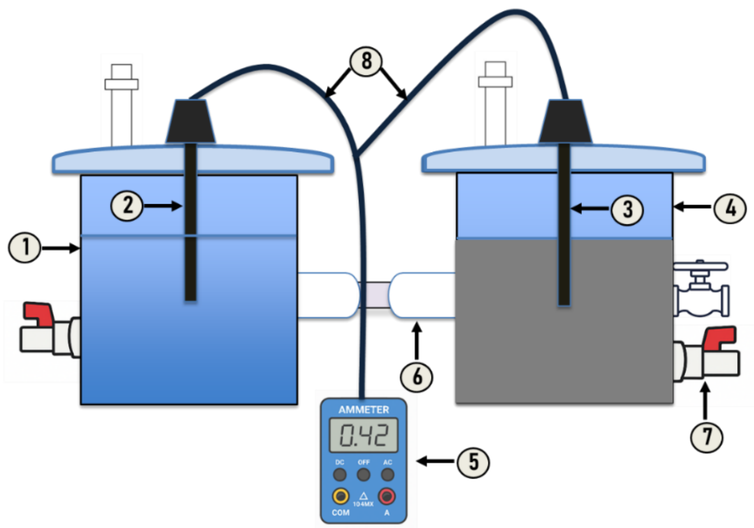
Table 1: Specifications of the lab-scale MFC Setup

Parameters	Descriptions
Type of MFC	Mediator-free microbial fuel cell
Fuel cell compartments	Anodic and cathodic chambers constructed using locally available 2.5 L plastic containers
Electrodes	Graphite rods used as electrodes in both chambers, each with a length of 200 mm and a diameter of 10 mm
Anodic chamber	Filled with 2 L of starch industry effluent
Substrate	Active anaerobic sludge from a working UASB reactor used as the microbial inoculum

Cathodic chamber	Filled with 2 L of 70 mM NaCl solution
Salt bridge	Constructed using a PVC pipe (60 mm diameter × 120 mm length), filled with 10% agar-agar gel mixed with varying concentrations of KCl
External circuit	An external electrical circuit was completed using alligator clips to connect the electrodes and measure voltage output via a digital multimeter

Electrode configuration

Graphite rods were used as electrodes in both chambers due to their high conductivity, stability, and non-toxic nature. Each electrode had a length of 200 mm and a diameter of 10 mm. The electrodes were immersed vertically into the respective chambers and connected externally using alligator clips to complete the circuit and enable the flow of electrons from the anode to the cathode.



Legend

1: Cathodic chamber (NaCl solution)
2: Graphite electrode (cathode)
3: Graphite electrode (anode)
4: Anodic chamber (Starch industrial wastewater)
5: Anemometer
6: Salt Breeze
7: Sampling port
8: Alligator clip wires

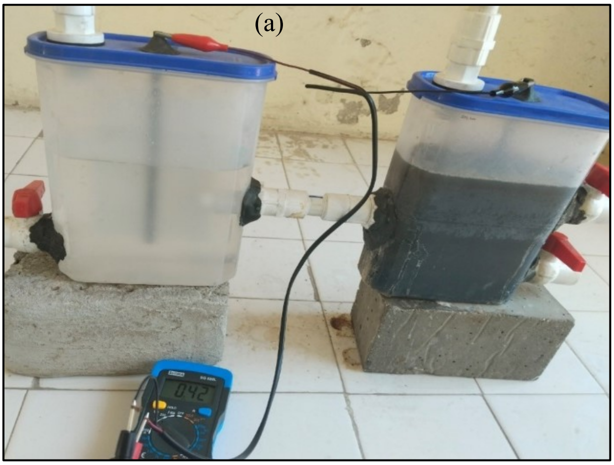


Figure 1: MFC experimental set up. (a) Schematic diagram; (b) Actual photo during the experimental work

Anodic chamber setup

The anodic chamber was filled with 2 L of starch industry wastewater. The characteristics of the collected starch wastewater for various parameters, along with their standard deviations, are given in Table 2. To initiate microbial activity, anaerobic sludge from a functioning UASB reactor was added as the microbial inoculum. The noted values of MLSS and MLVSS are 46,422 mg/L and 23,120 mg/L, respectively, for collected UASB sludge. The sludge served as the electron donor and facilitated the oxidation of organic compounds in the wastewater.

Table 2: Characteristics of the collected starch wastewater

Sr. No.	Parameters	Value
1	COD	40,765±541 mg/l
2	BOD	27,555±302 mg/l
3	MLSS	24,466±325 mg/l
4	MLVSS	18,349±321 mg/l
5	pH	6.7±0.4

Cathodic chamber setup

The cathodic chamber was filled with 2 L of 70 mM NaCl solution, which acted as the electrolyte and electron acceptor medium. The purpose of the cathodic solution was to receive protons transported through the salt bridge and allow reduction reactions at the cathode, primarily involving dissolved oxygen from the air.

Creation of salt bridge

A salt bridge was created to allow proton transfer between the anodic and cathodic chambers. It was prepared using a PVC pipe with a diameter of 60 mm and length of 120 mm. The salt bridge was filled with a gel composed of agar-agar and potassium chloride (KCl) to ensure ionic conductivity while preventing bulk mixing of fluids between the two chambers. The concentration of KCl in the salt bridge was varied (1M, 2M, 4M) during experiments to assess its effect on electricity generation.

Process optimization of MFC under varied operation conditions

The process optimization of performance of the MFC was done by systematically varying key operational parameters like microbial culture dose (i.e. anaerobic sludge- 7.5%, 10%), temperature (14 ^{0}C,16 ^{0}C, 28 ^{0}C), and salt concentration in the salt bridge (KCl conc.- 1M, 2M, 4M). These experiments were conducted in a lab-scale setup to evaluate their effects on %COD reduction and electricity generation (V) using starch industry wastewater as the substrate (Dhakal, 2015; Hazan, 2023).

Microbial culture dose

To investigate the impact of microbial culture loading, two different doses of anaerobic sludge from a working UASB reactor were introduced into the anodic chamber: 7.5% (150 mg/L) and 10% (200 mg/L). No external mediators were used in the anodic chamber, allowing for a mediator-free electron transfer environment (Pant et al., 2010, Xu et al., 2015). The objective was to examine whether an increased microbial population enhances the degradation of organic matter and improves electron transfer efficiency.

Effects of temperature

To simulate seasonal variations, the MFC units were operated during winter (Nov–Jan) and summer (Mar–Apr) months, representing temperature ranges of 14°C to 28°C. These conditions allowed evaluation of the temperature-dependent activity of anaerobic microbes and their impact on biodegradation efficiency and electricity output output (Logan et al., 2004; Santoro et al., 2017; Sevda and Sivasubramanian, 2012). Temperature was not controlled artificially, enabling observation of the reactor's natural behavior under ambient environmental fluctuations (Mercer, 2010).

Effects of salt concentration in salt bridge

The salt bridge was prepared using a 10% agar-agar solution combined with three concentrations of Potassium Chloride (KCl): 1 M, 2 M, and 4 M, to assess the impact of ionic conductivity on MFC performance (Logan et al., 2008; Muralidharan et al., 2011**).** Specifically, 7.455 g, 14.91 g, and 22.365 g of KCl were dissolved in 100 mL of distilled water to make 1 M, 2 M, and 4 M solutions, respectively. These mixtures were then solidified with agar and poured into a PVC pipe salt bridge (diameter 60 mm, length 120 mm) positioned between the anodic and cathodic chambers. The variation in KCl concentration was aimed at improving proton transfer and reducing internal resistance (Singh and Dharmendra, 2010; Sevda and Sivasubramanian, 2012).

Experimental batches and setup conditions

The experiments were conducted in seven batches (batch B1 to B7) under different conditions as summarized in Table 3. Each batch was optimized based on a combination of KCl concentration, microbial dose, and seasonal temperature:

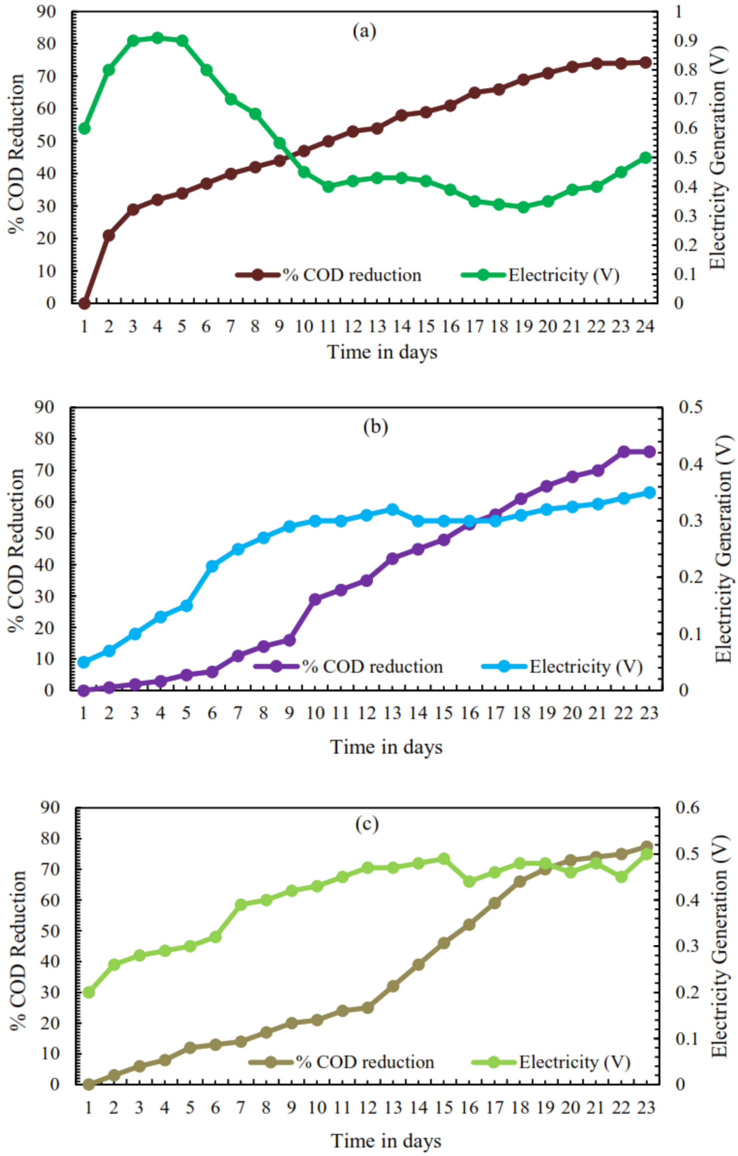
Table 3: Experimental batches and set up conditions

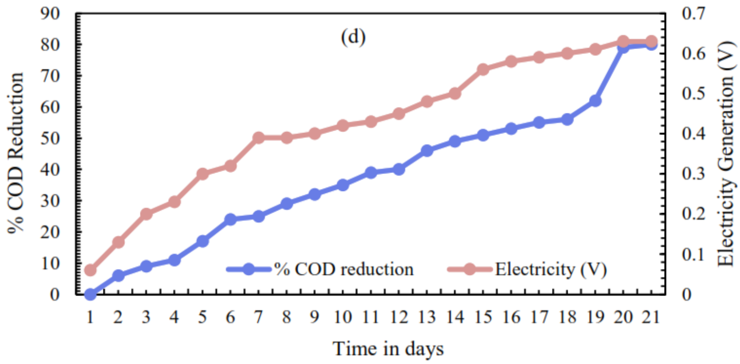
Batch	KCl concentration	Aagar- agar (%)	Microbial culture dose
B1	1 M	10	150 mg/L (7.5%)
B2	2 M	10	150 mg/L (7.5%)
B3	2 M	10	200 mg/L (10%)
B4	4 M	10	150 mg/L (7.5%)
B5	4 M	10	200 mg/L (10%)
B6	2 M	10	150 mg/L (7.5%)
B7	2 M	10	200 mg/L (10%)

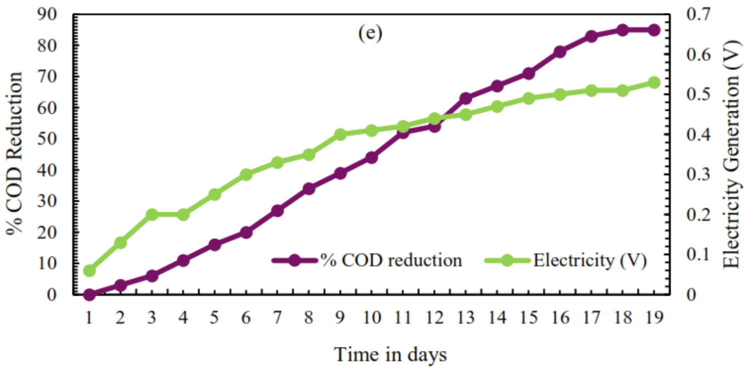
Each batch was optimized over several days until a stable COD reduction was achieved at the outlet. The reactors were operated during both winter and summer, and COD reduction (%) and voltage generation (V) were measured daily using the closed reflux method and a digital multimeter, respectively (Xu et al., 2015; Dhakal, 2015).

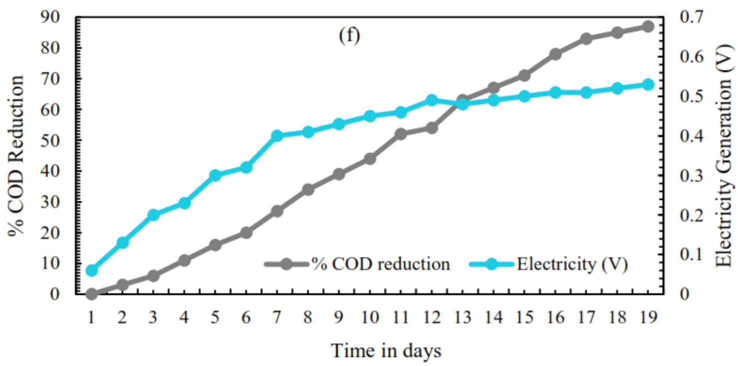
RESULTS AND DISCUSSION

The performance of the MFC was evaluated based on COD reduction and electricity generation (V) under varying conditions of microbial culture dose, KCl concentration in the salt bridge, and seasonal temperature variation. The results emphasize the effects of each parameter on the %COD reduction and electricity generation. Detailed comparative data from various MFC batch runs i.e. B1 to B7 are presented in Fig. 2a to Fig. 2g and summarized as a Table 4.


(a)
% COD Reduction
Electricity Generation (V)
% COD reduction
Electricity (V)
Time in days
(b)
% COD Reduction
Electricity Generation (V)
% COD reduction
Electricity (V)
Time in days
(c)
% COD Reduction
Electricity Generation (V)
% COD reduction
Electricity (V)
Time in days


(d)
% COD Reduction
Electricity Generation (V)
% COD reduction
Electricity (V)
Time in days


(e)
% COD Reduction
Electricity Generation (V)
% COD reduction
Electricity (V)
Time in days


(f)
% COD Reduction
Electricity Generation (V)
% COD reduction
Electricity (V)
Time in days

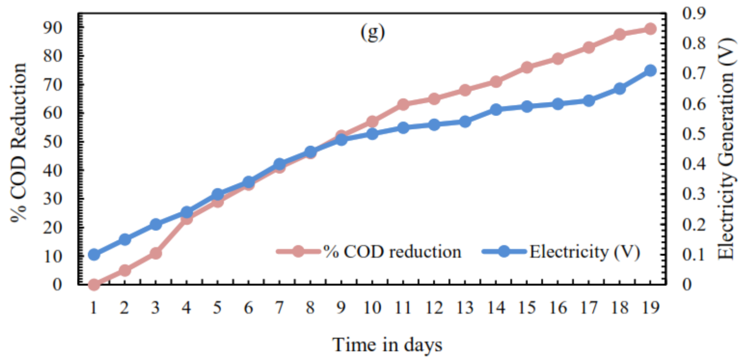


Figure 2: Results of %COD reduction and electricity generation during various MFC batch conditions. (a) B1; (b) B2; (c) B3 ;(d) B4; (e) B5; (f) B6; (g) B7

The obtained results of seven experimental batches (B1–B7) were discussed in the following section to evaluate the effect of MFC selected parameters.

Batch B1 (1 M KCl, 7.5% culture, 16 °C)

During the start-up of the MFC system in the batch B1, slight fluctuations in electricity generation were observed during the initial 10 days. Thereafter, a stable electricity output was recorded, ranging from 0.33 V to 0.91 V. The highest COD reduction achieved in this batch was 74%, with a peak voltage of 0.50 V over 24 days (Fig. 2a). The lower KCl concentration limited ionic conductivity across the salt bridge, which likely constrained proton transfer and overall electrical output.

Batch B2 (2 M KCl, 7.5% culture, 14 °C)

The optimized period for the batch B2 was 23 days. During the 23 days operational period of the MFC system, a progressive increase in both COD reduction and electricity generation was observed as shown in Fig. 2b. In the initial phase (1 to 10 days), COD reduction improved gradually from 0% to 29%, while electricity generation increased from 0.05 V to 0.30 V. From day 11 onwards, the MFC system exhibited more stable electricity generation (up to 0.35 V) and COD reduction (up to 76%). Increasing KCl concentration to 2 M improved proton transfer, leading to a slightly higher COD reduction (76%). However, the colder temperature (14 °C) reduced microbial metabolic activity, lowering the maximum voltage to 0.35 V despite faster ion transport.

Batch B3 (2 M KCl, 10% culture, 14 °C)

It is observed that in batch B3, both COD reduction and electricity generation showed a consistent upward trend from the first day, indicating faster microbial adaptation compared to batch B2 due to the higher culture dose. COD reduction peaked at 77% and electricity generation reached 0.5 V (Fig. 2c). The increased microbial culture dose (from

7.5% to 10%) enhanced biodegradation rates and electron transfer efficiency, resulting in a higher voltage output compared to batch B2 under the same salt concentration. However, the low operating temperature (14 °C) still limited microbial metabolic activity, preventing further improvement in COD reduction.

Batch B4 (4 M KCl, 7.5% culture, 16 °C)

The ideal operating period for Batch B4 was determined to be 21 days. In batch B4, both COD reduction and electricity generation increased steadily from day 1. The initial phase (days 1–10) showed a sharp rise, with COD reduction reaching 35% and voltage 0.42 V, indicating rapid microbial adaptation due to the higher culture dose. After day 10, both parameters continued to improve, with COD reduction peaking at 80% and electricity generation stabilizing at 0.63 V (Fig. 2d), reflecting enhanced biodegradation rates and efficient electron transfer despite the low operating temperature. The higher KCl concentration (4 M) significantly improved proton conductivity, leading to better electron flow and power generation. The moderate temperature supported better microbial activity than batch B2 and batch B3, improving overall performance.

Batch B5 (4 M KCl, 10% culture, 16 °C)

Batch B5 observed progressive improvement in both COD reduction and electricity generation over 19 days. In this batch B5, COD reduction reached 85% and electricity generation up to 0.53 V by the end of the cycle. The first 10 days noted an active adaptation phase, with COD removal increasing up to 44% and voltage to 0.41 V as presented in Fig. 2e. Subsequent days showed sustained gains, reflecting enhanced microbial activity, effective organic matter degradation, and steady bioelectric performance. However, the electricity generation (0.53 V) was slightly lower than batch B4, possibly due to increased internal resistance from biomass accumulation at the anode surface.

Batch B6 (2 M KCl, 7.5% culture, 28 °C)

Batch B6 exhibited a sustained improvement in both COD reduction and electricity generation in 19 days of operational period. The early phase (days 1–10) reflected enhanced microbial acclimatization, with COD reduction increasing to 44% and electricity generation reaching 0.45 V. From day 11 onwards, the batch B6 maintained stable performance, achieving a maximum COD reduction of 87% and electricity generation of 0.53 V (Fig. 2f). These results highlight that elevated temperature accelerate microbial metabolism and significantly affect reaction kinetics in MFC systems.

Batch B7 (2 M KCl, 10% culture, 28 °C)

During the first week of batch B7, COD reduction increased from 0% to 60%, while electricity generation rose rapidly from 0.11 V to 0.55 V. From day 8 onwards, the batch B7 MFC system stabilized, achieving the highest recorded performance of all batches:

89.5% COD reduction and peak voltage generation of 0.71 V. The optimized period for Batch B7 was 19 days as highlight in Fig. 2g. The optimal combination of elevated temperature (28 °C), moderate KCl concentration (2 M), and higher microbial culture dose (10%) created synergistic conditions for efficient biodegradation and enhanced electron transfer, making batch B7 the benchmark for process optimization.

Across all batches, results indicate that **temperature** and **microbial culture dose** have a greater influence on COD removal, while **KCl concentration** strongly affects electricity generation through enhanced proton conductivity. The best COD removal and electricity generation were observed in B7, confirming the importance of balanced optimization of all three parameters.

Table 4: Summary of performance of various MFC batches

Batch	KCl conc.	Microbial culture dose	Temp. (^{0}C)	%COD reduction	Electricity Generation (V)	Optimization time (days)
B1	1 M	150 mg/L (7.5%)	16	74	0.50	24
B2	2 M	150 mg/L (7.5%)	14	76	0.35	23
B3	2 M	200 mg/L (10%)	14	77	0.50	23
B4	4 M	150 mg/L (7.5%)	16	80	0.63	21
B5	4 M	200 mg/L (10%)	16	85	0.53	19
B6	2 M	150 mg/L (7.5%)	28	87	0.53	19
B7	2 M	200 mg/L (10%)	28	89.5	0.71	19

Effect of KCL concentration in agar-salt bridge on wastewater treatment and electricity generation

Salt concentration in the agar-salt bridge significantly influenced the performance of the MFC process in terms of both % COD reduction and electricity generation. As the KCl concentration increased from 1 M (Batch B1) to 4 M (Batches B4 and B5), voltage output rose from 0.3 V to 0.6 V, and maximum COD reduction increased from 74% to 87%. This enhancement is attributed to improved proton conductivity across the salt bridge, which reduces internal resistance and supports efficient electron flow between anodic and cathodic chambers.

This finding aligns with previous studies. The earlier study reported that increasing ionic strength (using 3 M KCl) led to better current production in MFCs by minimizing internal resistance (Jadhav and Ghangrekar, 2009). Similarly, other study emphasized the importance of ionic conductivity in maintaining potential gradients essential for electron flow (Logan et al. 2004). Thus, Batches B4 and B5, with 4 M KCl, demonstrated superior performance compared to lower KCl concentration setups.

Effect of microbial culture dose on treatment efficiency and electricity generation

The effect of anaerobic sludge dose was evaluated by comparing 150 mg/L (B1, B2, B4, B6) with 200 mg/L (B3, B5, B7). Higher sludge concentrations yielded faster COD reduction and higher voltage output. Specifically, Batch B7, with 200 mg/L sludge, achieved 89.5% COD removal and 0.71 V output in just 19 days, compared to B1, which reached only 74% COD in 24 days with lower microbial culture biomass.

The enhancement in microbial activity with increased biomass is consistent with observations by pervious study (Pant et al. 2010). The previous study noted that a higher inoculum dose provides more active sites for biodegradation and accelerates electron generation. Another work showed that higher sludge loading enhances biofilm development and electron transfer (He et al. 2008) also.

Impact of temperature on MFC performance

Temperature variation between 14°C (Batch B2) and 28°C (Batches B6 and B7) demonstrated a strong impact on performance. Despite having the same KCl concentration (2 M) and same sludge doses (150 mg/L in B2 and B6; 200 mg/L in B3 and B7), Batches at higher temperature consistently showed faster treatment and greater electricity generation.

Batch B2 (14°C) reached a maximum of 76% COD reduction in 23 days with peak electricity generation of 0.35 V. In contrast, Batch B6 (28°C) reached 87% COD reduction in just 19 days with 0.53 V electricity generation. The enhanced results at 28 °C are consistent with earlier findings reporting that microbial metabolism and bioelectrogenesis are significantly improved at mesophilic temperatures (25–35 °C) (Kim et al., 2007). Hence, temperature optimization is critical for maximizing MFC efficiency, especially in cold seasons or climates.

The most optimized performance was achieved in Batch B7, achieving 89.5% COD reduction and 0.71 V electricity generation within 19 days. These results clearly highlight the synergistic effect of moderate KCl concentration (2 M), higher microbial dose (200 mg/L), and elevated temperature (28°C). These conditions created a balanced system for enhanced biodegradation and efficient electricity generation.

A comparative assessment across all batches suggests that temperature exerts a stronger control on microbial kinetics, salt concentration affects the conductivity and internal resistance, while microbial dose enhances the biodegradation of wastewater. Hence, optimal performance needs a balanced combination of all these factors to maximize both biodegradation efficiency and energy recovery in MFC systems.

Comparison with previous similar studies

Compared to other published works, the present study demonstrates higher COD reduction efficiency and higher voltage output, underscoring the importance of optimizing multiple process parameters simultaneously rather than in isolation (Table 5).

Table 5: Comparison with previous studies

Conditions	COD Reduction	Voltage Output	Remarks	Study
3 M KCl, moderate inoculum	82%	0.58 V	High salt enhanced power	(Jadhav et al., 2009)
30°C, domestic sludge	80%	0.48 V	High temp boosted MFC	(Kim et al., 2007)
Higher inoculum and acclimation	85%	0.62 V	Better biofilm formation	(He et al., 2008)
Nano-pumice anode, 4,000 mg/L COD	--	0.804 V	Low-cost electrodes with high OCV	(El-Mallah et al., 2024)
Dual-chamber leachate MFC (3,325 mg/L COD)	--	Max power density 877 mW/m²	High influent COD enhanced power via biofilm activity	(Rahmani et al., 2024)
2 M KCl, 200 mg/L sludge, 28°C	89.5%	0.71 V	Optimized across all parameters	Present Study (batch B7)

The present study (B7) achieves a COD reduction of 89.5 % and an output voltage of 0.71 V, outperforming many earlier MFC experiments that reported COD removals between 80–85 % and voltages below 0.62 V. Notably, the recent approach attained a high open-circuit voltage of 0.804 V using low-cost nano-pumice electrodes with a 4,000 mg/L COD feed, demonstrating that innovative electrode materials are key aspect (El-Mallah et al., 2024).

The recent study adopted the dual-chamber leachate MFC reported a maximum power density of 877 mW/m² for a leachate-fed dual-chamber system, underscoring how high COD loading can significantly boost electrochemical performance (Rahmani et al. 2024). Another investigation demonstrated the value of material engineering with their nano-FeS hybrid biocathode, showing enhanced voltage stability and higher power density (40.8 mW/m²) during heavy metal removal (cr) by mitigating cathode passivation (Zhou et al., 2024).

Overall, the present study excels by combining high COD removal (89.5 %) and superior voltage output (0.71 V), validating that simultaneous optimization of salt concentration, sludge inoculation, temperature, and innovative materials can outperform both conventional and recent MFC implementations.

The findings demonstrate that process optimization in MFCs—especially through adjustments in salt bridge conductivity, microbial dosing, and operational temperature—significantly enhances both treatment efficiency and bioelectricity production. The optimized conditions in Batch B7 can serve as a reference point for scaling up MFCs for industrial wastewater treatment, especially from starch-based industries.

CONCLUSION

The present study assessed the potential of a 2.5 L mediator free MFC for starch industry wastewater treatment. The anaerobic sludge from a functioning UASB reactor has used as the microbial inoculum. The MFC process was optimized with varied KCl concentration in the salt bridge, microbial culture dose, and operating temperature with seven batches. Among all batches, Batch B7 (2 M KCl, 10% microbial culture dose, 28°C) showed the most effective result, achieving a maximum COD reduction of 89.5% and electricity generation of 0.71 V in 19 days, confirming the effect of optimized conditions.

The experimental results of all seven batches clearly indicate that salt concentration, microbial dose, and temperature affect the MFC performance. Increasing KCl concentration from 1 M (B1) to 4 M (B4 and B5) enhanced electricity generation, likely due to improved proton transfer and reduced internal resistance, while a higher microbial culture dose (7.5% and 10%) enhanced higher COD reduction, emphasizing the role of biomass concentration in pollutant degradation for wastewater treatment. Temperature exerted a strong effect on both wastewater treatment efficiency and optimization time, with an increase from 14 °C (Batch B2) to 28 °C (Batch B6) at similar KCl concentration (2 M) and sludge dose (7.5%) improving COD removal from 76% to 87% and reducing the optimization period from 23 to 19 days, confirming that mesophilic temperature range is most suitable for microbial degradation and electron transfer. Overall, these findings demonstrate that strategic optimization of salt concentration, microbial culture dose (biomass loading), and operating temperature can substantially improve MFC performance, offering a viable pathway for sustainable industrial wastewater treatment coupled with bioelectricity generation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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