Indian Journal of Chemical Technology
Vol. 32, November 2025, pp. 778-789
DOI: 10.56042/ijct.v32i6.16244

Performance evaluation of cost-effective two-chamber microbial fuel cell for simultaneous domestic wastewater treatment and bioenergy generation

Murugesan Manik Kampatti Palanisamy[1]*, Padmapriya Veerappan[2], Priya Dharshini Kothavadi Rajendran[2] & Kalaivani Ramanathan[2]

[1]Department of Petrochemical Technology, Excel Engineering College, Komarapalayam, Tamil Nadu-637303, India
[2]Department of Electronics and Communication Engineering, Erode Sengunthar Engineering College, Erode, Tamil Nadu-638057, India
*E-mail: engineermurugesh@gmail.com

Received 10 August 2025; accepted 31 October 2025

Microbial Fuel Cells (MFCs) offer a sustainable solution for addressing sanitation challenges by simultaneously treating wastewater and generating bioenergy. In this study, a two-chamber MFC has been constructed and employed to treat domestic wastewater while recovering energy. The MFC operates by converting the chemical energy stored in organic matter into electrical energy through electrochemical reactions facilitated by microorganisms. Key physiochemical and microbiological parameters of untreated and treated wastewater have been analyzed, including chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), total dissolved solids (TDS), and microbial counts. Significant reductions are observed post-treatment, with BOD reduced by 99% (from 684 mg/L to 118 mg/L), COD by 92% (from 444 mg/L to 266 mg/L), and microbial count by 74.68%. Furthermore, the removal efficiencies for TDS, TSS, and Total Solids (TS) were 84% (1051 mg/L to 589 mg/L), 95% (861 mg/L to 136 mg/L), and 90% (1952 mg/L to 725 mg/L), respectively. The constructed MFC also demonstrated energy recovery potential, generating a maximum power output of 1774 mW/h. These findings highlight the dual benefits of MFC technology as an environmentally friendly approach for wastewater purification and renewable energy production.

Keywords: Bioenergy, Microbial fuel cells (MFCs), Pollution reduction, Parameter predictions, Water purification

Introduction

Microbial Fuel Cell (MFC) functions as an electrode in microbial catalysis can convert chemical energy into electrical energy through a bio-electrochemical device[1-3]. MFCs produce clean energy directly from the organic matter found in wastewater, bypassing the need for any separation, purification, and conversion processes for the energy products[4,5]. MFCs are ecologically favourable technologies because they may directly generate clean power and operate under moderate operating conditions, particularly at ambient temperatures. These techniques considered a promising technology for pollutant removal and energy recovery among various wastewater treatment methods, including chemicals supplied the treatment, aerobic treatment, anaerobic digestion in biological ways, and membrane filtration for removal of unwanted components from wastewater[6,7]. Hence, these provide several advantages over other water treatment technologies, such as substantial energy savings, lower environmental impact, high operational stability, and strong economic efficiency[8]. MFCs produce very less sludge and consume less energy than aerobic treatment. It may better than anaerobic treatment due to ability to operate in very punitive conditions, such as used acceptable limits of low temperatures and low substrate concentrations. In MFCs technology that has the potential to address two key issues such as pollution management and depleting energy supply[9,10].

The early twenty-first century saw foundational research on simultaneous wastewater treatment and energy generation utilizing MFC[11,12]. Since then, researchers have significantly advanced the design of structures and optimization of electrode materials to enhance MFC treatment mechanism[13-15]. The conventional MFC consists of two chambers which was separated under semi-permeable membrane, each with its own electrode made of carbon cloth, graphite, or carbon paper, with the anodic chamber sustaining anaerobic conditions and the cathodic chamber maintaining aerobic conditions[16,17]. Nitrogen gas is employed in anodic chambers to maintain this anaerobic environment. In this chamber, wastewater containing various types of microorganisms will be treated electrochemically[18]. The cathodic chamber is made up of a high potential electron acceptor electrode, which is often oxygen[19]. To create

electricity, protons (H^+) and electrons (e^-) are transported from the anode chamber and mixed with an electron acceptor in the cathode chamber[20]. To divide the two chambers, a proton exchange membrane consisting of Nafion and Ultrex is often utilized. They serve as an effective membrane for PEM fuel cells by enabling cations to flow through.

Several types of wastewater have been studied as substrates in the MFC, including dairy, paper recycling, molasses, chemical, household, and brewery effluent. Bacteria metabolize the substrate by first breaking it down into H^+ ions, CO^2, and electrons. Therefore, ions break under MFCs to the shuttle electrons to anode part by using mediator molecules[4]. In many ways, a MFC is an extension of the electron transport chain, with the final step being moved outside of the bacterial cell and allowing energy to be captured[6,21,22]. Nafion is a semi-permeable membrane widely utilized in microbial fuel cells. Using Nafion as a proton exchange membrane (PEM) has, however, been associated to operational issues[23]. Because of the raw material high cost, the majority of research has focused on developing alternatives, such as j-cloth trails, nylon fibers, glass fibers, ceramics, and biodegradable shopping bags[9]. The passage of protons over the membrane creates electro-neutrality between the two chambers, which is crucial for the proper operation of MFC technology. PEM has the following desirable features: low cost, improved proton conductivity, good segregation properties, increased mechanical strength, resistance to heat and chemicals, and electronic resistance[22]. Proton exchange membranes (PEMs) applied to MFCs to separate the liquid through anode and cathode chambers while allowing protons to pass line[6]. In two-chambered MFCs, the separate the liquid contents of the reactors while allowing protons to pass between the chambers. Hence, principal function of PEM is to separate the liquid contents from reactors while allowing protons to pass between the chambers. In addition to that, Nafion commonly using in chemical fuel cells and also constructed two-chambered MFCs, catalytic ion exchange membranes (CEMs) are also used in MFCs since they are less expensive and typically stronger structurally than Nafion[14,24]. The use of membranes may limit the utilization of MFC in wastewater treatment. Here, one way membrane allow the Proton transport it is also constructed a large-scale wastewater fullends, treatment process, particularly when fouling by suspended particles and soluble contaminants is anticipated.

The present study differentiates itself from previously published literature in several key aspects. While many studies focus on optimizing either pollutant removal efficiency or bioenergy generation, this research achieves both simultaneously using a constructed two-chamber MFC. The domestic wastewater used in this study, sourced from the Mettur Dam drainage channel in Salem, Tamil Nadu, India, represents an underexplored substrate in microbial fuel cell research, providing insights into its practical applicability. Unlike earlier works that primarily emphasize synthetic or industrial wastewater, this study investigates real-world domestic wastewater, addressing challenges related to its diverse composition. Additionally, significant advancements are demonstrated in pollutant removal, with reductions of 99% in biological oxygen demand (BOD), 92% in chemical oxygen demand (COD), and 95% in total suspended solids (TSS), while simultaneously generating a notable energy output of 1774 mW/h. Furthermore, this work tackles operational limitations often cited in literature, such as the high cost and fouling issues associated with Nafion membranes, by employing a cost-effective and scalable MFC design. By integrating performance optimization for both wastewater treatment and energy recovery, the study presents a holistic approach to addressing pollution and energy challenges. These innovations set this research apart as a practical, sustainable, and economically viable solution for wastewater management, bridging critical gaps in the existing body of knowledge.

The novelty of this research lies in the dual application of a constructed two-chamber MFC for achieving efficient domestic wastewater treatment and bioenergy recovery. Unlike previously published works, which often focus on either optimizing energy generation or improving pollutant removal efficiency, this study achieves both simultaneously. The work also introduces a performance analysis of pollutant removal and energy generation using sample wastewater, an underexplored substrate in MFC studies. Moreover, by utilizing a cost-effective and operationally stable design, the study addresses key challenges in scaling up MFC technology for practical applications.The primary objective of this study is to develop and evaluate a cost-effective, two-chamber microbial fuel cell for the simultaneous treatment of domestic wastewater and generation of bioenergy. The study aims to assess the microbial fuel cell's ability to reduce key wastewater

pollutants, including BOD, COD, TSS, TDS, and microbial counts. A unique feature of this research is its focus on real-world domestic wastewater in India, providing practical insights into the potential of MFCs technology for treating diverse wastewater compositions. Furthermore, the study seeks to optimize energy recovery during the treatment process by analyzing the generation of electricity, with the aim of achieving maximum power output under conditions suitable for scaling up. By addressing both pollution control and renewable energy generation, this research emphasizes the potential of microbial fuel cells as an innovative and sustainable solution for integrated wastewater management and energy recovery.

Experimental Section

Sample collection and preparation

Domestic wastewater was collected from Mettur Dam drainage channel, Salem, Tamil Nadu. The sample was then filtered through Whatman filter paper. Therefore, filtered sample was kept under the process of aerobic fermentation condition and attained the growth rate of micro-organisms. After the microorganism's growth, they were directly used for the bio-electricity generation and physicochemical parameters were analyzed with respect to time periods.

Buffer solution preparation

Solution (buffer) prepared surely about 3.29 g of potassium ferricyanide powder was dissolved in a 200 mL of distilled water. After that, about 8.5 g of KH_2PO_4, 21.7 g of K_2HPO_4, 33.4 g of Na_2HPO_4 and 7 g of NH_4Cl were diluted 1 L of distilled water for solution preparation with continues stirring to form the homogeneous mixture for maintain the uniform concentration buffer solution. Then, both the solutions prepared were combined in the right proportion and kept in the cathode chamber it was feed to the MFCs. In this mixture of combined homogeneous solutions were applied as a separating or minimizing media for abnormal limits of physicochemical parameters. It's a right component for DWT under MFCs bioenergy generation.

MFC construction, operation, and research methodology

A dual-chamber MFC was fabricated and operated under batch mode to evaluate its performance in simultaneous domestic wastewater treatment and bioelectricity generation. The MFC comprised two compartments an anodic and a cathodic chamber each with a working volume of 500 mL. The anodic chamber received 45 mL of domestic wastewater, serving as both the substrate and inoculum source, while the cathodic chamber contained 50 mL of potassium ferricyanide (35 mL ferricyanide and 15 mL phosphate buffer) as the electron acceptor solution. Plain graphite electrodes (5 cm × 5 cm) were employed in both chambers as anode and cathode materials due to their high conductivity, chemical stability, and biocompatibility. The electrodes were connected externally using copper wire, enabling electron transfer from the anode to the cathode through an external circuit. The two chambers were separated by a polymer electrolyte membrane (PEM) (Nafion 117), positioned within a 1.5 cm diameter opening to allow selective ion exchange (H^+ and OH^-) between the chambers while preventing oxygen diffusion into the anode. The membrane was carefully sealed using epoxy resin to avoid leakage and maintain anaerobic conditions in the anodic compartment. The experimental configuration is illustrated in Fig. 1. During operation, the MFC was maintained at ambient temperature (28 ± 2 °C) and at a neutral pH of 7.5 ± 0.3 to support microbial activity. The oxidation of organic matter in wastewater by electroactive bacteria released protons and electrons; the protons migrated through the PEM, while the electrons travelled through the external circuit to the cathode, generating electricity. At the cathode, these electrons combined with oxygen and ferricyanide to form water, completing the redox cycle.

Voltage readings were recorded at 10 min intervals using a digital multimeter across a 16 Ω external resistor to monitor cell performance. The system was operated until a stable voltage output was achieved over a total period of 177 h. The physicochemical parameters of wastewater, including pH, COD, BOD, TDS, TSS, and TS, were analyzed before and after MFC treatment to

Fig 1 — Experimental setup and operational configuration of the MFC

assess pollutant removal efficiency. The generated bioelectricity was quantified by calculating current (I), power (P), current density (J), power density (Pd), and cumulative energy (E) using Ohm's law and standard electrochemical equations. These measurements enabled the evaluation of electrochemical efficiency and treatment performance under dynamic microbial growth conditions. This integrated system demonstrates the capability of a two-chamber MFC to simultaneously achieve wastewater treatment and energy recovery, offering a sustainable bio electrochemical approach for decentralized wastewater management and renewable power generation.

Characterization studies for MFC

The experimental evaluation focused on assessing the electrochemical and treatment performance of the constructed MFC during the bioelectrochemical degradation of domestic wastewater. The system employed graphite electrodes separated by a Nafion 117 proton exchange membrane (PEM) and was operated in batch mode for 177 h under ambient conditions (28 ± 2 °C). Domestic wastewater collected from the Mettur Dam drainage channel served as the substrate in the anode chamber, while the cathode chamber contained potassium ferricyanide in a phosphate buffer solution.

Experimental procedure and data monitoring

The voltage across a 16 Ω external resistor was measured every 10 min using a digital multimeter to evaluate cell potential under both open- and closed-circuit conditions. The MFC's bioelectrochemical activity was monitored through time-dependent variations in voltage (mV), current (mA), power (mW), energy (mW·h), current density (mA/m²), and power density (mW/m²). Concurrently, physicochemical parameters pH, COD, BOD, TDS, TSS, and TS were measured to determine treatment efficiency.

Electrochemical performance

The voltage initially recorded was 174 mV (open circuit), gradually increasing to a peak of 301 mV at 8 h, indicating enhanced microbial activity and stable electron transfer. Correspondingly, the current output rose from 0.38 mA to 0.63 mA during the same period, reflecting maximum metabolic activity and organic substrate oxidation. Beyond 24 h, both voltage and current declined steadily, reaching near zero by 177 h, attributed to substrate depletion and reduced microbial electron generation. The power output was calculated as per Eq. 1.

$$Pd = \frac{P}{A} = \frac{V}{A} \times \frac{I}{A} \quad \ldots(1)$$

The power output followed a similar trend, peaking at 181.88 mW at 8 h. The energy production (integration of power over time) increased cumulatively, reaching 1774.5 mW·h by the end of the experiment, signifying consistent though gradually declining energy recovery. Where: P= power output (Mw), V= voltage (mV), I= current (mA), A= surface area of anode electrode (m²).

Power and current density

To normalize performance relative to electrode surface area, current density and power density were computed. The maximum current density attained was 531.01 mA/m², while the power density peaked at 154.52 mW/m², both recorded at 8 h. These values illustrate optimal electron flux and electrochemical conversion efficiency during peak microbial growth. The subsequent decline correlates with reduced substrate concentration and biofilm activity. The current density and power density were calculated to evaluate the efficiency of the MFC relative to the electrode surface area. Electric current per unit area of the anode electrode and is calculated using Eq. (2).

$$J = \frac{I}{A} \quad \ldots(2)$$

Where I= current measured (mA), A= surface area of the anode electrode (m²)

Wastewater treatment efficiency

The MFC exhibited substantial pollutant reduction efficiency. The COD decreased from 684 mg/L to 266 mg/L, and the BOD reduced from 442 mg/L to 118 mg/L, demonstrating effective microbial oxidation of organic matter. The pH remained relatively stable (7.46–7.8), supporting favourable conditions for microbial metabolism. Additionally, reductions in TDS, TSS, and TS were observed, reflecting the system's ability to remove suspended and dissolved solids during treatment. The microbial population (CFU/100 mL) declined over time, consistent with nutrient depletion and completion of the degradation cycle. Overall, the results confirmed that the MFC system efficiently converted chemical energy from wastewater organics into electrical energy while simultaneously improving effluent quality. The highest energy yield of 1774.5 mW·h and significant COD/BOD removal demonstrate the dual capability of MFCs for bioelectricity generation and wastewater remediation. These findings establish

Table.1 — Characterization of electrochemical and physicochemical performance of the MFC during domestic wastewater treatment

S. No	Time (h)	Voltage (without load)	Voltage (with load)	Current (mA)	Power (mW)	Energy (mW/hr)	Cum. Energy (mW/h)	Current density (mA/m²)	Power density (mW/h)	pH	COD (mg/L)	BOD (mg/L)	Microbial count (CFU/100 mL	TDS (mg/l)	TSS (mg/L)	TS (mg/L)
1	0	174	168	0.38	63	63	63	318.6	53.53	7.46	684	684	79×10^3	1051	861	1469
2	1	193	187	0.38	70.13	70.13	133.13	318.6	59.58	7.46	535	390	80×10^3	959	789	1368
3	2	221	213	0.5	106.5	106.5	239.63	424.81	90.48	7.49	450	341	81×10^3	901	721	1241
4	4	278	268	0.63	167.5	167.5	566.5	531.01	142.31	7.5	326	299	82×10^3	736	693	1103
5	8	301	291	0.63	181.88	181.88	1282.1	531.01	154.52	7.55	319	263	83×10^3	649	672	1087
6	24	280	271	0.56	152.44	152.44	1593.7	477.91	88.78	7.6	302	196	54×10^3	624	588	982
7	120	170	167	0.19	31.31	31.31	1656.9	159.3	26.6	7.7	294	171	49×10^3	613	424	972
8	160	168	165	0.19	30.94	30.94	1687.8	159.3	26.29	7.7	290	146	34×10^3	608	351	856
9	175	7	5	0.13	0.63	0.63	1774.3	106.2	0.36	7.8	267	138	25×10^3	595	222	802
10	176	3	2	0.06	0.13	0.13	1774.5	53.1	0.11	7.8	267	118	17×10^3	589	152	728
11	177	0	0	0	0	0	1774.5	0	0	7.8	266	118	20 x 103	589	136	725

MFCs as a promising sustainable technology for decentralized wastewater management and renewable energy production.This study showed the positive report for the efficacy of MFCs as a sustainable solution for addressing the dual challenges of energy production and wastewater treatment were tabulated in Table 1. The table presents time-dependent variations in voltage, current, power, energy, and corresponding densities, alongside wastewater quality indicators (COD, BOD, TDS, TSS, TS, and pH). Results demonstrate the MFC's peak electrochemical activity at 8 h, with a maximum power output of 181.88 mW, and substantial pollutant reductions COD (61%) and BOD (73%) by the end of the 177 h operation.

Microbial count (CFU)

The results of the MFC experiment treating domestic wastewater reveal the dynamic changes in microbial count and current over time. Initially, the microbial count rises from 79×10³ CFU/100 mL to 83×10³ CFU/100 mL within the first 8 h, accompanied by an increase in current from 0.38 mA to 0.63 mA. This indicates vigorous microbial growth and high activity due to the availability of organic substrates. At 24 h, the microbial count drops to 54×10³ CFU/100 mL, and the current slightly decreases to 0.56 mA. This decline suggests that the easily accessible substrates are being depleted or that microbial community dynamics are changing. From 24 to 120 h, the microbial count continues to decrease to 49×10³ CFU/100 mL, and the current drops significantly to 0.19 mA. This trend indicates a reduction in microbial population and activity, likely due to substrate limitation or accumulation of inhibitory by-products. Between 120 and 177 h, the microbial count further declines to 20×10³ CFU/100 mL, with the current reaching 0 mA at 177 h. This significant drop reflects severe substrate depletion or unfavourable conditions within the MFC, leading to almost complete cessation of microbial activity and electron transfer which finally results in high initial microbial growth and current generation, peaking at 8 h. However, as substrates are consumed, microbial counts and current output gradually decrease. By 177 h, the system exhibits minimal microbial activity and no current production, highlighting the need for effective substrate management for sustained MFC operation.MFCs effectively reduced TDS (1051 to 589 mg/L), TSS (861 to 136 mg/L), and TS (1469 to 725 mg/L), enhancing water quality by removing solids and reducing turbidity. The study demonstrates MFCs as a dual-purpose technology for bioelectricity generation and wastewater treatment, with significant reductions in COD, BOD, and microbial counts. Initial efficiency peaks in electrical metrics highlight operational potential, while substrate replenishment is needed to sustain performance. This case study from the Mettur Dam drainage channel showcases MFCs' role in sustainable wastewater management.

Results and Discussion

Bioelectricity generation

In this MFC experiment, by the specific time the voltage developed was systematically monitoring. It shows that the initial stage of the experimental results showed a significant increase in voltage, indicating effective active microbial metabolism developments and efficient electron transfer processes identified. However, after attaining a peak power output of 1774.5 mW/h, a predictable range decline in voltage was observed, which is bring into line with the expected life time cycle and metabolic activity of the microorganisms involved in over a system. Therefore,

In MFC, the voltage was measured. After a while, the voltage begins to fall. Table 1 displays the current, voltage, power, and energy collected from the experiment, as well as the current density and power density, and a graphical depiction is presented below the discussions.

Physicochemical parameter analysis

Voltage generation and treatment rate with respect to time

During the initial phase (0-8 h), the voltage increased significantly from 174 mV to 301 mV, indicating that the microorganisms were highly active, efficiently catalyzing the oxidation of substrates to generate electrons, which were transferred to the anode, resulting in increased voltage. In the intermediate phase (8-120 h), the voltage started to decrease gradually, dropping slightly to 280 mV at 24 h and further to 170 mV by 120 h, likely due to a reduction in substrate availability, accumulation of metabolic byproducts, or partial microbial decay. In the late phase (120-177 h), there was a sharp decline in voltage, with levels falling to 168 mV at 160 h, plummeting to 7 mV at 175 h, and eventually reaching 0 mV by 177 h, likely due to the substantial breakdown of microbial cells, significantly reducing their ability to generate electricity.

Fig. 2 indicates the voltage generation over time for microbial activity to the effluent. It clearly reports a primarily steep rise in voltage, peaking within the first 8 h, followed by a steady decline. After 120 h, the decline becomes more pronounced, reflecting the declining efficiency of the microbial population. It was Interpreted under the activity of microbes, decline and efficiency drop. The initial rise in voltage is indicative of favourable conditions for microbial growth and activity, resulting in efficient substrate conversion and electron transfer.

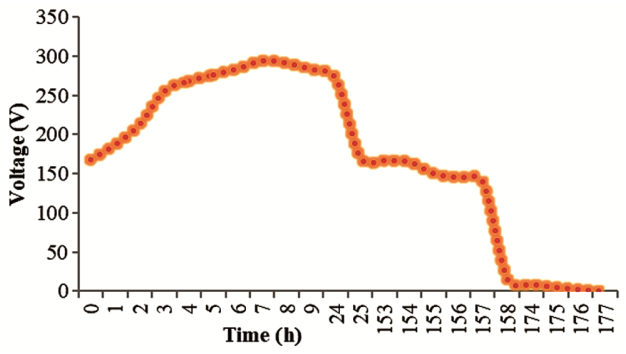

Fig 2 — Voltage generation and microbial activity profile of the MFC during wastewater treatment

The experimental results demonstrate that MFCs effectively generate bioelectricity and treat domestic wastewater. The pH remained stable, starting at 7.46 and ending at 7.8, indicating conditions favourable for microbial activity. Significant reductions in COD from 684 mg/L to 266 mg/L and BOD from 442 mg/L to 118 mg/L were observed, highlighting the MFC's efficiency in breaking down organic pollutants it shown in Fig. 3. The microbial count initially increased, reflecting substrate availability, but later decreased, likely due to substrate depletion and metabolic by products. TDS, TSS, and TS values also showed marked decline, enhancing water quality. These results underscore the dual role of MFC in energy production and wastewater treatment, showcasing its potential for sustainable environmental management and resource recovery. Future research should aim to optimize MFC design and operation for improved performance and scalability, ensuring sustained microbial activity and efficient voltage generation.

Analysis for Time vs Current

As demonstrated in Fig. 4, the current (mA) in the MFC for wastewater treatment initially rise with increasing time, peaking at 0.63 mA at 8 h, before slightly declining to 0.56 mA at 24 h. Beyond 24 h, the current steadily decreased, dropping to 0.19 mA by 120 h and continuing to fall to 0.13 mA at 175 h, 0.06 mA at 176 h, and eventually reaching 0 mA by 177 h. This trend indicates that the microbial population was initially effective at converting substrates into electrons, resulting in increased current output, but over time, the conditions within the MFC became less favourable for microbial activity due to factors such as substrate depletion, accumulation of inhibitory by-products, or microbial senescence, leading to a significant decline in current generation. This understanding is crucial for optimizing the operational parameters of MFCs to maintain efficient and sustainable energy production from wastewater treatment.

Microbial activity vs Current productions

Between the microbial count and current output of MFC, the experimental results indicate a strong initial correlation. At the beginning, a current of 0.38 mA corresponds to microbial counts of 79 x 10^3 and 80 x 10^3 CFU/100 mL, while a current of 0.5 mA corresponds to a count of 81 x 10^3 CFU/100 mL. The peak current of 0.63 mA is observed with microbial counts of 82 x 10^3 and 83 x 10^3 CFU/100 mL. However, as microbial count decreases to 54 x 10^3,

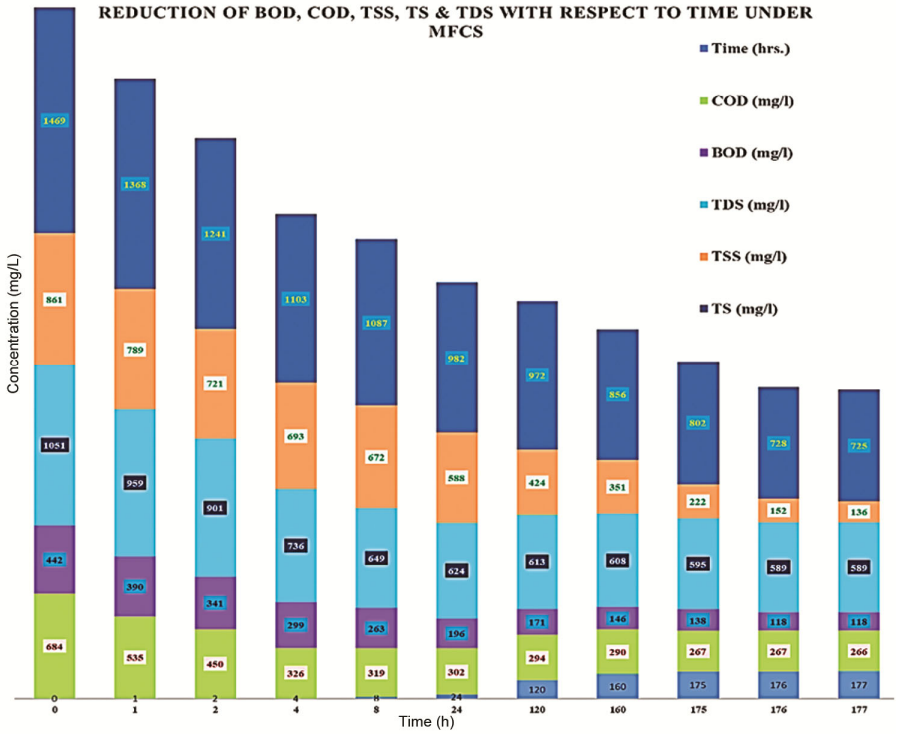

Fig. 3 — Temporal variation in BOD, COD, TSS, TS, and TDS removal during MFC operation

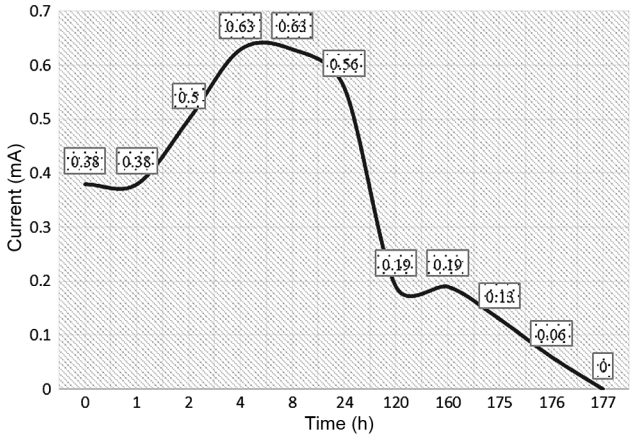

Fig. 4 — Time–current profile of the MFC during wastewater treatment, illustrating microbial electroactivity and bioenergy generation

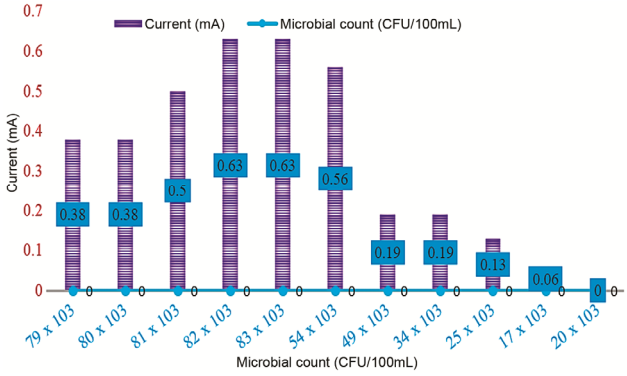

Fig. 5 — Correlation between microbial activity and current generation in the MFC during wastewater treatment

49 x 10^3, and 34 x 10^3 CFU/100 mL, the current significantly drops to 0.56 mA, 0.19 mA, and 0.19 mA, respectively. Further declines in microbial count to 25 x 10^3 and 17 x 10^3 CFU/100 mL result in even lower currents of 0.13 mA and 0.06 mA. Finally, when the microbial count is 20 x 10^3 CFU/100 mL, the current output ceases entirely as shown in Fig. 5, indicating that higher microbial populations are crucial for optimal current generation in MFCs.

Furthermore, the current generated will be enhanced by scaling up methods. Similarly, electricity and energy follow similar tendencies and may be enhanced further by scaling up processes. Scaling up MFC design, on the other hand, is a substantial difficulty that will be addressed in future study. The current density seemed to increase somewhat while the microbe developed exponentially and reduced to 159.30 mA/m^2 when the microorganism disintegrated as shown in Fig. 6. It shows the power density generation during the MFC experiment, which increased about 24 h and dropped after that. The

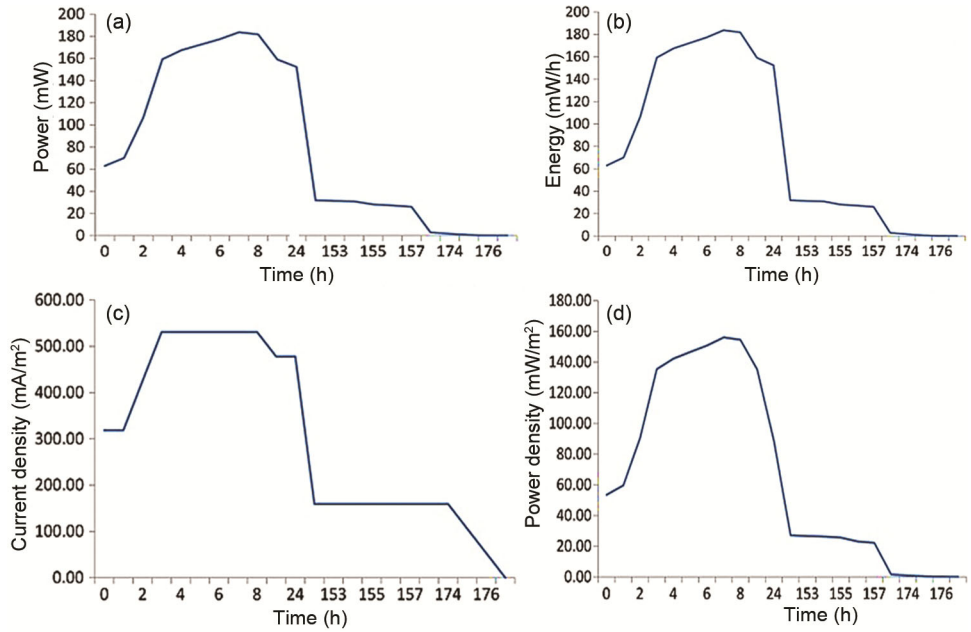

Fig. 6 — Performance characteristics of the MFC during wastewater treatment showing microbial electrochemical activity and energy generation

authorized MFC cell generated a total energy of about 1774 mW/h as the highest power generation in a 50 mL effluent sample, according to the data.

Fig. 6 provides information about, (a) time vs. power, (b) time vs. energy, (c) time vs. current density, and (d) time vs. power density profiles. The MFC exhibited an initial rise in power and energy generation during the first 24 h, corresponding to active microbial metabolism and efficient substrate oxidation. As microbial activity declined, both current and power densities gradually decreased, with the current density reaching 159.30 mA/m² during the microbial disintegration phase. The system achieved a peak total energy output of approximately 1774 mW/h from a 50 mL effluent sample. These results highlight the MFC's capability for simultaneous bioenergy recovery and wastewater treatment, while emphasizing the need for scale-up optimization to enhance long-term stability and performance.

Microbial characterization and morphological observation

Basic microbial characterization was conducted to support the biological interpretation of the MFC's performance. Gram staining results confirmed the predominance of Gram-negative, rod-shaped bacteria in the anodic biofilm, suggesting the presence of electroactive microorganisms capable of efficient electron transfer. These bacteria play a key role in substrate oxidation and current generation within the system. The observed microbial morphology is consistent with previously reported genera such as *Pseudomonas* and *Shewanella*, which are known for their electrochemical activity in wastewater-fed MFCs due to their extracellular electron transfer capabilities and adaptability to wastewater environments[25,26]. This finding reinforces the correlation between microbial activity and bioelectricity generation, as discussed in the earlier sections. Advanced microbial community analysis, including 16S rRNA sequencing, is planned for future research to further elucidate species-level interactions and their role in bio electrogenic activity and system stability.

Wastewater Treatment

The untreated wastewater was first analyzed for its physicochemical characteristics before being treated using a microbial fuel cell. The physio-chemical parameters of untreated and treated wastewater utilizing the MFC device are shown in Table 2. The data highlights the effectiveness of using a MFC in treating wastewater by comparing the physicochemical parameters of untreated and treated wastewater. The analysis shows that the MFC significantly reduces various pollutants: BOD, COD, TDS, TSS, and TS decreased from initial levels of 684, 442, 1051, 861, and 1912 mg/L to 118, 266, 589, 136, and 725 mg/L, respectively. These results of BOD 574, COD 192, TDS 551, TSS 761, and TS 1312 mg/L, fall within acceptable limits being 110, 250, 500, 100, and 600 mg/L, respectively. The pH remained neutral at 7

Table 2 — Physicochemical characteristics of wastewater before and after MFC treatment

Characteristics	Before treatment (mg/L)	Acceptable Limit as per government norms (mg/L)	Abnormal presence rate in wastewater (mg/L)	After treatment (mg/L)	Treatment Efficiency (%)
BOD (mg/L)	684	110	574	118	99
COD (mg/L)	442	250	192	266	92
TDS (mg/L)	1051	500	551	589	84
TSS (mg/L)	861	100	761	136	95
TS (mg/L)	1912	600	1312	725	90
P^H	7	6-9		7	-

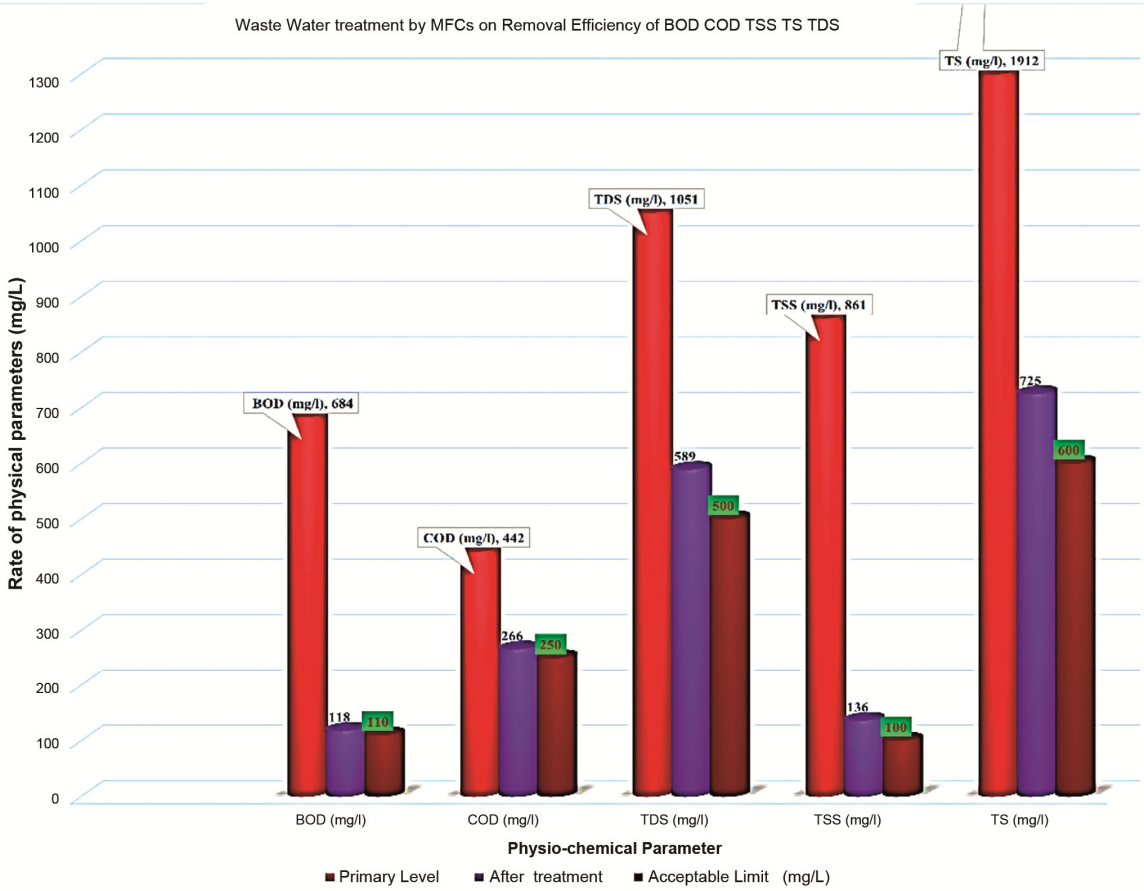

Fig. 7 — Comparative analysis of wastewater characteristics before and after MFC treatment

before and after treatment, within the acceptable range of 6-9. Graphical representation in Fig. 7 further illustrates the MFC's impact, comparing the values before and after treatment and highlighting the reduction percentages. The graphical comparison highlights substantial decreases across all parameters, demonstrating the MFC's effectiveness in organic pollutant degradation and solid reduction. Although most values approached regulatory limits, further post-treatment optimization is recommended to achieve full environmental compliance and maximize pollutant removal efficiency.

The MFC's treatment efficiency was determined and shown in Fig. 8. The values are 99% for BOD, 92% for COD, 84% for TDS, 95% for TSS, and 90% for TS, all within the acceptable limits for the Mattur dam drainage channel. The MFC experiment exhibited a dynamic voltage profile, initially increasing from 174 mV to 301 mV within the first 8 h, peaking at 1774.5 mW/h. This rise indicated active microbial metabolism and efficient electron transfer. However, voltage and current output declined to 0 mV and 0 mA, respectively by 177 h due to substrate depletion, accumulation of metabolic byproducts, and microbial aging,

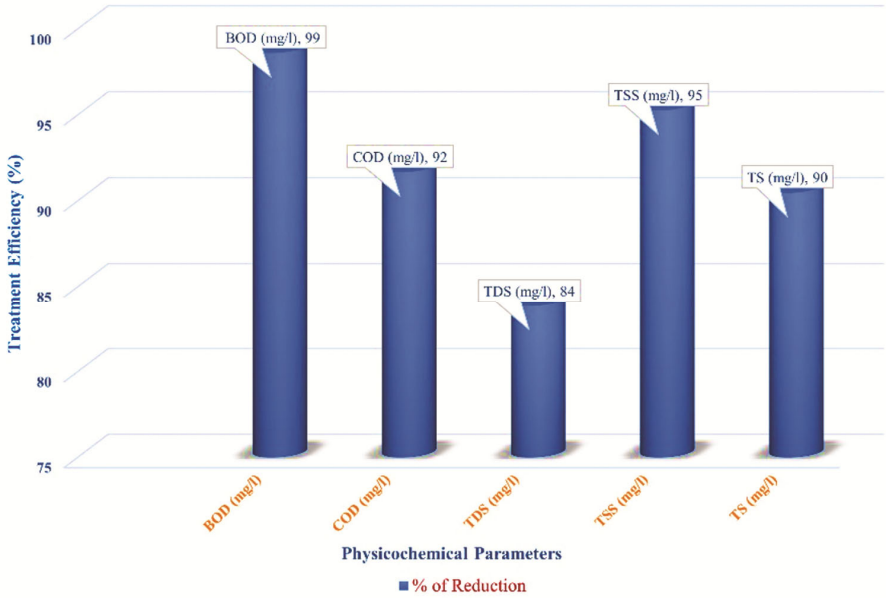

Fig. 8 — Treatment efficiency of domestic wastewater by the MFC system

underscoring the need for optimal conditions for sustained voltage generation. Graphical representations effectively show, these reductions and overall water quality improvement post-treatment, highlighting MFCs' dual role in bioelectricity generation and pollutant reduction.

Comparative analysis

A comparative evaluation was carried out to assess the performance of the developed two-chamber MFC against previously reported systems. The results demonstrated that the present MFC exhibited superior treatment and energy generation efficiency. Conventional MFCs treating domestic wastewater typically achieve BOD removal efficiencies between 70-90% and COD removal efficiencies around 60-85%, whereas the current study achieved 99% BOD and 92% COD removal, indicating enhanced microbial oxidation and system stability. Similarly, the TSS reduction of 95% in this work surpasses several earlier reports of 60-85%. In terms of energy recovery, the cumulative output of 1774 mW·h demonstrates a higher energy yield compared to other cost-effective MFC configurations reported in the literature (typically ranging from 500-1500 mW·h). This improvement may be attributed to the optimized electrode materials, chamber configuration, and operational parameters adopted in this study. Overall, the results validate the efficiency and sustainability of the proposed MFC design, confirming its potential for simultaneous wastewater treatment and bioenergy generation with improved performance and cost-effectiveness compared to conventional systems. The MFC showed high pollutant removal efficiencies (BOD: 99%, COD: 92%, TSS: 95%) along with a maximum power output of 1774 mW/h. A comparative cost analysis of different domestic wastewater treatment approaches is presented in Table 3, highlighting the favourable balance between operational feasibility, environmental sustainability, and energy recovery potential offered by the MFC system. Overall, the results suggest that MFC-based treatment can serve as a promising alternative to conventional technologies when optimized for long-term operation and scalability.

Membrane performance and cost considerations

In this study, membrane fouling and cost considerations were identified as critical factors influencing the practical scalability of MFC systems. Although Nafion membranes exhibited excellent proton conductivity and chemical stability, their high cost and susceptibility to fouling under real wastewater conditions limit their industrial applicability. Membrane fouling generally arises from organic deposition, microbial biofilm formation, and inorganic scaling, which collectively increase internal resistance and reduce proton transfer efficiency. To mitigate these issues, several low-cost and antifouling membrane alternatives have been investigated. Cation exchange membranes, polyvinyl alcohol (PVA)-based membranes, sulfonated polyether ether ketone (SPEEK),

Table 3 — Comparative Cost Analysis of Domestic Wastewater Treatment Technologies

SI. No	Parameter	Microbial Fuel Cell (MFC)	Activated Sludge Process (ASP)	Membrane Bioreactor (MBR)	Anaerobic Digestion (AD)
1	Capital Cost (USD/m³)	Low–Moderate (graphite electrodes low-cost; membrane contributes to cost)	Moderate	High (membrane modules costly)	Moderate
2	Operational Cost (USD/m³)	Low (no external aeration in anodic chamber)	High (continuous aeration energy demand)	High (membrane cleaning and replacement)	Low–Moderate
3	Energy Demand	Net positive (electricity generation)	High (aeration accounts for 50–60% of energy cost)	Moderate-High (pump/filtration energy)	Low (biogas may offset demand)
4	Energy Recovery	Yes (bioelectricity)	No	No	Yes (biogas)
5	Pollutant Removal Efficiency (BOD/COD)	High (99% / 92%)	High	Very High	High
6	Sludge Production	Low	High (excess sludge handling required)	Moderate	Low-Moderate
7	Membrane Fouling Concerns	Medium-High (Nafion prone to fouling)	Not Applicable	High	Not Applicable
8	Scalability	Moderate (requires membrane alternatives)	High (widely commercialized)	Moderate (high cost limits adoption)	High (mature technology)
9	Environmental Footprint	Low (minimal sludge, energy recovery)	Moderate (sludge disposal impact)	Moderate -High (chemical cleaning)	Low (biogas utilization)
10	Maintenance Complexity	Moderate	Moderate	High	Moderate
11	Cost per kg COD Removed	Low	Moderate	High	Low
12	Suitability for Decentralized Treatment	High	Low	Low	Moderate
13	Overall Cost-Effectiveness	High (when optimized)	Moderate	Low (mainly due to cost)	High

and biopolymer composites such as chitosan and agar blends have demonstrated comparable proton conductivity with improved fouling resistance and reduced manufacturing costs. Additionally, membrane-less MFC configurations and salt bridge systems present viable, low-cost options, though they may slightly compromise voltage generation and long-term operational stability. Future research should therefore focus on optimizing cost-effective proton exchange materials, integrating antifouling surface treatments, and developing durable membrane designs. These advancements will be essential for enhancing the scalability, operational lifespan, and economic feasibility of MFC-based wastewater treatment systems for sustainable bioenergy generation[25,26].

Conclusion

The experimental results demonstrate that MFCs are highly effective in both bioelectricity generation and wastewater treatment, showcasing an environmentally friendly approach with significant benefits. The MFC experiment displayed an initial increase in voltage from 174 mV to 301 mV within the first 8 h, achieving a peak power output of 1774.5 mW/h, before declining to 0 mV by 177 h due to substrate depletion and microbial aging. Current output peaked at 0.63 mA at 8 h and gradually decreased, reaching 0 mA by the end of the experiment. In terms of wastewater treatment, the MFCs achieved substantial reductions in key pollutants. The initial concentrations of BOD, COD, TDS, TSS, and TS were 684, 442, 1051, 861, and 1912 mg/L, respectively. After treatment, these values were reduced to 118, 266, 589, 136, and 725 mg/L, respectively. The MFC's treatment efficiency was determined to be 99% for BOD, 92% for COD, 84% for TDS, 95% for TSS, and 90% for TS. While the results of this study successfully met government norms and demonstrated the dual role of the MFC in energy production and pollutant reduction, certain limitations remain. MFC performance can be influenced by factors such as low power output, start-up time, and sensitivity to environmental conditions, which may affect long-term efficiency. Future research should

focus on optimizing MFC design, scalability, CV and EIS characterization and operational stability to enhance practical applicability. Addressing these challenges will further strengthen the potential of MFCs for sustainable environmental management, resource recovery, and renewable energy production.

Acknowledgement

The authors gratefully acknowledge Excel Engineering College for providing the resources and facilities to conduct the research.

Conflict of interest

The authors declare no conflict of interest.

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