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Technoeconomic Assessment of Microbial Fuel Cell for Wastewater Treatment: Bangladesh Perspective

Md. Sazid Khan, Anik Hasan Badhon, Md. Hasibul Hasan Himel, and Mim Mashrur Ahmed*

Department of Mechanical Engineering, Rajshahi University of Engineering & Technology, Rajshahi-6204, Bangladesh

ABSTRACT

Microbial fuel cells (MFCs) are bio-electrochemical systems that transform organic pollutants in wastewater into electricity while simultaneously treating the water. This study conducts a site-specific technoeconomic and environmental evaluation of a 1,000 m^3/day double-chamber microbial fuel cell system for industrial wastewater treatment in Rajshahi, Bangladesh. We integrate literature-based performance indicators (Chemical Oxygen Demand (COD) elimination, Coulombic efficiency, energy recovery) with locally obtained cost and tariff data to model a 15-year project at a 10% discount rate. Financial indicators Net Present Value (NPV), Internal Rate of Return 9IRR), deferred payback and environmental metrics (CO_2 reduction and sludge minimization) are assessed for a baseline scenario and across sensitivity ranges for discount rate, wastewater flow, electrode lifespan, and energy tariff. Under baseline assumptions, the system is expected to produce approximately 3.72×10^6 kWh annually, with a net present value of approximately Tk 1.03×10^8, an internal rate of return of approximately 18.3%, and a discounted payback period of around 7 years. Sensitivity analysis indicates that NPV is predominantly influenced by the discount rate and flow rate, whereas environmental benefits correlate with COD removal efficiency. We address critical uncertainties (scale-up losses, electrode longevity, cost projections) and advocate for focused pilot trials and vendor estimates to substantiate assumptions for implementation in Bangladesh.

Keywords: MFC, Renewable Energy, Techno-economic Analysis, Environmental Analysis.

1. Introduction

The worldwide clean water crisis is intensifying due to population expansion and heightened water demand, which are straining freshwater systems and treatment capacities. By 2030, the worldwide urban population is expected to exceed 5 billion, consequently exacerbating pollution levels and increasing the demand for reliable sanitation and wastewater services [1]. In Bangladesh, wastewater management predominantly relies on on-site sanitation methods, such as pit latrines and septic tanks, with centralized sewer networks serving only a minor fraction of urban areas. For instance, Dhaka's sewer system accommodates approximately one-fifth of its population [2]. In rural and peri-urban regions, economical conventional methods like stabilization, oxidation ponds, trickling filters, built wetlands, and small package treatment units are prevalent due to their ease of operation and lower installation costs compared to large mechanical plants [3]. Nonetheless, these traditional methods are recognized for their high energy use and considerable environmental repercussions [4]. As sustainability gains prominence, highlighted by the United Nations' Sustainable Development Goals (SDGs), various alternative methods for wastewater treatment have emerged. A primary difficulty that persists is identifying which of these sustainable alternatives presents the minimal environmental impact [5]. From this perspective, microbial fuel cells (MFCs) have been found to be a very promising solution. Microbial fuel cells (MFCs) are bio-electrochemical systems capable of directly converting the chemical energy stored in biodegradable organic matter within wastewater into electrical energy. At the same time, they facilitate pollutant degradation, offering a dual benefit of wastewater treatment coupled with partial energy recovery rather than net energy consumption [6]. Rossi et al. (2022) deployed pilot-scale air-cathode MFC modules (hundreds to ≈1000 L) to treat real wastewater. They reported methodology-driven observations of sustained Chemical Oxygen Demand (COD) removal, but only modest power densities that declined with scale due to increased ohmic and mass-transport losses [7]. Jacobs et al. (2024) conducted an assessment of the field/bench integrations of constructed wetland–MFC (CW-MFC) and reported that they were able to improve COD and nutrient removal while simultaneously producing low-grade electricity [8].

To integrate the facility of MFC for wastewater treatment, site specific technoeconomic and environmental analysis is essential as the concentration of COD varies depending on various types of wastewater. Although numerous experimental investigations have demonstrated the effectiveness of microbial fuel cells (MFCs) across different reactor configurations and feedstocks, research remains limited in terms of site-specific technoeconomic and sustainability assessments in developing nations such as Bangladesh. To date, only a single technoeconomic study has been reported, conducted within an industrial zone in Dhaka. [9]. This study conducts a technoeconomic and environmental assessment tailored to Bangladesh, analyzing potential scales for MFC deployment utilizing locally

*Corresponding Author Email Address: hasibul.hasan@me.ruet.ac.bd

sourced capital and operational and maintenance inputs, and performs a focused sensitivity analysis to determine the most influential parameters for practical deployment and pilot validation. We chose a double-chamber configuration for the Rajshahi case study, as it facilitates independent regulation of anolyte and catholyte conditions (beneficial for high-COD industrial wastewater), simplifies performance monitoring in a pilot setting, and minimizes oxygen crossover relative to membrane-less designs, elements that enhance treatment reliability and data integrity during initial deployments.

2. Classification

Microbial fuel cells (MFCs) are generally classified by their configuration into single-chamber, dual-chamber, multi-chamber, and stacked systems. They can also be grouped according to the type of separator employed, while their most common applications are found in wastewater treatment, biosensing, and renewable power generation [6]. The configuration of the reactor and the selection of separators are pivotal in determining the performance of MFCs. Table 2 provides a concise comparative study of the primary MFC types documented in the literature, categorized by cell configuration, separator approach, and application. The table outlines distinguishing characteristics and significant technical or operational constraints for each category.

Category	Sub-Type	Limitations	References
Cell Configuration	Single Chamber	Lower power output	[6]
	Double Chamber	More complex, requires a membrane	[6]
	Stacked	Complex hydraulics	[10]
	H-type	Large liquid volume	[6]
Separator	Membrane (PEM/CEM/AEM)	Expensive, prone to fouling, pH splitting	[6]
	Membrane-less	Oxygen crossover	[11]
	Salt-Bridge	Very high internal resistance	[11]
Application	Wastewater Treatment	Slow treatment rate	[6]
	Biosensors	Requires calibration	[6]
	Power Source	Low power density	[6]

3. METHODOLOGY

The technoeconomic and environmental analysis of MFCs for wastewater treatment determines whether or not technology has the potential to offer financial and environmental benefits under conditions that are representative of the actual world. The analysis incorporates key economic factors such as capital expenditure (CAPEX), operating expenditure (OPEX), energy pricing, and treatment credits. It also evaluates technical aspects, including energy generation and system uptime, along with environmental considerations such as CO_2 emissions and sludge production. The techno-economic analysis evaluates the financial feasibility of MFC systems in comparison with conventional treatment technologies. Key indicators used in this assessment include the net present value (NPV), internal rate of return (IRR), and discounted payback period (DPP). These metrics collectively indicate the profitability, investment efficiency, and payback time of the system, thereby providing a comprehensive measure of its economic viability.

3.1 Power estimation

Bangladesh, a rapidly growing country in South Asia, faces increasing challenges in managing urban and industrial wastewater. Rajshahi, a major city of Bangladesh in the northwest known for its silk industry and agriculture, produces a significant amount of industrial wastewater that needs effective treatment. MFCs offer a way to not only treat this wastewater but also generate electricity by directly converting the chemical energy in organic matter into electrical energy through microbial activity. In Rajshahi, industrial wastewater from the silk industry typically has a COD concentration of 2550 mg/L [12]. Theoretical calculations suggest that MFCs can recover approximately 4 kWh of energy per kilogram of COD removed [13]. Based on this, the potential energy recovery from the wastewater can be estimated considering a 1000 m^3/day wastewater flow rate using equation 2. All relevant technical analysis formulas are summarized in Table 3.

3.2 Economic analysis

Economic analysis of MFC involves determining the NPV, IRR, and DPP of the MFC plant. For this calculation, a plant that can treat 1000 m^3/day with a lifetime of 15 years and operating 365 days in a year was considered [14]. To calculate the revenue from electricity, an average electricity price of 1 kWh in Bangladesh is considered 8 TK [15]. To calculate the revenue from the byproduct, it was assumed that 50 Tk was earned from the byproduct of 1 m^3 of wastewater treatment. The capital cost of the double-chamber MFC plant was estimated at around 20 cr by considering the labor cost, instrument cost, and depreciation cost. Operational costs, generally amounting to 3–4% of the capital cost annually, mainly cover maintenance, replacement of components like electrodes, and labor expenses [16]. For the base case estimation, the operational cost is assumed at the upper limit of the typical range, set at 4% of the annual capital cost [17]. For this analysis, a discount rate was considered as 10%. Based on these, the economic analysis was done. All relevant economic analysis formulas are summarized in Table 3.

3.3 Environmental Analysis

Compared to conventional wastewater treatment, MFC technology offers significant environmental benefits by reducing energy consumption and greenhouse gas emissions. Traditional aerobic wastewater treatment plants typically consume 0.3–0.6 kWh per cubic meter, with approximately 50–60% of this energy used for aeration [18]. In contrast, MFCs do not consume energy; they generate electricity. Moreover, the electricity generated from fossil fuels produces around 0.942 kg CO_2 per kWh of electricity [19]. A traditional wastewater treatment plant has a sludge yield of 0.42 g SS (suspended solids)/g COD.

Table 3: Summary of parameters for Techno-Economic and Environmental Analysis

	Metric	Equation	Eq. No
Technical Analysis [13]	COD Load Calculation	$\text{COD Load} = 1000\text{m}^3/\text{day} \times 2.550\text{kg/m}^3 = 2550\ \text{kgCOD/day}$	1
	Annual Energy (KWh)	$\text{Energy Recovery} = \text{COD Load} \times 4\text{KWh/KgCOD} \times 24 \times 365$	2
Economic Analysis [22]	Electricity Revenue (Tk/yr)	$\text{R}_{\text{elec}} = \text{E} \times \text{Price of Electricity(tk/KWh)}$	3
	Treatment Credit (Tk/yr)	$\text{R}_{\text{treat}} = \text{V} \times \text{d} \times \text{Treatment credit}$	4
	OPEX (Tk/yr)	OPEX=CAPEX×4%	5
	CAPEX (Tk)	CAPEX = Initial equipment cost + Recycling cost – Depreciation value	6
	Net Cash Flow (Tk/yr)	$\text{C}=R_{elec} + R_{treat} - \text{OPEX}$	7
	Discounted Cash Flow (Tk)	$\text{DCF} = \frac{\text{C}}{(1+\text{r})^{\text{t}}}$	8
	NPV(Tk)	$\text{NPV} = \sum_{0}^{\text{t=n}} \frac{\text{C}}{(1+\text{r})^{\text{t}}} - \text{Capex}$	9
	IRR(%)	$0 = \sum_{0}^{t=n} \frac{C}{(1+IRR)^{t}} - Capex$	10
	DPP(Year)	$DPP = n + \frac{CAPEX - DCF_n}{DCF_{n+1}}$	11
Environmental Analysis	CO_2 Emission (Ton) [19]	$\text{Amount of CO}_2 = 0.942 \times \text{AnnualEnergy}$	12
	Sludge Formation (Ton) [20]	$\text{Amount of Sludge} = 0.42 \times \text{COD Load}$	13

Implementing MFCs, which can reduce sludge yield by 24.2%, could prevent the generation of sludge each year by a portion [20]. This reduction not only decreases greenhouse gas emissions but also lowers operational costs associated with sludge handling, transportation, and disposal [21]. All relevant environmental analysis formulas are summarized in Table 3.

3.4 Sensitivity Analysis

A sensitivity analysis was conducted to assess how variations in discount rate and wastewater flow rate influence the NPV of the MFC system. The discount rate was considered to directly affect the present value of cash flows and thus has a strong impact on NPV. In contrast, the amount of flow governs treatment credit, which determines annual cash flow, thereby indirectly influencing NPV. The analysis was based on Equation 9 presented in Table 3. The results of the study are more practically applicable because of this sensitivity analysis, which makes it easier to comprehend how financial indicators react in dynamic conditions.

4. RESULTS and DISCUSSION

4.1 Technoeconomic Assessment of MFC

The techno-economic analysis of microbial fuel cells (MFCs) shows their strong potential for wastewater treatment in Rajshahi, where both cost-effectiveness and reliability are critical. To estimate energy recovery, the COD concentration of local wastewater was used, and the annual energy production was calculated to be approximately 3.72 million kWh. Economic feasibility was assessed over a 15-year project horizon with a 10% discount rate using three financial indicators, including NPV, DPP, and IRR. The NPV was Tk 1.03×10^8, reflecting strong long-term profitability. The DPP was 7.02 years, meaning the investment could be recovered within a reasonable timeframe. This shorter payback period reduces risks for investors by limiting exposure to factors such as policy shifts, performance loss, or unstable operating conditions. The IRR was found to be 18.29%, nearly double the discount rate, which further strengthens the financial case for MFCs by providing a solid buffer against uncertainty and making the project attractive to investors and financing institutions.

4.2 Environmental Impact

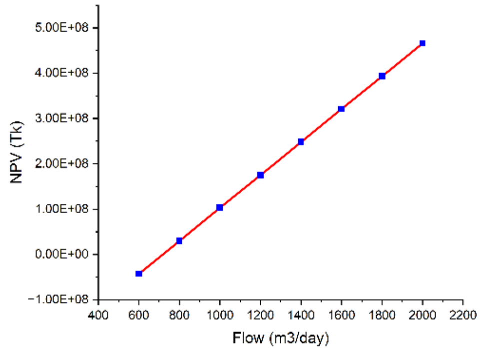
Beyond the financial benefits, MFCs offer important environmental advantages. Conventional treatment methods consume significant amounts of electricity and generate large volumes of sludge, both of which add to operational and environmental burdens. By contrast, MFCs can prevent large amounts of CO_2 emissions while substantially reducing sludge formation. A conventional 1,000 m³/day wastewater treatment plant emits approximately 100-200 tons of CO_2 annually, according to Equation 12, whereas using MFC technology can eliminate these emissions, which greatly reduces the carbon footprint and saves the environment from air pollution. Additionally, a conventional plant treating a daily COD load of 2,550 kg would produce around 390 tons of sludge annually. On the contrary, by implementing MFC, it could prevent the generation of 95 tons of sludge each year compared to a conventional plant. Implementation of MFCs reduced sludge production by approximately 24%, substantially lowering greenhouse gas emissions and the logistical burden associated with sludge transport and disposal. When combined with stabilization and resource-recovery measures (e.g., anaerobic digestion, drying, phosphorus recovery), the smaller sludge stream can be converted into a low-risk, value-bearing resource, thereby enhancing the overall environmental performance of wastewater treatment. This makes them not only a cost-effective choice but also an environmentally safer solution for wastewater treatment. In summary, the findings indicate that MFCs are technically feasible, economically viable, and environmentally sustainable for Rajshahi. Their ability to generate renewable electricity from wastewater while delivering financial returns and reducing environmental impacts positions them as a compelling alternative to conventional treatment technologies. The main techno-economic and environmental outcomes of the MFC system in Rajshahi are summarized in Table 4. These results highlight the system's energy recovery potential, financial performance, and environmental benefits compared to conventional treatment methods.

Table 4: Techno-economic and environmental performance of MFCs for wastewater treatment in Rajshahi, Bangladesh.

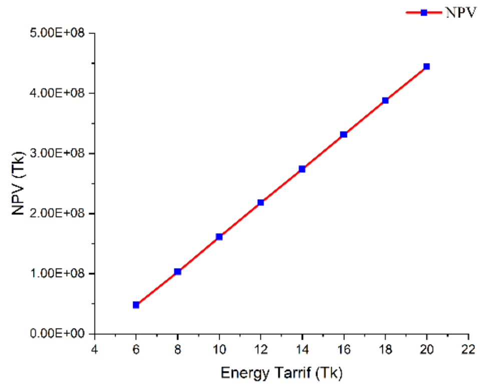
Parameters	**Outcomes**
Energy Recovery	3.723 Million KWh/Year
NPV	$1.03 \times 10^8\ Tk$
DPP	7.02 Year
IRR	18.29%
CO_2 emission reduced	100-200 tons annually
Sludge formation reduced	Around 95 tons annually

4.3 Sensitivity Analysis

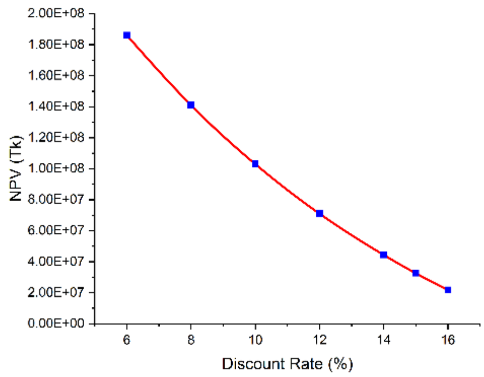
A sensitivity study was performed to assess the impact of variations in discount rate and wastewater flow on the financial performance of microbial fuel cells (MFCs). The findings indicate that fluctuations in the discount rate substantially affect Net Present Value (NPV), which is shown in Figure 1(a). As the discount rate rises, the current value of future cash inflows declines, resulting in a decline in profitability. Under conditions of higher discount rates, investors encounter increased risks and a longer delay in profits, making the project less attractive. Conversely, a reduction in the discount rate enhances the NPV, thereby strengthening the financial attractiveness of MFCs. The flow of wastewater demonstrated a clearly beneficial impact on financial results. As the flow rate increased from 600 m³/day to 2,000 m³/day, the system effectively processed larger volumes of wastewater, leading to enhanced COD removal and increased energy recovery. This resulted in enhanced treatment credits, increased revenue, and faster recovery of capital investment. Figure 1(b) demonstrates that increased flow rates resulted in enhanced NPVs, hence increasing project profitability and minimizing financial risks. Figure 1(c) also shows that with increasing energy tariff the NPV of the plant increases linearly indicating improved economic viability as revenue from energy generation rises. The sensitivity analysis indicates that although profitability is dependent on variations in discount rates, the scalability of MFC systems significantly influences economic performance. Increasing the treated volume not only increases financial results but also improves the strength and attraction of MFCs as a wastewater treatment method. The findings indicate that extensive implementations of MFCs in Rajshahi would yield more dependable returns, quicker payback, and enhanced overall profitability relative to smaller-scale systems.



(a)



(b)



(c)

Figure 1: Sensitivity analysis (a) NPV vs Discount Rate, (b) NPV vs Flow Rate, (c) NPV vs Energy Tariff

5. Conclusion

The techno-economic and environmental analysis indicates that a 1,000 m³/day double-chamber MFC can feasibly treat industrial wastewater in Rajshahi, producing 3.72×10^6 kWh annually, with a positive NPV, 18.3% IRR, and a payback period of about seven years. The system also reduces sludge generation and lowers CO_2 emissions by 100–200 tons per year. Outcomes are sensitive to COD removal, energy recovery, material durability, and cost factors, underscoring the need for pilot-scale validation. Policy incentives, durable low-cost materials, and monetization of co-benefits will be crucial to scaling MFCs as a sustainable alternative to conventional treatment in Bangladesh.

To validate modeled outcomes and facilitate scale-up, we propose a 6–12 month pilot utilizing modular double-chamber units (approximately 0.1–1% of plant flow) to assess site-specific COD removal, Coulombic efficiency, power output, and actual operational and maintenance requirements.

Integrate MFC modules as pre-treatment or sidestream units at selected ETPs, ensuring provisions for power conditioning and options for onsite utilization or grid export. Additionally, obtain vendor quotations to confirm capital and operational expenditures, and conduct targeted materials testing (accelerated aging, electrochemical impedance spectroscopy, scanning electron microscopy/energy dispersive spectroscopy) alongside 12–24 months of field monitoring (continuous electrical logs, monthly mass balances, maintenance records) to evaluate electrode/membrane durability and update lifecycle techno-economic analysis/lifecycle assessment. These measures mitigate the primary risks mentioned above and are necessary before extensive implementation.

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