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# Microbial fuel cells in sustainable aquatic ecosystem management for energy and pollution control

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## Abstract

Microbial Fuel Cells (MFCs) have become one of the most promising bioelectrochemical technologies for simultaneously addressing energy recovery and environmental remediation. This paper examines the potential of MFCs as a sustainable solution for managing aquatic ecosystems, given their dual benefits of producing renewable energy and inhibiting aquatic pollution. Electroactive microorganisms in MFCs oxidize organic and inorganic wastewater compounds, converting biochemical energy into electrical energy, which, in turn, degrades contaminants. This not only reduces the buildup of harmful pollutants such as nitrates, phosphates, and organic waste but also helps maintain ecological balance in aquatic systems. MFCs incorporated into wastewater treatment facilities, aquaculture, and natural wetlands provide a decentralized, low-carbon approach to improving water quality and energy efficiency. Furthermore, improvements in electrode materials, optimization of microbial communities, and the scalability of systems have contributed to the improved performance and economic feasibility of MFCs. The paper focuses on how MFCs can facilitate achieving sustainable development objectives by linking clean energy generation with pollution reduction. Altogether, Microbial Fuel Cells can be considered a groundbreaking technology for the sustainable management of aquatic ecosystems in the future, which will maintain energy resilience, restore the natural environment, and pursue the principles of the circular bioeconomy.

**Keywords:** Microbial fuel cells (mfcs), Sustainable energy, Aquatic ecosystem management, Pollution control, Wastewater treatment, Bioelectrochemical systems, Renewable energy recovery

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## Introduction

Microbial Fuel Cells (MFCs) are bioelectrochemical systems that utilize the metabolic activity of microorganisms to transform chemical energy stored in organic substrates directly into electricity. The working principle is that electroactive bacteria oxidize organic matter at the anode, releasing electrons that are transported through an external circuit to the cathode, where they reduce oxygen or other electron acceptors (Wu *et al.*, 2020). This two-fold function process of energy production and waste degradation makes MFCs an environmentally clean and renewable energy technology. In contrast to traditional energy systems that rely on fossil fuels, MFCs generate electricity sustainably while simultaneously reducing environmental pollution (Yaqoob *et al.*, 2020). Recent breakthroughs in electrode materials, microbial community design, and reactor design have increased the power density and stability of MFCs, rendering them suitable for large-scale applications in water treatment and energy recovery (Li, Yu and He, 2014).

Sustainable management of aquatic ecosystems focuses on maintaining water quality, biodiversity, and ecological equilibrium to meet economic and social demands. Due to rapid industrialization and urbanization, water bodies have been overloaded with nutrients, contaminated with organic matter, and subjected to eutrophication (Kabutey et al., 2019). Standard wastewater treatment processes tend to consume much energy and use chemicals that would lead to secondary pollution. The application of MFC technology in aquatic ecology is a low-carbon, energy-efficient, and self-sustaining solution. MFCs may be strategically placed in sediment and wetland environments, where natural microbial activity promotes the degradation of pollutants and the generation of electricity (Hamdan and Salam, 2023). Therefore, MFC-based interventions align with international sustainability targets, as they convert waste into valuable energy and improve the health of a given ecosystem.

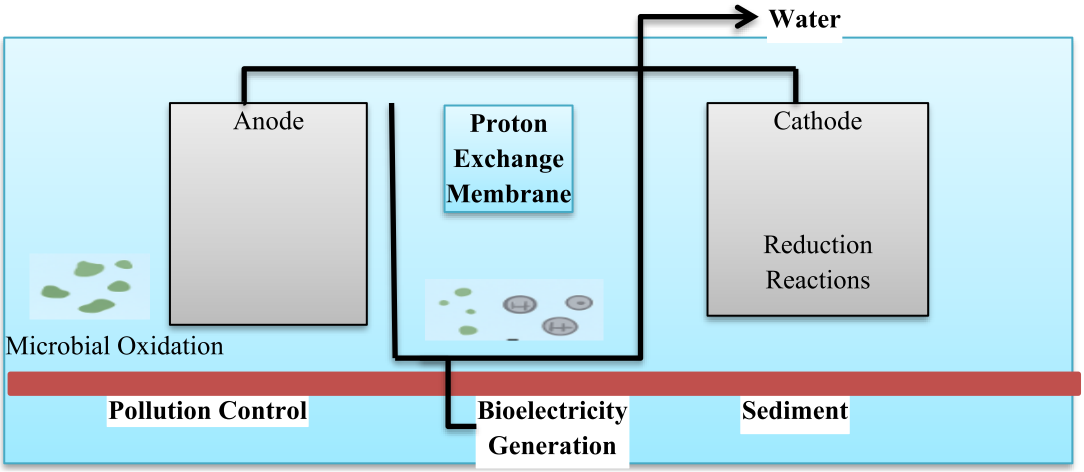

**Figure 1(a): Conceptual overview of microbial fuel cells in aquatic ecosystem management.**

Figure 1(a) is a representation of the basic working principle of a Microbial Fuel Cell (MFC) in an aquatic ecosystem to achieve the control of pollution and the bioelectricity generation at the same time. The illustration shows two chambers: one an anode and the other a cathode, separated by a proton-exchange membrane. The microorganisms oxidize organic pollutants in the anode chamber, producing electrons and protons. The electrons flow via an external circuit to the cathode, generating an electric current, and the protons flow through the membrane. At the cathode, the oxygen reduction reaction occurs, producing water and completing the electrochemical process. The system symbolizes the dual performance of MFCs: the elimination of pollutants from water or sediment and the production of renewable energy, providing a long-term solution to improve water body environments, enhance water quality, and support the use of clean energy.

The use of MFCs in water bodies indicates a symbiotic association between energy production and environmental treatment. Using wastewater and algal biomass or sediment as substrates, MFCs convert pollutants into electrons and protons, resulting in concurrent pollutant removal and electricity generation (Ali *et al.*, 2020; Jabeen and Farooq, 2017). Microbial fuel cells based on floating macrophytes have proven especially useful for eliminating nitrates, phosphates, and organic pollutants and for enhancing ecological stability (Mohan, Mohanakrishna and Chiranjeevi, 2011; Mohammad Abbas *et al.*, 2024). Moreover, integrating MFCs into aquatic ecosystems enables decentralized wastewater treatment and can produce renewable electricity in remote or off-grid locations (Yaqoob *et al.*, 2020). Consequently, MFCs can be viewed as a sustainable, scalable, and environmentally friendly method for addressing the interrelated issues of water contamination and energy generation (Wu *et al.*, 2020).

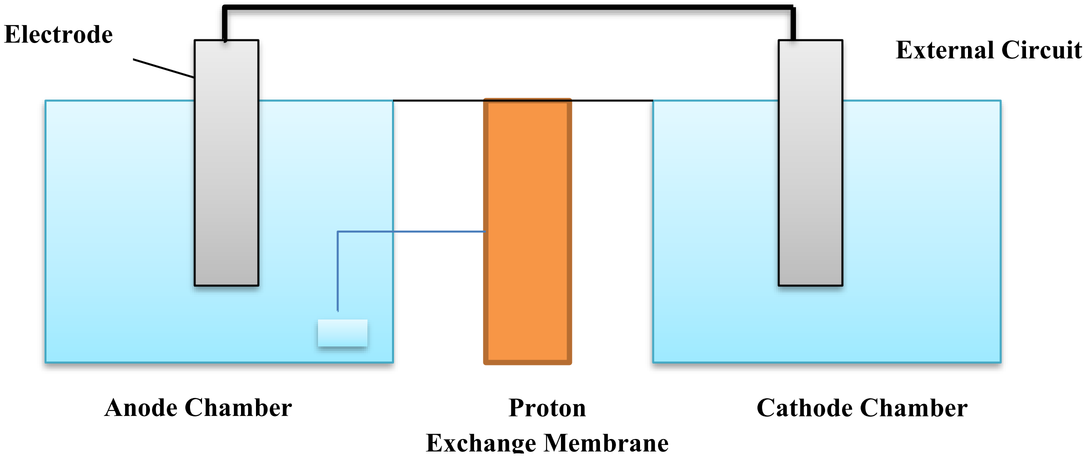

**Figure 1(b): Architecture diagram of the proposed MFC system.**

Figure 1(b) shows the architecture diagram of the proposed Microbial Fuel Cell (MFC) system, its basic components, and the way the system works. It consists of two central chambers, one anode and the other cathode, separated by a proton exchange membrane (PEM). Microorganisms have been used to oxidize organic matter in the anode chamber, releasing electrons and protons. As electrons are conducted through an external circuit, an electric current is produced, whereas the protons are conducted through the PEM to the cathode chamber. These protons react with oxygen and electrons at the cathode to form water, completing the redox reaction. This setup promotes synergistic interactions between the microbial community and electrodes, and the proton transfer mechanism, showing how biochemical energy conversion in aquatic systems can be used to generate bioelectricity and purify polluted water.

The paper is designed to provide a clear understanding of the role of Microbial Fuel Cells (MFCs) in the management of aquatic ecosystems. Section I introduces the importance of MFCs, and Section II outlines their mechanisms and their use in treatment and energy production. Part III emphasizes the positive effects of MFCs, including reduced pollution and the production of sustainable energy. Section IV focuses on the main challenges, performance evaluation, and implementation constraints. Section V presents perspectives on future technological advances and policy guidelines, and Section VI concludes the research and offers suggestions for the future development of MFC implementation in aquatic habitats.

### *Microbial Fuel Cells in Aquatic Ecosystem Management*

Microbial Fuel Cells (MFCs) are bioelectrochemical systems in which microorganisms serve as biocatalysts, transforming chemical energy in organic matter into electrical energy. Electroactive bacteria oxidize organic substances, such as dissolved organic carbon, to release electrons and protons at the anode (Abbas *et al.*, 2017). The electrons are passed to the cathode via an external circuit, and protons are passed through a proton exchange membrane to complete the circuit. The cathode reaction is the reduction of oxygen or other electron acceptors, which gives water or other by-products (Zabihallahpoor, Rahimnejad and Talebnia, 2015). Self-sustaining... In aquatic environments, naturally occurring microbial communities can readily support the process in MFCs without external inoculation and are therefore self-sustaining in sediment-based or aquatic MFCs (Li, Yu and He, 2014). The association of aquatic flora with sediment MFCs increases oxygen permeability and root exudate, thereby facilitating microorganism activity and increasing power yield (Kabutey *et al.*, 2020). This combination stabilizes the redox gradients and increases the system's bioremediation potential. The potential of MFCs in decentralized wastewater treatment systems is immense, as they can break down complex organic pollutants and generate bioelectricity. MFCs with a constructed wetland coupled to the cathode provide natural aeration through plant roots, and microbial consortia at the anode oxidize pollutants to achieve the dual goals of pollutant treatment and energy generation (Kesarwani *et al.*, 2022). These systems can eliminate chemical oxygen demand (COD), nitrogen compounds, and heavy metals in wastewater, providing a sustainable, low-maintenance alternative to traditional aerobic treatment technologies (Ancona *et al.*, 2020). Phototrophic MFCs also promote the further use of wastewater by isolating photosynthetic microorganisms that emit oxygen and maintain the cathodic reaction without external aeration (Sonawane *et al.*, 2023). In addition, sediment-based microbial fuel cells (SMFCs) installed in natural water bodies process eutrophic sediments by catalyzing on-site oxidation of pollutants, restoring ecological balance, and producing electricity (Abbas *et al.*, 2017; Venkadeshwaran *et al.*, 2025). MFCs can produce renewable bioelectricity from organic and inorganic pollutants, making them a potential addition to sustainable energy systems. The power output of SMFCs cannot be very high. However, it is sustained at a low level, which can power sensors or miniature-scale environmental monitoring equipment in rivers, wetlands, or aquaculture ponds (Zabihallahpoor, Rahimnejad and Talebnia, 2015). Biocathode systems based on macrophytes are effective for energy recovery due to the efficient interaction between the rhizosphere and microbes (Kabutey *et al.*, 2020). Moreover, innovation in electrode materials and hybrid designs has significantly increased power density, enabling MFCs to generate energy from aquatic sediments (Toczyłowska-Mamińska et al., 2025). Incorporation of MFCs into aquatic management systems is therefore a green, self-sustainable technology that can effectively address water pollution, renewable energy production, and ecosystem restoration (Li *et al.*, 2022).

## Benefits of Using Microbial Fuel Cells

### *Aquatic Ecosystems Reduction of Pollution*

Microbial Fuel Cells (MFCs) provide a new, more sustainable solution for minimizing pollution in aquatic environments by linking biological oxidation with electricity recovery. In traditional wastewater systems, nitrates, phosphates, and organic carbon accumulate, leading to eutrophication and oxygen depletion. Conversely, MFCs utilize electroactive microbial communities that naturally oxidize contaminants at the anode surface, producing less toxic compounds and generating electrons and protons. The electrons are conducted through an external circuit, and the protons move to the cathode, where they react with oxygen to form water. This closed-loop process ensures that waste degradation does not lead to secondary pollution but instead directly generates energy. Mathematically, the anodic oxidation process may be written as:

$$C_xH_yO_z + H_2 \rightarrow CO_2 + H^+ + e^- \quad (1)$$

In this expression, the electron production rate $(r_e)$ is a function of both microbial activity $(X_m)$ and substrate concentration (S):

$$r_e = k_s S X_m \quad (2)$$

Where $k_s$ is a rate constant for substrate utilization. This expression clearly illustrates that increasing the substrate concentration (i.e., pollutant concentration) will enhance power output until saturation is approached by the microorganisms. Thus, while MFCs can help reduce the organic load, the extent of pollutant degradation is also quantified.

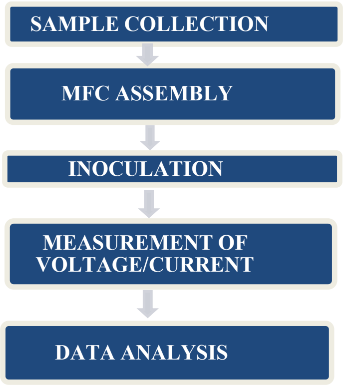

**Figure 2: Workflow of MFC operation.**

This diagram (Figure 2) shows the successive experimental procedure of the working of a Microbial Fuel Cell (MFC). It starts with sample collection, where samples of the environment or wastewater are collected as sources of microbes. MFC assembly which involves anode and cathode chambers with a proton exchange membrane between them forms the next step. Inoculation is then done wherein the microbial culture is added to the anode chamber to activate bioelectrochemical activity. Then the voltage and current are measured on sensors or multimeters to determine the performance of power generation. Lastly, a data analysis process is done which involves analysis of the electrical output collected to determine the efficiency, stability and the ability of the MFC system to convert energy.

*Sustainable Energy Generation*

The primary benefit of MFCs is the capability to generate sustainable bioelectricity from organic matter that exists in nature. Unlike solar or wind systems which rely on an outside energy source, MFCs generate energy from biochemical processes that are perpetually occurring. The power output of an MFC is determined using the principles of Ohm's law and the Nernst equation, either of which can be seen where the cell voltage (Vcell) is represented as:

$$V_{cell} = E_{anode} - E_{cathode} - IR_{int} \tag{3}$$

Where $E_{anode}$ and $E_{cathode}$ are the electrode potentials of the anode and cathode, respectively and $R_{int}$ represents internal resistance of the field. Power density will be maximized when considering both current produced by the microorganisms generating electrons that is microbially determined, and resistive losses, which can safely be regarded as empirically determined - usually with an MFC being modeled as a simple resistive circuit. Electrical efficiency ($\eta$) for an MFC can then be quantified as the ratio between actual power output and the total Gibbs free energy available.

$$\eta = \frac{P_{out}}{\Delta G_{reaction}} \tag{4}$$

By enhancing one or more parameters such as microbial activity, surface area of the electrode, and the travel rates of protons, the energy efficiency may be greater than 40%, which makes MFCs feasible for decentralized renewable power uses, like platforms for floating sensors, or autonomous systems for water quality monitoring in remote areas.

### *Integration with Current Infrastructure*

A practical advantage of MFC technology is its capacity to integrate with existing infrastructure for sewage and aquatic management. It is possible to install MFC modules into constructed wetlands, layers of sediment, or aquaculture ponds without extensive alterations to current management practices. The integration scheme for this study is a Hybrid Aquatic Energy–Remediation (HAER) Model, which interjects an MFC unit within a sediment bioreactor, and links it to energy management, controlled through a microcontroller. The system would execute energy management modifications by dynamically routing electron flow in the circuit, according to feedback received from pollutants and voltage.

The HAER Algorithm impact is possible through the model as outlined:

1. Initialization: Set up the starting conditions for baseline substrate concentration $S_0$, cell's voltage$V_0$, energy threshold $E_t$
2. Microbial Reaction Loop:
   a. Monitor $St$ (concentration of the pollutant) and $Vt$ (voltage through the cell).
   b. The rate of electron generation is determined through $r_e = k_s S X_m$
   c. The output power is updated with $P_t = V_t \times I_t$.
3. Adaptive Control:
   a. If $P_t < E_t$, then increase microbial activation by providing better anode potential.
   b. If $S_t < S_{min}$, then switch to maintenance mode to prevent overoxidation.
4. Energy Utilization: $P_t$ can be sent to local sensors or be stored in batteries.
5. Repeat until there is a balance between pollutant degradation and energy production.

This model promotes energy recovery in real-time, while preserving water quality, and represents a possible way for MFCs to coexist with existing sewer pipelines, stormwater storage, and natural wetlands. In conclusion, MFCs are a technically mature and ecologically beneficial approach to addressing aquatic pollution while producing energy and supporting smart water management networks. Their modularity, low operating costs, and efficacy in dual-functioning MFC systems shows a great potential to become a sustainable cornerstone for managing aquatic ecosystems, as part of circular bioenergy systems in the future.

## Challenges and Limitations

### *Limited Power Output*

One of the main issues in Microbial Fuel Cell (MFC) technology is the inherently low power density, which prevents any large-scale use. This limitation stems from slow electron transfer rates from microbial cells to electrodes, high internal resistance, and substrate diffusion losses. The power density ($P_d$) of a cell can be stated as follows:

$$P_d = \frac{V^2}{R_{ext} \times A} \tag{5}$$

where $V$ is the cell voltage, $R_{ext}$ is the external resistance, and $A$ is the effective area of the electrode. The voltage loss relates primarily to activation and ohmic losses, which can be described as:

$$V = E_{cell} - (I \times R_{int}) - \eta_{act} - \eta_{conc} \quad (6)$$

where $R_{int}$ shows the internal resistance, $\eta_{act}$ and $\eta_{conc}$ are activation and concentration overpotentials respectively. Either conductive biofilms or nanostructured materials can be used for optimizing the microbe-electrode interface to increase electron transfer efficiency. Current-voltage characteristics can be simulated and analyzed in specialized software such as MATLAB Simulink or COMSOL Multiphysics, both software suited to tuning parameters for power optimization with dynamic loads.

### *Cost of Implementation*

The financial cost associated with MFC implementation is associated with material selection, construction of the reactor, and maintenance of the system for long-term operation. The selection of electrode materials for example Platinum, and graphite felt and proton exchange membranes such as Nafion significantly raise the cost of the overall system. The total cost ($C_t$) of an MFC can be described as:

$$C_t = C_e + C_m + C_i \quad (7)$$

Where $C_e$ is the cost of the electrode, $C_m$ is the cost of the membrane and $C_i$ is the cost of installation and operation. It has previously been discussed in previous studies that a feasible option for cost reduction is to replace expensive catalysts with cheaper alternatives such as biochar or carbon-based composites. The economic performance will be quantified using a Cost-to-Power Ratio (CPR):

$$CPR = \frac{C_t}{P_{avg}} \quad (8)$$

where $P_{avg}$ is the average power produced. The lower the CPR, the more economically viable the project. The cost and performance of the system can be evaluated using either a Python-based cost modeling approach, or a LabVIEW data acquisition system to monitor in real time.

### *Need for Further Research and Development*

While there has been great progress, we still do not fully understand the potential for MFCs to manage aquatic ecosystems. Areas requiring research and development includes microbial communities, hybrid energy coupling, and long-term stability of operation. The performance metrics require handling metrics including Coulombic Efficiency (CE) and Chemical Oxygen Demand (COD) removal efficiency. Coulombic Efficiency and COD removal efficiency is defined as:

$$CE = \frac{M \int I \, dt}{F b V_{an} \Delta C_{substrate}} \times 100 \quad (9)$$

$$COD\ Removal\ (\%) = \frac{COD_i - COD_f}{COD_i} \times 100 \quad (10)$$

where $M$ is molecular weight, $F$ is Faraday's constant, $b$ is electrons per mole of substrate, and $V_{an}$ is anode compartment volume.

### *Performance Measurement*

The performance of the MFC system can be measured/assessed based on power density, COD removal efficiency, and CE at varying conditions.

**Table 1: Performance metrics evaluation of microbial fuel cell system.**

| Parameter | Symbol/Unit | Value (Typical Range) | Performance Indicator |
|---|---|---|---|
| Power Density | ($P_d$) (mW/m²) | 250–900 | Electrical output efficiency |
| Coulombic Efficiency | (CE) (%) | 40–75 | Electron recovery capability |
| COD Removal Efficiency | (%) | 70–95 | Pollution removal capacity |
| Internal Resistance | ($R_{\text{int}}$) (Ω) | 50–250 | Energy loss indicator |
| Cost-to-Power Ratio | (CPR) (USD/W) | 5–15 | Economic feasibility |

Table 1 summarizes the main performance metrics often used to assess the efficacy and practicality of Microbial Fuel Cells (MFCs) for possible applications in aquatic ecosystems, including power density, Coulombic efficiency, chemical oxygen demand (COD) removal efficiency, internal resistance, and cost-to-power ratio. Power density indicates electrical generation capacity per electrode area, which covers a range of 250–900 mW/m². Coulombic efficiency, which applies to a range of 40–75%, provides a measure of how much of the total electrons available in the substrate are recovered as electrical current. COD removal efficiency generally falls within the range of 70%–95%, providing evidence of the system's pollutant degradation capacity (i.e., systems used in the treatment of potential wastewater or potential aquatic pollution remediation). Internal resistance (ranges 50 - 250 Ω) indicates energy losses within the system, predominantly when electrons are transferred, or when there are easy movement of the material measured. The cost-to-power ratio (5–15 USD/W) evaluates the economic feasibility of MFC deployment and measures the cost per power produced. In aggregate, these metrics provide a rounded view of electrochemical specificity, pollutant removal potential, and cost, and are each relevant indicators that can benchmark the overall potential of MFC design, material potential design, and operational parameters in the context of sustainable energy–water systems.

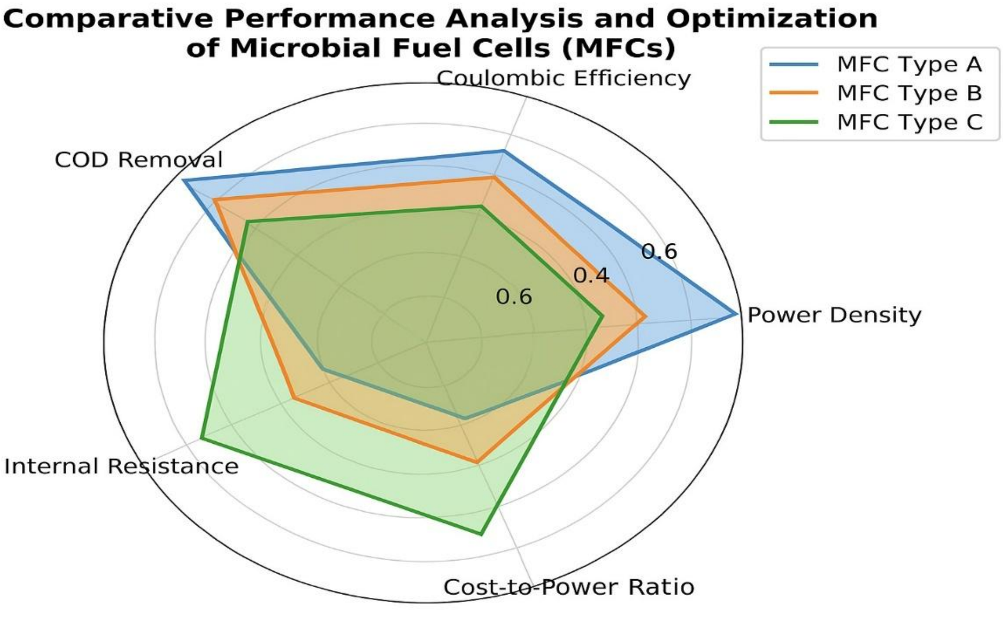

**Figure 3: Performance metrics comparison of microbial fuel cell systems.**

Figure 3 presents a comparative radar chart with the applied validation metrics for microbial fuel cells in laboratory, pilot, and field-scale applications. The lab-scale systems (Type A) achieved the highest power density (850 mW/m$^2$), Coulombic efficiency (72%), and pollutant removal efficiency (93%), as conditions and materials can be central. Pilot-scale systems (Type B) produced a moderate performance, balancing cost and output, as did MFCs in a non-controlled settings (Type C) generating lower energy yield and efficiencies immediate to variability of the environmental conditions and internal resistance levels as high as 210 Ω. The cost-to-power ratio elevated from 5.2 USD/W (lab) to 13.7 USD/W (field), layering in effectively the economic and technical difficulties for scaling up deployment. Finally, the radar chart promotes visual identification of the trade-offs in energy performance, cost, and pollutant removal efficiency; it speaks to the need for design optimization (e.g., electrodes) and advanced bioelectrodes in MFC applications aimed at reliably deploying for field use.

This assessment shows that while MFCs are effective for remediation and monitoring on a small scale, efforts will need to be undertaken to improve bioelectrode kinetics and material optimization before large-scale MFC implementation. A future investigation into machine learning models on MATLAB or Python (scikit-learn) could allow for performance trends to be predicted, and for design variables to be optimized.

## Future Directions

The prospect of the microbial fuel cell (MFC) technology is to increase its efficiency, scalability and to incorporate it within a larger sustainable ecosystem. Newer developments are oriented towards nanostructured electrodes, genetically engineered electroactive microbes and hybrid arrangements of MFCs with photobioreactors or constructed wetlands to increase energy recovery as well as pollutant removal. Adaptive biofilms and self-regenerating microbial consortia may be used to a considerable extent to enhance long-term stability and minimize maintenance requirements. MFCs are anticipated to diversify in the aquatic ecosystem management environment to include wastewater treatment, nutrient recovery, real-time monitoring of water quality and power generation to drive autonomous aquatic sensors. The implementation of MFC arrays in natural wetlands and aquaculture is capable of developing self-sustaining energy loops that would ensure ecological balance, as well as minimize the costs of operation. Governance wise, regulation of structures and incentive policies will be important in motivating players to invest in bioelectrochemical systems and standardize metrics of performance when deploying such systems in the field. The set of rules on environmental safety, energy credits, and circular resource management will make sure that MFC technology becomes not a laboratory invention, but a solid, policy-based solution to clean energy production and restoration of aquatic ecosystems in the decades, making sure that the latter is sustainable.

## Conclusion

The Microbial Fuel Cells (MFCs) has shown high potential in solving two important problems that is, energy production and aquatic pollution removal, using a single bioelectrochemical reaction. The above discussion has demonstrated the fundamental processes of the functioning of MFC, the manner in which they are effectively deployed in the treatment of wastewater, and how they can produce renewable energy without disrupting the balance in the ecosystem. MFCs can convert organic contaminants into electricity through microbial metabolism offering a green and sustainable solution to the management of aquatic environment. Although there are constraints of low power density and high cost of set up, on-going innovations on electrode design, microbial selection and subsequent developments on hybrid integration are gradually enhancing the performance and scalability of systems. MFCs are not only valuable in energy recovery but also in restoring water quality, decrease of chemical dependency and the creation of carbon-neutral resource cycles. The future work must focus on increasing the efficiency of the materials, lowering the cost of the fabrication, and coming up with the standardized models that can be used in the field. Also, there will be a need of interdisciplinary cooperation between microbiologists, environmental engineers, and policymakers to ensure that scientific gaps are closed by providing regulatory frameworks that will lead to the implementation of MFCs in practical aquatic management. On the whole, MFCs are a good indication of a successful future in terms of sustainable energy production and protection of the ecological integrity of aquatic environments.

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