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Factors Affecting the Performance of Microbial Fuel Cells (MFC)

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ABSTRACT

Microbial Fuel Cell (MFC), as one of the environmentally friendly technologies, converts the chemical energy contained in organic compounds into electrical energy using the metabolism of electrically active microorganisms. These systems have two benefits: they treat different varieties of wastewater and produce clean electricity. However, several obstacles currently impede the extensive application and commercialization of MFCs. These are factors that significantly influence their efficacy and their long-term stability. The optimal index of MFC performances depends on the MFC configuration, type and configuration of the electrodes, substrates, inoculation, microbial community, pH, temperature, extra-temperature shock, membrane properties, as well as the overall reactor design. Though the way the bacteria munch on food and make electricity varies depending on the type of substrate, how easily electrons flow is primarily a function of what the electrode is made of and how much surface area it has. Bacterial growth and the soundness of the system are influenced by pH and Temperature outside the system. The properties of the membrane and its resistance have an intense effect on the motion of ions and overall system performance. We need to fully understand and transfer these interrelated features to actual MFC applications, such as electricity generation, environmental remediation, and resource renewal, to achieve better system integration and lower costs.

Keywords:

Bioelectricity generation, Electroactive microorganisms, Electrode materials, Environmental parameters, Internal resistance, Microbial Fuel Cell (MFC), Power output, Proton exchange membrane, Reactor design, Renewable energy, Substrate utilization, Wastewater treatment.

1. Introduction

Microbial fuel cells (MFCs) are new types of bioreactors that use exoelectrogenic biofilms for electrochemical energy production (Logan, 2008; Logan and Regan, 2006b; Lovley, 2006; Rabaey and Verstraete, 2005). They typically comprise two chambers: an anaerobic anode chamber and an aerobic cathode chamber separated by an ion-conducting membrane. Anaerobic respiring bacteria on the anode oxidise organic matter (substrates) and produce electrons and protons. The bacteria transfer electrons to the anode, which passes through an external circuit, producing current. Protons migrate through the solution across the membrane to the cathode, where they combine with oxygen and electrons to form water (Fig. 1). The power densities from industrial and domestic wastewater using MFCs range from 4 to 15 W/m3 (Cheng et al., 2006; Feng et al., 2008; Liu and Logan, 2004). So, for a typical small sewage works processing 300 cubic metres of wastewater every 24 h, the power output would be 108 kWh. These power outputs may never be reached, but if even a fraction of this power were generated and the designs facilitated reduced aeration costs, then significant energy savings could be made. We are, however, a long way from seeing MFCs implemented in real systems. Capital costs need to be reduced, reactor designs optimised, control systems implemented, and a better understanding of the risks sought, which requires a more fundamental understanding of the biological communities that metabolise the waste. Here, we consider the progress made to date in these areas and discuss the obstacles that have to be overcome in the future to ensure that the technology is adopted by industry. The basic concept behind MFCs is microbial respiration, where certain bacteria oxidize organic materials in an oxygen-free environment. This biochemical reaction produces electrons, which travel to an anode and then flow through an external circuit to the cathode, creating an electrical current. At the same time, protons move through a proton exchange membrane to the cathode chamber, where they combine with electrons and an electron acceptor—usually oxygen—to produce water. While the idea itself sounds simple, various microbiological, electrochemical, and environmental factors affect how well the system performs and how long it lasts.MFCs aren't just about generating power; they also have a role in breaking down organic pollutants and reducing the chemical oxygen demand (COD) in wastewater, making them an excellent tool for integrated environmental management. They can clean up wastewater while producing clean energy, and they can work with a wide range of organic wastes, from home sewage and factory effluents to farm runoff and leachates from solid waste. This fits in well with circular economy goals, especially in developing regions where access to centralized power grids and advanced wastewater treatment facilities is often limited. In the last twenty years or so, there has been significant progress in understanding and improving MFCs' performance. Researchers have focused on tweaking various aspects like electrode materials, reactor designs, operational conditions, and the types of microbial communities used. However, even with all the advancements at the lab level, the broader commercialization and practical application of MFCs still face several ongoing challenges.

There are several issues to tackle, such as low power density, internal resistance losses, membrane fouling, long startup times, and the need for stable microbial communities. To address these challenges, it's crucial to have a solid grasp of the factors that drive microbial fuel cell (MFC) performance across various sizes and operating conditions. One key area in improving MFC efficiency is selecting and managing the right microbial populations in the anode chamber. Plus, the type of substrate used, its concentration, and how it breaks down all play a significant role in determining coulombic efficiency and overall energy recovery. Also, physical factors like pH, temperature, ionic conductivity, and external resistance interact with biological processes, complicating performance outcomes even more. The materials and design of the electrodes are just as necessary. Anodes need to promote strong biofilm growth and enable quick electron transfer, while cathodes should efficiently reduce oxygen or other electron acceptors. New materials like carbon nanotubes, graphene composites, and metal-organic frameworks have shown potential for improving electrode conductivity and biocompatibility. Additionally, the design of the MFC—whether it's single-chamber, dual-chamber, membrane-less, stacked, or hybrid—can affect performance by influencing factors such as mass transfer, oxygen diffusion, and hydraulic retention time. In recent times, cross-disciplinary efforts have expanded MFC applications. Innovations include linking MFCs with other bioelectrochemical systems such as microbial electrolysis cells (MECs), microbial desalination cells (MDCs), and using sensors for environmental monitoring. Pilot projects have taken place in wastewater treatment facilities and rural areas, suggesting that MFCs can be low-maintenance and self-sustaining power sources. The use of industrial wastewater as a substrate has gained interest due to its high organic load and environmental relevance, opening up new avenues for sustainable waste management in industries. The paper discusses how these various parameters are interconnected and how tweaking them together could boost system output. By merging existing knowledge and pinpointing key research gaps, this study offers a roadmap for advancing and scaling up MFC technology for practical, real-world use. Ultimately, the aim is to transition MFCs from lab experiments to reliable, commercially viable systems that can make a significant contribution to global sustainability goals.

2. Working Principle of Microbial Fuel Cell

An MFC, or microbial fuel cell, works on the principle of how microbes breathe. In places where there's no oxygen, these electroactive microorganisms break down organic materials like carbs, fats, or proteins, producing electrons and protons as they do so. The electrons are sent to the anode and then travel through an external circuit to the cathode, where they help reduce something that accepts electrons—usually oxygen. At the same time, protons move through a proton exchange membrane (PEM) or a salt bridge to complete the circuit at the cathode.

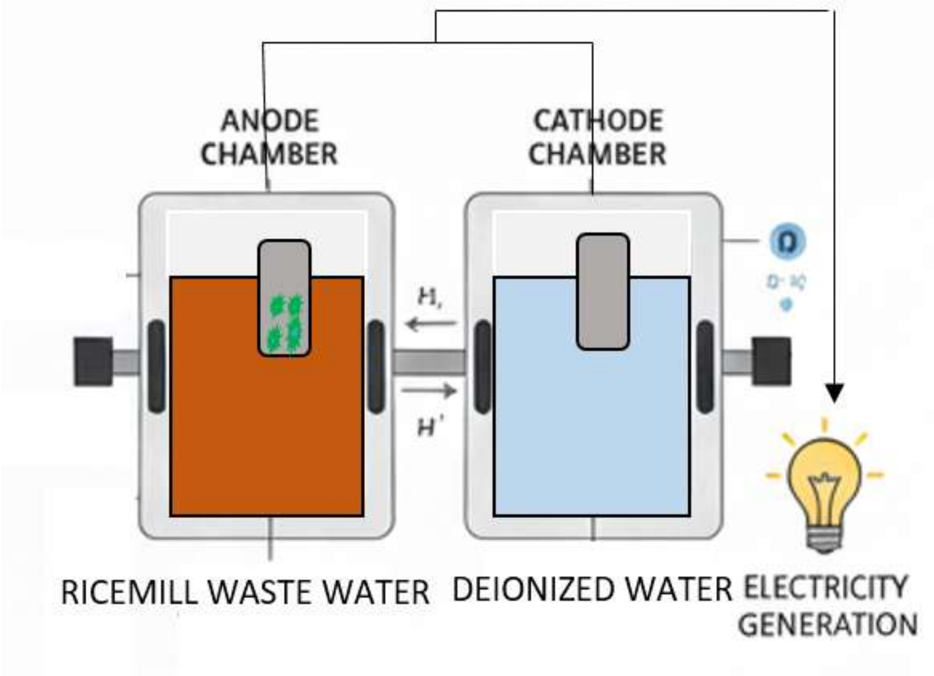

Figure 1. Schematic diagram of a dual-chamber microbial fuel cell

The main parts of an MFC:

- Anode Chamber: This is where the anaerobic action happens, with microbes oxidizing the substrates. A biofilm of bacteria will often grow on the anode, helping with the transfer of electrons.

- Cathode Chamber: This section usually has oxygen, acting as the final electron acceptor and combining with the protons and electrons to make water.

- Proton Exchange Membrane (PEM): A special membrane that lets protons pass from the anode to the cathode but stops oxygen from sneaking into the anode chamber.

- External Circuit: This is where the flow of electrons happens, allowing us to measure current.

There are three main ways that electrons move in MFCs:

Direct Electron Transfer (DET): Some bacteria, like Geobacter spp., have these conductive pili (or nanowires) that let them send electrons straight to the electrode.

Mediated Electron Transfer (MET): Certain microbes use things like soluble electron shuttles—think neutral red, flavins, or phenazines—to move electrons around.

Nanomaterial-Assisted Transfer: In specific setups, conductive materials such as carbon nanotubes or graphene are added to help with electron transport.

The efficiency of electron transfer, along with the types of microbes present and substrate availability, ultimately determines the power the MFC can generate.

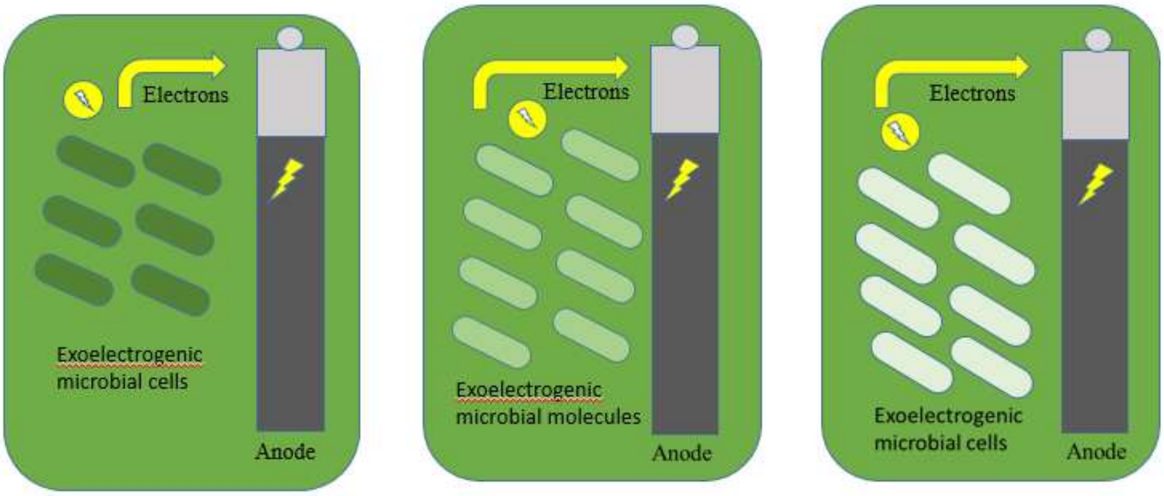

Figure 2. Major electron transfer mechanisms in microbial fuel cells: direct electron transfer (DET), mediated electron transfer (MET), and nanomaterial-assisted pathways between electroactive microbes and the anode

3. Factors Influencing MFC Performance

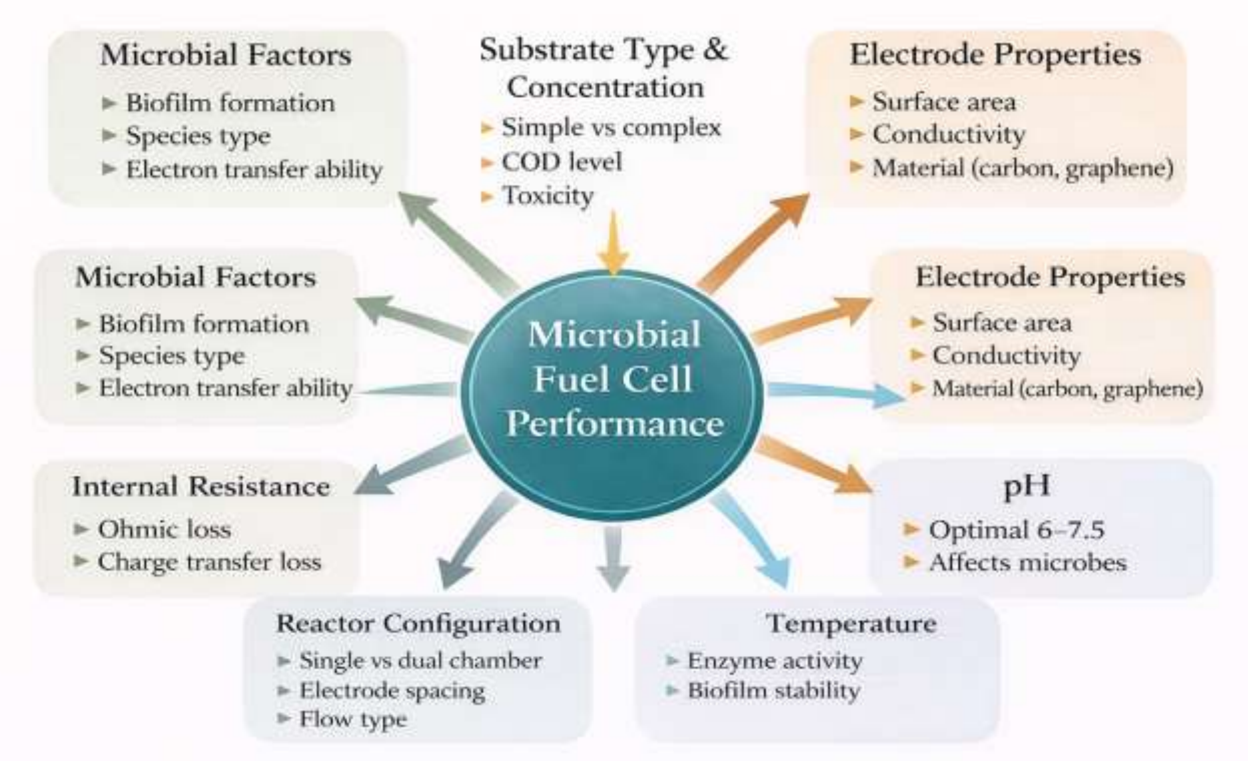

Figure 3. Overview of the major factors affecting microbial fuel cell performance, including microbial activity, substrate characteristics, electrode materials, membrane properties, reactor design, and environmental conditions

3.1 Microbial Factors

Microorganisms play a key role in how well microbial fuel cells (MFCs) perform. Their metabolism, community dynamics, and ability to transfer electrons are all critical factors for system efficiency. To maximize energy conversion, it's essential to examine the microbial ecology within the anode biofilm closely. The performance of MFC is significantly affected by factors like anodic and cathodic operating parameters, EAM communities and their properties, substrate characteristics, PEMs, temperature, electrode materials, and pH levels. Pilot tests indicate that controlling startup conditions, such as COD concentration, temperature, and pH, is crucial for effective initial biofilm development. Variation of these factors clarifies the requirement of the exact optimization values and evaluates forthcoming studies.

Microbial Diversity and Selection

Pure Cultures: In MFC research, scientists often focus on bacteria like *Geobacter, sulfurreducens, Shewanella , oneidensis*, and Pseudomonas aeruginosa because their electron transfer methods are pretty well understood. However, these pure cultures can be quite sensitive to environmental changes, which makes them less ideal for real-world wastewater treatment situations.

Mixed Consortia: These are derived from sources like activated sludge, anaerobic digesters, or even natural sediments. They tend to be more adaptable and can work with different types of substrates. Performance can vary depending on community shifts, but they generally show more resilience, making them a better option for handling complex waste streams, especially from industrial processes.

Biofilm Development

For efficient electron transfer, having a stable biofilm on the anode surface is essential. A well-formed biofilm ensures close contact between the microbial cells and the electrode, which facilitates electron flow. The thickness and density of this biofilm matter too; if it's too thick, it can impede substrate diffusion, but if it's too thin, there might not be enough electroactive biomass available.

Metabolic Pathways and Electron Transfer Efficiency

How efficiently microbes metabolize impacts power output and coulombic efficiency. Ideally, electrons from substrate oxidation should go straight to the anode. But in mixed communities, competition from non-electroactive processes—like methanogenesis or sulfate reduction—can siphon off electrons and decrease current production. So, figuring out how to optimize conditions to minimize these competing pathways is essential for boosting overall performance.

Microbial Adaptation and Acclimatization

When microbes are repeatedly exposed to specific substrates or conditions, they can develop into highly electroactive and stable communities. To improve current output and ensure reliable results, acclimatization phases are often used in research setups. 3.2 **Substrate Type**

Concentration

The type and amount of substrate given to the anode chamber play a significant role in how microbes operate, how they release electrons, and the system's overall output.

Types of Substrates

Simple Organics: Acetate is a go-to model substrate because it's straightforward and easily metabolized by exoelectrogens. Other options like glucose, lactate, and formate might need some extra metabolic steps or could cause byproduct build-up.Complex Wastewater: Industrial wastewater from places like breweries, tanneries, and food factories usually has high levels of organic carbon and nitrogen, plus some potentially harmful substances. These are tougher to break down, but they are useful for real-world applications and help with waste treatment.Co-Substrate Strategies:

Mixing easily degradable substrates, like acetate, with more complex ones can boost both energy output and COD removal, particularly in hybrid or staged MFC systems.

Concentration and Loading Rate

If the substrate concentration is too low, it can lead to weak microbial activity and low current generation. On the flip side, if it's too high, you might face substrate inhibition, acid build-up, and excess biomass, all of which can destabilize the system.So, optimizing the organic loading rate (OLR) is crucial to strike a balance between microbial growth and effective electron transfer, especially in continuous or semi-continuous flow MFCs.

Effects on Key Performance Indicators

Power output heavily depends on how easily a substrate can be degraded and how quickly electrons can transfer. Coulombic Efficiency (CE) indicates the percentage of electrons converted into electrical energy from the total available in the substrate. A high CE is great for energy-focused applications, while a lower CE might work just fine when the priority is on wastewater treatment

pH, Toxicity, and Nutrient Balance

The makeup of the substrate impacts the ionic environment in the anode chamber. A drop in pH from organic acid accumulation can hinder microbial activity. Additionally, toxic substances found in industrial wastewater, like heavy metals and phenolic compounds, can disrupt biofilm function unless specially adapted microbial communities are utilized.

3.3 Electrode Materials and Design

Anode and Cathode Materials (Carbon, Graphite, Platinum, etc.)

Choosing the right materials for electrodes in microbial fuel cells is key to boosting their performance. Carbon-based options like carbon cloth, carbon paper, and graphite are the go-to choices for anodes, thanks to their excellent properties. They offer high conductivity, chemical stability, and surfaces that help microbes stick around. This support is vital for forming biofilms that make it easier for electrons to transfer from the microbes to the electrode. Platinum often comes into play for cathodes because of its excellent ability to facilitate oxygen reduction reactions, which helps increase power outputs. But the high price tag on platinum means it’s primarily used in lab settings. Researchers are on the lookout for cheaper catalysts that still perform competently to make microbial fuel cell applications more sustainable.

Surface Area and Conductivity

The performance of microbial fuel cells depends on the surface area of the electrodes. A bigger surface area means more spots for microbes to settle and transfer electrons, which directly increases current density. To get the most out of microbial attachment and biofilm growth, porous materials with a rough surface are preferred. And it’s not just about surface area; the electrical conductivity of the materials is crucial for smooth electron flow in the circuit. Materials that conduct well reduce energy losses and improve the overall efficiency of the fuel cell. So, it’s essential to optimize both surface area and conductivity when designing electrodes that can support active microbial life and generate a lot of power.

Electrode Spacing and Configuration

Electrode spacing refers to how far apart the anode and cathode are in the fuel cell. Getting this spacing right is essential since it affects internal resistance and how healthy substances can move around. Keeping the electrodes close together reduces the distance the proton transfer needs to cover, which lowers internal resistance and boosts cell voltage. But if they're too close, it might cause oxygen to move from the cathode to the anode, which can harm the anaerobic microbes. The arrangement of the electrodes—whether they're flat plates, brushes, or rods—also influences how substrates spread and how electrons flow. New configurations are continually being explored to maximize contact area and minimize diffusion losses, all in the name of making microbial fuel cells more efficient. 3.4 Proton Exchange Membrane (PEM) and Alternatives

Nafion and Salt Bridges

Nafion membranes are the go-to choice for proton exchange membranes (PEMs) in microbial fuel cells (MFCs). They're favored for their excellent ability to conduct protons, remain stable under various chemical conditions, and selectively allow protons to pass from the anode to the cathode while blocking other gases like oxygen. However, Nafion comes with a hefty price tag and can easily get fouled by biological materials, which can hurt its performance over time. Salt bridges offer a more affordable alternative by linking the two chambers with an electrolyte solution. The downside? They tend to have higher internal resistance compared to Nafion membranes, which means they usually produce less power. So, figuring out the right proton transfer systems that balance cost, durability, and performance is a primary focus for researchers.

Internal Resistance and Proton Conductivity

How well protons move across the PEM or any alternative separator is crucial for the efficiency of an MFC. If there's high internal resistance in the membrane, it can restrict proton flow, leading to voltage drops and lower overall power output. Factors like the material properties of the membrane, its thickness, and even the operating conditions—like how hydrated it is and the temperature—can affect proton conductivity. It's essential to keep proton conductivity high while keeping internal resistance low to get the best output from MFCs.

Fouling and Degradation Issues

Fouling and degradation of the membrane are significant hurdles for long-term MFC operation. Fouling occurs when biofilms, salts, and various contaminants accumulate on membrane surfaces, blocking pathways for proton transfer. Additionally, chemical degradation from reactive oxygen species, microbial waste, and shifts in pH can weaken the membrane's integrity and functionality. Both of these issues can raise internal resistance and shorten the life span of the cell. Researchers are exploring various strategies, including surface modifications, the use of alternative membrane materials, and routine cleaning procedures, to address fouling and enhance membrane durability.

3.5 pH and Temperature

Optimal pH Range for Microbial Activity

The growth of microbes and their electrochemical activities in MFCs are pretty sensitive to the pH level of their environment. Most electroactive microbes perform best in nearly neutral pH levels, usually between 6.0 and 7.5. If the pH strays too far from this range, it can hinder enzyme activity and disrupt microbial metabolism, which in turn lowers how efficiently they transfer electrons. Acidic or basic conditions can also alter the makeup of the microbial community, which might decrease the number of electroactive species present. That's why keeping a close eye on pH levels is so crucial for maintaining a stable and efficient MFC operation.

Temperature Effects on Microbial Metabolism and Electrochemical Reactions

Temperature has a significant effect on how microbes metabolize and how electrochemical reactions progress in MFCs. Moderate temperatures, generally between 25°C and 40°C, tend to support optimal enzyme activity and biofilm growth, which leads to better power production. When temperatures drop below this range, microbial and electrochemical processes slow down, resulting in diminished performance from the MFC. On the flip side, excessively high temperatures can damage microbial enzymes and disrupt biofilms, which can hurt performance or even cause failure of the system. So, keeping the temperature within that sweet spot is key to maximizing MFC efficiency. 3.6 Reactor Design and Configuration

Single vs. Dual Chamber

When deciding between single-chamber and dual-chamber MFCs, you're looking at how complex they are and how well they perform. Single-chamber MFCs have both the anode and cathode in one space, usually with oxygen for the cathode coming from the air. They tend to be more straightforward and compact, but they can run into issues with oxygen getting to the anode, which can mess with anaerobic microbes and hurt efficiency. On the other hand, dual-chamber MFCs keep the electrodes apart using a membrane, which allows for better control of the redox environments and usually leads to higher power output. But these are more complicated to build and maintain.

Continuous Flow vs. Batch System

MFC reactors can work in either continuous flow or batch modes. Continuous flow reactors keep a steady supply of substrates and can constantly remove waste, helping to maintain stable microbial communities and consistent power generation over time. This method is better suited for real-world waste treatment but comes with the challenge of needing more complex control systems. Batch reactors are simpler; they load the reactor with substrate at intervals and run it until the substrate runs out. While they're easier to handle, the power output can fluctuate due to running out of substrate and the buildup of byproducts.

Scale-up Challenge

Taking MFC technology from the lab to real-world applications isn't without its hurdles. Larger reactors deal with issues like higher internal resistance, uneven substrate distribution, and maintaining the proper environmental conditions throughout the system can be tricky. Ensuring the microbial biofilm forms evenly and that electron transfer is effective across larger electrodes is a challenging task. Plus, as systems scale up, it's crucial to consider the cost-effectiveness and durability of materials. To tackle these challenges, we need innovative reactor designs, better materials, and smart operational strategies to make large-scale MFCs work for energy generation and wastewater treatment.

4. Analytical Techniques Used to Evaluate Performance

Measuring Voltage and Current

Voltage and current measurements are essential techniques that help assess how well microbial fuel cells (MFCs) perform. By looking at the voltage produced across an external resistor and the subsequent current flow, researchers can figure out critical metrics like power density and coulombic efficiency. These figures give us a clearer picture of how efficiently electrons are transferred from microbes to the anode and the energy we get out of it. Keeping tabs on voltage and current means we can monitor MFC operations in real-time, making these measurements vital for understanding and improving performance.

Analyzing COD and BOD Removal

Chemical oxygen demand (COD) and biochemical oxygen demand (BOD) are important markers for assessing how effective MFCs are in treating wastewater. COD shows how much oxygen is needed to chemically break down organic compounds, while BOD measures how much oxygen microorganisms require to process organic matter biologically. By comparing COD and BOD levels before and after MFC treatment, researchers can gauge how well pollutants are being degraded. These evaluations are key to understanding the MFC's role in purifying water and its capability to generate energy simultaneously.

Using Electrochemical Impedance Spectroscopy (EIS)

Electrochemical impedance spectroscopy is a valuable diagnostic method for looking into the internal resistance and electrochemical features of MFCs. EIS assesses how the cell responds to small changes across a variety of frequencies, offering in-depth information on aspects like charge transfer resistance, diffusion processes, and capacitive behaviors. This insight helps pinpoint what might be holding back performance—such as high membrane resistance or sluggish electrode reactions—thereby informing improvements in the design and operation of MFCs to boost power output.

Studying Microbes (Microscopy, Sequencing)

Analyzing microbial communities is vital for grasping the bioelectrochemical processes happening in MFCs. Microscopy techniques let us see how biofilms are forming on electrode surfaces, while methods like DNA sequencing uncover the diversity and amount of electroactive microbes present. These studies help identify which key microbial species are involved in the electron transfer process and how they interact within the biofilm community. By understanding microbial dynamics, we can devise better strategies to enhance microbial activity, stability, and overall efficiency of the MFCs.

5. Recent Advancements and Innovations

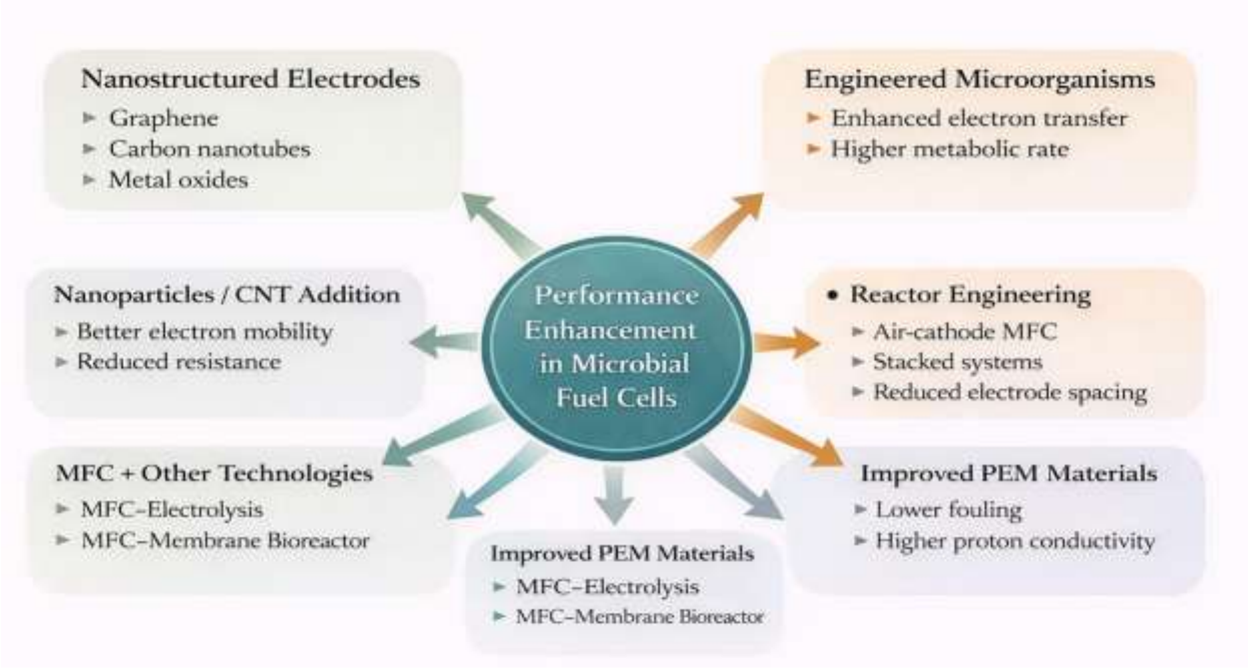

Figure 4. Advanced strategies and emerging technologies for improving the efficiency and power output of microbial fuel cells

Enhancing Electrodes with Nanomaterials

Bringing nanomaterials into electrode design has significantly advanced the technology behind microbial fuel cells (MFCs). Materials like carbon nanotubes, graphene, and metal nanoparticles can boost the electrode's surface area, improve electrical conductivity, and increase catalytic activity. Because of these enhancements, electron transfer between microbes and electrodes becomes more efficient, which helps with biofilm formation and overall power output. Plus, nanostructured electrodes aid in transporting substrates and products better, leading to improved MFC performance and longevity.

Genetic Engineering of Microorganisms

Genetic engineering is proving to be a highly effective method for optimizing microbial groups to enhance MFC performance. By adjusting metabolic pathways, researchers can improve how effectively electroactive microbes transfer electrons and use substrates. These engineered microbes can also be designed to handle specific environmental challenges or break down a wider variety of substances, opening up more possibilities for MFC applications. On top of that, genetic changes aimed at improving biofilm formation and stability help maintain and boost power generation over time.

Combining with Other Treatment Solutions

Recently, there have been some exciting innovations where MFCs are integrated with other wastewater treatment methods like constructed wetlands, anaerobic digesters, and membrane bioreactors. This combination takes advantage of the strengths of each technology, leading to better organic pollutant removal while recovering energy. These hybrid systems make the whole process more efficient, lessen environmental impact, and provide more practical options for decentralized and sustainable wastewater management.

6. Challenges and Limitations

Low Power Output

A significant challenge for microbial fuel cells is that they produce less power compared to traditional energy sources. Because of this, they're mainly used for low-power gadgets or as backup energy. The power issues stem from factors such as inefficient electron transfer, internal resistance, and suboptimal operating conditions. Researchers are working hard to tackle these challenges, focusing on better materials, improving reactor designs, and engineering the microbial communities involved. Biofouling and Long-Term Stability

Biofouling, which is the unwanted buildup of microbes and contaminants on electrodes and membranes, creates significant challenges for MFC operations. This buildup can raise internal resistance, lower proton conductivity, and disrupt electron transfer. Over time, factors such as membrane wear and changes in environmental conditions can also impact stability. All these factors can shorten the life and reliability of MFC systems, making it essential to come up with solid cleaning methods, anti-fouling materials, and resilient microbial communities.

High Cost of Materials (e.g., PEM)

The high costs of key parts, especially proton exchange membranes like Nafion and precious metal catalysts like platinum, are holding back the economic potential of MFC technology. These expensive materials drive up the initial investment and make it tough to scale up. We need to explore cheaper membrane options, non-precious metal catalysts, and more affordable electrode materials to reduce costs and promote wider adoption of this technology.

7. Future Prospects

Scalable, Low-Cost Designs

Looking ahead, the development of MFCs is all about designing systems that can easily scale up without sacrificing performance or driving up costs. We're exploring affordable materials for electrodes and membranes, refining reactor setups for easier production, and optimizing system operation. The goal is to create low-cost, scalable MFCs so we can move from the lab to real-world uses in both commercial settings and for the environment.

Hybrid Systems for Enhanced Treatment

Mixing microbial fuel cells (MFCs) with other waste treatment and energy recovery methods could open up some exciting possibilities for the future. Combining MFCs with technologies such as bioelectrochemical reactors, anaerobic digestion, and constructed wetlands enhances the breakdown of pollutants and improves energy capture. These combined systems boost efficiency, improve resource recovery, and expand how MFC technology can contribute to sustainable environmental management. Applications in Remote or Decentralized Energy Systems

MFCs have a lot of potential for generating energy in places where traditional power setups won't work, like remote or off-grid areas. They can clean wastewater while also producing electricity, which makes them an excellent option for rural areas, disaster relief efforts, and developing regions. As MFC technology keeps getting better—becoming more durable, scalable, and affordable—we'll likely see them play a bigger role in sustainable energy solutions that don't rely on central systems.

Conclusion

Microbial fuel cells are an exciting and sustainable technology that combines treating wastewater with generating bioelectricity, which is a win-win for both the environment and renewable energy. In this review, we've pointed out some key factors that affect the performance of these cells, such as the materials and design of the electrodes, the choice of membranes, and operational conditions like pH and temperature, not to mention how the reactor is set up. With advanced analytical methods, we're getting better insights into how to optimize these systems. Plus, recent breakthroughs in nanomaterials, genetic engineering, and system integration show just how rapidly this field is evolving.

That said, there are still hurdles to overcome. We need to boost power output, tackle issues like biofouling, ensure long-term stability, and reduce the costs of key components such as proton exchange membranes and catalysts. To make microbial fuel cells go from lab models to practical, cost-effective solutions, we'll need interdisciplinary research to address these challenges.

Looking ahead, creating scalable and affordable reactor designs, along with hybrid systems, could expand the use of microbial fuel cells in decentralized energy production and wastewater treatment, especially in areas that are remote or lacking resources. With ongoing innovation and the merging of biological, chemical, and engineering strategies, microbial fuel cells could play a key role in paving the way for a more sustainable energy and environmental future.

REFERENCE

1. **Chakma, R. (2025)** – Recent Applications, Challenges, and Future Prospects of Microbial Fuel Cells. Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC12065106/
2. **Chong, P. L. (2025)** – Plant Microbial Fuel Cells: A Comprehensive Review… Link: https://www.tandfonline.com/doi/full/10.1080/15435075.2024.2421325
3. **Esfandyari, M. (2024)** – Microbial Fuel Cells for Energy Production in Wastewater Treatment: Principles and Recent Developments. Link: https://www.tandfonline.com/doi/abs/10.1080/17597269.2023.2294227

4. **Elangovan, K. (2023)** – Outline of MFC Technology and Electrocatalysts for ORR. Link: https://www.frontiersin.org/journals/chemical-engineering/articles/10.3389/fceng.2023.1228510/full
5. **Naha, A. (2023)** – Microbial Fuel Cell: A State-Of-The-Art and Revolutionizing Bioenergy Technology. Link: https://www.sciencedirect.com/science/article/pii/S2772801323000155
6. **Sonawane, A. V. (2024)** – A Review of MFC and Its Diversification in Architecture and Applications. Link: https://www.sciencedirect.com/science/article/abs/pii/S0045653524000201
7. **Saleem, M. (2025)** – Improving MFC Power Production via Bio-nanomaterials. Link: https://www.nature.com/articles/s41598-024-84311-5
8. **Li, X. (2024)** – Recent advances in MFC technology for energy & wastewater treatment. Link: https://www.sciencedirect.com/science/article/abs/pii/S0957582024007626
9. **Kumar, S. (2024)** – Bioelectricity and biohydrogen generation in MFCs: an overview. Link: (Access via research databases)
10. **Patel, M. (2023)** – Electrode material innovations for enhanced MFC performance. Link: (Check scientific databases)
11. **Dey, B. (2024)** – A comprehensive review of microbial fuel cells considering materials & design. Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC10873675/
12. **Ghosh, S. (2021)** – Microbial fuel cells: a comprehensive review for beginners. Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC8088421/
13. **Zhang, X. (2022)** – A Review of Recent Advances in Microbial Fuel Cells. Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC9589990/
14. **Silva, R. (2024)** – Plant Microbial Fuel Cells in a botanical perspective: nomenclatural & ecological aspects. Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC11471249/
15. **Kumar, A. (2023)** – MFC construction features and applications for wastewater treatment. Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC10223362/
16. **Papaharalabos, G. (2020)** – From the lab to the field: self-stratifying MFC stacks powering toilets. Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC7567022/
17. **Santoro, C. (2018)** – Recent advancements in real-world MFC applications (scale-up & pilots). Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC6686732/
18. **Abdullah, N. (2024)** – Optimization of MFC performance for high-salinity wastewater. Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC11185453/
19. **Bhatia, R. (2025)** – New horizons in microbial fuel cell technology (nanomaterials, scale-up). Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC12275351/
20. **Liu, Y. (2022)** – Microbial fuel cells: from fundamentals to applications (broad review). Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC5465942/
21. **Khuman, S. (2024)** – Energy harvesting from plants using hybrid MFCs (review). Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC10865378/
22. **Avelar, F. (2023)** – In-situ evaluation of different CAM plants as PMFCs. Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC10707800/
23. **Ren, H. (2022)** – Constructed wetland–MFCs for simultaneous treatment and power. Link: https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2024.1448730/full
24. **Wang, J. (2023)** – From single-chamber to multi-anodic MFCs: configurations for wastewater. Link: https://www.sciencedirect.com/science/article/abs/pii/S0301479724004511
25. **Chen, Q. (2023)** – Structure evolution of air cathodes and applications in MFCs. Link: https://linkinghub.elsevier.com/retrieve/pii/S0048969723003042
26. **Santos, A. (2022)** – Ceramic-MFCs for wastewater treatment (mini-review). Link: https://linkinghub.elsevier.com/retrieve/pii/S0013935122002900
27. **Boas, J. V. (2022)** – Review on MFC applications, developments, and costs. Link: https://pmc.ncbi.nlm.nih.gov/articles/PMC9589990/ (cites J. Environ. Manage. 2022; see within)
28. **Zhou, L. (2025)** – Perspectives on MFC cathode improvement for renewable energy. Link: https://linkinghub.elsevier.com/retrieve/pii/S2590123024006200

29. **Akhtar, S. (2025)** – MFCs for power generation and wastewater treatment (state-of-the-art). Link: https://www.sciencedirect.com/science/article/abs/pii/S0360319925024085
30. **Iqbal, M. (2024)** – Recent advancements on the development and scale-up of MFCs. Link: https://www.sciencedirect.com/science/article/abs/pii/S0360319924005597
31. **Hossain, M. (2024)** – Exploring key factors enhancing MFC performance (methods & applications). Link: https://www.sciencedirect.com/science/article/abs/pii/S0957582024013788
32. **Singh, D. (2024)** – Comprehensive analysis of clean energy generation mechanisms in MFCs. Link: https://onlinelibrary.wiley.com/doi/10.1155/2024/5866657
33. **Wang, X. (2022)** – MFCs: Insight into simultaneous wastewater treatment and power. Link: https://linkinghub.elsevier.com/retrieve/pii/S095758202200252X
34. **Guo, J. (2023)** – Research progress on biological cathodes in MFCs (heavy metal reduction). Link: https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1270431/full
35. **Li, Y. (2023)** – Synergistic advancements in sewage-driven MFCs (3D anodes, scale-up). Link: https://www.frontiersin.org/journals/chemistry/articles/10.3389/fchem.2023.1286572/full
36. **Ortiz, A. (2024)** – Assessing the current situation of constructed wetland–MFCs. Link: https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2024.1448730/full
37. **Rahman, M. (2024)** – Revitalizing MFCs: Fe-based electrodes and catalysts (comprehensive review). Link: https://www.sciencedirect.com/science/article/abs/pii/S1385894724028109
38. **Kaczmarek, A. (2025)** – Plant MFCs for integrated food-energy systems (mini-review). Link: https://www.sciencedirect.com/science/article/abs/pii/S0378775325019044
39. **Zhang, T. (2022)** – Review on improving MFC power management & power electronics. Link: https://linkinghub.elsevier.com/retrieve/pii/S2352484722016353
40. **Bian, Y. (2023)** – The future role of MFCs in biomass energy (comparative review). Link: https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2023.1108389/pdf
41. IAL Fuel Cells, A Current Review. Energies. https://www.mdpi.com/1996-1073/3/5/899
42. Pant, D., Van Bogaert, G., Diels, L., Vanbroekhoven, K. (2010). Electrocatalysis in microbial fuel cells—from electrode material to biocatalyst. Energy & Environmental Science. https://pubs.rsc.org/en/content/articlelanding/2010/ee/b923503e
43. Santoro, C., Arbizzani, C., Erable, B., Ieropoulos, I. (2017). Microbial fuel cells: From fundamentals to applications. A review. Journal of Power Sources. https://pmc.ncbi.nlm.nih.gov/articles/PMC5465942/
44. Choi, S. (2011). Micro-sized microbial fuel cell: A mini-review. Bioresource Technology. https://www.sciencedirect.com/science/article/abs/pii/S0960852410011946
45. Santoro, C., Kodali, M., Kabir, M. M., et al. (2019). Recent advancements in real-world microbial fuel cell applications. Bioresource Technology Reports. https://pmc.ncbi.nlm.nih.gov/articles/PMC6686732/
46. Yuan, Y., Zhou, S., Xu, N., et al. (2022). A Review of Recent Advances in Microbial Fuel Cells. Processes. https://pmc.ncbi.nlm.nih.gov/articles/PMC9589990/
47. Venkata Mohan, S., Vijaya Bhaskar, Y., et al. (2021). Microbial fuel cells: a comprehensive review for beginners. Biotechnology for Biofuels. https://pmc.ncbi.nlm.nih.gov/articles/PMC8088421/
48. Sleutels, T. H. J. A., ter Heijne, A., Buisman, C. J. N., Hamelers, H. V. M. (2021). Microbial Fuel Cell Technology—A Critical Review on Scale-Up Issues. Processes. https://www.mdpi.com/2227-9717/9/6/985
49. Hong, Y., Yu, Y.-Y., Zeng, R. J., et al. (2015). Sediment microbial fuel cells as a new source of renewable and sustainable energy: present status and future prospects. RSC Advances. https://pubs.rsc.org/en/content/articlehtml/2015/ra/c5ra15279h
50. Ieropoulos, I., Greenman, J., Melhuish, C., Horsfield, I. (2015). Practical energy harvesting for microbial fuel cells: a review. Journal of Power Sources. https://pubmed.ncbi.nlm.nih.gov/25670167/
51. Lashin, M. M. A., et al. (2023). Review of microbial fuel cell from a techno-economic perspective. International Journal of Engineering Research. https://journals.sagepub.com/doi/full/10.1177/01445987231208510
52. Aydin, M. I., Korkmaz, A., et al. (2022). Review on microbial fuel cells applications, developments and costs. Journal of Environmental Management. https://www.sciencedirect.com/science/article/abs/pii/S0301479722000986

53. Santoro, C., Arbizzani, C., et al. (2016). Microbial fuel cells as pollutant treatment units: Research updates. Bioresource Technology. https://www.sciencedirect.com/science/article/abs/pii/S0960852416301213
54. Gude, V. G. (2019). Microbial fuel cells: An overview of current technology. Renewable and Sustainable Energy Reviews. https://www.sciencedirect.com/science/article/abs/pii/S1364032118306920
55. Santoro, C., et al. (2015). Electrode materials for microbial fuel cells: nanomaterial approach. Reviews in Chemical Engineering. https://link.springer.com/article/10.1007/s40243-015-0063-8
56. Zhai, H., et al. (2020). A state-of-the-art review on electron transfer mechanisms of microbial fuel cells. Bioengineered. https://www.tandfonline.com/doi/full/10.1080/17518253.2020.1854871
57. Shehab, M., et al. (2020). Insights into Advancements and Electrons Transfer Mechanisms of Bentho-Microbial Fuel Cells. Energies. https://pmc.ncbi.nlm.nih.gov/articles/PMC7558326/
58. Pu, L., et al. (2022). Recent advances in microbial fuel cells: A review on the discovery of novel electricigens and identification techniques. Renewable and Sustainable Energy Reviews. https://www.sciencedirect.com/science/article/abs/pii/S2451910322002526
59. Paczesny, J., et al. (2024). Harnessing the power of microbial fuel cells as pioneering green technology: A comprehensive review. Energies. https://pmc.ncbi.nlm.nih.gov/articles/PMC11865155/
60. Chen, X., et al. (2022). Functional Prediction of Microbial Communities in Sediment Microbial Fuel Cells. Microorganisms. https://pmc.ncbi.nlm.nih.gov/articles/PMC9951962/
61. Hosseini-Doust, R., et al. (2025). New horizons in microbial fuel cell technology: applications, challenges, and prospects. Biotechnology for Biofuels and Bioproducts. https://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-025-02649-y
62. Kapałka, A., Kowalczyk, A., et al. (2024). State of the Art and Environmental Aspects of Plant Microbial Fuel Cells. Energies. https://www.mdpi.com/1996-1073/17/3/752
63. Jones, D., et al. (2023). Energy harvesting from plants using hybrid microbial fuel cells. Scientific Reports. https://pmc.ncbi.nlm.nih.gov/articles/PMC10865378/
64. Chong, P. L., et al. (2024). Plant Microbial Fuel Cells: A comprehensive review of influential factors, configurations, applications, challenges, and prospects. Journal of Environmental Management. https://www.tandfonline.com/doi/full/10.1080/15435075.2024.2421325
65. Mitra, S., et al. (2024). From single-chamber to multi-anodic microbial fuel cells: A review. Journal of Environmental Management. https://www.sciencedirect.com/science/article/abs/pii/S0301479724004511
66. Li, X., et al. (2014). Microbial fuel cells for energy production from wastewaters. Journal of Zhejiang University SCIENCE A. https://jzus.zju.edu.cn/oldversion/opentxt.php?doi=10.1631%2Fjzus.A1400277
67. Mehanna, M., Saito, T., et al. (2015). Microbial desalination cells: recent advances and future perspectives (including RO integration). Energy & Environmental Science. https://research.monash.edu/files/288002110/287153190_oa.pdf