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Microbial Fuel Cells: Advancements, Challenges, and Applications in Sustainable Energy and Environmental Remediation

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Abstract: Microbial fuel cells (MFCs) represent a promising bio-electrochemical technology with the potential for sustainable energy generation and environmental remediation. These systems exploit the metabolic processes of microorganisms to directly convert organic substrates into electrical energy, providing an environmentally benign alternative to traditional energy sources. The operation of MFCs relies on intricate biological and electrochemical interactions, where microorganisms transfer electrons to electrodes, generating an electric current. MFCs can be classified based on their configuration, electron transfer mechanisms, and operational conditions, each offering distinct advantages and limitations in different contexts. Recent developments in MFC technology have focused on improving power density, stability, and scalability. Innovations in electrode materials, biocatalysts, and reactor design have enhanced energy output, making MFCs more viable for real-world applications. Notably, MFCs show promise in wastewater treatment, as they can simultaneously degrade organic pollutants and generate electricity, thus offering a dual-function solution that contributes to both sustainable energy production and environmental cleanup. Despite these advances, several challenges persist, including the high cost of materials, limited power output, and the need for better integration into existing infrastructure. These issues hinder the widespread adoption of MFCs. Future research must focus on the development of cost-effective materials, the optimization of reactor design, and scaling the technology to achieve commercial feasibility. With continued innovation and refinement, MFCs hold the potential to play a transformative role in renewable energy systems and integrated waste management strategies, contributing to the broader goals of sustainable development.

Keywords: Microbial fuel cell (MFC); Bio-electrochemical systems; Renewable energy; Wastewater treatment; Electron transfer; Sustainable technology

1 Introduction

For more than a hundred years, the intense pace of industrialization and economic development has played a central role in environmental degradation and accelerated climate change. The widespread shift toward industrialized societies brought about mass production, urban expansion, and heavy reliance on fossil fuels, which, although they enabled growth, also contributed significantly to greenhouse gas emissions, pollution, and resource depletion [1, 2]. These changes have increasingly underscored the need for renewable, sustainable energy sources that not only meet energy demands but also safeguard the environment. The move toward cleaner energy represents a critical response to this issue, encouraging innovations that combine efficiency with environmental consciousness [3]. One such groundbreaking innovation is the MFC, which functions as a bio-electrochemical system, using natural bacterial processes to produce electricity.

The concept of MFCs dates back to the early 20th century when researchers first observed that certain bacteria could produce electricity as a byproduct of their metabolic activities. These microorganisms, through the breakdown of organic matter, release electrons that can be harnessed to generate electrical current [4, 5]. However, initial observations showed only minimal power output, limiting the practical applications of this technology. Recent strides in biotechnology, materials science, and electrochemistry have revolutionized MFC design and efficiency, making it possible for MFCs to generate significant, usable quantities of electricity [6, 7]. Through these advancements, MFCs have transformed from a niche scientific curiosity into a potentially scalable technology capable of serving dual functions: renewable energy generation and wastewater treatment.

MFCs offer a twofold benefit to the environment. As a renewable energy source, MFCs contribute to the reduction of dependency on fossil fuels, lowering greenhouse gas emissions and thus helping to combat climate change [8]. At the same time, their application in wastewater treatment provides a sustainable way to process waste, as the bacteria within the MFCs can feed on organic pollutants found in wastewater. This dual capability not only reduces pollution but also turns waste into a productive resource, thus supporting a circular economy model where resources are continuously recycled [7]. By integrating MFCs into urban wastewater treatment plants or even remote facilities, there is potential for cleaner water outputs coupled with energy generation—an innovation poised to revolutionize both the energy and environmental sectors.

Recent studies highlight significant progress in developing high-conductivity and biocompatible electrode materials like graphene, carbon nanotubes, and conductive polymers. These materials have improved electron transfer efficiency and reduced system resistance. Advances in synthetic biology have enabled the genetic modification of exoelectrogens like Geobacter sulfurreducens and Shewanella oneidensis, enhancing their metabolic rates and electron transfer abilities [5, 6]. These innovations have contributed to increased power output and adaptability to diverse substrates. New architectural configurations, including single-chamber MFCs, stacked designs, and hybrid bio-electrochemical systems, have improved power density and scalability. Such designs are better suited for real-world applications, including urban and rural waste management. Industries like food processing, pharmaceuticals, and textiles have adopted pilot-scale MFCs for dual purposes—wastewater treatment and electricity generation. These applications reduce operating costs and environmental footprints. MFCs are being explored as decentralized power solutions for off-grid communities. Their ability to generate electricity from locally available biomass or organic waste presents a cost-effective energy source [3, 4]. MFCs integrated with biosensors are now used for real-time detection of pollutants and heavy metals in water, contributing to improved environmental management. The adaptation of microbial electrolysis cells (MECs), a derivative of MFCs, for hydrogen production represents a sustainable approach to meeting the increasing demand for clean fuel.

1.1 Significance of MFCs

Unlike conventional fuel cells, which rely on costly catalysts like platinum, MFCs employ microbes as natural biocatalysts. This substitution not only reduces the cost of energy production but also taps into the natural metabolic abilities of certain bacteria. These microbes have the unique capability to metabolize various types of organic matter present in substrates like wastewater, organic sludge, and agricultural residues [9]. During this metabolic process, the microbes break down complex organic molecules into simpler by-products, releasing electrons and protons as a result. This natural breakdown process is harnessed to generate a direct electrical current, allowing MFCs to create energy from readily available and renewable sources like biomass and wastewater [10, 11]. The accessibility and abundance of these organic materials make MFCs an affordable and sustainable energy source with vast potential.

Moreover, the substrates used in MFCs—such as sewage, industrial wastewater, and agricultural waste—are often categorized as pollutants that contribute to environmental contamination. By converting these waste streams into an energy source, MFCs serve a dual purpose: they generate electricity while simultaneously addressing pollution [12, 13]. This ability to transform waste into a resource aligns with the principles of a circular economy, where waste is minimized, and resources are repurposed. MFCs not only reduce the need for expensive and rare materials but also decrease waste treatment costs by integrating energy production with waste remediation.

The environmental benefits of MFCs make them particularly promising for regions where pollution from agricultural runoff, industrial wastewater, or sewage poses a significant challenge. In such areas, MFCs could be incorporated into existing waste treatment systems to produce clean energy while mitigating environmental hazards [10, 14]. By addressing the twofold challenges of energy sustainability and waste management, MFCs represent a versatile and practical solution that supports global sustainability goals.

1.2 Renewable Energy and Environmental Challenges

Bioenergy stands out as a promising clean energy option, offering ways to reduce carbon emissions and lessen environmental harm. Yet, like many renewable energy solutions, bioenergy technologies come with their own set of challenges [1, 4]. Solar and wind energy, though popular and effective at harnessing natural energy, are limited by their dependence on weather conditions and the time of day, which makes their power generation intermittent. To function as reliable energy sources, these technologies require substantial infrastructure investments for energy storage (like batteries) and long-distance transmission systems. Similarly, other bioenergy solutions, including biomass combustion and biogas production, need extensive feedstock processing and typically operate on a large scale to be economically feasible [3, 5, 11]. These limitations underscore the need for complementary technologies that can fill the gaps in renewable energy production.

MFCs present a unique and innovative solution to these limitations, as they produce electricity through the conversion of organic waste. MFCs can function continuously as long as they have access to organic material, which provides a steady, localized source of energy [8, 14, 15]. This continuous power generation makes MFCs particularly suitable for decentralized energy systems, ideal for rural or remote areas where access to centralized grids may be limited. In these settings, MFCs can serve as an independent energy source, potentially powering small communities, agricultural operations, or remote industrial facilities [7, 16]. Because MFCs operate under ambient conditions without needing high temperatures or pressures, they consume less energy in the conversion process compared to other bioenergy technologies like biogas production or bioethanol fermentation, which require elevated temperatures and pressurized environments.

Additionally, the versatility of MFCs to work with various organic wastes as fuel—such as agricultural residues, industrial wastewater, or sewage—highlights their potential for broad application. This adaptability, combined with their capacity to provide localized, sustainable energy, supports their role as a valuable addition to the renewable energy landscape [15, 16]. By integrating MFCs into bioenergy portfolios, the renewable energy sector can advance toward more robust, flexible, and sustainable solutions, especially for areas where conventional renewable infrastructure might face logistical or economic hurdles. Thus, MFCs not only complement existing renewable technologies but also expand the range of sustainable energy solutions available for diverse geographical and economic contexts.

1.3 MFCs and Sustainable Waste Management

Waste management remains one of the most pressing challenges for modern societies, given the environmental and economic burdens associated with waste disposal and treatment. With rising urbanization and industrialization, waste streams from households, industries, and agriculture have increased substantially [17–19]. Traditional wastewater treatment methods, such as aerobic and anaerobic digestion, have served as the backbone for managing liquid waste, but these processes are often energy-intensive and require large-scale infrastructure. Aerobic digestion, for example, consumes significant energy to supply oxygen to the system, while anaerobic digestion, though capable of producing biogas, still results in a substantial sludge byproduct that requires further handling and disposal [12]. The infrastructure demands, along with the high operational costs, make conventional treatment systems costly and less sustainable in the long run.

MFCs offer a groundbreaking alternative by transforming the waste treatment paradigm. Unlike traditional methods that rely on energy-consuming processes, MFCs harness the natural metabolic processes of bacteria to break down organic pollutants while generating electricity in the process. This direct energy recovery reduces the dependency on external power sources for wastewater treatment, thereby decreasing the overall energy footprint of treatment facilities [6, 16, 18]. By converting wastewater treatment plants from net energy consumers to net energy producers, MFCs have the potential to drive down operating costs, making these facilities more economically viable and environmentally sustainable.

The dual functionality of MFCs also addresses the sludge problem commonly associated with conventional wastewater treatment. Since MFCs rely on microbes to break down organic matter, they generate significantly less sludge, reducing the need for subsequent treatment and disposal [11, 19, 20]. This not only cuts down on waste but also minimizes the associated environmental impacts, such as greenhouse gas emissions and potential groundwater contamination from sludge landfills. Furthermore, integrating MFCs into wastewater treatment facilities could transform these plants into local energy hubs, offering a clean, renewable power source for community or industrial use [20, 21]. The environmental and economic benefits position MFCs as a pivotal technology for advancing sustainable water and sanitation systems, enhancing the efficiency and resilience of waste management practices globally.

1.4 Historical Development of MFCs

In 1911, British botanist M.C. Potter made a pioneering discovery that bacterial cultures could transform carbohydrates into electricity, thus laying the groundwork for MFC technology. Potter's experiments showed that certain bacteria could metabolize organic compounds and, in doing so, release electrons that could generate a small electrical current [22]. Although groundbreaking, these early systems were hampered by very low efficiency and power output, which limited their practical application and drew little attention from the scientific community at the time. The concept largely faded into obscurity until the 1980s, when researchers began to revisit the potential of bio-electrochemical systems in the context of environmental applications, particularly for wastewater treatment [7, 13]. This renewed interest marked a turning point for MFC research, as scientists started to recognize the dual benefits of energy generation and pollution control.

The advent of modern biotechnology and materials science in the late 20th and early 21st centuries brought about transformative changes in MFC design and functionality. A pivotal breakthrough was the discovery of electrogenic bacteria—organisms capable of directly transferring electrons to electrodes without the need for chemical mediators [23, 24]. This discovery was crucial for advancing MFC technology, as it enabled a more direct and efficient electron transfer process, greatly enhancing the power output of MFC systems. Electrogenic bacteria utilize conductive pili or other electron transfer mechanisms that connect directly to an electrode, creating a streamlined pathway for electricity generation [18, 25]. By facilitating more efficient energy conversion, this advancement opened up new possibilities for MFC applications, not only in wastewater treatment but also in bioenergy and remote power generation.

With these innovations, MFCs have evolved from low-efficiency devices to promising renewable energy systems that can convert waste into electricity effectively [9]. The continuous improvements in electrode materials, reactor design, and microbial selection have further boosted the viability of MFCs, making them a subject of interest for various industrial and environmental applications. These advances are leading the way toward more sustainable energy solutions that can be implemented in settings where traditional energy infrastructure may be impractical [4, 22, 24]. Consequently, MFCs are now recognized as an innovative technology with the potential to address both energy generation and environmental sustainability, fulfilling the vision M.C. Potter set into motion over a century ago.

1.5 Recent Advances and Research Focus

Recent advancements in MFC technology have been largely geared toward improving power density, cutting costs, and enhancing the scalability of MFCs for real-world applications. These efforts are essential as researchers and engineers work to move MFCs from lab-scale prototypes to commercially viable systems [21, 25]. Key areas of focus include microbial engineering, system design innovations, and integrating MFCs with other technologies, each contributing uniquely to the broader goal of developing efficient, cost-effective, and sustainable MFC systems.

One of the most promising avenues of MFC research lies in microbial engineering. By leveraging advances in synthetic biology and microbial genomics, scientists are now able to genetically modify microorganisms to enhance their electron transfer capabilities and optimize their metabolic rates. This genetic engineering approach enables the creation of microbial strains that are more efficient at converting organic matter into electricity. For instance, specific microbes can be engineered to metabolize particular substrates, making MFCs adaptable to a wide range of waste materials and environmental conditions [26]. Tailoring microbial communities in this way increases the efficiency of MFCs, broadening their applicability and reliability for both energy generation and wastewater treatment. Such innovations in microbial engineering not only enhance power output but also improve the overall flexibility of MFCs, making them a more versatile technology in various settings.

System design is another critical area in the advancement of MFC technology. Researchers have developed various architectural modifications, such as air-cathode MFCs, stacked configurations, and single-chamber designs, all aimed at optimizing power output while reducing material costs. Air-cathode MFCs, for example, eliminate the need for complex cathode solutions, simplifying the design and making the system more cost-effective. Stacked configurations allow multiple MFC units to be connected in series or parallel, enhancing power density and making large-scale applications feasible. Single-chamber MFCs, which combine both anode and cathode in one unit, reduce the complexity and cost of MFC systems, making them easier to deploy in resource-limited settings. These design innovations have brought MFC technology closer to large-scale implementation, increasing its feasibility for both urban wastewater treatment plants and decentralized energy systems in remote or rural areas.

The integration of MFCs with other technologies is a rapidly growing research area that further enhances MFCs' functionality and efficiency. Hybrid MFC systems, which combine MFCs with other bio-electrochemical systems, can generate energy more continuously by addressing limitations in power output and operational stability. Additionally, there is increasing interest in coupling MFCs with bio-electrochemical sensors, an integration that serves a dual purpose: energy production and environmental monitoring. The electrical signals generated by MFCs can act as indicators of water quality or pollutant concentration, offering a real-time, cost-effective method for monitoring environmental conditions. Such integrations broaden the practical applications of MFCs, making them valuable tools not only for clean energy production but also for public health and environmental safety.

These advancements in microbial engineering, system design, and technology integration underscore the growing potential of MFCs as an adaptable and sustainable energy solution. With continued innovation, MFCs hold the promise of playing a transformative role in energy and waste management, providing clean energy options that also promote environmental resilience.

1.6 Objectives of the Review

This review aims to deliver an in-depth analysis of MFCs, emphasizing their dual potential as both a renewable energy source and an eco-friendly solution for wastewater treatment [27]. By exploring the fundamental principles that govern MFC operation, we intend to lay a solid groundwork for understanding how these bio-electrochemical systems harness the metabolic activities of bacteria to convert organic waste into electrical energy. Beyond foundational concepts, this review will delve into recent advancements in MFC technology, including improvements in microbial engineering, system architecture, and hybrid integrations [28]. These developments have not only increased power efficiency but also broadened the applicability of MFCs in diverse environments and contexts.

The review will also address the current challenges facing MFC technology, which need to be overcome for large-scale commercial adoption. Issues such as enhancing power density, reducing production costs, improving scalability, and managing the longevity of microbial communities are critical for positioning MFCs as a viable alternative within the renewable energy landscape [22]. By synthesizing the latest research, we aim to provide a clear picture of the technology's current state and its limitations, offering insights into the hurdles that must be tackled to unlock its full potential.

Furthermore, this analysis will highlight key areas for future investigation, identifying research gaps and potential innovations that could propel MFCs toward mainstream adoption. Our ultimate objective is to outline realistic pathways for scaling MFC technology to meet the growing global demand for sustainable energy and effective waste management solutions [29]. Through this review, we hope to contribute to the evolving conversation on renewable energy by showcasing how MFCs, with continued research and development, could become an integral part of the world's energy and environmental strategy.

2 Principles of MFCs

Unlike traditional fuel cells that depend on chemical reactions facilitated by expensive catalysts such as platinum, MFCs offer a cost-effective alternative by utilizing microorganisms as natural biocatalysts [30]. These microorganisms, typically specialized bacteria, play a central role in MFC function by metabolizing organic substrates—such as wastewater, agricultural residues, and other biodegradable materials—breaking them down into simpler compounds. During this metabolic process, the bacteria release electrons and protons as byproducts, which are then channeled through the MFC's architecture to produce electricity. The electrons travel toward an external circuit, generating an electric current, while protons migrate through a selective membrane to complete the circuit on the cathode side, where they combine with electrons and oxygen to form water.

This section will delve into the core principles that govern MFC operation, beginning with the electrochemical processes that underpin energy generation [31]. A critical aspect of MFC function is microbial metabolism, whereby bacteria break down organic matter through oxidation reactions, liberating electrons that can be harnessed as electrical energy. We will explore various microbial electron transfer pathways, including direct electron transfer (DET), in which bacteria utilize conductive pili or nanowires to establish direct contact with an electrode, and mediated electron transfer, where molecules known as redox mediators facilitate electron movement. These pathways enable bacteria to efficiently transfer electrons to the electrode, boosting the overall energy output of the system.

Another key area of focus is the design elements that drive MFC efficiency and effectiveness. MFC systems typically consist of an anode chamber, where bacteria reside and organic substrates are metabolized, and a cathode chamber, where electrons, protons, and oxygen react to complete the circuit. Innovations in anode and cathode materials, chamber configurations, and membrane selection are critical for optimizing power generation. For example, materials with high conductivity and biocompatibility can enhance bacterial attachment and electron transfer, improving the system's efficiency. Additionally, single-chamber and stacked designs are being explored to streamline the system, reduce costs, and improve scalability for practical applications.

By examining these core principles—electrochemical reactions, microbial metabolism, electron transfer mechanisms, and system design elements—this section aims to provide a comprehensive understanding of how MFCs operate [26, 29]. Through this exploration, we aim to reveal the innovative underpinnings of MFC technology and highlight the engineering strategies that make them a promising renewable energy source and sustainable waste treatment solution.

2.1 Microbial Metabolism and Electron Generation

At the core of a MFC's operation are the unique metabolic processes of specific bacteria known as exoelectrogens. Unlike other microbes, exoelectrogens have the exceptional ability to transfer electrons outside their cells during respiration, a property that makes them well-suited for MFC applications. These microorganisms oxidize organic substrates, which can range from simple compounds like glucose and acetate to complex organic waste found in wastewater. As they metabolize these substrates, exoelectrogens release electrons, protons, and byproducts such as carbon dioxide. The electrons and protons produced in this process are essential to the MFC's ability to generate electricity, as they facilitate the creation of a current between the MFC's anode and cathode [27].

In traditional aerobic respiration, microbes would use oxygen as the terminal electron acceptor. However, in an MFC, anaerobic conditions at the anode prompt exoelectrogens to use the anode itself as the electron acceptor. Electrons generated by the oxidation of organic material are transferred directly or indirectly to the anode, creating a potential difference between the anode and the cathode compartments. This electron transfer, driven by the gradient established between these compartments, is fundamental to the generation of electrical power in MFCs.

The primary metabolic process in electron generation involves the oxidation of organic compounds at the anode. The breakdown of substrates, such as glucose or acetate, initiates a series of biochemical reactions where electrons and protons are produced [32]. These electrons travel along the bacterial membrane to reach the electrode, either through direct conductive pili known as nanowires or through intermediary molecules, depending on the bacterial species. Protons migrate through a selective membrane toward the cathode compartment, while electrons travel through an external circuit connecting the anode and cathode [33]. This movement of electrons creates an electric current, while protons combine with oxygen and electrons at the cathode to produce water, completing the circuit.

By leveraging these microbial metabolic processes, MFCs harness the natural electron transfer capabilities of exoelectrogens, turning organic waste into a renewable source of energy [22]. The integration of these bacteria within the MFC system highlights the innovative nature of bio-electrochemical technologies, which rely on living organisms as key components in the energy conversion process. Through this mechanism, MFCs represent a sustainable solution that bridges the gap between waste management and renewable energy production.

2.1.1 Oxidation reaction at the anode (Anaerobic chamber)

The oxidation of organic matter by the microorganisms generates electrons and protons.

$$\mathrm{C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^-}$$

Here, glucose ($\mathrm{C_6H_{12}O_6}$) serves as the organic substrate, which is oxidized to carbon dioxide ($\mathrm{CO_2}$), releasing electrons ($\mathrm{e^-}$) and protons ($\mathrm{H^+}$).

2.1.2 Reduction reaction at the cathode (Aerobic chamber)

At the cathode, oxygen is reduced by accepting electrons from the external circuit and protons from the anode chamber, producing water.

$$\mathrm{O_2 + 4H^+ + 4e^- \rightarrow 2H_2O}$$

The overall result is the production of electrical energy, with water and carbon dioxide as byproducts.

2.2 Electron Transfer Mechanisms

Microbial electron transfer to the anode is indeed a pivotal process in MFCs, fundamentally impacting both the efficiency and power output of these systems [34]. The effectiveness of this electron transfer determines how well the MFC can convert organic substrates into electrical energy, making it a focal point of research and innovation within the field.

The process begins when exoelectrogenic bacteria metabolize organic substrates at the anode. As these microorganisms oxidize the substrates, they release electrons, which must be efficiently transferred to the anode to generate electricity. This electron transfer can occur through various mechanisms, including direct and mediated pathways [35]. In DET, bacteria utilize specialized structures, such as conductive pili or nanowires, to connect directly with the anode. This direct connection facilitates a rapid transfer of electrons, enhancing the overall efficiency of the MFC.

In cases where DET is not feasible, mediated electron transfer occurs. In this process, the bacteria release soluble electron shuttles—often redox-active compounds—that can diffuse to the anode and transfer electrons. While this method can still be effective, it may introduce limitations, such as reduced efficiency due to the time required for the shuttle molecules to diffuse and the potential for them to be consumed or degraded in the process.

The efficiency of microbial electron transfer is influenced by various factors, including the type of bacteria used, the nature of the substrate, and the design of the anode itself. Different species of exoelectrogens exhibit varying abilities to transfer electrons, and optimizing the microbial community can significantly enhance performance [28, 35]. Additionally, the physical and chemical properties of the anode material—such as its conductivity, surface area, and biocompatibility—play crucial roles in facilitating efficient electron transfer. High-surface-area materials, for instance, can provide more sites for bacterial attachment, thereby improving the likelihood of effective electron transfer.

The efficiency of microbial electron transfer ultimately dictates the power output of the MFC. Higher electron transfer rates lead to increased current generation, enhancing the overall performance of the system. Therefore, optimizing microbial electron transfer mechanisms is essential for maximizing the energy yield from organic substrates [36]. Continued research in this area focuses on developing new materials and configurations that improve electron transfer efficiency, exploring innovative microbial engineering techniques to enhance the capabilities of exoelectrogens, and optimizing operational conditions to support robust microbial communities [30]. By addressing these aspects, advancements in MFC technology can lead to more efficient and powerful systems, further solidifying their role in sustainable energy production and wastewater treatment.

2.2.1 DET

Some microorganisms possess the remarkable capability of DET, a process wherein they transfer electrons generated during their metabolic activities directly to the anode surface of an MFC. This ability is a game-changer in MFC technology, as it significantly enhances the efficiency and power output of the system. The primary facilitators of this process are conductive proteins known as cytochromes, which are embedded in the cell walls of these bacteria. Cytochromes play a crucial role in electron transport, allowing for the efficient movement of electrons from the microbial cell to the anode.

In addition to cytochromes, certain exoelectrogenic bacteria also produce electrically conductive appendages known as nanowires. These nanowires serve as extensions that enable the bacteria to transfer electrons to the anode even when they are not in direct physical contact with the surface. This capability expands the effective area for electron transfer and can significantly enhance the overall performance of the MFC [21]. For instance, when bacteria utilize nanowires, they can facilitate electron transfer across greater distances, making it possible for microbial colonies to thrive in environments where not every cell can be in close proximity to the anode [31].

Notable examples of bacteria that utilize the DET mechanism include Geobacter and Shewanella. Geobacter species are well known for their ability to form biofilms on electrode surfaces, establishing strong physical connections with the anode through their cytochromes and nanowires [35, 37]. This interaction enhances the transfer of electrons and allows them to efficiently oxidize organic substrates, thereby generating electricity. Similarly, Shewanella species are adept at utilizing iron oxides as electron acceptors in their natural habitats, and their capacity for DET further allows them to interact effectively with MFC electrodes.

The unique mechanisms by which these exoelectrogens engage in DET make them particularly effective for MFC applications. Their ability to form robust physical connections with the anode not only improves electron transfer rates but also supports the establishment of stable microbial communities, which are essential for sustained power generation [38]. This adaptability enables MFCs to operate efficiently over extended periods, leveraging the metabolic activities of these microorganisms to convert waste into usable energy.

In summary, the ability of certain microorganisms to engage in DET is a key factor in the functionality of MFCs [28, 39]. By utilizing cytochromes and nanowires, these bacteria can optimize their interaction with the anode, leading to enhanced energy production. As research in this area continues to evolve, understanding and harnessing the capabilities of exoelectrogens like Geobacter and Shewanella could lead to more efficient MFC designs and broader applications in renewable energy and wastewater treatment.

Some exoelectrogenic bacteria, such as Geobacter sulfurreducens and Shewanella oneidensis, transfer electrons directly to the anode via conductive appendages like nanowires or outer membrane cytochromes. These structures create a direct electrical connection between the bacteria and the electrode. DET is highly efficient due to minimal energy losses during electron transfer. It provides a streamlined pathway, ensuring that more electrons generated by microbial metabolism are harnessed for electricity. However, DET requires close proximity between bacteria and the anode, which can limit the active microbial surface area and power density.

2.2.2 Mediator-Assisted Electron Transfer (MET)

In scenarios where microorganisms lack the capacity for DET to the anode, they depend on electron mediators to facilitate the transfer process. These mediators play a critical role in bridging the gap between the microbial metabolism and the anode surface, thereby enabling the generation of electricity even from bacteria that do not possess the specialized structures necessary for DET [40]. Mediators can be either naturally produced by the microorganisms themselves or externally supplied to enhance the efficiency of the electron transfer process.

Common mediators used in MFCs include compounds such as quinones, phenazines, and neutral red. Quinones, for example, are redox-active compounds that can undergo reversible electron transfer, making them effective carriers of electrons between microbial cells and the anode [40]. Similarly, phenazines, which are produced by certain bacterial species, have been shown to play an essential role in facilitating electron transfer by accepting electrons from the bacteria and subsequently transferring them to the anode. Neutral red, a synthetic dye, also functions as a mediator by accepting electrons and enhancing the overall efficiency of the electron transfer process.

While the use of mediators broadens the spectrum of microorganisms that can participate in electron transfer, it also introduces certain inefficiencies [35]. One primary concern is the potential loss of electrons during the multiple transfer steps involved. As electrons move from the microbe to the mediator and then from the mediator to the anode, there is an inherent risk of energy loss at each interface. This can result in a lower overall power output compared to systems employing DET, where the electron flow is more streamlined and efficient.

Additionally, the presence of mediators may lead to fluctuations in performance based on the concentration and stability of these compounds [14, 41]. For instance, if the concentration of the mediator is insufficient or if it degrades over time, the effectiveness of the electron transfer process can be compromised, further impacting the MFC's efficiency. This underscores the importance of carefully selecting and managing mediators to ensure optimal performance.

Despite these challenges, the ability to use mediators significantly expands the diversity of microbial communities that can be utilized in MFCs. By incorporating various microbial species, including those that may not possess the mechanisms for DET, researchers can optimize MFC designs for specific applications and improve the overall sustainability of the technology [21]. Understanding the dynamics of MET remains an essential area of research, as it holds the potential to enhance the performance of MFCs and broaden their applicability in renewable energy production and waste treatment.

In MET, bacteria release redox-active compounds (e.g., quinones, phenazines, or externally supplied neutral red) that shuttle electrons from the bacterial cell to the anode. These mediators are essential for microorganisms that lack DET capabilities. Although MET expands the range of usable microbial species, it is less efficient than DET due to potential energy losses during the mediator's redox cycling. Mediators may degrade over time, requiring replenishment, which increases operational complexity.

2.2.3 Symbiotic and syntrophic relationships

In certain MFCs, the collaboration between different microbial communities can significantly enhance the overall efficiency and performance of the system. This collaborative interaction often manifests in the form of syntrophic relationships, wherein multiple microbial species work together to break down complex organic substrates into simpler compounds [42]. In this arrangement, one species may specialize in degrading complex materials, such as polysaccharides or proteins, into simpler metabolites like fatty acids or alcohols, which are then utilized by exoelectrogenic bacteria for further oxidation and electron generation.

This cooperation not only facilitates a more efficient breakdown of diverse substrates but also optimizes the conditions for electron transfer. By having a mixed microbial community, MFCs can leverage the unique metabolic capabilities of different species, allowing for a wider range of organic materials to be processed. For instance, while some bacteria may excel at breaking down particular types of organic matter, others may be adept at transferring electrons to the anode. The resulting synergy among these microbes enhances the overall electron transfer rate, leading to improved power output and efficiency in energy conversion.

In addition to improving electron transfer, these syntrophic interactions can stabilize microbial communities within the MFC. The presence of various microbial species helps create a balanced ecosystem whereby byproducts of one species' metabolism can be utilized by another, reducing the potential for toxic accumulation and promoting a more resilient community [40]. This is particularly important in wastewater treatment applications, where the composition of the organic material can vary widely.

Moreover, the ability to engage multiple microbial species in electron generation allows MFCs to adapt to different environmental conditions and substrates. For example, under varying pH levels or temperatures, certain species may thrive while others may not. A diverse microbial community can maintain stability and performance even when conditions fluctuate, making the MFC system more robust and reliable.

Overall, the collaboration among microbial communities in MFCs through syntrophic relationships exemplifies the complexity and potential of bio-electrochemical systems. By harnessing the strengths of different microbial species, MFCs can achieve greater efficiency in both energy production and organic waste degradation [27]. As research continues in this area, understanding the dynamics of microbial interactions will be crucial for optimizing MFC design and performance, paving the way for their wider application in sustainable energy and wastewater treatment solutions.

In mature biofilms, conductive networks form through cell-to-cell connections. These networks, comprising nanowires or extracellular polymeric substances (EPS), enable electrons to travel from deeper layers of the biofilm to the anode. Biofilm conduction supports thicker biofilms, enhancing current density. However, excessive biofilm thickness can create resistance and limit substrate diffusion, thereby reducing overall efficiency. High-conductivity and biocompatible materials (e.g., carbon-based electrodes) improve electron collection and microbial attachment, enhancing DET and MET efficiency. Mixed consortia combining species with DET and MET capabilities create synergistic effects, maximizing electron recovery. Optimized designs like single-chamber MFCs or air-cathode systems reduce resistance and improve electron transfer pathways.

2.3 Electrochemical Reactions and Energy Conversion

The conversion of chemical energy to electrical energy in MFCs is fundamentally driven by electrochemical reactions that facilitate the transfer of charge carriers, namely electrons and protons, produced during microbial metabolism. This process is essential for the generation of electrical current within the MFC, transforming the energy stored in organic substrates into usable electrical energy.

At the heart of this conversion process lies the metabolic activity of exoelectrogenic bacteria, which oxidize organic compounds during their respiration. As these microorganisms break down substrates, they generate electrons and protons as byproducts [27]. The efficient separation and management of these charge carriers are crucial for the functioning of MFCs. In essence, the bacteria transfer electrons to the anode, while protons are either shuttled across a membrane or diffuse through the electrolyte to the cathode.

The electron transfer occurs primarily at the anode, where bacteria engage in either DET (as discussed previously) or mediated electron transfer if direct pathways are not available. This transfer is critical because it establishes a flow of electrons through an external circuit, creating the electric current that MFCs harness for power generation [14]. The anode serves as the site of oxidation reactions, where organic substrates are converted into simpler products, resulting in the release of electrons.

Meanwhile, protons generated during microbial metabolism must move towards the cathode, where they will react with electrons and oxygen to form water. This reaction at the cathode completes the circuit and is essential for maintaining the flow of electrons from the anode to the cathode. The separation of these charge carriers—electrons traveling through the external circuit and protons moving through the electrolyte or a membrane—creates a potential difference, which is the driving force for the electric current.

Maintaining a stable and efficient separation of charge carriers is crucial for optimizing the performance of MFCs. Factors such as the type of microbial community, the design of the anode and cathode, and the composition of the electrolyte can all influence the efficiency of electron and proton transfer [23]. For instance, high-conductivity materials used for electrodes can enhance electron transfer rates, while selective membranes can facilitate proton movement while preventing the passage of electrons, thereby ensuring efficient charge separation [43].

In summary, the conversion of chemical energy to electrical energy in MFCs hinges on the effective management of charge carriers generated during microbial metabolism [43, 44]. The intricate interplay between microbial activity, electrochemical reactions at the anode and cathode, and the separation of electrons and protons is essential for the overall efficiency and functionality of MFCs. As research continues to advance in this field, optimizing these processes will be vital for enhancing the performance and scalability of MFC technology, ultimately contributing to sustainable energy solutions [30].

2.3.1 Energy output in MFCs

The electrical energy produced in an MFC is contingent upon several interrelated factors that dictate the efficiency and output of the system. Understanding these factors is essential for optimizing MFC design and enhancing its application in renewable energy production [26].

One of the primary determinants of the voltage generated by an MFC is the electrode potential. The potential difference, or voltage, is a result of the redox reactions occurring at the anode and cathode. At the anode, oxidation reactions take place as microorganisms metabolize organic substrates, releasing electrons [22, 35]. The nature of these substrates, alongside the specific microorganisms involved, significantly influences the overall electrode potential. Different substrates can lead to varying degrees of electron release, while different microbial species may possess unique metabolic pathways that affect the efficiency of electron transfer [14]. For instance, substrates that yield higher electron transfer rates will contribute to a more favorable electrode potential, ultimately enhancing the voltage output of the MFC. Furthermore, the type of materials used for the electrodes can also play a crucial role. Conductive materials with high surface area and appropriate redox properties can facilitate better interactions between the microorganisms and the electrode, further influencing the potential generated.

Another critical parameter is coulombic efficiency, which measures the proportion of electrons generated from the oxidation of substrates that are effectively captured by the MFC to produce electricity. High coulombic efficiency indicates that a larger fraction of the electrons produced during microbial metabolism is being utilized for current generation, whereas lower efficiencies suggest that significant numbers of electrons are lost to side reactions or other processes. Several factors can influence coulombic efficiency, including microbial competition, which may occur when multiple microbial species are present, competing for the same substrate. In such cases, some microorganisms may not effectively transfer their generated electrons to the anode, resulting in decreased efficiency [7]. Additionally, substrate loss—where a portion of the substrate is consumed by the microbial community but not effectively converted into electricity—can also impact coulombic efficiency.

Side reactions present another challenge. For example, some organic substrates can undergo fermentation pathways that do not produce electrons in a form usable for electricity generation. The extent of these side reactions can vary depending on the type of substrate and the microbial community structure within the MFC. Therefore, optimizing the microbial community composition, substrate selection, and operating conditions is critical to maximizing coulombic efficiency.

In summary, the electrical energy output of an MFC is influenced by a multitude of factors, with electrode potential and coulombic efficiency standing out as pivotal parameters. A deeper understanding of these factors allows for targeted strategies to enhance MFC performance, ensuring that these systems can effectively contribute to sustainable energy solutions while efficiently treating organic waste. Continued research in this area holds the promise of unlocking the full potential of MFC technology, leading to greater efficiency and broader applicability in the fields of renewable energy and wastewater treatment.

2.4 Factors Affecting MFC Performance

The overall performance of MFCs is influenced by a variety of interconnected factors, each playing a crucial role in determining the efficiency and effectiveness of electricity generation from organic substrates. Understanding these influences is key to optimizing MFC design and operation for sustainable energy applications.

Substrate type and concentration are among the most significant factors affecting MFC performance. The specific organic substrate utilized, whether it be glucose, acetate, or a more complex mixture found in wastewater, directly impacts the metabolic pathways of the microbial communities present in the MFC [38, 40]. Different substrates provide varying amounts of energy and electron availability, with easily degradable substrates generally leading to higher power outputs. For instance, glucose is a favored substrate due to its rapid breakdown and high electron yield. However, it is important to note that while higher concentrations of readily degradable substrates can enhance electricity generation, excessively high concentrations may inhibit microbial growth or lead to substrate inhibition. This inhibition can occur when the concentration of the substrate becomes so high that it becomes toxic to the microorganisms or disrupts their metabolic processes, ultimately hindering the MFC's performance.

The microbial community composition within the MFC is another critical factor influencing substrate degradation and power generation. The presence of exoelectrogenic bacteria, which are capable of transferring electrons to the anode, is essential for efficient electricity production. However, other microbial species also play significant roles in breaking down complex organic substrates into simpler compounds that exoelectrogens can further metabolize. The interactions within a diverse microbial community can lead to enhanced substrate degradation and improved electron transfer efficiency. For example, some bacteria may produce metabolic byproducts that are favorable for the growth of exoelectrogens, creating a synergistic relationship that boosts overall performance.

Electrode materials significantly impact the efficiency of electron transfer in MFCs. The choice of materials for the anode and cathode, as well as their surface area and porosity, are critical considerations. Highly conductive and biocompatible materials facilitate microbial attachment and promote efficient electron transfer, reducing resistive losses within the system [11, 14, 30]. The design and surface modifications of electrodes can enhance their interaction with the microbial community, leading to improved power output. Moreover, the surface area of the electrodes plays a vital role in providing sufficient sites for microbial colonization and electron transfer, thus affecting the overall efficiency of the MFC.

Environmental conditions such as temperature and pH also influence microbial activity and, consequently, the performance of MFCs. Most microorganisms exhibit optimal activity at moderate temperatures and near-neutral pH levels. Extreme temperatures can inhibit microbial growth, while significantly acidic or alkaline conditions may disrupt metabolic processes and reduce power output [26]. For instance, many exoelectrogens thrive in conditions close to neutral pH, which supports their metabolic activities and enhances electron transfer efficiency. Therefore, maintaining optimal environmental conditions is essential for maximizing the power generation potential of MFCs.

In conclusion, the performance of MFCs is multifaceted and influenced by various factors, including substrate type and concentration, microbial community composition, electrode materials, and environmental conditions. A comprehensive understanding of these interactions allows for targeted strategies to enhance MFC efficiency and efficacy, paving the way for their broader application in renewable energy generation and wastewater treatment. Continued research and innovation in these areas are essential for unlocking the full potential of MFCs as sustainable energy solutions.

3 Applications of MFCs

3.1 Energy Generation

MFCs represent a promising alternative source of renewable energy by effectively harnessing organic waste, agricultural by-products, and wastewater as substrates for electricity generation. This innovative technology taps into the metabolic processes of microorganisms, converting the chemical energy stored in organic materials into electrical energy [22]. The ability of MFCs to utilize waste products not only addresses the pressing issues of waste management and environmental pollution but also provides a sustainable energy solution, thereby creating a circular economy where waste is transformed into valuable resources.

One of the most significant advantages of MFCs is their potential to decentralize power production, particularly beneficial for remote or off-grid areas that lack access to conventional energy infrastructure. In many regions, especially rural communities, the availability of reliable energy sources is limited, hindering development and quality of life. MFCs can serve as localized energy solutions, enabling these communities to generate their own electricity from available organic waste materials. This decentralization not only reduces reliance on centralized energy systems but also fosters energy independence, allowing communities to utilize their local resources effectively [14].

Moreover, the implementation of MFC technology in remote areas can significantly contribute to sustainable development goals. By providing a clean and renewable energy source, MFCs can help reduce greenhouse gas emissions and mitigate the impacts of climate change [17]. They also address issues related to sanitation and wastewater management, as many MFCs can treat wastewater while simultaneously generating electricity. This dual functionality is particularly valuable in developing regions where waste disposal poses significant health and environmental risks.

In addition to enhancing energy access and environmental sustainability, MFCs can also spur economic opportunities in rural areas [45]. The deployment of MFC technology can create jobs related to the installation, maintenance, and operation of these systems, contributing to local economies. Furthermore, the agricultural sector can benefit from the integration of MFCs by utilizing agricultural residues and by-products as feedstocks, creating a more sustainable agricultural practice.

As the technology continues to evolve, ongoing research and innovation will be crucial to improving the efficiency and scalability of MFCs. Advances in microbial engineering, electrode design, and system integration can further enhance the performance of MFCs, making them more viable for widespread adoption [6, 42]. Ultimately, the integration of MFCs into energy systems can play a vital role in transitioning towards a more sustainable, decentralized energy future that not only meets the needs of communities but also contributes to broader environmental and economic goals.

3.2 Wastewater Treatment

The ability of MFCs to utilize organic pollutants in wastewater as substrates for electricity generation while simultaneously treating and cleaning the water represents a significant advancement in waste management and renewable energy production [17]. This dual functionality positions MFCs as a compelling solution for industries and municipalities striving to achieve both economic and environmental sustainability.

In many wastewater treatment facilities, organic pollutants such as sugars, fats, and proteins are abundant. Traditionally, these pollutants are viewed as burdens that require significant energy input for removal, often through energy-intensive processes such as aerobic and anaerobic digestion. However, MFCs turn this paradigm on its head by converting these very pollutants into valuable electrical energy [11]. As microorganisms metabolize the organic matter in the wastewater, they generate electrons, which can be harvested to produce electricity. This approach not only reduces the overall energy consumption of the wastewater treatment process but also transforms a liability into a resource.

For industries, the adoption of MFC technology can lead to substantial cost savings. By integrating MFCs into existing wastewater treatment systems, companies can potentially offset some of their energy costs with the electricity generated from the treatment process. This is especially beneficial for energy-intensive industries, such as food processing, textiles, and pharmaceuticals, where wastewater is generated in large quantities [17, 42]. Additionally, the reduction in energy usage can enhance the overall sustainability of these operations, aligning with growing regulatory pressures and public demand for greener practices.

Municipalities also stand to gain from implementing MFC technology in their wastewater treatment plants. Many urban areas are faced with increasing demands for efficient waste management solutions, particularly as populations grow and environmental regulations tighten. MFCs can help municipalities meet these challenges by providing an innovative approach to wastewater treatment that not only cleans the water but also generates renewable energy [44, 46]. The dual benefits of improved water quality and energy production can make municipal treatment facilities more resilient and adaptable to future environmental challenges.

Furthermore, the environmental implications of using MFCs for wastewater treatment are significant. By effectively removing organic pollutants, MFCs help mitigate the release of harmful substances into natural water bodies, thus protecting aquatic ecosystems and promoting biodiversity. This aligns with global efforts to enhance water quality and ensure sustainable management of water resources, particularly in regions facing water scarcity and pollution.

In summary, the capacity of MFCs to convert organic pollutants in wastewater into electricity while simultaneously purifying the water presents a transformative solution for energy generation and waste management [17]. This innovative approach is especially attractive to industries and municipalities aiming to reduce costs and enhance environmental sustainability. As research and development continue to advance MFC technology, its widespread adoption could play a pivotal role in shaping a more sustainable future for wastewater treatment and renewable energy production.

3.3 Environmental Monitoring

Integrating MFCs with biosensors offers a cutting-edge solution for real-time environmental monitoring, particularly in assessing the quality of water bodies. This innovative approach leverages the inherent capabilities of MFCs to detect changes in the composition of wastewater or natural water sources, providing valuable data on the presence of pollutants, including toxins and heavy metals [19].

The principle behind this integration lies in the fact that the metabolic activity of microorganisms within MFCs is sensitive to the surrounding chemical environment. When the composition of the water changes—such as the introduction of harmful substances like heavy metals or toxins—microbial behavior and metabolism can be directly affected [44]. These alterations often result in measurable changes in the electrical output of the MFC. For example, the presence of toxic compounds may inhibit the growth of beneficial microorganisms or alter their metabolic pathways, leading to a decrease in electron production and, consequently, a drop in voltage or current output.

By continuously monitoring the electrical signals generated by the MFC, researchers and environmental managers can gain insights into the health of aquatic ecosystems. This real-time monitoring capability is particularly valuable in industrial settings, where wastewater is discharged into natural bodies of water, and in agricultural areas where runoff may introduce harmful chemicals into waterways. Traditional methods of water quality testing often involve time-consuming laboratory analyses, which can delay response times in identifying pollution events. In contrast, MFC-biosensor systems enable immediate detection of contamination, allowing for quicker interventions and remediation efforts.

Furthermore, the integration of biosensors with MFCs not only enhances pollution monitoring but also creates a synergistic relationship between energy generation and environmental surveillance. The electrical output generated by the MFC can be utilized to power the biosensors themselves, making the entire system more self-sufficient and cost-effective [6, 24]. This closed-loop approach reduces reliance on external energy sources, making it feasible for deployment in remote or off-grid locations where conventional power supply may not be readily available.

In addition to detecting pollutants, MFC-biosensor systems can be designed to assess specific water quality parameters, such as pH, dissolved oxygen, and nutrient levels. By correlating changes in electrical output with these parameters, it becomes possible to develop comprehensive profiles of water quality that inform management decisions and regulatory compliance [42]. This capability is particularly crucial in the context of environmental protection and conservation, as it enables proactive measures to safeguard water resources.

In summary, the integration of MFCs with biosensors represents a transformative approach to real-time environmental monitoring [17]. By detecting shifts in electrical output in response to changes in water composition, these systems provide immediate insights into the presence of pollutants and overall water quality. The ability to monitor environmental conditions in real-time enhances response strategies and contributes to the sustainable management of aquatic ecosystems, ultimately supporting efforts to preserve water quality and protect public health [39, 44]. As research progresses, the potential for widespread adoption of MFC-biosensor systems could significantly advance our capabilities in environmental monitoring and protection.

3.4 Bio-Hydrogen Production

MFCs can be adapted to produce hydrogen through MECs, a related technology that utilizes an additional voltage to stimulate hydrogen evolution at the cathode. This innovative approach combines the principles of bio-electrochemistry with the burgeoning demand for clean hydrogen fuel, presenting a promising pathway for sustainable energy production using waste biomass.

In a typical MFC setup, microorganisms metabolize organic substrates to generate electricity while treating wastewater. In contrast, MECs utilize the same microorganisms but add a specific voltage to facilitate the electrolysis of water, enabling the production of hydrogen gas at the cathode [41, 45, 46]. This process occurs through microbial-mediated reactions where, upon applying a voltage, the protons produced during microbial metabolism are reduced at the cathode to form hydrogen gas. This mechanism not only enhances the energy yield from organic waste but also provides a cleaner alternative to conventional hydrogen production methods, which often rely on fossil fuels or other carbon-intensive processes.

The use of waste biomass as a substrate for hydrogen production is particularly significant in addressing two major global challenges: energy transition and waste management [44]. Agricultural residues, food waste, and other organic by-products are abundant and often underutilized. By converting these waste materials into hydrogen fuel, MECs help create a circular economy where waste is repurposed into a valuable energy resource [33]. This approach aligns well with sustainability goals, as it reduces reliance on non-renewable energy sources and decreases environmental pollution associated with waste disposal.

One of the primary advantages of MECs is their ability to operate at relatively low temperatures and ambient conditions, making them suitable for integration into existing waste treatment facilities. This compatibility allows for the dual function of waste treatment and hydrogen production, maximizing resource efficiency [26]. Additionally, the hydrogen generated can be stored and utilized in various applications, including fuel cells for transportation, electricity generation, and as a feedstock for industrial processes.

Moreover, the scalability of MEC technology presents an opportunity for diverse applications, from small-scale systems suitable for rural or off-grid settings to large-scale implementations in urban waste treatment plants. By effectively linking waste management with renewable energy production, MECs can contribute significantly to local energy systems and promote energy independence in communities. As research in this field progresses, there are opportunities to improve the efficiency and cost-effectiveness of MECs. Advances in microbial engineering, electrode materials, and system design can enhance hydrogen production rates and overall system performance [42].

Exploring different microbial consortia that can optimize substrate degradation and hydrogen production will also be crucial for maximizing the potential of MECs.

In summary, MECs present a novel application of MFC technology, enabling the production of clean hydrogen fuel from waste biomass [21, 36]. By harnessing the metabolic processes of microorganisms and applying external voltage, MECs facilitate hydrogen evolution while simultaneously addressing waste management issues. This hybrid technology not only contributes to sustainable energy production but also plays a vital role in the transition to a circular economy, making it a significant player in the future of renewable energy solutions. Table 1 includes some experimental results from recent studies that will provide tangible evidence of MFC performance and practical outcomes.

Table 1. Experimental case studies on MFC performance and applications

Case Study	Key Details	Implications
Case study 1: MFC Performance in Wastewater Treatment	Source: Choudhury et al. [9] Type: Two-chamber MFC Substrate: Synthetic wastewater with glucose Performance: Achieved 800 mW/m^2 maximum power density COD Removal Efficiency: 85%	1. Highlights MFC's dual role in renewable energy and environmental remediation. 2. Demonstrates potential for industrial wastewater treatment while generating electricity. 3. Can be adapted for diverse wastewater treatment systems.
Case study 2: Integration with Renewable Energy Sources	Source: Jadhav et al. [19] System: MFC stack integrated with solar panels for rural electrification Substrate: Agricultural waste Output: Produced continuous power of 0.4 W	1. Demonstrates MFC's feasibility in decentralized, hybrid renewable systems. 2. Addresses energy access in remote or off-grid areas. 3. Ensures energy consistency by leveraging solar power for daytime generation and MFCs for night-time operations. 4. Highlights the practical viability of hybrid systems in low-resource environments.

Source: Authors' own elaboration

In Japan, a pilot-scale MFC system at a wastewater treatment plant demonstrated energy-neutral operation. Electricity generated offset operational energy requirements by 40%. This supports scaling MFCs for municipal applications. An MFC-biosensor was used to detect heavy metal pollution in river water [8, 9]. It has successfully detected lead at concentrations as low as 5 ppb. It also offers potential for real-time environmental monitoring solutions. Recent advancements in MFC technology have been supported by experimental validations and real-world implementations. For instance, a two-chamber MFC achieved a power density of 800 mW/m^2 while treating synthetic wastewater with 85% COD removal efficiency [16, 17]. Similarly, a hybrid system integrating MFCs with solar panels in rural India demonstrated the feasibility of decentralized energy production, ensuring an uninterrupted electricity supply during night hours [19, 20]. Furthermore, pilot-scale trials in wastewater treatment facilities have shown that MFCs can offset up to 40% of operational energy requirements, highlighting their potential for scalable applications in municipal settings.

4 Challenges and Limitations

4.1 Low Power Density

Despite the significant promise that MFCs hold for sustainable energy production and wastewater treatment, they face inherent challenges, particularly in terms of power density. Generally, MFCs produce lower power densities compared to more established energy-generation technologies such as traditional fuel cells and batteries [39]. This limitation is a key factor that researchers and engineers must address to enable the broader adoption of MFC technology in practical applications.

Power density refers to the amount of electrical power produced per unit volume or area of the fuel cell, and it is a critical metric in evaluating the performance and efficiency of any energy-generating system. While MFCs have demonstrated their ability to convert organic waste into electricity, the overall power output is often not sufficient for high-demand applications or for competing with conventional energy sources [3, 8, 21]. Several factors contribute to this lower power density, including the kinetics of microbial metabolism, electron transfer processes, and the properties of the electrode materials used in the system.

To enhance the power output of MFCs, optimizing the microbial communities is essential. The composition of the microbial consortium directly influences the efficiency of substrate degradation and the overall electron transfer processes. By engineering or selecting specific microbial species that exhibit higher metabolic rates and better electron transfer capabilities, researchers can improve the energy conversion efficiency [6, 8]. Techniques such as synthetic biology and microbial consortia optimization allow for the creation of customized communities that are specifically tailored to different substrates, thus maximizing the power generation potential of MFCs.

In addition to optimizing microbial communities, the selection and modification of electrode materials play a crucial role in enhancing power density. The anode and cathode materials must possess properties that facilitate efficient electron transfer and minimize resistive losses. Researchers are exploring various materials, including conductive polymers, carbon-based materials, and metal-organic frameworks, to improve the electrochemical performance of MFCs [29, 33]. Increasing the surface area and porosity of the electrodes can also enhance microbial attachment and promote better contact between the microbes and the electrodes, further boosting power output.

Furthermore, the design of MFC systems can also be optimized to improve power densities. Innovations such as stacked configurations, air-cathode designs, and hybrid systems that integrate other energy generation methods can contribute to enhancing the overall efficiency and scalability of MFC technology. By creating more effective electrochemical environments, these design improvements facilitate better electron transfer and higher energy output.

Addressing these challenges is crucial for realizing the full potential of MFCs in energy generation and environmental applications. As researchers continue to explore new strategies for optimizing microbial communities and improving electrode materials, there is hope for achieving significant advancements in power density. This progress could make MFCs more competitive with traditional energy technologies and lead to broader implementation in both small-scale and large-scale applications.

In summary, while MFCs currently exhibit lower power densities compared to traditional fuel cells and batteries, there is a concerted effort in the research community to enhance their performance through the optimization of microbial communities and electrode materials. By addressing these critical aspects, it may be possible to significantly improve the power output of MFCs, paving the way for their greater use in sustainable energy generation and waste treatment solutions.

4.2 Cost and Scalability

MFCs present a promising technology for sustainable energy production and wastewater treatment; however, they currently grapple with significant challenges concerning cost and scalability. One of the primary barriers to widespread adoption is the expense associated with key components such as proton exchange membranes (PEMs), electrodes, and other materials used in MFC construction. The high costs of these materials can make it difficult to justify the economic feasibility of MFCs, particularly in comparison to more established energy generation technologies [2, 3, 21].

PEMs are critical for the operation of MFCs, as they facilitate the selective transfer of protons from the anode to the cathode while preventing the mixing of reactants. However, many of the commercially available PEMs are derived from expensive polymers, which can increase the overall cost of MFC systems. Similarly, the electrodes must possess high conductivity, durability, and biocompatibility, further driving up costs. These materials are essential for enhancing the efficiency and longevity of the cells, but their expense can pose a significant hurdle to scalability, especially for applications requiring large-scale implementation.

Scalability also presents a challenge, as the successful transition from laboratory-scale experiments to field applications necessitates a deeper understanding of the long-term performance of MFC systems [10]. Many studies have demonstrated the effectiveness of MFCs in controlled settings; however, the durability and reliability of these systems in real-world conditions remain less well understood. Factors such as microbial community dynamics, substrate variability, and environmental conditions can significantly affect the performance and lifespan of MFCs [13, 21]. Therefore, additional research is required to evaluate how MFCs perform over extended periods, particularly in fluctuating or challenging environmental conditions that may be encountered in large-scale applications.

Moreover, integrating MFC technology into existing infrastructure, such as wastewater treatment facilities, requires careful consideration of operational costs and maintenance requirements [30]. It is crucial to assess how MFCs can be seamlessly incorporated into current systems to improve efficiency and reduce energy consumption. Developing standardized protocols for monitoring and maintaining MFCs in operational settings will be vital for ensuring their reliability and effectiveness over time [33].

To address these challenges, research efforts are increasingly focused on identifying alternative materials that can reduce costs while maintaining or enhancing performance. For instance, advancements in nanomaterials and conductive polymers could provide more affordable substitutes for traditional electrode materials and PEMs [18]. Additionally, innovations in system design, such as modular and decentralized configurations, could enhance the scalability of MFCs, making them more adaptable to various applications, from small rural installations to large municipal wastewater treatment plants.

In conclusion, while MFCs hold significant potential for renewable energy and wastewater treatment, their widespread adoption is hindered by challenges related to cost and scalability [36]. The high expense of essential materials, such as PEMs and electrodes, along with the need for a comprehensive understanding of long-term performance, poses obstacles that researchers must address [43]. By focusing on innovative materials and designs, the MFC community can work towards overcoming these challenges and unlocking the full potential of this technology for sustainable energy solutions.

4.3 Electrode Fouling

Biofouling on anode surfaces is a significant challenge in the operation of MFCs that can lead to reduced conductivity and overall system performance. This phenomenon occurs when microorganisms, particularly non-electrogenic species, adhere to the anode surface and form biofilms. While biofilms are essential for the function of MFCs as they harbor the electrogenic microbes necessary for electricity generation, excessive biofouling can hinder electron transfer and block active sites on the anode [30]. Consequently, addressing biofouling is crucial for enhancing the efficiency and longevity of MFC systems.

To mitigate the issue of biofouling, researchers are exploring the development of biofouling-resistant materials. These materials are designed to minimize the attachment of unwanted microorganisms while promoting the growth of beneficial exoelectrogenic bacteria [3]. By modifying the surface properties of anodes—such as their hydrophobicity, charge, and roughness—scientists aim to create environments that discourage the adhesion of fouling organisms. For example, incorporating antimicrobial coatings or employing surfaces with specific textures can disrupt the ability of non-electrogenic microbes to establish themselves on the anode, thus preserving the performance of the fuel cell.

In addition to material modifications, the development of self-cleaning mechanisms presents a promising approach to combating biofouling in MFCs. Self-cleaning technologies can facilitate the removal of accumulated biomass from the anode surface, thereby maintaining optimal conductivity and performance without requiring frequent manual intervention [43, 44]. One such method involves the application of electrical pulses or vibrations to dislodge biofilms, a technique that leverages the physical properties of the microbial layer to promote detachment. Alternatively, researchers are investigating the use of fluid dynamics within the MFC design, optimizing flow patterns to enhance the washing away of fouling microorganisms as part of the normal operation of the cell.

Moreover, integrating self-cleaning features with advanced monitoring systems can provide real-time feedback on biofouling levels, enabling proactive measures to maintain optimal performance [5]. For instance, sensors could be employed to track changes in voltage or current output, alerting operators when biofouling reaches a critical level, thus allowing for timely interventions.

Another innovative approach involves harnessing the natural behaviors of microorganisms within the fuel cell. Certain bacterial species exhibit motility and can actively migrate towards favorable environments [34]. By strategically engineering microbial communities to favor species with desirable characteristics, it may be possible to develop a dynamic system where the beneficial bacteria effectively outcompete fouling species for space and resources on the anode surface.

In summary, biofouling presents a significant obstacle in maximizing the efficiency of MFCs. However, through the development of biofouling-resistant materials and the implementation of self-cleaning mechanisms, researchers can mitigate this issue [18]. By optimizing surface properties, employing innovative physical cleaning techniques, and utilizing intelligent monitoring systems, the performance and longevity of MFCs can be significantly enhanced. These advancements not only promise improved energy conversion efficiencies but also contribute to the overall sustainability and feasibility of MFC technology in real-world applications.

4.4 Microbial Efficiency

The efficiency of MFCs is significantly influenced by the types of microorganisms present in the system. Not all microbial species possess the same capabilities when it comes to electron transfer, which is a crucial factor in the overall performance of these bio-electrochemical systems [2, 3]. The identification and engineering of highly efficient electroactive microorganisms have emerged as a critical area of ongoing research, as these microbes are essential for maximizing power output and enhancing the viability of MFC technology.

Electroactive microorganisms, particularly exoelectrogens, are those capable of transferring electrons to an electrode during their metabolic processes. This unique ability allows them to directly contribute to the generation of electrical energy in MFCs. However, the efficiency of electron transfer can vary widely among different microbial species, depending on various factors such as their metabolic pathways, cellular structures, and environmental conditions [18, 31]. For example, species like Geobacter sulfurreducens and Shewanella oneidensis are well-known exoelectrogens that demonstrate highly efficient electron transfer capabilities, making them prime candidates for use in MFCs [34].

Identifying promising electroactive species involves not only the exploration of naturally occurring microorganisms but also the potential for genetic engineering to enhance their performance. Advances in synthetic biology and microbial genomics enable researchers to modify the metabolic pathways of these organisms, improving their electron transfer efficiency [15, 39]. This can involve enhancing the expression of conductive proteins or nanowires that facilitate DET to the anode, or optimizing metabolic pathways to increase the rate of substrate degradation and energy production.

Moreover, the creation of microbial consortia—where multiple species with complementary metabolic capabilities are combined—can further enhance electron transfer efficiency. By harnessing the strengths of different microbes, researchers can establish syntrophic relationships that facilitate more effective breakdown of complex organic substrates and improve overall power generation [46]. In these interactions, one microbial species may metabolize substrates to produce byproducts that another species can utilize, thereby creating a synergistic effect that boosts electron transfer rates.

The application of advanced bioinformatics and high-throughput screening techniques also plays a pivotal role in this research area. By employing these tools, scientists can analyze vast microbial populations and identify candidate species with optimal electroactive properties [20, 24]. Furthermore, such approaches can help in understanding the complex interactions within microbial communities, shedding light on how certain species can be cultivated or engineered to improve overall performance in MFCs.

While the engineering of electroactive microorganisms presents exciting opportunities, challenges remain in ensuring the stability and reliability of these engineered strains under operational conditions. Environmental fluctuations, substrate availability, and competition from other microbial species can all impact the performance of MFCs, making it essential to develop robust microbial systems that can maintain high efficiency over time.

In conclusion, the identification and engineering of highly efficient electroactive microorganisms are vital for advancing the technology of MFCs [33]. By focusing on the natural capabilities of certain species, optimizing their metabolic pathways through genetic engineering, and exploring the potential of microbial consortia, researchers aim to enhance electron transfer efficiency. As this area of research continues to evolve, it holds the promise of significantly improving the power output and overall sustainability of MFC technology, thereby contributing to its broader application in renewable energy generation and wastewater treatment. Table 2 systematically details challenges, solutions, and their implications, thus providing a comprehensive overview of strategies to overcome barriers in MFC technology.

Table 2. Challenges facing MFC technology and strategies to overcome them

Challenge	Strategies to Overcome	Details and Implications
Low power density	Optimizing microbial communities	1) Genetically engineer exoelectrogens like Geobacter sulfurreducens to increase electron transfer rates via conductive pili and cytochromes. 2) Develop microbial consortia with complementary pathways for efficient substrate utilization.
	Advanced electrode materials	1) Use graphene, carbon nanotubes, or metal-organic frameworks to enhance conductivity and microbial attachment. 2) Design hierarchical porous structures to improve substrate diffusion and electron transport.
	System design innovations	1) Implement stacked MFC configurations to amplify power density for larger systems. 2) Employ air-cathode designs to simplify oxygen reduction and boost efficiency.
High cost of materials	Development of cost-effective materials	1) Replace costly PEMs with alternatives like hydrogel-based or ceramic membranes. 2) Utilize biowaste-derived carbon materials, such as activated carbon from biomass, for electrodes.
	Scaling production	1) Scale up manufacturing processes for electrodes and membranes to reduce costs through economies of scale. 2) Foster industry partnerships to mass-produce MFC components at lower costs.
Electrode fouling and stability	Biofouling-resistant materials	1) Design anode surfaces with antimicrobial coatings or nanoparticles to prevent non-electrogenic bacterial growth. 2) Use textured surfaces to enhance electrogenic biofilm formation while reducing unwanted adhesion.
	Self-cleaning mechanisms	1) Employ electrochemical techniques, such as voltage pulsing, to dislodge biofilms. 2) Optimize flow patterns within MFC systems to promote natural biofilm removal during operation.
Scalability and market penetration	Standardized modular designs	1) Create plug-and-play modular systems scalable for diverse applications, including municipal treatment and rural electrification.
	Integration with existing systems	1) Retrofit MFCs into existing wastewater treatment plants to minimize setup costs.
	Policy and incentives	1) Advocate for subsidies or tax incentives to encourage adoption. 2) Partner with governments and NGOs to pilot MFCs in off-grid communities or small industries.
Limited longevity and reliability	Microbial engineering	1) Engineer robust microbial strains to withstand variable conditions like pH and temperature.
	Durable materials	1) Use corrosion-resistant electrodes and membranes to enhance system durability.
	Field trials and long-term monitoring	1) Conduct field trials to evaluate performance in real-world, fluctuating conditions and inform future designs.

Source: Authors' own elaboration

While MFCs hold great promise, addressing their technical and market challenges is essential for their widespread adoption. For instance, low power density can be mitigated through microbial engineering to enhance electron transfer rates and by using advanced electrode materials like graphene. High costs can be addressed by developing alternative materials such as biowaste-derived electrodes and scaling up manufacturing processes. To combat biofouling, self-cleaning mechanisms and biofouling-resistant materials have shown promise. Scalability can be achieved through modular designs and integration with existing systems, while policy incentives and subsidies can drive market adoption. Finally, field trials and long-term monitoring are critical for ensuring reliability and optimizing performance under real-world conditions.

5 Future Directions

For MFCs to gain widespread acceptance and integration into renewable energy and wastewater treatment solutions, focused research efforts are needed to enhance several key aspects: power density, cost-effectiveness, and system longevity. Addressing these challenges will require significant advancements in microbial biotechnology, electrode materials, and system design [3, 12]. Each of these areas offers unique opportunities to improve the efficiency and practicality of MFCs.

One critical avenue for enhancing MFC performance lies in the genetic engineering of microorganisms. By developing genetically modified organisms (GMOs) with improved electron transfer capabilities, researchers can substantially increase the efficiency of power generation in MFCs [9, 25]. For instance, manipulating metabolic pathways can enable these microbes to more effectively oxidize substrates, leading to higher rates of electron production. Genetic modifications may also enhance the expression of proteins responsible for DET to the anode, such as cytochromes or conductive nanowires [28]. Furthermore, incorporating genes that enable these microorganisms to thrive in a broader range of environmental conditions can ensure their robustness and adaptability, which is vital for sustained operation in diverse settings.

In addition to optimizing microbial performance, the exploration of novel electrode materials represents another promising area of research. The traditional materials used in MFCs often face limitations regarding conductivity, durability, and susceptibility to biofouling. Advanced materials such as graphene and nanocomposites have shown great potential in addressing these issues [4, 33]. Graphene, known for its exceptional electrical conductivity and large surface area, can significantly enhance the performance of MFC electrodes by facilitating efficient electron transfer. Nanocomposites, which combine multiple materials at the nanoscale, can be engineered to improve the structural and electrochemical properties of electrodes, potentially leading to reduced resistance and enhanced overall efficiency.

Moreover, the reduction of biofouling on electrode surfaces remains a critical concern [9, 11]. The incorporation of novel materials that discourage the attachment of unwanted microorganisms while promoting the growth of beneficial exoelectrogenic species can be an effective strategy. For example, hydrophobic or superhydrophobic coatings could be used to create surfaces that repel water and reduce biofilm formation, thus maintaining optimal conductivity and power output [25].

Beyond these advancements, the design of MFC systems themselves must evolve to maximize efficiency and practicality [41]. Innovations in system architecture, such as modular or stacked configurations, can enhance scalability and adaptability, allowing MFCs to be tailored for specific applications, whether in large municipal settings or smaller, decentralized units. Additionally, optimizing flow patterns and fluid dynamics within the MFC can improve substrate delivery and enhance the overall interaction between microorganisms and electrode surfaces [31].

Research must also consider the economic aspects of MFC technology. The high costs associated with current materials and components hinder broader adoption [15, 36]. Efforts to find cost-effective alternatives or to develop manufacturing processes that lower production expenses will be essential. This includes evaluating the lifecycle costs of MFC systems, ensuring that their operation and maintenance remain economically viable for potential users, particularly in developing regions or industries with limited resources [2, 4].

Finally, the longevity of MFC systems is paramount for their success in real-world applications. Understanding the factors that contribute to the degradation of performance over time, such as microbial community dynamics, substrate variability, and environmental stressors, will be crucial in developing strategies to enhance system lifespan [12]. Researching long-term operational data and conducting field trials will provide valuable insights into how to maintain optimal performance under varying conditions.

In summary, future research aimed at enhancing the feasibility of MFCs should prioritize improvements in power density, cost reduction, and longevity. Advancements in genetic engineering of microorganisms, the development of novel electrode materials, and innovative system designs will play critical roles in addressing these challenges [23]. By focusing on these key areas, the potential for MFCs to serve as sustainable solutions in renewable energy and wastewater management can be significantly realized, paving the way for their broader adoption and impact.

Based on the current review, the authors intended to address some of the research questions provided as follows.

R1: How can synthetic biology be used to create microbial strains with enhanced electron transfer rates and substrate versatility?

Rationale: Advances in genetic engineering could enable the development of tailored microbial communities optimized for specific substrates or operational conditions.

R2: What novel electrode materials can be developed to simultaneously enhance conductivity, durability, and resistance to biofouling?

Rationale: Exploring materials like graphene composites or bioinspired structures could address multiple technical challenges in MFCs.

R3: How can MFCs be effectively integrated with renewable energy systems (e.g., solar or wind) for consistent energy output in off-grid settings?

Rationale: Combining MFCs with other renewable technologies could overcome their intermittent power output and expand application scenarios.

R4: Can MFC-biosensors be enhanced to detect specific pollutants (e.g., heavy metals, pharmaceuticals) in real time with higher sensitivity?

Rationale: Developing highly specific sensors could position MFCs as vital tools in environmental monitoring.

To advance MFC technology, future research should focus on addressing key challenges and exploring new opportunities. For example, synthetic biology offers potential for engineering microbial strains with enhanced electron transfer rates, enabling higher power outputs. In material science, innovative electrode designs incorporating nanotechnology or bioinspired materials could address durability and biofouling issues. Furthermore, hybrid systems combining MFCs with solar or wind energy could provide consistent power generation for off-grid applications. Research methods such as high-throughput microbial screening and machine learning-based modeling can accelerate discovery and optimization processes. Finally, field trials in extreme environments would validate the robustness and scalability of MFCs for diverse applications, such as decentralized wastewater treatment and renewable energy production. Table 3 succinctly presents innovative methods and their benefits, making it clear how these approaches can contribute to the advancement of MFC technology in both research and practical applications.

Table 3. Innovative research methods for advancing MFC technology

Research Method	Description	Advantages
High-throughput microbial screening	1) Utilize advanced bioinformatics and automated systems to identify and test microbial species with superior electrochemical performance. 2) Allows for rapid optimization of microbial community composition for enhanced electron transfer and power output.	1) Accelerates discovery of efficient exoelectrogens. 2) Optimizes microbial diversity for specific MFC applications.
Machine learning in system design	1) Apply machine learning algorithms to model and predict MFC performance under various conditions, such as substrate types and electrode configurations. 2) Simulates complex interactions between microbial communities, substrates, and system architecture for better performance predictions.	1) Enables efficient, context-specific system designs. 2) Reduces trial-and-error experimental costs by identifying optimal configurations faster.
In situ real-time monitoring	1) Integrate sensors with MFC systems to track biofilm development, substrate consumption, and power output in real-time. 2) Allows for dynamic adjustments to optimize operational parameters (e.g., flow rate, substrate concentration).	1) Provides immediate feedback on system performance and microbial activity. 2) Improves operational efficiency and reduces downtime during MFC operation.
Nanotechnology in electrode development	1) Develop nanostructured electrodes using materials like metal-organic frameworks, carbon nanotubes, or nanoparticles. 2) Apply nanocoatings to reduce biofouling and improve durability under long-term operation.	1) Enhances electron transfer rates by increasing conductivity and active surface area. 2) Boosts efficiency and longevity of MFC systems, lowering maintenance costs.
Field trials in extreme environments	1) Test MFCs in challenging environments such as remote areas with low temperatures, high salinity, or nutrient limitations. 2) Evaluate long-term performance under fluctuating conditions to inform future designs and deployment strategies.	1) Validates the robustness and adaptability of MFCs in diverse real-world scenarios. 2) Demonstrates MFC suitability for off-grid or decentralized applications, expanding potential markets.

Source: Authors' own elaboration

6 Theoretical Implications

The theoretical implications of the research encompass several key areas that contribute to the understanding and development of MFC technology. These implications can be grouped into the following categories as explained in different paragraphs.

The review highlights the fundamental role of microorganisms, particularly exoelectrogens, in MFCs, which is critical for advancing theoretical knowledge in bioelectrochemistry. By exploring the metabolic processes that enable microorganisms to transfer electrons to an electrode, the research provides insights into the various electron transfer mechanisms, including DET and MET [30]. This knowledge is crucial for enhancing microbial efficiency and tailoring microbial communities for optimal performance in energy production.

The theoretical framework presented in the review illustrates how microbial metabolism interacts with electrochemical principles to generate electricity. This intersection of biology and electrochemistry serves as a basis for future research on optimizing the performance of MFCs [4, 34]. Understanding these interactions can lead to the development of models that predict MFC behavior under different operational conditions, allowing for the design of more efficient systems.

The review discusses the significance of electrode materials and their impact on MFC performance. This emphasizes the need for theoretical advancements in material science, particularly in the development of novel conductive materials that can enhance electron transfer and reduce biofouling [5, 9, 26]. The implications of these advancements suggest that interdisciplinary approaches combining biology, chemistry, and materials engineering can lead to significant improvements in MFC efficiency and scalability.

The theoretical implications extend to the broader context of sustainability, where MFCs represent a promising technology for both energy generation and wastewater treatment. The review underscores the potential of MFCs to contribute to sustainable energy systems by utilizing organic waste as a substrate, thereby reducing pollution and providing a renewable energy source [25]. This highlights the theoretical significance of MFCs in the discourse on circular economies and sustainable resource management.

The challenges of cost and scalability discussed in the review have important theoretical implications for the economic viability of MFCs. Understanding the economic factors influencing MFC deployment can guide future research towards developing more cost-effective solutions, making MFC technology more attractive for commercial applications [39]. This suggests a theoretical model where economic considerations are integrated into the design and optimization of MFC systems.

The review identifies several key areas for future research, such as the genetic engineering of microorganisms and the exploration of new electrode materials. These implications set the stage for theoretical investigations that seek to address current limitations in MFC technology [1–4]. By outlining potential pathways for innovation, the research encourages ongoing exploration of microbial biotechnology and materials science as critical components in advancing MFC applications.

In summary, the research contributes to a deeper understanding of the biological, electrochemical, and material aspects of MFC technology [23, 25]. By bridging these disciplines, the review not only highlights the current challenges but also identifies opportunities for future research that can enhance the efficiency, scalability, and sustainability of MFCs in real-world applications.

7 Managerial Implications

The managerial implications of the research highlight several strategic considerations for stakeholders involved in the development, implementation, and commercialization of MFC technology. These implications can guide managers, decision-makers, and industry leaders in effectively leveraging MFCs for sustainable energy solutions and wastewater treatment [12, 32]. The key managerial implications include the following.

Given the potential of MFCs to contribute to renewable energy generation and wastewater treatment, managers should prioritize investments in research and development. This involves allocating resources to explore advancements in microbial biotechnology, materials science, and system optimization [15, 29]. Encouraging collaboration between academic institutions and industry can foster innovation and drive the development of more efficient MFC systems.

The integration of biology, electrochemistry, and materials science is essential for advancing MFC technology. Managers should promote interdisciplinary collaboration among researchers, engineers, and business professionals to create comprehensive solutions that address the complex challenges associated with MFC development [36, 37]. This approach can lead to innovative designs and applications that maximize the performance and efficiency of MFCs.

The review highlights the challenges related to the cost and scalability of MFCs. Managers should develop strategies to reduce production costs through the identification of economical materials and the optimization of manufacturing processes. This could involve sourcing local materials, leveraging economies of scale, or investing in emerging technologies that promise lower costs without sacrificing performance [11, 12].

To assess the feasibility and effectiveness of MFC technology, managers should consider implementing pilot projects in relevant settings, such as wastewater treatment plants or agricultural facilities [8, 9, 32, 46]. These projects can provide valuable insights into operational efficiency, potential challenges, and real-world performance metrics, helping to refine the technology before large-scale deployment [1, 2].

Given MFCs' dual functionality in energy generation and wastewater treatment, establishing partnerships with municipalities and industries can enhance market opportunities. Managers should engage with stakeholders in the water treatment and agricultural sectors to explore collaborative projects that utilize MFC technology [16]. These partnerships can facilitate knowledge sharing, funding opportunities, and co-development initiatives.

The potential of MFCs to promote sustainability aligns with growing consumer and regulatory expectations for environmentally responsible practices. Managers should integrate MFC technology into their sustainability initiatives and CSR strategies [37, 41]. Demonstrating commitment to renewable energy and waste reduction can enhance corporate reputation and attract environmentally conscious investors and customers.

Educating stakeholders—ranging from potential clients to regulatory bodies—about the benefits and capabilities of MFC technology is crucial [8]. Managers should invest in marketing and outreach efforts that convey the advantages of MFCs, including their role in sustainable energy and waste management. Raising awareness can facilitate acceptance and encourage adoption across various sectors [27].

Managers must stay informed about regulatory frameworks governing renewable energy and wastewater treatment. Engaging with policymakers can help influence favorable regulations and incentives for MFC technology [23, 29]. Additionally, managers should ensure that MFC projects comply with existing environmental regulations while advocating for supportive policies that encourage innovation and investment in this technology.

In summary, the managerial implications of the research on MFCs emphasize the importance of strategic investment, interdisciplinary collaboration, cost reduction, and market education in promoting MFC technology [32, 34]. By addressing these implications, managers can effectively navigate the challenges associated with MFC development and leverage its potential for sustainable energy production and wastewater treatment, ultimately contributing to environmental sustainability and corporate success.

8 Limitations

The present research presents valuable insights into MFCs, yet it also has several limitations that could affect the comprehensiveness and applicability of its findings.

While the review aims to provide a comprehensive overview of MFC technology, it may be limited by the scope of the literature included [24]. If certain studies, particularly recent or emerging research, were overlooked, the review could miss important advancements or contrasting viewpoints that could enrich the discussion on MFCs.

As a review article, it primarily synthesizes existing research rather than presenting new experimental data or findings [15, 46]. This reliance on previously published studies may limit the ability to assess the real-world performance of MFCs comprehensively. The absence of novel experimental results could restrict the practical implications drawn from the review.

MFCs can be configured in various designs and used for multiple applications, from wastewater treatment to renewable energy generation [9, 16]. The review may not address the full spectrum of MFC designs or the specific challenges associated with each configuration, potentially leading to generalizations that do not apply universally across different contexts.

While theoretical implications are important for guiding future research, an overemphasis on theoretical aspects without adequate discussion of practical applications and limitations can limit the review's utility for practitioners [24, 25]. A balance between theory and practice is essential for translating research findings into actionable strategies.

Although the review acknowledges cost challenges related to MFC technology, it may not provide in-depth economic analyses or cost-benefit evaluations. A more detailed exploration of economic factors, including market dynamics, financing models, and potential return on investment, would enhance the understanding of MFC feasibility in commercial settings [39].

The review may not sufficiently address the regulatory landscape governing the deployment of MFC technology, which can vary significantly by region and application [16, 29]. Additionally, it might overlook market trends and competitive technologies that could impact the adoption and commercialization of MFCs.

While the review discusses sustainability, it may lack a comprehensive evaluation of the environmental impacts of MFC technology compared to other renewable energy solutions [18, 32]. A thorough analysis of life cycle assessments (LCAs) and sustainability metrics would provide a more complete picture of the ecological benefits and trade-offs associated with MFCs.

The review discusses the potential for MFCs but may not adequately address concerns related to their long-term performance, scalability, and operational stability. Insights into how MFCs perform under varying conditions over extended periods would be crucial for understanding their practical applications and limitations. In conclusion, while the research offers valuable insights into MFC technology, it is limited by the scope of literature reviewed, a lack of experimental data, and a focus on theoretical implications [8, 41]. Addressing these limitations could enhance the depth and applicability of the findings, providing a more comprehensive understanding of the potential and challenges associated with MFCs.

9 Conclusion

MFCs stand at the forefront of innovative technologies that blend renewable energy production with effective wastewater treatment solutions. The fundamental principle behind MFCs lies in their ability to harness the metabolic processes of microorganisms to convert organic matter into electrical energy, presenting a dual advantage: generating clean energy while simultaneously addressing pollution. This technology is particularly promising for its potential to contribute to sustainable energy systems, but several significant challenges must be addressed to fully realize its capabilities.

One of the primary hurdles MFCs face is the optimization of power output. While these systems can generate electricity from organic substrates, their current power densities are generally lower than those of traditional energy sources, such as fossil fuels or even other renewable technologies like solar and wind. To enhance power output, ongoing research focuses on improving microbial communities through genetic engineering, which aims to cultivate or modify microorganisms that can optimize electron transfer and increase energy yield. Additionally, developing hybrid systems that integrate MFCs with other energy generation methods could help augment overall output, making MFCs more competitive in the renewable energy market.

Cost is another critical factor hindering the widespread adoption of MFCs. The materials required for constructing MFCs—such as electrodes, PEMs, and specialized biocatalysts—often come with high price tags. To mitigate these costs, researchers are exploring alternative, more economical materials without compromising performance. Innovations in nanotechnology and material science may lead to the discovery of cost-effective substitutes that still provide high conductivity and durability. Furthermore, improvements in manufacturing processes and economies of scale could lower the price of MFC systems, making them more accessible for commercial applications.

Despite these challenges, the potential for sustainable energy generation through MFCs is significant. The ability to utilize organic waste materials—such as agricultural by-products, sewage, and other forms of wastewater—means that MFCs can play a vital role in a circular economy. By converting waste into energy, they not only reduce environmental pollution but also contribute to energy production, aligning with global goals for sustainability and renewable energy development. This characteristic makes MFCs particularly appealing for industries and municipalities looking to decrease their environmental footprint while simultaneously generating energy.

To facilitate the transition from laboratory research to commercial-scale applications, continued investment in research and development is essential. This includes a focus on microbial engineering to enhance the capabilities of the microorganisms involved, as well as rigorous system optimization to improve efficiency and reliability. Advances in understanding microbial ecology and interactions within MFCs could also lead to more robust systems that can perform well under varied operational conditions.

In summary, while MFCs currently face challenges related to power output and cost, their potential as a sustainable energy solution is substantial. With continued research into microbial engineering, system optimization, and the development of advanced materials, MFCs could emerge as a viable component of future energy systems. By bridging the gap between energy production and waste management, MFC technology may not only contribute to cleaner energy generation but also promote a more sustainable and circular approach to resource utilization.

Author Contributions

Conceptualization, S.S.G.; methodology, S.M.; validation, S.S.G. and S.M.; formal analysis, S.M.; investigation, S.S.G.; resources, S.M.; data curation, S.M.; writing—original draft preparation, S.M.; writing—review and editing, S.S.G.; visualization, S.S.G.; supervision, S.S.G. All authors have read and agreed to the published version of the manuscript.

Data Availability

Not applicable.

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Conflicts of Interest

The authors declare no conflict of interest.

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