International Journal of Tropical Agriculture
Volume 42, Numbers (1) • 2024 : pp. 105-114
ISSN: 0254-8755

Green Energy from Wastewater: Advancements in Microbial Fuel Cell Technology

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Abstract: Microbial Fuel Cells (MFCs) are emerging as a promising technology for wastewater treatment and green bioelectricity generation. Recent advancements in MFC technology have led to significant improvements in their structural architecture, integration with novel biocatalysts, and optimization of electrode materials. Despite encountering challenges such as high costs, limited treatment efficiency, and maintenance requirements, MFCs are increasingly recognized as effective solutions for integrating bioenergy production with wastewater treatment processes.The ecological advantages of MFCs, coupled with the utilization of cellulosic materials to enhance power output, highlight their growing potential for sustainable power generation. Moreover, advancements in power densities, contaminant removal capabilities, and CO_2-free electricity generation underscore the increasing feasibility of MFCs for diverse applications.Despite facing limitations, including the cost and efficiency of treatment, electrode performance, power density, and high maintenance expenditure, MFCs are widely acknowledged as a promising solution for integrating bioenergy production and wastewater treatment. The use of MFC technologies offers ecologically favorable techniques for wastewater treatment and energy production. Furthermore, enhancements in power densities, chemical oxygen demand (COD) removal, pollutant degradation, and the growing demand for electricity generation without CO_2 emissions indicate that MFCs are increasingly practical for power production. Therefore, it can be concluded that MFCs may be commercialized in large-scale industries by enhancing power density and overall efficacy while reducing resource budgets. The ongoing advancements in MFC technology hold promise for overcoming existing challenges and expanding their applications in sustainable energy production and wastewater management. This represents a significant step towards achieving a more environmentally friendly and efficient approach to addressing the dual challenges of wastewater treatment and energy generation.

Keywords: Microorganism, Bio-energy, Microbial fuel cell (MFC), Sewage, Contamination

INTRODUCTION

In the contemporary epoch marked by technological progress, the depletion of non-renewable resources and the concomitant environmental degradation they induce stand as pivotal global concerns. The rampant exploitation of energy reservoirs has precipitated multifaceted adverse repercussions, including the release of greenhouse gases, the exacerbation of global warming, and profound disruptions to the climate system. The dependency and the negative environmental impacts of fossil fuels for energy consumption have prompted the urgent requirement to focus on the development of alternate technologies and sources that could prove advantageous in meeting energy demands together with environmental protection. Along with this energy deficit, the treatment of wastewater containing contaminants is also one of the rising issues from many in most parts of the world(1). A significant portion of the overall

Article History: Received: 24 February 2024; Revised: 07 March 2024; Accepted: 09 March 2024; Published: 25 March 2024

energy consumed by the wastewater treatment industry has been recognized as a renewable asset, offering a potential avenue to tackle both energy generation and treatment challenges alongside the reclamation of valuable nutrients (2). Accomplishing the need to treat wastewater and generate energy, microbial fuel cells (MFCs) are one of the recent techniques that could be utilized. Microbial Fuel Cells (MFCs) efficiently harness chemical energy from municipal and industrial wastewaters, generating electrical power by employing electroactive bacteria (EAB) (3). These bacteria facilitate substrate oxidation and oxidant reduction reactions, thereby aiding energy production and reducing wastewater treatment expenses. Domestic wastewater, for instance, contains approximately 13 kJ/g of chemical oxygen demand (COD), which is nine times more than the energy needed for its treatment (4). Thus, if the energy included in wastewater could be efficiently retrieved, then this could lead to no external energy input requirement for operating wastewater treatment plants (WWTPs) (5).However, if a fraction of the energy could be retrieved, then it could benefit in the reduction of economic costs of wastewater treatment. MFCs' performance can also be increased by managing operational parameters, i.e., the organic loading rate (OLR), hydraulic retention time (HRT), pH, and applied electric resistance (6). Despite advancements in mathematical modelling and design management, there remains a gap in understanding the operational intricacies of Microbial Fuel Cells (MFCs) (2, 3 and 6). Commercialization of MFCs is hindered by several challenges, such as limited efficiency and high operational and maintenance costs. Practical implementation across various domains is constrained by system instabilities, scaling limitations, competitive microbial reactions, and restricted power generation (7). The application of MFCs in wastewater treatment is still obscured at various junctures and warrants further investigation. For example, the advances realized at a low scale have been not translated to a larger scale, suggesting that an additional understanding of the progress is still mandatory (8 and 9). Rapid advancements in MFC research have resulted in the publication of various illuminating reviews on organic biomass resources, the assessment of various configurations, specialized themes such as resource recovery, robustness, and repeatability, and waste-to energy transformation using MFC technologies. The present article focuses on the various types, processes, applications, challenges, recent advances, and futuristic aspects of wastewater treatment-related MFCs are provided.

CHARACTERISTICS OF MFCS

Microbial Fuel Cells (MFCs) stand at the forefront of innovative technologies, offering a groundbreaking approach to both wastewater treatment and renewable energy production. By harnessing the metabolic activity of microorganisms, MFCs can simultaneously treat wastewater and generate electricity through electrochemical processes. This unique capability has sparked widespread interest and research into the potential applications and advancements of MFC technology (10).

1. Energy Generation: MFCs convert organic matter in wastewater into electrical energy through microbial processes.
2. Sustainable: MFCs utilize renewable resources, such as organic waste, for energy production, promoting sustainability.
3. Wastewater Treatment: MFCs simultaneously treat wastewater by removing organic pollutants, pathogens, and nutrients, contributing to environmental remediation.
4. Versatility: MFCs can be applied in various settings, including municipal wastewater treatment plants, industrial facilities, and remote locations, providing flexible solutions for energy and wastewater management.
5. Scalability: MFC technology is adaptable to different scales, from laboratory prototypes to large-scale applications, enabling widespread implementation.
6. Potential for Integration: MFCs can be integrated with existing wastewater

treatment systems or renewable energy infrastructure, enhancing overall efficiency and resource utilization.

7. Research and Development: Ongoing research aims to improve MFC performance, increase energy output, and address operational challenges, driving innovation in renewable energy and environmental technology.

TYPES OF MFCS

Microbial Fuel Cells (MFCs) can be categorized into several types based on their design, configuration, and operational characteristics (11). Some common types include:

1. *Single-chamber MFCs*: These MFCs consist of a single chamber containing both the anode (where oxidation occurs) and the cathode (where reduction occurs), separated by a proton exchange membrane (PEM) or a non-conductive separator.

Advantages

- Simpler design and construction.
- Lower internal resistance, leading to higher power densities.

Disadvantages

- Limited separation between anode and cathode may result in lower efficiency due to crossover of reactants.
- Potential for pH imbalance and substrate inhibition near the electrodes.

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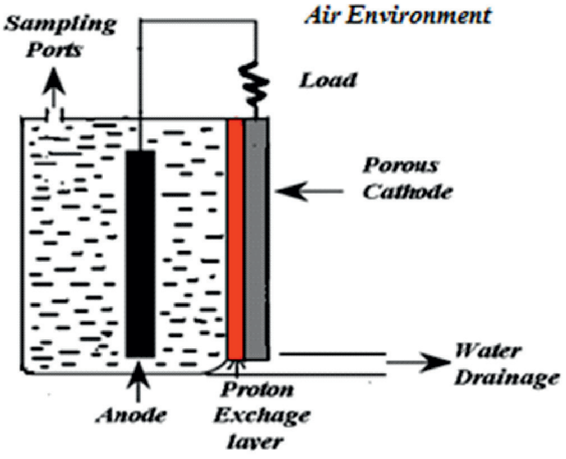

Figure 1. Single-chamber MFC (Aziz *et al.*, 2013)

2. *Double-chamber MFCs*: In this configuration, the anode and cathode are placed in separate chambers, connected by an external circuit and a salt bridge or membrane to facilitate ion transport.

Advantages

- Enhanced control over reaction conditions, such as pH and substrate concentration, leading to improved performance.
- Reduced crossover of reactants, enhancing efficiency.

Disadvantages

- More complex design and assembly compared to single-chamber MFCs.
- Requires additional components (membrane, salt bridge), increasing cost and maintenance requirements.

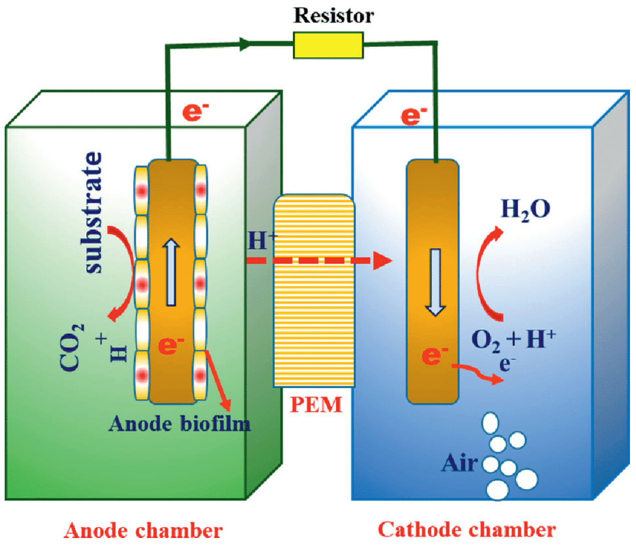

Figure 2: Double chamber MFC (Rahmani *et al.*, 2020)

3. *Stacked MFCs*: Multiple MFC units are connected in series or parallel to increase power output or treat larger volumes of wastewater.

Advantages

- Increased power output and treatment capacity by connecting multiple MFC units.
- Modular design allows for scalability and flexibility in application.

Disadvantages

- Higher initial investment and operational costs due to the need for multiple units and additional infrastructure.
- Challenges in maintaining uniform conditions across stacked units, such as substrate availability and microbial activity.

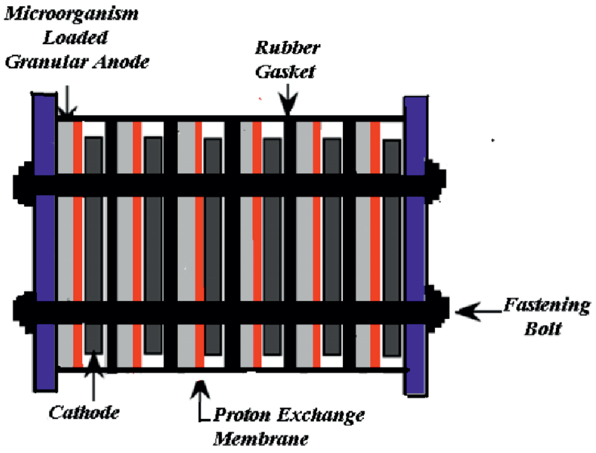

Figure 3. Stacked MFC (Shaikh *et al,.* **2016)**

4. *Air-breathing MFCs*: These MFCs use oxygen from the air as the electron acceptor at the cathode, eliminating the need for a liquid catholyte and simplifying the system design.

Advantages

- Simplified design and operation by eliminating the need for a liquid catholyte.
- Reduced system complexity and maintenance requirements.

Disadvantages

- Limited by oxygen availability in the air, which may constrain power output, especially in anaerobic environments.
- Potential for oxygen crossover to the anode, leading to decreased performance.

5. Flow-through MFCs: Wastewater continuously flows through the MFC system, enhancing mass transfer and improving treatment efficiency.

Advantages

- Continuous flow of wastewater promotes efficient substrate utilization and mass transfer.
- Enhanced treatment efficiency and power generation compared to batch systems.

Disadvantages

- Higher hydraulic resistance and pressure drop may require additional pumping energy.
- Increased risk of clogging and fouling, necessitating regular maintenance and cleaning.

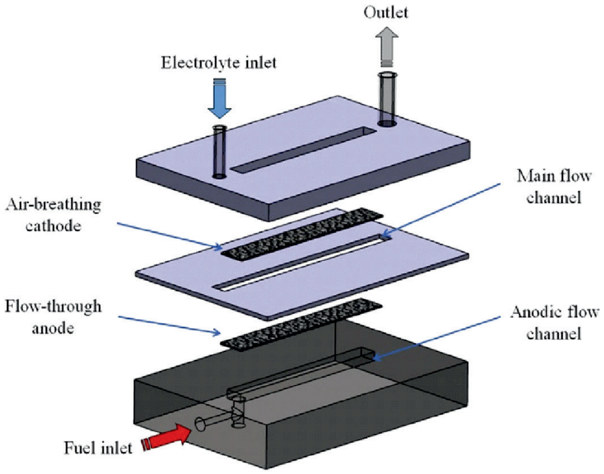

Figure 4: Air breathing MFC (Zhang *et al.***, 2014)**

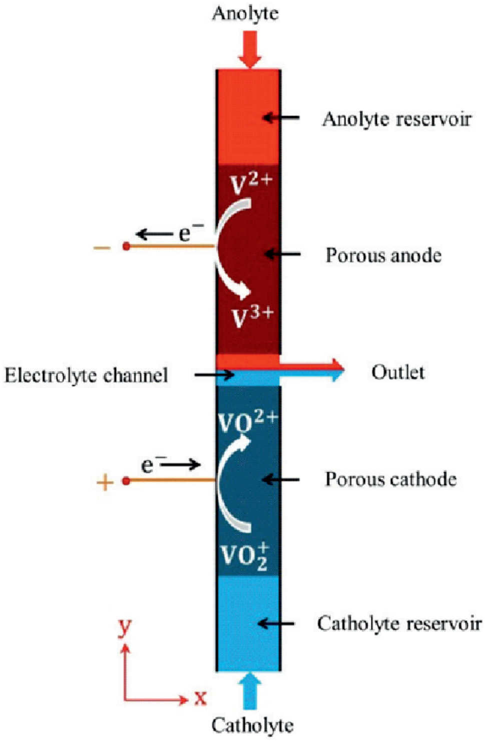

Figure 5: Flow through MFC (Li *et al.***, 2022)**

6. *Microfluidic MFCs*: These MFCs utilize microfluidic channels to improve mass transport and enhance the interaction between microorganisms and substrates, leading to higher power densities.

Advantages

- Precise control over fluid flow and mixing, improving mass transport and reaction kinetics.
- Compact size and high surface area-to-volume ratio, leading to higher power densities.

Disadvantages

- Complex fabrication and integration processes, limiting scalability and mass production.
- Susceptibility to biofilm formation and channel fouling, affecting long-term performance and stability.

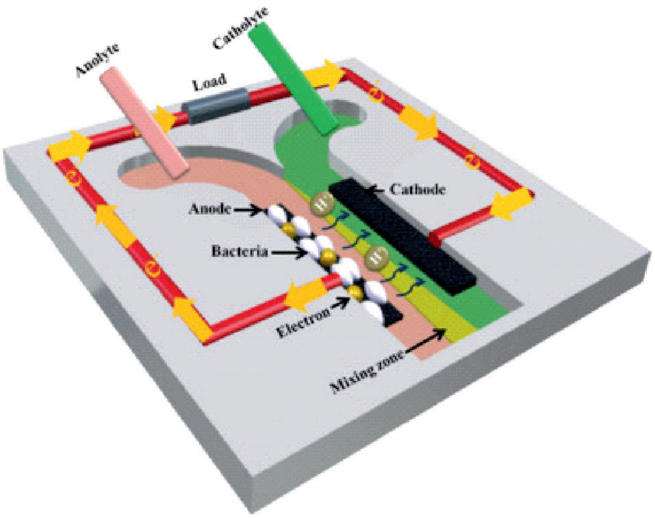

Figure 6: Microfluid MFC (Yang *et al*,.2016)

7. *Sediment-based MFCs*: Electrodes are embedded in sediment or soil, allowing for the direct extraction of energy from organic matter present in the environment.

Advantages

- Direct extraction of energy from organic matter in sediment or soil, eliminating the need for external substrates.
- Natural microbial communities present in sediment contribute to stable and resilient operation.

Disadvantages

- Limited by the availability and accessibility of suitable sediment or soil environments.
- Challenges in maintaining consistent performance over time due to fluctuations in environmental conditions and microbial activity.

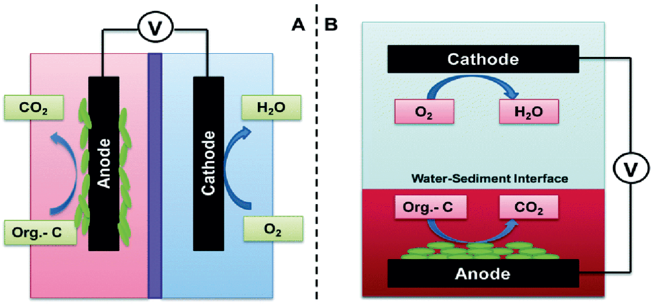

Figure 7: Sediment based MFC (Xu *et al*., 2015)

APPLICATIONS OF MFC

Microbial Fuel Cells (MFCs) boast a wide array of applications across various fields due to their unique ability to simultaneously treat wastewater and generate electricity (12). Some notable applications of MFCs include:

- Wastewater Treatment Plants: MFCs can be integrated into conventional wastewater treatment systems to enhance organic matter removal and energy recovery. By harnessing the microbial activity inherent in wastewater, MFCs offer a sustainable and cost-effective solution for treating municipal and industrial wastewater.
- Remote and Off-Grid Locations: In areas lacking access to centralized electricity and wastewater infrastructure, MFCs provide a decentralized solution for both wastewater treatment and power generation. They can be deployed in remote communities, military outposts, or disaster relief operations to meet basic sanitation needs while producing renewable energy.
- Environmental Monitoring: MFCs can be utilized as biosensors for environmental monitoring applications. By monitoring

changes in electrical output or microbial activity within the MFC, researchers can detect and quantify the presence of pollutants or contaminants in water bodies, soil, or air.

- Bioremediation: MFCs offer a promising approach for bioremediation of contaminated environments. By leveraging the metabolic capabilities of microorganisms, MFCs can facilitate the degradation of organic pollutants, heavy metals, and other contaminants present in soil or groundwater, leading to environmental cleanup.
- Sustainable Agriculture: MFCs can be incorporated into agricultural practices to treat agricultural runoff and livestock wastewater while generating renewable energy. This application helps mitigate pollution from agricultural activities and provides farmers with an alternative energy source for powering farm operations.
- Desalination: MFCs have been explored as a potential energy-efficient method for desalinating brackish water or seawater. By harnessing the energy produced during wastewater treatment, MFC-based desalination systems offer a sustainable approach to freshwater production in water-scarce regions.

WORKING OF MFC IN WASTEWATER TREATMENT

Microbial Fuel Cells (MFCs) represent a groundbreaking technology at the intersection of renewable energy generation and wastewater treatment. At the heart of an MFC lies a sophisticated yet natural process driven by microorganisms. When wastewater enters the anode compartment of the MFC, it encounters a diverse community of microorganisms (12). These microorganisms, particularly bacteria, engage in the biochemical breakdown of organic compounds present in the wastewater as part of their metabolic processes. This breakdown process, known as oxidation, releases electrons and protons as metabolic by-products. These liberated electrons are the key to the MFC's operation (14). They flow from the anode through an external circuit to the cathode, creating an electric current. Simultaneously, protons migrate through the membrane separator, maintaining the electrochemical balance within the cell (15). This flow of electrons not only generates electrical power but also serves as a means to facilitate the removal of electrons from the anode compartment, allowing the microbial community to continue its metabolic processes. On the cathode side, a separate reaction occurs. Electrons arriving from the external circuit combine with oxygen and protons, usually sourced (fig 8) from the catholyte solution or the wastewater itself. This reduction reaction results in the formation of water molecules, effectively closing the electrochemical circuit (16). The synergistic processes of organic oxidation at the anode and reduction at the cathode yield two significant outcomes. Firstly, the organic pollutants present in the wastewater are broken down into simpler, less harmful compounds. This contributes to a reduction in the chemical oxygen demand (COD) and biochemical oxygen demand (BOD) of the wastewater, thus improving its quality (14). Secondly, electrical power is generated, providing a sustainable and renewable energy source. While MFCs offer immense potential for sustainable wastewater treatment and energy generation, several challenges remain (15 and 16). These include optimizing MFC performance, enhancing energy efficiency, and addressing scalability issues for broader implementation. Nonetheless, the intricate interplay between microbial metabolism and electrochemical processes in MFCs (17) holds promise for revolutionizing the way we approach both wastewater management and renewable energy production.

FACTORS AFFECTING IN WORKING OF MFCS

Several factors influence the performance of Microbial Fuel Cells (MFCs). Firstly, the composition of the substrate, which refers to the organic matter present in the wastewater, directly impacts microbial activity and energy generation within the MFC. Additionally, the diversity and composition of the microbial

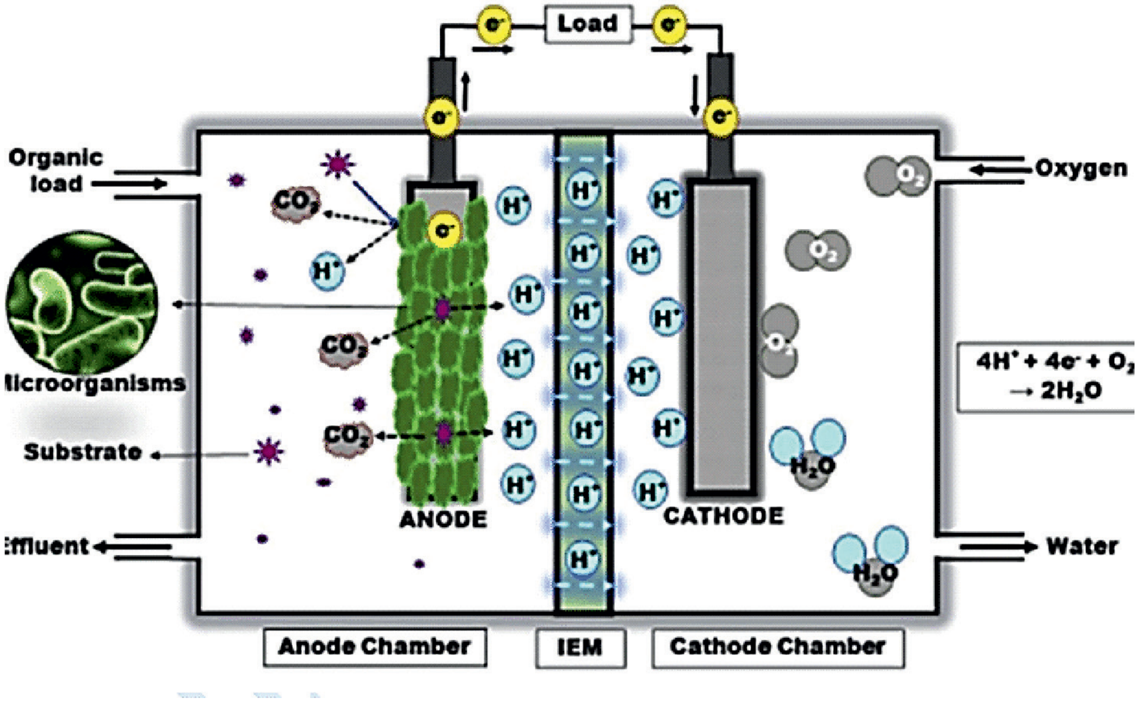

Figure 8: Schematic Diagram of MFC's (Ahmed *et al,* 2022)

community colonizing the anode play a crucial role in substrate oxidation and electron transfer processes. The choice of electrode material also significantly affects electron transfer kinetics and overall MFC efficiency. Moreover, environmental factors such as temperature and pH influence microbial metabolism and electrochemical reactions within the MFC. The hydraulic retention time (HRT), or the duration of contact between wastewater and the microbial biofilm, also impacts substrate utilization and treatment efficiency (8 and 12). Furthermore, the composition of the electrolyte, membrane properties, external resistance, and system configuration, including reactor design and electrode spacing, all contribute to the overall performance of MFCs by influencing mass transport, ion migration, and internal electrochemical reactions (18). Optimization of these factors is essential for enhancing MFC efficiency and applicability in various environmental and energy-related applications.

PRODUCT RECOVERY FORM WASTEWATER USING MFCS

Microbial Fuel Cells (MFCs) offer a promising platform for recovering various products from wastewater due to their ability to simultaneously treat wastewater while generating electricity. One key product that can be recovered from wastewater using MFCs is bioelectricity, which is produced through the microbial oxidation of organic matter at the anode. This electricity can be harnessed for powering electronic devices, sensors, or even contributing to the grid. Additionally, MFCs can facilitate the recovery of valuable resources such as metals and nutrients (19). Through electrochemical reactions at the electrodes, MFCs can capture and concentrate metals present in wastewater, enabling their recovery for reuse or recycling. Similarly, MFCs can promote the recovery of nutrients such as nitrogen and phosphorus, which are essential for agricultural fertilizers (20). By leveraging the metabolic activity of microorganisms, MFCs can facilitate the conversion of these nutrients into forms that are easier to recover and reuse. Furthermore, MFCs have been explored for the production of value-added products such as hydrogen gas and organic acids through microbial fermentation processes occurring in the anode chamber (21). Overall, the versatility of MFCs in recovering multiple products from wastewater underscores their potential as sustainable and resource-efficient technology for wastewater treatment and resource recovery.

RECENT ADVANCEMENTS IN MFC

Microbial Fuel Cells (MFCs) are a promising technology for both renewable energy production and wastewater treatment, but their widespread use is limited by certain drawbacks. Recent research has focused on addressing these limitations by exploring novel materials, particularly nanomaterials, for key components such as electrodes and separators. Nanostructured materials offer enhanced properties such as high surface area, improved conductivity, and cost-effectiveness, making them attractive for MFC applications (21). Various types of nanomaterials have been investigated for their potential in improving MFC performance. Metal nanoparticles, including copper, gold, platinum, and palladium, as well as metal oxides like CeO2, TiO2, ZnO, SiO2, and MnO2, have shown promise for electrode applications due to their catalytic activity and conductivity (22). Graphene, a two-dimensional nanomaterial, stands out for its exceptional properties such as high surface area and electrical conductivity, making it an ideal candidate for MFC electrodes. Carbon nanotubes (CNTs) have also garnered significant interest for their unique properties, including high mechanical strength, large specific surface area, and excellent conductivity. Integration of multi-walled carbon nanotubes (MWCNTs) into MFC electrodes has demonstrated improvements in power generation and stability. Moreover, modifications such as layer-by-layer self-assembly have been employed to enhance electrode performance, resulting in lower internal resistance and increased power density (21 and 22). Recent studies have shown promising results with graphene-modified stainless steel mesh anodes achieving power densities exceeding 2000 mW/m^2. Additionally, modifications with MWCNTs have led to significant improvements in power generation and stability, with power densities of up to 560.4 mW/m^2 observed using MWCNT-COOH modified anodes (23). Overall, advancements in nanomaterial-based electrode materials offer a pathway to overcome the limitations of MFC technology and improve its efficiency and viability for wastewater treatment and energy production. As research continues, further optimization and development of nanomaterial-based MFCs hold the potential to revolutionize sustainable energy and wastewater management practices.

LIMITATIONS AND OPPORTUNITIES OF MFC TECHNOLOGY

Microbial Fuel Cells (MFCs) exhibit considerable promise for sustainable energy production and wastewater treatment, yet they confront several challenges that impede their widespread application. Chief among these challenges is the relatively low power density often observed in MFCs, limiting their practical viability for large-scale energy generation. Additionally, the cost of MFC components, particularly electrodes and membranes, remains a barrier to widespread adoption. Durability and stability issues, such as biofouling and electrode degradation, pose further obstacles to long-term MFC performance (18). Scaling up MFCs from laboratory-scale prototypes to commercial-scale systems presents engineering and logistical hurdles, including challenges in maintaining uniform conditions and optimizing mass transfer (20 and 22). Moreover, the inherent complexity of MFC systems requires comprehensive understanding and management to ensure efficient operation. Despite these challenges, ongoing research and development efforts offer promising future prospects for MFC technology. Advances in materials science, including the exploration of nanomaterials for electrode and membrane fabrication, hold the potential to address many of the existing challenges and enhance MFC performance (24). Furthermore, innovations in system design, process optimization, and integration with complementary technologies may further improve the efficiency, reliability, and scalability of MFCs (25), paving the way for their broader adoption in renewable energy production and wastewater treatment applications.

SUMMARY AND CONCLUSION

Microbial Fuel Cells (MFCs) demonstrate significant potential in both wastewater treatment and green bioelectricity generation. Recent advancements in MFC technology have addressed various aspects, including structural architecture improvements, novel biocatalyst integration, and optimization of electrode materials. Despite challenges such as cost, treatment efficiency, and maintenance requirements, MFCs are recognized as effective solutions for combining bioenergy production with wastewater treatment. Their ecological benefits, coupled with the utilization of cellulosic materials to enhance power output, underscore their growing practicality for power generation. Moreover, improvements in power densities, contaminant removal, and CO2-free electricity generation highlight the increasing feasibility of MFCs for various applications. Finally, with enhancements in power density and overall efficacy, coupled with resource budget reductions, MFCs hold promise for commercialization in large-scale industries, marking a significant achievement in sustainable energy production and wastewater management.

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