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Energy Recovery Applications of Microbial Fuel Cells in Wastewater Treatment

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Abstract Microbial fuel cell (MFC) is a potential technology that combines pollution reduction and renewable energy generation in wastewater treatment. Microbial fuel cell (MFC) technology, as an innovative solution for achieving pollutant degradation and renewable energy production in wastewater treatment, has received widespread attention in recent years. This study explores the principles, mechanisms, and applications of MFC in wastewater treatment. Through case studies of industrial wastewater, the practical application and energy recovery potential of MFC are demonstrated, and its performance is compared with traditional methods. By optimizing and promoting MFC technology, this study expects to improve the energy efficiency of wastewater treatment, achieve environmental sustainability, and provide policy support recommendations.

Keywords Microbial fuel cells; Wastewater treatment; Energy recovery; Bioelectrochemical pathways; Environmental sustainability

1 Introduction

Microbial Fuel Cells (MFCs) represent an innovative bio-electrochemical system that leverages the metabolic processes of microorganisms to convert organic substrates directly into electrical energy. This technology has garnered significant attention due to its dual capability of treating wastewater while simultaneously generating electricity. MFCs operate by utilizing electroactive bacteria that oxidize organic matter in the anode chamber, releasing electrons and protons. The electrons travel through an external circuit to the cathode, generating an electric current, while the protons migrate through a proton exchange membrane to combine with oxygen at the cathode, forming water (Pant et al., 2010; Zhao et al., 2021). The versatility of MFCs allows them to treat various types of wastewater, including domestic, municipal, agricultural, and industrial effluents, making them a promising solution for sustainable energy production and environmental remediation (Liu et al., 2013; Zhang et al., 2019).

Wastewater treatment is traditionally an energy-intensive process, often requiring substantial amounts of electricity for aeration, pumping, and other operations. The integration of energy recovery systems, such as MFCs, into wastewater treatment processes can significantly reduce the overall energy footprint and operational costs. By converting the chemical energy stored in organic pollutants into electrical energy, MFCs not only enhance the efficiency of wastewater treatment but also contribute to renewable energy generation. This dual benefit is particularly crucial in the context of increasing energy demands and the need for sustainable waste management practices (Du et al., 2007; Munoz-Cupa et al., 2021). Moreover, the ability of MFCs to recover valuable resources, such as nitrogen and phosphorus, further underscores their potential in creating a circular economy within the wastewater treatment sector (Srikanth et al., 2016).

The study is to provide a comprehensive review of the current state of MFC technology, with a particular focus on its applications in energy recovery during wastewater treatment. This includes an analysis of the various configurations and operational conditions that influence MFC performance, the types of substrates used, and the challenges and opportunities associated with scaling up this technology for real-world applications. By synthesizing findings from recent studies, this study aims to highlight the advancements made in MFC research and enhance the efficiency and feasibility of MFCs in sustainable wastewater treatment and energy recovery.

2 Principles of Microbial Fuel Cells

2.1 Detailed explanation of the working mechanism of MFCs

The working mechanism of MFCs begins with the microbial oxidation of organic substrates at the anode. Electroactive bacteria, such as Geobacter and Shewanella species, metabolize the organic matter, releasing electrons and protons. The anode, typically made of conductive materials like carbon cloth or graphite, collects the electrons and channels them through an external circuit to the cathode, creating an electric current. The protons generated at the anode migrate through a proton exchange membrane to the cathode. At the cathode, a reduction reaction occurs, where the electrons, protons, and an electron acceptor (usually oxygen) combine to form water. This process not only generates electricity but also aids in the degradation of organic pollutants in wastewater (Srikanth et al., 2016; Kumar et al., 2019).

2.2 Key components: anode, cathode, and microbial catalysts

The key components of MFCs include the anode, cathode, and microbial catalysts. The anode is where the oxidation of organic matter occurs, facilitated by electroactive bacteria. Materials commonly used for anodes include carbon-based materials such as graphite, carbon cloth, and carbon paper, which provide a large surface area for microbial colonization and electron transfer. The cathode is the site of the reduction reaction and is typically made of materials like platinum or nitrogen-doped graphene, which serve as catalysts for the oxygen reduction reaction. The microbial catalysts, or electroactive bacteria, play a crucial role in the MFC process by oxidizing the organic substrates and transferring the electrons to the anode. These bacteria can form biofilms on the anode surface, enhancing the efficiency of electron transfer (Liu et al., 2013; Moqsud et al., 2013).

2.3 Types of MFCs used in wastewater treatment

Several types of MFCs have been developed for wastewater treatment, each with unique configurations and operational modes. Single-chamber MFCs, which have a single compartment for both the anode and cathode, are simple and cost-effective but may suffer from oxygen diffusion to the anode. Dual-chamber MFCs, with separate anode and cathode compartments connected by a proton exchange membrane, offer better control over the electrochemical environment but are more complex and expensive. Tubular MFCs, which use a cylindrical design, provide high scalability and are suitable for continuous flow operations. Integrated systems, such as the combined microbial fuel cell-membrane bioreactor (MFC-MBR) and photoelectrocatalytic microbial fuel cell (PEC-MFC), enhance wastewater treatment efficiency and energy recovery by combining MFCs with other treatment technologies (Zhang et al., 2019; Zhao et al., 2021).

3 Wastewater Treatment with MFCs

3.1 Specific pollutants and contaminants targeted by MFCs

Microbial Fuel Cells (MFCs) have emerged as a promising technology for wastewater treatment, targeting a variety of specific pollutants and contaminants. MFCs have been effectively used to degrade emerging contaminants (ECs) such as dyes, pharmaceuticals, and pesticides, which are often bio-refractory and pose significant environmental risks (Sathe et al., 2021). Additionally, MFCs have shown efficacy in treating petroleum refinery wastewater, which contains high levels of chemical oxygen demand (COD), ammonium nitrogen (NH_4^+-N), and total nitrogen (TN) (Zhao et al., 2021). Other specific pollutants targeted by MFCs include phenol, aniline, oil, grease, and sulfide, which are commonly found in industrial effluents (Srikanth et al., 2016; Zhang et al., 2019).

3.2 Electrochemical reactions involved in pollutant degradation

The electrochemical reactions involved in pollutant degradation within MFCs are complex and multifaceted. In the anodic chamber, organic matter is oxidized by electrochemically active bacteria, releasing electrons and protons. These electrons travel through an external circuit to the cathode, generating electricity, while the protons migrate through a proton exchange membrane to the cathode. In the cathodic chamber, various reduction reactions occur, such as the reduction of oxygen to water or the reduction of other electron acceptors like ferricyanide (Mohan et al., 2019). In some advanced configurations, such as the bio-electro-Fenton MFC (BEF-MFC), additional oxidizing agents like hydroxyl radicals (•OH) are generated in situ to enhance the degradation of refractory pollutants (Sathe et al., 2021).

3.3 Performance metrics: COD removal efficiency, energy output, etc.

Performance metrics for MFCs in wastewater treatment are typically evaluated based on COD removal efficiency, energy output, and other specific removal efficiencies. For instance, COD removal efficiencies as high as 96.3% have been reported in MFC systems treating petroleum refinery wastewater, with corresponding energy recoveries of up to 0.002 58 kWh/m³ (Yang et al., 2020). Similarly, combined photoelectrocatalytic MFCs (PEC-MFCs) have achieved COD removal efficiencies of 96% for phenol and 70% for aniline, while also producing significant amounts of electricity. In continuous mode operations, MFCs treating refinery wastewater have demonstrated power densities of (225±1.4) mW/m² and substrate degradation rates of (1.05±0.01) kg COD/m³-day (Srikanth et al., 2016). These metrics highlight the dual benefits of MFCs in both pollutant removal and energy recovery, making them a viable option for sustainable wastewater treatment.

4 Energy Recovery Mechanisms

4.1 Bioelectrochemical pathways for energy generation

The bioelectrochemical pathways in MFCs are driven by the metabolic activities of microorganisms that oxidize organic matter in wastewater, releasing electrons and protons. These electrons are transferred to the anode and flow through an external circuit to the cathode, generating electricity. The integration of microalgae in MFCs, forming microalgae-microbial fuel cells (mMFCs), further enhances this process by utilizing photosynthesis to convert light energy into biochemical energy, which is then converted into electricity (Kusmayadi et al., 2020). Additionally, the use of MFCs as biosensors in combined systems, such as MFC-MBR (membrane bioreactor), has shown to improve process control and energy recovery, with a maximum energy recovery of 0.002 58 kWh m^{-3}, five times higher than control systems (Zhao et al., 2021).

4.2 Optimization of electrode materials for enhanced energy recovery

The performance of MFCs is significantly influenced by the materials used for electrodes. Optimizing these materials can lead to enhanced energy recovery. For example, non-platinum (non-Pt) electrodes in a scalable MFC stack have demonstrated high power output and efficient wastewater treatment under continuous flow conditions (Zhuang et al., 2012). The choice of catholyte also plays a crucial role; ferricyanide catholytes have been shown to produce higher power outputs compared to aerated catholytes, with significant improvements in power density and current generation (Mohan et al. 2008; Mohan et al., 2009). Furthermore, the use of glass wool as a proton exchange membrane (PEM) in single-chambered MFCs has been evaluated, showing that operating conditions such as pH and organic loading rates can markedly influence power output and substrate degradation efficiency.

4.3 Role of biofilms in electron transfer processes

Biofilms, which are communities of microorganisms that adhere to the anode surface, play a critical role in the electron transfer processes in MFCs. These biofilms facilitate the transfer of electrons from the microbial cells to the anode, enhancing the overall efficiency of electricity generation. The formation and maintenance of biofilms are influenced by various factors, including the nature of the substrate and the operating conditions. Studies have shown that biofilms can significantly improve the performance of MFCs by increasing the rate of electron transfer and reducing internal resistance (Srikanth et al., 2016; Zhang et al., 2019). Additionally, the microbial community within the biofilm, including nitrifiers and denitrificans, contributes to simultaneous pollutant degradation and power recovery, as observed in air-cathode MFCs treating low C/N ratio wastewater (Yang et al., 2021).

5 Technological Advancements

5.1 Innovations in MFC design for improved efficiency

Recent advancements in microbial fuel cell (MFC) technology have focused on optimizing various parameters to enhance efficiency and power output. Innovations include optimizing reactor configurations, electrode construction, and the addition of redox-active mediators to improve electron transfer processes (Li et al., 2018). Additionally, the integration of anaerobic acidification and forward osmosis membranes into MFCs has shown promise in enhancing bio-electricity and water recovery from low-strength wastewater, achieving a maximum power density of 4.38 W/m³ (Liu et al., 2017). The development of hybrid systems, such as the combination of MFCs with membrane bioreactors (MBRs), has also been explored to mitigate membrane fouling and improve overall system performance (Wang et al., 2016; Zhao et al., 2021). These advancements have significantly contributed to the feasibility of MFCs for practical applications in wastewater treatment and energy recovery.

5.2 Integration of MFCs with existing wastewater treatment infrastructure

The integration of MFCs with existing wastewater treatment processes has been a key area of research to enhance treatment efficiency and energy recovery. Hybrid systems combining MFCs with anaerobic treatment processes (AnTPs) and MBRs have shown synergistic effects, improving energy conversion efficiency and reducing membrane fouling. For instance, a two-stage MFC-MBR system demonstrated improved chemical oxygen demand (COD) removal and reduced transmembrane pressure (Figure 1), highlighting the potential of MFCs as biosensors for process control. Additionally, the integration of MFCs with forward osmosis membranes has been explored to enhance bio-electricity production and water recovery, further demonstrating the versatility of MFCs in various treatment configurations (Liu et al., 2017). These integrated systems not only improve wastewater treatment efficiency but also contribute to sustainable energy recovery, making them a viable option for modern wastewater treatment facilities.

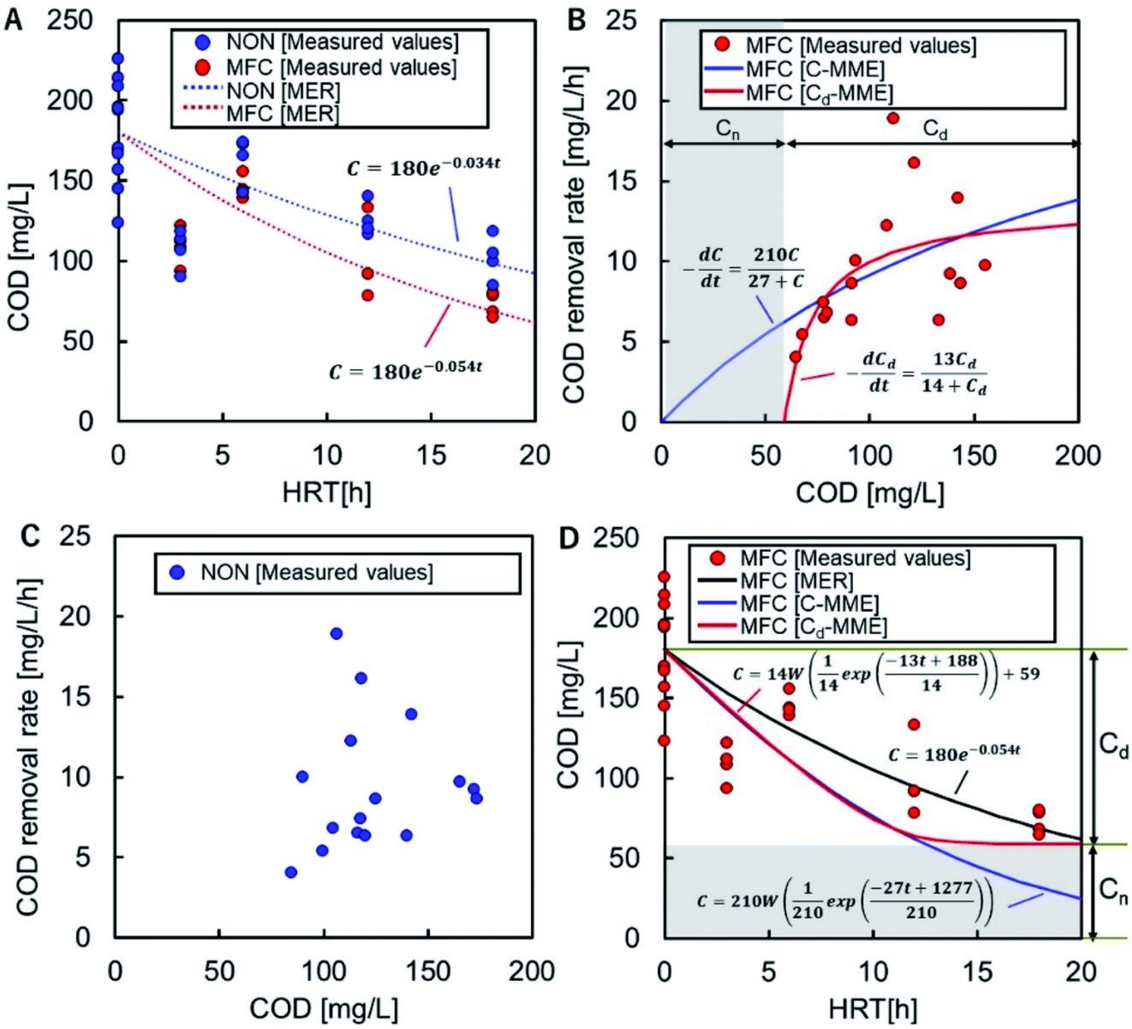

Figure 1 Calculation of COD removal based on single exponential regression (MER) and Michaelis-Menten equation (Adopted from Yamane et al., 2021)

Image caption: Caption: Figure (A) compares the COD reductions for MFC and non-reactors calculated using MER. The CRR in the MFC reactor is shown in Figure (B), the CRR in the non-reactor is shown in Figure (C), and Figure D shows three different model calculations of COD in the MFC reactor under each HRT (Adopted from Yamane et al., 2021)

Yamane et al. (2021) demonstrated the chemical oxygen demand (COD) removal performance of microbial fuel cells (MFCs) at different hydraulic retention times (HRT). As can be seen from the figure, MFC has a significant effect in reducing COD, especially at lower HRT, and its removal efficiency is higher than that of non-reactor systems. Combined with single exponential regression and the Michaelis-Menten model, the COD degradation kinetics in MFC can be accurately described. Integrating MFC technology with existing wastewater treatment infrastructure can improve treatment efficiency and reduce energy consumption. MFC not only effectively removes organic matter, but also generates electricity at the same time, increasing the possibility of energy recovery for wastewater treatment, which is of great significance for improving the sustainability and economy of wastewater treatment. The potential of MFC to treat low-concentration wastewater is particularly high, helping to promote its use in a wider range of industrial applications.

5.3 Challenges and limitations in current MFC technologies

Despite the promising advancements, several challenges and limitations hinder the widespread adoption of MFC technologies. One of the primary challenges is the low power density and high costs associated with MFC systems, which limit their economic viability for large-scale applications (Ardakani and Gholikandi, 2020). Additionally, issues such as membrane fouling, substrate cross-conduction, and the need for continuous process optimization pose significant hurdles (Zhuang et al., 2012). The complexity of microbial communities and the need for precise control over environmental conditions further complicate the operation of MFCs. Moreover, the integration of MFCs with existing infrastructure requires careful consideration of system compatibility and operational parameters to ensure optimal performance (Kumar et al., 2019). Addressing these challenges through continued research and technological innovation is crucial for the successful implementation of MFCs in wastewater treatment and energy recovery applications.

6 Case Study: Energy Recovery from Industrial Wastewater Using MFCs

6.1 Description of the industrial wastewater source

The industrial wastewater used in this study was sourced from a petroleum refinery, which is known for its high chemical oxygen demand (COD) and the presence of specific contaminants such as oil, grease, phenol, and sulfide. Refinery wastewater (RW) poses a significant challenge due to its complex composition and high pollutant load, making it an ideal candidate for treatment using advanced technologies like MFCs (Zhao et al., 2021).

6.2 MFC system setup and operational parameters

The MFC system employed for this study was a dual-chamber setup operated under continuous mode. The system was designed to handle high hydraulic retention times (HRT) of 8 to 16 hours, which is crucial for effective substrate degradation and energy recovery. The MFC was equipped with non-platinum air-cathodes to reduce material costs and enhance scalability. The system was operated at two different organic loading rates (ORLs) of 1.2 and 4.9 kg COD/m³/day to evaluate its performance under varying conditions (Srikanth et al., 2016) (Figure 2).

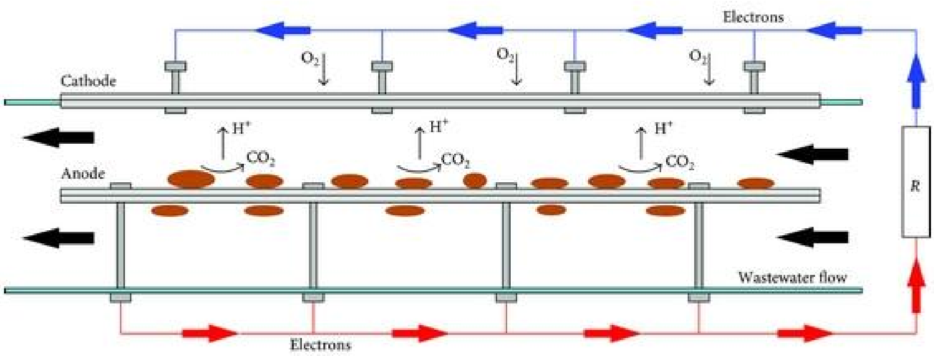

Figure 2 The working principle of the MFC prototype (Adopted from Cecconet et al., 2018)

6.3 Energy recovery results and efficiency analysis

The MFC system demonstrated impressive results in terms of both wastewater treatment and energy recovery. At an HRT of 16 hours, the system achieved a power density of (225±1.4) mW/m² and a substrate degradation rate of (84.4±0.8)%, including a (95±0.6)% reduction in oil content. The columbic efficiency was recorded at (2±0.8)%, with a projected power yield of (340±20) kWh/kg CODR/day. These results indicate that the MFC system not only effectively treated the refinery wastewater but also generated a significant amount of electricity, making it a viable option for energy recovery (Abbasi et al., 2016).

6.4 Comparison with traditional wastewater treatment methods

Traditional wastewater treatment methods, such as activated sludge processes and trickling filters, are energy-intensive and often require constant aeration and sludge management. In contrast, MFCs offer a sustainable alternative by enabling simultaneous wastewater treatment and energy recovery. The MFC system in this study achieved higher COD removal efficiencies and lower energy consumption compared to conventional methods. For instance, the MFC-MBR integrated system showed a 96.3% COD removal efficiency and a 50% reduction in transmembrane pressure, highlighting its superior performance and lower operational costs (Kumar et al., 2019; Munoz-Cupa et al., 2021).

7 Economic and Environmental Benefits

7.1 Cost analysis of implementing MFCs in wastewater treatment plants

The implementation of microbial fuel cells (MFCs) in wastewater treatment plants presents a promising avenue for cost reduction and energy recovery. Studies have shown that integrating MFCs with existing treatment processes can significantly reduce operational costs by generating electricity from organic waste, which can offset the energy requirements of the treatment process. For instance, a study on a hybrid MFC-MBR system demonstrated that the energy recovered from the MFC could be used to power the membrane bioreactor, thereby reducing the overall energy consumption of the system (Wang et al., 2016). Additionally, the use of low-cost materials in the construction of MFCs, such as non-platinum catalysts, further enhances their economic feasibility (Zhuang et al., 2012). The potential for cost savings is also evident in the reduced need for aeration and sludge management, which are major cost drivers in conventional aerobic treatment processes.

7.2 Environmental impact: reduction in greenhouse gas emissions and energy savings

The environmental benefits of MFCs are substantial, particularly in terms of reducing greenhouse gas emissions and achieving energy savings. MFCs offer a dual advantage of treating wastewater while simultaneously generating electricity, which can be used to power the treatment process or other applications. This reduces the reliance on external energy sources, thereby lowering the carbon footprint of wastewater treatment plants. For example, the integration of MFCs with anaerobic treatment processes has been shown to enhance energy recovery and reduce the overall energy consumption of the system (Ardakani and Gholikandi, 2020). Furthermore, MFCs can significantly reduce the emission of greenhouse gases by minimizing the need for energy-intensive aeration processes and by capturing methane produced during anaerobic digestion (Rahman et al., 2017; Kumar et al., 2019). The use of MFCs in treating industrial wastewater also helps in the removal of pollutants such as nitrogen and phosphorus, which can otherwise contribute to environmental degradation.

7.3 Long-term sustainability and scalability of MFC applications

The long-term sustainability and scalability of MFC applications in wastewater treatment are promising, although challenges remain. The scalability of MFCs has been demonstrated in various studies, with systems being able to treat real wastewater continuously and efficiently (Zhuang et al., 2012). The integration of MFCs with other treatment processes, such as membrane bioreactors and anaerobic digestion, has shown to improve treatment efficiency and energy recovery, making the system more sustainable in the long run (Ardakani et al., 2020). However, issues such as low power density and high initial investment costs need to be addressed to make MFCs commercially viable on a larger scale. Advances in materials science and engineering, as well as a better understanding of microbial communities, are expected to enhance the performance and reduce the costs of MFCs, paving the way for their widespread adoption in wastewater treatment plants (Kusmayadi et al., 2020). The potential for MFCs to be used as biosensors for process control further adds to their long-term sustainability by improving system performance and reducing maintenance costs.

8 Future Prospects and Research Directions

8.1 Potential for MFC technology in various types of wastewater treatment

Microbial Fuel Cell (MFC) technology holds significant promise for treating a wide array of wastewater types, ranging from domestic to industrial effluents. The versatility of MFCs in handling different substrates has been well-documented, showcasing their ability to treat complex wastewaters such as those from the agro-food industry and dairy processing, which are rich in organic matter and highly biodegradable (Cecconet et al., 2018; Kumar et al., 2019). Additionally, MFCs have demonstrated efficacy in treating low-strength wastewater by integrating with other technologies like anaerobic acidification and forward osmosis, thereby enhancing both bioelectricity and water recovery (Liu et al., 2017). The modular design of MFCs also allows for scalable solutions that can adapt to varying organic loading rates, making them suitable for diverse wastewater treatment applications (Kim et al., 2018).

8.2 Emerging trends and future research areas

Recent advancements in MFC technology have focused on improving the efficiency of energy recovery and pollutant removal through innovative designs and materials. For instance, the use of nitrogen-doped graphene as a cathode catalyst has shown to significantly enhance power generation and stability in neutral pH conditions, outperforming traditional Pt/C catalysts (Liu et al., 2013). Another emerging trend is the integration of MFCs with other treatment processes, such as constructed wetlands and forward osmosis membranes, to create hybrid systems that maximize both energy recovery and wastewater treatment efficiency (Oon et al., 2016; Liu et al., 2017). Future research should continue to explore the optimization of biocatalysts and electrode materials, as well as the development of more efficient electron transfer mechanisms to further enhance the performance of MFCs (Guo et al., 2020).

8.3 Recommendations for policy and regulatory support

To facilitate the widespread adoption of MFC technology, it is crucial to develop supportive policies and regulatory frameworks. Governments and regulatory bodies should consider providing incentives for the implementation of MFCs in wastewater treatment plants, particularly in industries with high organic waste outputs such as the agro-food sector (Cecconet et al., 2018). Additionally, funding for research and development should be increased to address the current challenges in scaling up MFC systems and improving their economic viability (Gul et al., 2021). Standardizing performance metrics and establishing guidelines for the safe and effective operation of MFCs will also be essential in promoting their integration into existing wastewater treatment infrastructures (Malik et al., 2023). By fostering a supportive regulatory environment, the potential of MFC technology to contribute to sustainable energy recovery and environmental protection can be fully realized.

9 Concluding Remarks

Microbial Fuel Cells (MFCs) have demonstrated significant potential in the field of wastewater treatment by simultaneously addressing pollution and generating electricity. Various substrates, including low-strength wastewaters and lignocellulosic biomass, have been explored for their efficacy in MFCs, showing promise for sustainable energy production despite current limitations in power yields. The integration of MFCs with other systems, such as membrane bioreactors (MBRs) and microalgae, has further enhanced their performance, leading to improved chemical oxygen demand (COD) removal and energy recovery. Additionally, advancements in electrode materials, such as nitrogen-doped graphene, have contributed to more stable and efficient power generation. The scalability of MFCs has also been demonstrated, with systems capable of treating real wastewater continuously while maintaining high pollutant removal rates.

The application of MFC technology in wastewater treatment presents a dual benefit of pollution mitigation and energy recovery, making it a highly attractive alternative to conventional methods. The ability of MFCs to treat various types of wastewater, including industrial effluents, while generating bioelectricity, positions them as a sustainable solution for resource recovery. The integration of MFCs with other treatment systems, such as MBRs and microalgae, not only enhances treatment efficiency but also offers additional benefits like CO_2 sequestration and biomass production. These advancements suggest that MFCs could significantly reduce the energy footprint of wastewater treatment plants and contribute to the circular economy by converting waste into valuable resources.

The future of MFC technology in wastewater treatment looks promising, with ongoing research focused on overcoming current limitations and enhancing performance. Continued improvements in reactor design, electrode materials, and microbial community management are expected to increase the efficiency and economic viability of MFCs. The development of hybrid systems and the integration of MFCs with existing treatment technologies will likely play a crucial role in their widespread adoption. As the technology matures, MFCs have the potential to become a cornerstone of sustainable wastewater treatment, contributing to energy recovery, pollution reduction, and resource conservation. The ongoing exploration of novel substrates and innovative configurations will further expand the applicability and effectiveness of MFCs in diverse wastewater treatment scenarios.

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Conflict of Interest Disclosure
The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References
Abbasi U., Jin W., Pervez A., Bhatti Z., Tariq M., Shaheen S., Iqbal A., and Mahmood Q., 2016, Anaerobic microbial fuel cell treating combined industrial wastewater: Correlation of electricity generation with pollutants, Bioresource Technology, 200: 1-7. https://doi.org/10.1016/j.biortech.2015.09.088

Ardakani M., and Gholikandi G., 2020, Microbial fuel cells (MFCs) in integration with anaerobic treatment processes (AnTPs) and membrane bioreactors (MBRs) for simultaneous efficient wastewater/sludge treatment and energy recovery -A state-of-the-art review, Biomass and Bioenergy, 141: 105726. https://doi.org/10.1016/j.biombioe.2020.105726

Cecconet D., Molognoni D., Callegari A., and Capodaglio A., 2018, Agro-food industry wastewater treatment with microbial fuel cells: Energetic recovery issues, International Journal of Hydrogen Energy, 43: 500-511. https://doi.org/10.1016/j.ijhydene.2017.07.231

Du Z., Li H., and Gu T., 2007, A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy, Biotechnology Advances, 25(5): 464-482. https://doi.org/10.1016/j.biotechadv.2007.05.004

Gul H., Raza W., Lee J., Azam M., Ashraf M., and Kim K., 2021, Progress in microbial fuel cell technology for wastewater treatment and energy harvesting, Chemosphere, 281: 130828. https://doi.org/10.1016/j.chemosphere.2021.130828

Guo Y., Wang J., Shinde S., Wang X., Li Y., Dai Y., Ren J., Zhang P., and Liu X., 2020, Simultaneous wastewater treatment and energy harvesting in microbial fuel cells: an update on the biocatalysts., RSC Advances, 10: 25874-25887. https://doi.org/10.1039/D0RA05234E

Kim J., Premier G., Hawkes F., Rodríguez J., Dinsdale R., and Guwy A., 2010, Modular tubular microbial fuel cells for energy recovery during sucrose wastewater treatment at low organic loading rate, Bioresource Technology, 101(4): 1190-1198. https://doi.org/10.1016/j.biortech.2009.09.023

Kumar S., Kumar V., Malyan S., Sharma J., Mathimani T., Maskarenj M., Ghosh P., and Pugazhendhi A., 2019, Microbial fuel cells (MFCs) for bioelectrochemical treatment of different wastewater streams., Fuel, 254: 115526. https://doi.org/10.1016/j.fuel.2019.05.109

Kusmayadi A., Leong Y., Yen H., Huang C., Dong C., and Chang J., 2020, Microalgae-microbial fuel cell (mMFC): an integrated process for electricity generation wastewater treatment CO2 sequestration and biomass production, International Journal of Energy Research, 44: 9254-9265. https://doi.org/10.1002/er.5531

Li M., Zhou M., Tian X., Tan C., McDaniel C., Hassett D., and Gu T., 2018, Microbial fuel cell (MFC) power performance improvement through enhanced microbial electrogenicity, Biotechnology Advances, 36(4): 1316-1327.
https://doi.org/10.1016/j.biotechadv.2018.04.010

Liu J., Wang X., Wang Z., Lu Y., Li X., and Ren Y., 2017, Integrating microbial fuel cells with anaerobic acidification and forward osmosis membrane for enhancing bio-electricity and water recovery from low-strength wastewater, Water research, 110: 74-82.
https://doi.org/10.1016/j.watres.2016.12.012

Liu Y., Liu H., Wang C., Hou S., and Yang N., 2013, Sustainable energy recovery in wastewater treatment by microbial fuel cells: stable power generation with nitrogen-doped graphene cathode, Environmental science and technology, 47(23): 13889-13895.
https://doi.org/10.1021/es4032216

Malik S., Kishore S., Dhasmana A., Kumari P., Mitra T., Chaudhary V., Kumari R., Bora J., Ranjan A., Minkina T., and Rajput V., 2023, A Perspective Review on Microbial Fuel Cells in Treatment and Product Recovery from Wastewater, Water, 15(2): 316.
https://doi.org/10.3390/w15020316

Mohan S., Raghavulu S., Peri D., and Sarma P., 2009, Integrated function of microbial fuel cell (MFC) as bio-electrochemical treatment system associated with bioelectricity generation under higher substrate load, Biosensors and Bioelectronics, 24(7): 2021-2027.
https://doi.org/10.1016/j.bios.2008.10.011

Mohan S., Saravanan R., Raghavulu S., Mohanakrishna G., and Sarma P., 2008, Bioelectricity production from wastewater treatment in dual chambered microbial fuel cell (MFC) using selectively enriched mixed microflora: Effect of catholyte, Bioresource Technology, 99(3): 596-603.
https://doi.org/10.1016/j.biortech.2006.12.026

Moqsud M., Omine K., Yasufuku N., Hyodo M., and Nakata Y., 2013, Microbial fuel cell (MFC) for bioelectricity generation from organic wastes, Waste Management, 33(11): 2465-2469.
https://doi.org/10.1016/j.wasman.2013.07.026

Munoz-Cupa C., Hu Y., Xu C., and Bassi A., 2021, An overview of microbial fuel cell usage in wastewater treatment resource recovery and energy production, The Science of the Total Environment, 754: 142429.
https://doi.org/10.1016/j.scitotenv.2020.142429

Oon Y., Ong S., Ho L., Wong Y., Dahalan F., Oon Y., Lehl H., and Thung W., 2016, Synergistic effect of up-flow constructed wetland and microbial fuel cell for simultaneous wastewater treatment and energy recovery, Bioresource Technology, 203: 190-197.
https://doi.org/10.1016/j.biortech.2015.12.011

Pant D., Bogaert G., Diels L., and Vanbroekhoven K., 2010, A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production, Bioresource Technology, 101(6): 1533-1543.
https://doi.org/10.1016/j.biortech.2009.10.017

Rahman A., Borhan M., and Rahman S., 2017, Evaluation of microbial fuel cell (MFC) for bioelectricity generation and pollutants removal from sugar beet processing wastewater (SBPW), Water science and technology : a journal of the International Association on Water Pollution Research, 77(1-20): 387-397.
https://doi.org/10.2166/wst.2017.549

Sathe S., Chakraborty I., Dubey B., and Ghangrekar M., 2021, Microbial fuel cell coupled Fenton oxidation for the cathodic degradation of emerging contaminants from wastewater: Applications and challenges, Environmental Research, 112135.
https://doi.org/10.1016/j.envres.2021.112135

Srikanth S., Kumar M., Singh D., Singh M., and Das B., 2016, Electro-biocatalytic treatment of petroleum refinery wastewater using microbial fuel cell (MFC) in continuous mode operation, Bioresource Technology, 221: 70-77.
https://doi.org/10.1016/j.biortech.2016.09.034

Wang J., Bi F., Ngo H., Guo W., Jia H., Zhang H., and Zhang X., 2016, Evaluation of energy-distribution of a hybrid microbial fuel cell-membrane bioreactor (MFC-MBR) for cost-effective wastewater treatment, Bioresource Technology, 200: 420-425.
https://doi.org/10.1016/j.biortech.2015.10.042

Yamane T., Yoshida N., and Sugioka M.,2021, Estimation of total energy requirement for sewage treatment by a microbial fuel cell with a one-meter air-cathode assuming Michaelis-Menten COD degradation, RSC Advances, 11: 20036-20045.
https://doi.org/10.1039/D1RA03061B

Yang N., Liu H., Jin X., Li D., and Zhan G., 2020, One-pot degradation of urine wastewater by combining simultaneous halophilic nitrification and aerobic denitrification in air-exposed biocathode microbial fuel cells (AEB-MFCs), The Science of the Total Environment, 748: 141379.
https://doi.org/10.1016/j.scitotenv.2020.141379

Yang N., Zhou Q., Zhan G., Liu Y., Luo H., and Li D., 2021, Comparative evaluation of simultaneous nitritation/denitritation and energy recovery in air-cathode microbial fuel cells (ACMFCs) treating low C/N ratio wastewater, The Science of the Total Environment, 788: 147652.
https://doi.org/10.1016/j.scitotenv.2021.147652

Zhang M., Wang Y., Liang P., Zhao X., Liang M., and Zhou B., 2019, Combined photoelectrocatalytic microbial fuel cell (PEC-MFC) degradation of refractory organic pollutants and in-situ electricity utilization, Chemosphere, 214: 669-678.
https://doi.org/10.1016/j.chemosphere.2018.09.085

Zhao S., Yun H., Khan A., Salama E., Redina M., Liu P., and Li X., 2021, Two-stage microbial fuel cell (MFC) and membrane bioreactor (MBR) system for enhancing wastewater treatment and resource recovery based on MFC as a biosensor, Environmental Research, 112089.
https://doi.org/10.1016/j.envres.2021.112089

Zhuang L., Zheng Y., Zhou S., Yuan Y., Yuan H., and Chen Y., 2012, Scalable microbial fuel cell (MFC) stack for continuous real wastewater treatment, Bioresource Technology, 106: 82-88.
https://doi.org/10.1016/j.biortech.2011.11.019