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Microbial Fuel Cells: Sustainable Energy Production and Wastewater Treatment-Current Advances and Future Directions

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ABSTRACT: -

Microbial fuel cells, or MFCs, are an emerging method that uses microorganisms' metabolic processes to turn organic matter into electrical energy. This technology has a dual benefit: treating wastewater and providing sustainable energy. Recent developments in MFCs are covered in this study, emphasizing increasing power output and raising system efficiency. Important advancements include reactor designs, electrode materials, and microbial community optimization for improved electron transmission. A particular emphasis is placed on using single-chamber MFCs (SCMFCs) to treat wastewater and produce energy simultaneously. Large-scale adoption is hampered by obstacles such as poor power density, scaling problems, and economic viability notwithstanding these advancements. This study also looks at ways to get around these obstacles, like adding MFCs to already-existing treatment facilities and enhancing system architectures to boost Coulombic efficiency. MFC technology may be able to be used for environmental remediation and the production of renewable energy by addressing these important issues.

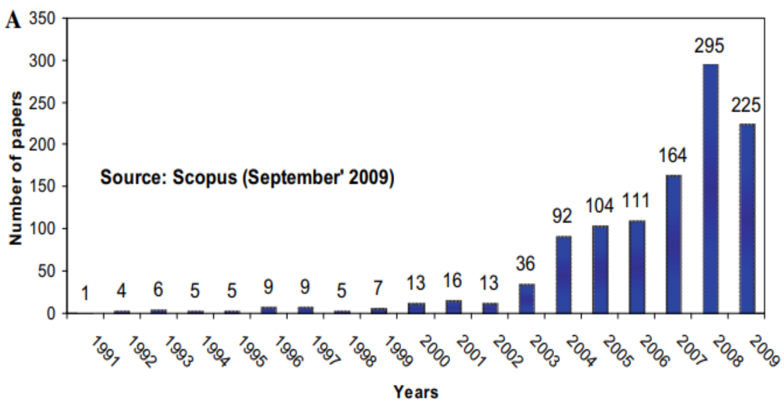
Keywords: - Microbial fuel cells, wastewater treatment, sustainable energy, bio electrochemical systems, power density, Coulombic efficiency, renewable energy

1 Introduction :

Worldwide energy production and utilization are the major hitch that are increasing day by day which eventually leads to energy demands in the modern world. During the previous decade, the rising use of fossil fuels unrelated to CO2 emissions, and related environmental issues initiated the exploration of alternative technologies to generate energy from renewable resources. With rising concern about sustainable energy supplies and waste minimization, biomass primarily gained attention to tap huge resources for powering upcoming generations. Green technologies are predominantly sought after in the field of environmental safety and restoration due to their sustainable life. Compared to conventional wastewater treatment systems, green treatment technologies have intrinsic advantages such as restricted or no use of chemicals, no foul odours, easy to function and inexpensive, etc., moreover, they are ecologically complex, mechanically simple, and environmentally friendly.

One potential alternative energy source is the use of microbial fuel cells (MFCs). However, the real interest in MFCs has tremendously grown in recent years, both in terms of number of researchers as well as the applications for these systems. Fig. 1 shows that 'Scopus' search with keyword ''microbial fuel cell" indicates almost 60-fold increase in the number of articles published over the last one decade (1998–2008). Microbial fuel cells (MFCs) are electrochemical devices that use the catalytic (metabolic) activity of living microorganisms to transform the chemical energy found in organic matter into electrical energy (Mathuriya and Sharma 2009; Allen and Bennetto 1993; Kim et al. 2002; Miriam et al. 2007). The anode and cathode of an MFC are divided by a cation-specific membrane. Microorganisms oxidize fuel, or substrate, in the anode compartment of an MFC, producing protons and electrons in the process. Protons diffuse through the solution to the cathode, where electrons interact with protons and oxygen to form water. Electrons are transported there by an external circuit (Jae et al. 2003). Oxygen is superior to other electron acceptors for its unlimited availability and its high redox potential (Zhao et al. 2006).

Fig 1 :- The number of articles on MFCs. The data is based on the number of articles mentioning MFC in the citation database Scopus in September 2009



History of MFCs

- Early Discoveries (1911): M.C. Potter demonstrated electricity generation by bacteria, marking the first recorded instance of bioelectricity.
- Mid-20th Century (1960s): Research by B. C. S. Domenico and J. B. Davis explored the potential of MFCs for waste treatment.
- (1980s-1990s): Increased focus on renewable energy sources revived interest in MFCs, leading to advancements in understanding the microbial and electrochemical processes.
- (2000s-Present): Significant technological advancements have improved MFC efficiency and applications, such as wastewater treatment, bioremediation, and power generation from organic waste.
- Current Research: Ongoing research aims to enhance MFC performance, scalability, and practical applications.

2 Literature Study :

- **Bruce E. Logan (2009): -**The paper reviews advancements in microbial fuel cell (MFC) technology. The main challenge in MFC development is scaling laboratory systems for practical applications. Key advancements include improved power densities, better electrode materials, and pilot-scale tests. However, issues like material costs, long-term durability, and environmental variations must be addressed for commercialization. Recent innovations in electrode materials, cathode designs, and membranes are highlighted, with pilot projects showing promise in wastewater treatment and bioenergy production.

- **Olivier Lefebvre et al., (2011): -** This study explores improvements in microbial fuel cell (MFC) efficiency for wastewater treatment. It focuses on overcoming proton limitations at the cathode by operating the MFC in a full-loop mode and acidifying the cathodic compartment. These strategies enhanced power generation and increased COD and suspended solids removal. Acidifying the cathodic compartment using hydrochloric acid (HCl) resulted in a substantial increase in power generation. Specifically, at a pH of 2, power generation increased by 180% in batch mode and 380% in continuous mode compared to the control at pH 7.6. The maximum power output observed during continuous acidification reached 7.4 mW, showcasing the efficacy of lowering the pH in enhancing electrochemical performance. The study highlights the potential of MFCs for energy recovery and wastewater treatment, although challenges in scaling up and optimizing performance remain.

- **Hong liu et al., (2004): -**A study on a single-chamber microbial fuel cell (SCMFC) demonstrated the production of electricity during the treatment of domestic wastewater. The SCMFC, using eight graphite anodes and an air cathode, achieved a maximum power output of 26 mW/m^2 and removed up to 80% of the chemical oxygen demand (COD) under continuous flow conditions. Power generation varied with hydraulic retention time (HRT) and wastewater strength, with an optimal performance observed at longer HRTs (up to 33 hours). Passive air transfer to the cathode proved more effective than forced air, leading to a 25% increase in voltage. However, the Coulombic efficiency was low (<12%), indicating that most of the organic matter was processed without generating electricity. This research highlights the potential of MFCs in offsetting energy costs for wastewater treatment, suggesting that further improvements could make the technology viable for broader applications.

- **D Chatzikonstantinou et al., (2018):-** A study on bioelectricity production using a dual-chamber microbial fuel cell (MFC) investigated food residue biomass (FORBI) as a substrate. The MFC achieved a peak power density of 29.6 mW/m^2 with a current density of 88 mA/m^2 at an organic load of 6 g COD/L. The study observed that increasing the FORBI concentration from 0.7 to 14 g COD/L raised the MFC voltage from 33.3 mV to 46 mV. The COD removal efficiency varied between 71% and 91%, while the Coulombic efficiency (CE) averaged around 2%, indicating that non-electrogenic microbes removed most organic matter.

- **Keiichi Kubota et al., (2010): -** A study on a single-chamber microbial fuel cell (MFC) treating synthetic sucrose-based wastewater (1 g COD/L) showed promising results in electricity generation and organic removal. At 20°C, the MFC achieved a stable power density of 56 mW/m^2 and a current density of 285 mA/m^2 over 45 days with a hydraulic retention time (HRT) of 25 hours. Initially, the coulombic efficiency (CE) was 21% with a COD removal rate of 25%. Over time, methane production increased, which reduced the CE to 5% after 220 days, despite a COD removal rate that increased to 60-75%. Adding electrolytes like 50 mM phosphate buffer improved power density to 127 mW/m^2 by reducing internal resistance.

- **Bruce E. Logana, Cassandro Muranob, Keith Scottb(2005):-** The study discusses electricity generation using cysteine as a substrate in a microbial fuel cell (MFC). Maximum power generation reached 39 mW/m^2 at a cysteine concentration of 770 mg/L. The microbial fuel cell, inoculated with anaerobic marine sediment, produced an initial peak power of 19 mW/m^2 at 385 mg/L of cysteine. Cysteine was shown to serve as a fuel for bacteria, particularly Shewanella species, which dominated the microbial community in the MFC. The electron recovery efficiency was 14% from cysteine oxidation, with an additional 14% potentially lost to oxygen diffusion through the proton exchange membrane.

- **Muralidharan, OK Ajay Babu, K Nirmalraman, M. Ramya (2011): -**The study focuses on the impact of varying salt concentrations on electricity production in microbial hydrogen-based salt bridge fuel cells (MFCs). The study explores how salt bridges, made with different concentrations of sodium chloride (NaCl) and potassium chloride (KCl), affect the fuel cell's performance in generating electricity from wastewater. The maximum current output was 256 µA using a 1M NaCl salt bridge. Comparisons between NaCl and KCl showed only

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minor differences in performance, with KCl yielding a peak current of 167 µA and NaCl producing 165 µA. Increasing the molar concentration of NaCl in the salt bridge reduced current production, with a sharp decline in output from 256 µA at 1M to 62 µA at 9M (7 salt). This study highlights that optimizing salt concentration is crucial for enhancing electricity generation in MFCs.

- **Zheng Ge, Liao Wu, Fei Zhang, Zhen He (2015):-** The study focuses on energy extraction from a large-scale microbial fuel cell (MFC) system treating municipal wastewater. The system, consisting of 48 MFC modules, generated power outputs between 84-130 mW and currents of 75-93 mA. It efficiently removed 75% of organic content and 80% of solid content. Three connected MFC rows achieved the highest energy conversion efficiency (~80%), demonstrating the system's potential for sustainable wastewater treatment.

- **Surajbhan Sevda & T. R. Sreekrishnan (2012): -** The paper studies the use of agar salt bridges as a cost-effective alternative for proton transport in MFCs, comparing various salt concentrations (1% to 10%) and their effects on power density and COD (Chemical Oxygen Demand) reduction. The highest power density was recorded at 5% salt concentration. Mediators such as methylene blue and neutral red were tested for their influence on electricity generation. Methylene blue at 0.08 mM concentration yielded the best results with a power density of 17.59 mW/m^2 and 89.22 mW/m^3. Neutral red showed a higher open-circuit voltage (0.730 V), but methylene blue performed better overall. The study highlights the role of mediators in enhancing electron transfer but notes that high concentrations can negatively impact microbial activity. SEM analysis revealed biofilm formation only in mediator-free conditions. The research demonstrates the feasibility of using salt bridges in MFCs to reduce costs while maintaining effective wastewater treatment

- **Yong Luo et al., (2010): -** The study investigates electricity generation using furfural as the sole fuel in microbial fuel cells (MFCs), focusing on ferricyanide-cathode and air-cathode setups. The ferricyanide-cathode MFC achieved a maximum power density of 103 W/m^3 using 6.68 mM furfural, while the air-cathode MFC reached 361 mW/m^2 with the same concentration. Furfural demonstrated higher power densities than glucose in both MFCs, and its complete degradation was achieved within about 60 hours. The study emphasizes the adaptability of certain bacteria to furfural, which could be converted to acetate, aiding electricity generation, and highlights the potential of MFCs for treating furfural-rich wastewater while producing energy.

- **Anand Parkash, Shaheen Aziz, and Soomro SA (2015**):- The study explores electricity generation using a double-chamber microbial fuel cell (MFC) with hostel sewage sludge as a substrate and varying salt concentrations in the salt bridge. Using 1M, 3M, and 5M concentrations of KCl and NaCl, the MFC's voltage output was evaluated. The results showed that 1M KCl produced the highest voltage (0.451 V), while 1M NaCl generated 0.372 V. Higher salt concentrations (3M and 5M) led to increased internal resistance and reduced current. The research highlights the potential of MFCs for renewable energy production using waste materials but emphasizes the need for optimization to minimize resistance and improve efficiency.

- **Debajyoti Bose et al., (2023):-** The study investigates bioelectricity production and bioremediation from sugarcane industry wastewater using microbial fuel cells (MFCs) with activated carbon (AC) cathodes. Biomass-derived AC was used as a sustainable alternative to expensive metal catalysts, showing high efficiency in oxygen reduction and stability for long-term use. The system achieved stable power output and contamination removal, with chemical oxygen demand (COD) reduced by 81% and biochemical oxygen demand (BOD) by 86%. The results highlight the potential of AC cathodes for both energy recovery and wastewater treatment, making it a cost-effective and eco-friendly solution.

- **Anoud Saud Alshammari et al., (2024): -**The study focuses on using oil palm biomass sap and rotten rice as organic substrates in a microbial fuel cell (MFC) to remove heavy metal ions (Pb^{2+}, Cd^{2+}, Cr^{3+}, and Ni^{2+}) from artificial wastewater and generate electricity. The MFC achieved a maximum voltage of 610mV and a power density of 3.164mW/m^2 after 18 days, with metal removal efficiencies reaching over 95% for Ni^{2+} and around 84% for other metals. The biofilm stability and electrochemical properties were thoroughly analyzed, highlighting the potential of combining sustainable organic waste with MFC technology for wastewater treatment and energy generation.

- **Sadia Sikder , Md. Mostafizur Rahman (2023):-** The study explores the use of Microbial Fuel Cells (MFCs) for treating municipal, textile, and tannery wastewater while generating bioelectricity. It compares the efficiency of Zinc-Copper (Zn-Cu) and Aluminum (Al) electrodes, finding that Zn-Cu electrodes are more effective. The research indicates that all wastewater types can generate electricity during treatment, highlighting MFCs' potential for sustainable waste management and energy recovery in Bangladesh, though challenges like cost and activity loss remain to be addressed. The study highlighted that all types of wastewater effectively generated electricity while being treated, indicating the potential of MFCs as a dual solution for waste management and energy recovery.

- **Majid Mohammadi, Mostafa Ghasemi, Mehdi Sedighi (2022): -** The study investigates the performance of microbial fuel cells (MFCs) in treating municipal and dairy wastewater while generating electricity. It aims to optimize the operating conditions for maximum efficiency in both energy production and wastewater treatment. The MFCs achieved a chemical oxygen demand (COD) reduction of 84% for municipal wastewater and 70% for dairy wastewater. The coulombic efficiencies were 37% and 17%, respectively, indicating that municipal wastewater is more effective for energy generation. Municipal wastewater microorganisms showed a higher attachment to electrodes compared to those from dairy wastewater, which contributed to better performance in energy production. The study identified optimal aeration at 125 ml/min and yeast extract concentration at 2 g/l for both types of wastewater. Under these conditions, the maximum power densities were 481 mW/m^2 for municipal wastewater and 410 mW/m^2 for dairy wastewater. The regression models used to predict power

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density and COD removal were validated with high coefficients of determination ($R^2 > 0.9$) and low mean absolute errors ($MAE < 3.9$), confirming their reliability. The research highlights the potential of MFC technology in simultaneously treating wastewater and generating clean energy, with municipal wastewater proving to be more effective than dairy wastewater in both aspects.

- **Youngho Ahn, Bruce E. Logan (2010):-** The study investigates the effectiveness of microbial fuel cells (MFCs) for domestic wastewater treatment at two different temperatures: ambient (23 ± 3 °C) and mesophilic (30 ± 1 °C).MFCs utilize a bio-electrochemical process where microbes oxidize biodegradable organic substrates to generate electricity, with CO_2 and biomass as byproducts. The research highlights that MFCs operated at mesophilic temperatures achieved better performance, with a maximum power density of 422 mW/m^2 (12.8 W/m^3) under continuous flow conditions, compared to 345 mW/m^2 (10.5 W/m^3) at ambient temperatures. The study also notes that the hydraulic retention time (HRT) significantly affects the organic loading rates and treatment efficiency, with optimal conditions leading to a total chemical oxygen demand (COD) removal of 25.8% at the highest power density. Energy recovery was found to be influenced by various operational conditions, including flow mode, temperature, and organic loading rate. The findings suggest that using temperature-phased, in-series MFC configurations can enhance treatment efficiency while reducing power consumption and solids production.

- **Amr El-Hag Ali et al.,(2015):-** The study focuses on microbial fuel cells (MFCs) as a method for treating domestic wastewater while generating electricity. It specifically examines a mediator-less double chamber MFC. Optimization of the anodic and cathodic conditions led to significant improvements in electricity production, achieving a maximum current of 0.784 mA for summer samples and 0.645 mA for winter samples, with corresponding power intensities of 209 mW/m^2 and 117 mW/m^2**.**The research highlights that summer samples, which had a higher microbial load, resulted in better electricity production and wastewater treatment compared to winter samples**.**The study also reports a notable reduction in biological oxygen demand (BOD5) and chemical oxygen demand (COD) values, reaching reductions of 71.8% and 72.85% for summer samples, while winter samples showed minimal decreases. Scanning electron microscopy revealed denser bacterial biofilm formation on the anode for summer samples, indicating a correlation between microbial activity and electricity production. Overall, the findings suggest that optimizing MFC conditions can enhance both electricity generation and the quality of treated wastewater.

- **Amira Suriaty Yaakop et al.,(2023**):- The paper discusses the potential of using domestic organic waste as a substrate in microbial fuel cells (MFCs) to generate renewable energy. It highlights the increasing challenge of managing food waste in developed nations and the environmental issues associated with its disposal, such as pollution and attracting pests. The study demonstrates that MFCs can effectively convert organic substrates into electrical energy, leveraging the natural processes of bacteria. The research specifically examines the electrogenic capabilities of bacteria found in household food waste, aiming to assess their ability to generate electrons. Results from the study indicate that a voltage of 110 mV was generated within 12 days of operation, showcasing the potential of using food waste as an energy source. The study also identifies specific bacterial strains, such as Pseudomonas aeruginosa and Acinetobacter schindleri, that contribute to energy production. Despite the promising findings, the paper notes that MFCs face challenges in practical applications, particularly regarding the efficiency of electron transfer between electrodes. The research suggests that advancements in electrode materials, particularly those derived from waste, could enhance the performance of MFCs.

- **Payel Choudhury et al., (2020): -**The study focuses on using microbial fuel cells (MFC) to generate power from dairy wastewater, employing a fed-batch strategy that enhances current and power densities compared to traditional batch methods. Dairy wastewater is highlighted as being rich in inorganic pollutants and organic matter, necessitating effective treatment methods. The research demonstrates high Columbia efficiencies and power densities, indicating the potential for sustainable energy generation while reducing dairy waste. The introduction discusses the need for alternative renewable energy sources and the role of MFC technology in both electricity production and wastewater treatment. The paper details the experimental setup, including the use of a single-chamber microbial fuel cell (SCMFC) and the specific materials used for the anode and cathode. Kinetic studies reveal that the chemical oxygen demand (COD) of the dairy wastewater decreased significantly throughout the experiment, indicating effective treatment.

- **Veera Gnaneswar Gude (2016): -**The paper discusses the potential of microbial fuel cells (MFCs) as a sustainable solution for wastewater treatment and energy generation, addressing the limitations of current technologies that are energy-intensive and costly. MFCs utilize the bio electrochemical activity of microbes to convert organic and inorganic substrates in various wastewaters into electricity, highlighting their role in environmental protection. The review emphasizes the need for advancements in electrode materials, reactor configurations, and pilot-scale studies to enhance the efficiency and practicality of MFCs for large-scale applications. It also notes the importance of understanding electron transfer mechanisms and optimizing system designs to improve power densities and overall performance. The future of MFC technology is seen as promising, with opportunities for significant breakthroughs that could lead to energy-positive wastewater treatment solutions.

- **Siddharth Gadkari et al., (2020):-**The study provides a comprehensive review of factors influencing microbial fuel cell (MFC) performance, particularly temperature and system parameters like electrode spacing and ionic strength. Temperature significantly impacts microbial activity, electrochemical reactions, and conductivity within MFCs. He found that power output generally increases as temperature rises from 20°C to 34°C, with a peak in performance. Beyond this temperature, power density declines due to reduced microbial efficiency and increased ohmic losses, leading to a nonlinear performance pattern. This aligns with observations by Moon et al., who noted a similar nonlinear trend at temperatures above 35°C (22). The study highlights that decreased electrode spacing reduces internal resistance, thereby

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improving power output—especially notable with weaker electrolyte solutions. Increased ionic strength, often achieved by adding salts or buffers, boosts ion transfer rates but also reaches a plateau, suggesting a limit to its effectiveness on power density in MFC's.

- **Eileen HaoYu et al., (2007):-** The study examines the performance of microbial fuel cells (MFCs) using non-platinum (non-Pt) cathode catalysts, particularly metal porphyrins, and phthalocyanines, which offer a cost-effective alternative to Pt. The research highlights that Fe-based phthalocyanine on high-surface-area carbon (Ketjenblack) outperforms Pt, achieving a maximum power density of 634 mW/m² under standard conditions, which increased to 2011 mW/m² under optimized conditions with a high-strength buffer, acetate substrate, and graphite brush anode. This study suggests non-Pt catalysts, especially FePc, as viable options for enhancing MFCs' cost-efficiency and scalability in renewable energy applications.

- **Xiachang Zhang and Aarne Halme (2007): -**The study investigates the impact of size and structure on the efficiency of microbial fuel cells (MFCs) for electricity production and energy conversion. Using two MFC designs—one larger with a higher anode volume and the other smaller—the research evaluates performance in terms of power output and internal resistance. Results reveal that the smaller cell achieves higher power density per anode volume, though both cells demonstrate similar polarization curves. This suggests that reducing the cell size and optimizing anode-membrane distance could enhance power and energy conversion rates, informing future design strategies for scalable biofuel cells.

- **G. Tayhas R. Palmore and George M. Whitesides (1994):-** This paper provides Microbial fuel cells (MFCs) as a promising approach to sustainable energy production by converting organic materials into electricity through the metabolic activity of microorganisms. MFCs are particularly valuable for simultaneous applications in energy generation and environmental remediation, such as wastewater treatment, by leveraging microbial activity to break down pollutants. Advancements in electrode materials, reactor configurations, and microbial community management have significantly improved the power output and efficiency of these systems. However, practical challenges—particularly low power density, scaling limitations, and economic viability—continue to hinder the widespread adoption of MFCs. Research focuses on addressing these limitations and on developing cost-effective solutions for large-scale integration of MFC technology into existing waste management and energy production systems**.**

- **H.P. Bennetto(1990):-** This paper explores microbial fuel cells (MFCs) as a tool for interdisciplinary science education and practical applications in biotechnology. By utilizing the natural metabolic processes of microorganisms, MFCs convert organic substrates into electricity through microbial oxidation and electron transfer to electrodes. The paper details experimental setups for MFCs suitable for both simple classroom demonstrations and advanced research, discussing key components like microbial cultures, redox mediators, and electrode materials. Bennetto emphasizes the educational value of MFCs, noting their ability to illustrate fundamental concepts in microbiology, chemistry, and physics, and their potential in renewable energy and environmental science.

- **Deepak Pant et al., (2009) :-** This paper says Microbial fuel cells (MFCs) are promising technologies that use microorganisms to convert organic waste and biomass into electricity. MFCs can process various substrates like low-strength wastewater, lignocellulosic biomass, and other organic materials, generating both power and environmental benefits through pollutant removal. Though power outputs are still low compared to large-scale energy needs, advances in microbial communities, electrode materials, and cell design are anticipated to improve efficiency. Future MFC applications may extend to areas like bioenergy from agricultural waste, wastewater treatment, and specialized biosensors.

- **Jaecheul Yu et al., (2012): -** The study focusses on submerged-exchangeable microbial fuel cell (SE-MFC) systems to demonstrate their potential to treat low-strength domestic wastewater while generating electricity. This SE-MFC system achieved increasing power densities with higher chemical oxygen demand (COD) loading rates when using synthetic wastewater, though efficiency decreased with increased loading. With real domestic wastewater, power density, and COD removal rates were lower due to the complex microbial communities and diverse electron acceptors in domestic wastewater. However, at a lower loading rate, the SE-MFC met effluent standards without additional processing. This research suggests SE-MFCs as a promising energy-efficient alternative for wastewater treatment.

- **Yaping Zhang et al., (2012):-** This study compares graphite felt (GF), carbon paper (CP), and stainless steel mesh (SSM) as bio-cathode materials in microbial fuel cells (MFCs), with GF emerging as the best performer. GF provided the highest power density, current density, and Coulombic efficiency due to its rough surface, which supports better microbial attachment and oxygen reduction reaction (ORR) activity. Electrochemical analysis showed that GF outperformed CP and SSM in catalytic efficiency, with lower charge transfer resistance and enhanced ORR rates. These findings suggest GF's suitability as a bio-cathode material for sustainable MFC applications, particularly in waste treatment and energy generation contexts.

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