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Advancements and Challenges in Microbial Fuel Cells for Sustainable Wastewater Treatment and Energy Generation

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Structured Abstract

Background: Microbial Fuel Cells (MFCs) represent a promising bioelectrochemical technology that harnesses electroactive bacteria to degrade organic pollutants in wastewater while generating electricity. This dual functionality addresses global challenges of energy scarcity and water pollution. Despite their potential, MFCs face limitations such as low power output, high material costs, and operational instability due to factors like biofouling and variable wastewater composition. This critical review evaluates the current state of MFC technology, its efficiency in energy production, and its feasibility for large-scale wastewater treatment.

Literature review: Recent studies highlight advancements in MFC design, including optimized electrode materials (e.g., cost-effective carbon-based anodes) and microbial consortia enhancement (e.g., *Pseudomonas aeruginosa* for higher electron transfer). The study emphasizes the significance of optimizing electrode materials, microbial populations, and operational conditions to improve MFC's performance. Carbon-based and altered electrodes (like nickel cobaltite and polyaniline composites) demonstrate potential in enhancing conductivity and microbial attachment. Likewise, the diversity of microbes, such as *Geobacter* and *Shewanella*, affects the stability of the system and the production of energy. The makeup of wastewater, such as organic matter, pH levels, and pollutants, significantly influences MFC's efficiency, where high loads or harmful substances can cause reductions in performance. Approaches such as incorporating advanced materials, enhancing microbial communities, and adjusting to various wastewater types are crucial for increasing scalability and practical applications.

Conclusion: MFCs offer a sustainable pathway to simultaneous wastewater treatment and renewable energy generation. However, their commercial viability depends on overcoming technical bottlenecks through innovations in material science, microbial engineering, and system scalability. Future research should prioritize cost reduction, long-term stability studies, and pilot-scale implementations to validate real-world applicability. By addressing these challenges, MFCs could revolutionize urban water management and contribute to global decarbonization efforts.

Keywords: Microbial Fuel Cells, Wastewater Treatment, Renewable Energy, Electroactive Bacteria, Biofouling

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