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Microbial fuel cell (MFC) technology for energy harvesting and wastewater treatment: recent progress and challenges

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Abstract

Microbial fuel cell technology has emerged as a pioneering innovation due to its dual capabilities of bioenergy production and wastewater treatment in an environmentally sustainable manner. Microbial fuel cells (MFCs) detoxify wastewater and eradicate contaminants via the sophisticated metabolic mechanisms of specialized microorganisms, concurrently facilitating potential bioenergy generation. Despite receiving a lot of attention, the scalability of microbial fuel cells (MFCs) is still a work in progress and has not yet been fully achieved. This review examines the factors influencing energy production through microbial fuel cells (MFCs) in wastewater treatment, focusing on operational parameters such as electrodes, microorganisms, aerobic biocatalysts, sediment characteristics, pH, and temperature. Challenges like poor power density, high material prices, biofouling, and operational stability arise when microbial fuel cells (MFCs) are scaled up for power production and wastewater treatment. The importance of electron transfer mechanisms and microbial metabolism is emphasized to maximize power generation in MFCs. The utilization of carbon nanotubes (CNTs) and CNT-based composites as anode materials, combined with the incorporation of biocathodes as an eco-friendly solution. Investigations have been conducted into the hybrid integration of Microbial Fuel Cells (MFCs) and Bio electrochemical Systems (BES) for the treatment of wastewater. This review outlines advancements in energy production, examines current challenges, and proposes future research directions. By integrating modern materials science, biotechnology, and system engineering, MFCs have the potential to revolutionize wastewater treatment and bioenergy production and contribute to a more resilient and sustainable future.

Keywords: Microbial Fuel Cell, Energy Harvesting, Wastewater, Sustainability.

1. Introduction

As the global energy needs are on the rise, there is a need to go beyond just trying to use fossil fuels as the primary energy source. Further, the problem of disposing of the industrial waste is another factor that endangers the prospect of having a livable environment. There is growing interest in microbial fuel cell technology because it can convert the chemical energy contained in organic and inorganic waste substances into electrical energy. Microbial fuel cells (MFCs) have an arrangement which has an anode and a cathode with the presence of electrolytes. Most arrangements in the MFCs include a proton exchange membrane between the anode and cathode chambers. In MFCs, microbes oxidize substrates, either free in the liquid or as attached biofilm on the anode. This oxidation generates protons, electrons and other metabolites. The electrons are detached from the microbes and shuttled to the anode through an external circuit and carried back to the cathode[1]. MFC being a promising technology, however, the key issues concern the scalability. It is necessary to pay attention to operational parameters and construction characteristics to get desired performance of this technology. Many of the operating parameters that influence the performance of microbial fuel cells (MFCs) include temperature, pH, salt concentration, configuration of the reactor and structure of the microbial community, whether in mixtures or discrete consortia. The creation of reactors and the structure of MFCs are also important to increase the surface area of contact and the movement of electrons. In addition, proper integration of microorganisms can augment the degradation of the substrates that the system relies on, hence improving the performance of the system[2]. Wastewater is not constant in nature and the differences in its organic content make it challenging to forecast and consistently optimize MFC. In municipal wastewater treatment, MFCs enhance the activated sludge process by improving organic matter removal. MFCs with halophilic bacteria are especially efficient at treating high-salinity wastewater, optimizing both pollutant removal and energy generation[3], [4]. Applications of MFCs include

bioremediation, power generation from waste in remote areas, food waste management, and potential uses in wastewater treatment.

2. Types of Microbial Fuel Cells

Despite the diversity of designs, all microbial fuel cells operate under the same fundamental principles. Some of these are illustrated below:

2.1 Double-Chamber MFC

The double-chamber MFC(Figure-1), considered the simplest and most commonly used design, consists of two separate chambers for the anode and cathode, divided by an ion exchange membrane[5]. In two-chamber MFCs, which are typically operated in batch mode with defined substrates in the anode and specific catholyte solutions for energy generation, the output is often severely limited by inherent design complexities, significant internal resistance, and considerable electrode-related losses[6]. The double-chamber MFCs, typically designed in bottle or cube shapes, are primarily employed in fundamental research. For instance, when air is utilized at the cathode to provide oxygen as the electron acceptor, the MFC is referred to as a two-chamber air-cathode MFC[7]. Figure 3 demonstrates that DCMFCs strike a balance between performance and operational longevity, making them ideal for applications that require reliable, long-term operation.

2.2 Single-Chamber MFC

In Single-Chamber Microbial Fuel Cells (Figure-2), both the anode and cathode are housed within a single chamber, divided by a Proton Exchange Membrane (PEM), as established by Doo Hyun Park and J. Gregory Zeikus. By positioning the anode in close proximity to the cathode, separated by a Proton Exchange Membrane (PEM), internal resistance is significantly reduced and power density is markedly increased[5]. This improvement is attributed to the diminished need for catholytes to link the two chambers. This configuration is characterized by a more economical and streamlined design, leading to enhanced efficiency in electricity generation compared to double-chamber microbial fuel cells (MFCs)[8]. The compact design of Single-Chamber MFCs is recognized for its ability to produce greater power output while minimizing internal resistance. Membrane-less configurations, lacking a proton exchange membrane (PEM), are subject to significant challenges, including microbial contamination and the diffusion of oxygen from the cathode to the anode, both of which adversely impact performance[9]. SCMFCs are quick to start but exhibit low efficiency, limited voltage output, and reduced stability, making them suitable for applications requiring low-cost setups with rapid deployment, as shown in Figure 3.

2.3 Up-flow MFC

The up-flow microbial fuel cell (MFC), designed in a cylindrical shape, features an anode at the bottom and a cathode at the top, with the two chambers separated by layers of glass wool and beads, through which the substrate is directed from the anode upward to the cathode[5]. The lack of a distinct physical barrier between the anode and cathode significantly minimizes proton transmission challenges, thereby enhancing the overall efficiency of the design[9]. The up-flow MFC design is considered highly scalable and advantageous for wastewater treatment,

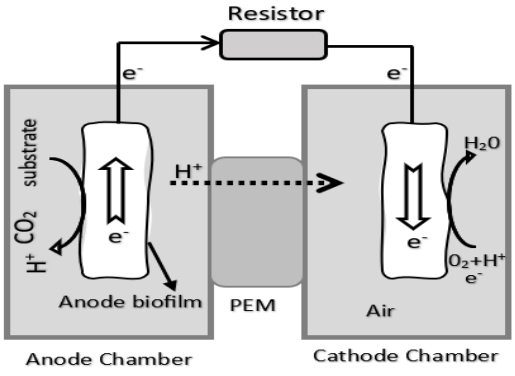


Fig. 1. Schematic design of double chamber microbial fuel cell

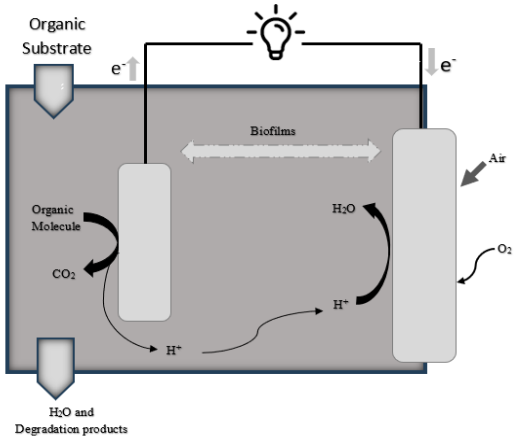


Fig. 2. Schematic design of single Chamber microbial fuel cell

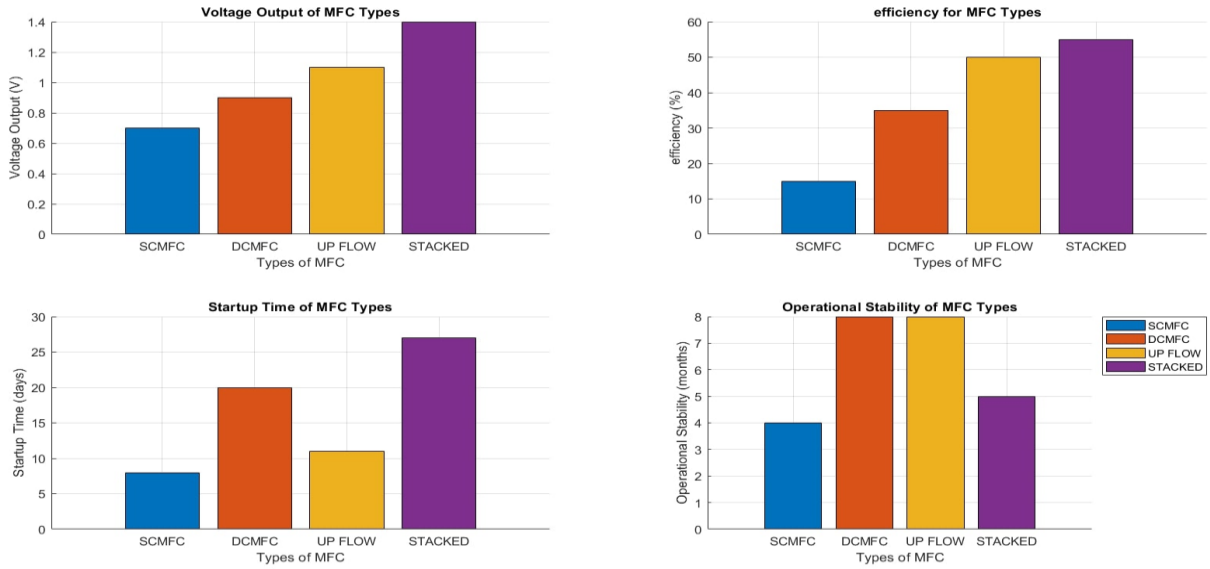


Fig. 3. Comparison of Various Attributes Among
Different Types of Microbial Fuel Cells (MFCs)

though its effectiveness for power generation is limited due to the significant energy costs associated with substrate pumping[6]. Figure 3 highlights that UP FLOW MFCs offer a balance of good performance, stable operation, and moderate startup time, making them well-suited for applications that require efficient and stable energy generation.

2.4 Stacked MFC

A stacked MFC which typically consists of multiple MFC units connected in series or parallel to enhance power output[8]. By combining MFCs in series or parallel connections, it can enhance the overall power or current output compared to a single MFC unit, which has a maximum open-circuit voltage. In parallel configurations, the rate of higher electrochemical reactions enables greater energy generation, although this configuration poses an increased risk of short-circuiting, whereas series connections are characterized by a reduced likelihood of such failures[5]. Figure 3 demonstrates that STACKED MFCs excel in efficiency and voltage output, although they require longer startup times and exhibit slightly reduced stability. These characteristics make them ideal for high-performance applications where efficiency is a priority.

3. Factors Affecting the Performance of Microbial Full Cell

The performance of a microbial fuel cell is influenced by a diverse array of physical and biological factors, including electrode types, substrate oxidation rate, electrolyte composition, microbial metabolic activity, proton exchange membrane, circuit resistance, and external operating conditions such as pH, temperature, salinity, and magnetic fields. An in-depth exploration of these factors are presented below.

Electrode Material: Electricity generation depends on biofilm formation at the anode, whereas biofilm growth on the cathode surface can reduce its effectiveness as an electron acceptor. An optimal anode material should exhibit high conductivity, large surface area, biocompatibility, corrosion resistance, and robust mechanical strength, while maintaining porosity and flexibility[10]. Different types of carbon materials are used including graphite rods, graphite granules, carbon veil, RVC (reticulated vitreous carbon), carbon nanotubes (CNTs) for their compatibility with environment. Graphite, RVC, and carbon paper can be effectively used with glucose or acetate substrates in two-chamber MFCs. In single-chamber MFCs, platinum or graphite with neutral red and sewage sludge substrate can be optimal anode choices[11]. Low reaction kinetics and internal resistance cause energy loss and high overpotential, hindering cathode performance. Conductive polymers, metal oxides, and platinum-based materials can reduce activation energy, while shorter electrode distances and aerophilic materials mitigate losses and improve mass transport[12].

Proton Exchange Membrane: The proton exchange membrane is a crucial component in microbial fuel cells, acting as a barrier between the anode and cathode chambers. Its primary function is to allow the passage of protons, which are essential for electricity generation, while effectively preventing the crossover of other substances such as oxygen, minerals, microorganisms, and substrates. This selective permeability is vital for maintaining an

anaerobic environment at the anode[13]. Nafion, a widely utilized proton exchange membrane (PEM) synthesized from tetrafluoroethylene copolymer, exhibits high cation conductivity due to its sulfonate functional groups. Nevertheless, it encounters limitations such as oxygen permeability, membrane fouling, and substrate loss[14]. Hyflon, an alternative PEM, demonstrates superior chemical stability and conductivity; however, it possesses higher internal resistance. Zirfon represents another option that offers lower resistance and reduces associated costs[13].

Substrate Type: The efficiency of microbial fuel cells is significantly influenced by the type and concentration of substrate utilized. Many researches have examined a diverse range of substrates, from simple organic compounds such as acetate and glucose to complex mixtures[15]. In two-chamber microbial fuel cells (MFCs), substrates such as cysteine, ethanol, landfill leachate, propionate, sucrose, and carboxymethyl cellulose are commonly used, while in single-chamber MFCs, substrates including arabitol, azo dye with glucose, galactitol, glucose, glucuronic acid, ribitol, xylose, and sorbitol are effective for bioelectricity generation[16].

Microbial Community and Metabolism: Microbes residing on the anode surface break down the organic substrate, and their metabolic activity plays a key role in determining the efficiency of the system. Recent research has identified Gram-negative proteobacteria as the dominant power-producing microorganisms in microbial fuel cells. These bacteria flourish in the anaerobic conditions of the anode compartment, utilizing electron transfer mechanisms adapted to this environment. This makes them highly suitable for electricity generation within MFCs. To optimize MFC performance, inoculation of the anodic chamber with either a pure culture or a mixed microbial consortium is essential. Gram-negative bacteria, particularly *Shewanella*, *Geobacter, sulfurreducens*, *Escherichia coli*, and *Enterobacter* species, are frequently employed in MFCs due to their inherent electrogenic capabilities[17].

pH and Temperature: Polarization losses during operation can arise from pH differences, with neutral pH (around 7) being optimal for bacterial growth. However, wastewater often exhibits acidic anodic conditions, which, along with proton exchange and cation transport, cause further pH fluctuations, hindering efficient power generation. Strategies such as buffer solutions, percarbonates, carbon dioxide addition, and hybrid electrodes can stabilize pH and address these challenges. Additionally, low temperatures can impede biofilm development, which typically occurs within a temperature range of 5 to 45°C[18].

4. Recent Advancement in Microbial Fuel Cell

MFC technology seeks to enhance reactor design, materials, and hybrid system integration to attain optimal scalability and efficiency. PVC and polypropylene dominate as materials in scale-up tubular and flat-plate reactors. Carbon nanotubes (CNT) augment bacterial activity and oxygen reduction, whereas biocathode microbial fuel cells (MFCs) promote green energy utilization by substituting chemical catalysis with microbial catalysis. Some of these advancements are listed below:

Table 1. Some of the factors recently improved microbial fuel cell (MFC) performance

Topic	Description
Reactor Design and Configuration	-Highly optimized reactor design, including CNT anode catheter. -Tubular or flat-plate reactors. - Tubular reactors are typically made from materials like PVC, polypropylene, nylon tubes, and graduated cylinders[19].
Scaling up MFCs	-Modular MFC units can be stacked in series or parallel for desired power output. - Challenges in scaling up: Voltage reversal, mass transmission limits, and internal resistance reducing power density. - Solutions: Adopting similar-performance MFCs, installing power[20].
Carbon Nanotubes (CNTs) in MFCs	-CNTs and CNT composites are used to enhance performance in two ways: improving bacterial electrochemical activity at the anode and enhancing oxygen reduction at the cathode[21].
Biocathode MFCs	-Microorganisms replace chemical catalysts at the cathode, reducing costs and increasing sustainability compared to abiotic cathode MFCs.
Porous Membranes for MFCs	-Alternative to proton exchange membranes (PEMs): ultrafiltration membranes (UFMs), microfiltration membranes (MFMs), and ceramic membranes (CMs). -Advantages: Simpler fabrication, low cost, and good sustainability. - Disadvantages: Biofouling and increased internal resistance over time. - Ceramic membranes offer high proton conductivity and low cost, but performance depends on polarization strength and material porosity[13].

MFCs Integrated with Other Technologies	-MFCs are integrated with other technologies like membrane bioreactors (MBRs) and anaerobic bioprocesses for enhanced wastewater treatment, energy production, and biosensing.
Combination with Other BES Technologies	-MFCs combined with other bioelectrochemical systems (BES) for advanced resource recovery[22].
Microbial Community Composition	-Pure cultures (e.g., Geobacter, Shewanella) support efficient electron transfer and bioenergy production but are costly and prone to contamination. -Mixed cultures are more resilient, can harness a broader range of electron-generating microbes for increased energy production.
System Control for Enhanced Efficiency	-Feedback control systems monitor and adjust operational conditions (e.g., dilution rates, nutrient addition, aeration).
MFCs as Biosensors	-MFCs can serve as electrochemical biosensors, especially for water quality monitoring (e.g., BOD and toxicity). -Benefits: Durability, self-sufficiency, and electric signal generation without external power sources or transducers.

5. MFCs in Wastewater Treatment

Municipal or domestic wastewater: Municipal wastewater is typically treated by the activated sludge process (ASP), in which organic matter, measured as chemical oxygen demand (COD), is oxidized by intensive aeration of a microbial population maintained in the reactor via a sludge recycling system[23], [24]. This conventional method has been significantly enhanced by biological wastewater treatment processes, which are recognized for their low operational costs, high removal efficiency, and decreased management requirements[3].

Agricultural Wastewater: The importance of treating animal manure wastewater in agriculture is highlighted by its production of significant quantities, with approximately 58 million tons generated annually in the United States[24]. The treatment of this wastewater is mandatory in order to comply with discharge regulations and thus avoid water contamination and odor nuisances. The presence of elevated concentrations of nitrates and phosphates in wastewater can lead to eutrophication of surface waters and negatively impact aquatic ecosystems[25]. Animal manure wastewater is characterized by high concentrations and often contains volatile organic acids, which contribute to the predominant odor of pig manure.

Industrial Wastewater: Treatment of various industrial wastewaters with microbial fuel cells (MFCs) has been extensively researched and has achieved high efficiencies in removing chemical oxygen demand (COD), metals and nutrients in various waste streams such as domestic, brewery, pharmaceutical and high salinity wastewater. Food processing wastewater containing biodegradable organic matter such as carbohydrates and proteins, as well as textile and dye wastewater, have been shown to be potential substrates for MFCs, resulting in effective pollutant removal and bioelectricity generation[24]. In particular, high-salinity wastewater from seafood, petroleum, leather and textile industries poses particular challenges for conventional methods due to salinity and operating costs[4]. Recent investigations have demonstrated that MFCs using halophilic bacterial strains can overcome these limitations and provide sustainable treatment solutions and improved energy production[4].

6. Conclusion

In conclusion, microbial fuel cell (MFC) technology offers a powerful solution for wastewater treatment and sustainable energy production. Recent improvements in MFC design and substances have appreciably advanced their efficiency and scalability, making them possible alternatives to traditional treatment methods. The variety of MFC configurations ranging from double-chamber to single-chamber and up-flow designs—demonstrates the ability and adaptableness of this technology to different wastewater, which includes municipal, agricultural, and industrial wastewater treatment. Innovations along with using carbon nanotubes, biocathodes, and bio electrochemical systems similarly enhance the overall performance of MFCs, facilitating higher electron switch and microbial metabolism. Future development should focus on several key areas, including new materials, nanomaterials, and conductive polymers; implementation of real-time monitoring and control systems; strategies to combat biofouling and internal resistance; and integration of new hybrid model with other technologies. Looking in advance, the potential for MFCs extends beyond wastewater remedy and bioenergy production. Their implementation may extend into areas consisting of environmental monitoring, biosensors, and valuable resource recovery, offering a complete strategy to sustainability. As research advances in addressing current limitations, microbial fuel cells could emerge as a key solution.

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