Advances and Prospects of Microbial Fuel Cells

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Advances and Prospects of Microbial Fuel Cells

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Abstract： *The increasing global energy demand and environmental concerns necessitate the development of sustainable and renewable energy sources. Microbial fuel cells (MFCs) present a promising technology by converting organic waste in wastewater into electrical energy through microbial metabolism. This paper reviews recent advancements in MFCs, focusing on optimizing their components and improving efficiency. The mechanisms of electron transfer in MFCs, including direct electron transfer (DET), mediated electron transfer (MET), and direct interspecies electron transfer (DIET), are discussed. Additionally, innovations in electrode materials, surface modifications, and genetic engineering to enhance electron transfer and microbial adhesion are highlighted. The review also addresses the potential of MFCs in various applications and the challenges in scaling up from laboratory to practical implementation. Despite technical and economic challenges, advancements in materials and technologies are paving the way for MFCs to become a significant contributor to sustainable energy solutions. Future research directions are proposed to further enhance the performance and economic viability of MFCs.*

Keywords: Microbial fuel cells; Bioelectricity; Microbial fuel cells anode; Microbial fuel cells cathode

1. INTRODUTION

In contemporary human society, the most utilized energy sources are fossil fuels, such as coal and natural gas, which provide thermal and electrical energy[1]. With the rapid growth of the global population, the consumption of fossil fuels is also increasing rapidly[2]. Fossil fuels are formed through natural processes over thousands of years and exist in limited quantities, making them an unsustainable long-term energy source for human society. However, other forms of energy, such as solar energy, radiation energy, chemical energy, and bioenergy, can be converted into the thermal and electrical energy needed by human society, thereby mitigating the energy crisis caused by the scarcity of fossil fuels[3], [4].

The use of water resources in human life inevitably generates wastewater, which contains a significant amount of organic waste[5], [6]. This Organic waste can pollute soil, water bodies, and the atmosphere. However, it also contains a substantial amount of energy, and wastewater treatment can convert these wastes into energy needed by human society[7], [8]. For instance, anaerobic digestion, a relatively mature technology, can produce methane and hydrogen, which are usable by humans, through the action of anaerobic microorganisms[5], [9]. As current energy resources are gradually depleted, new energy sources have become a primary focus for many researchers. New energy refers to renewable energy developed and utilized based on new technologies. The advantages of new energy are significant: it can greatly conserve energy, substantially reduce pollution, is renewable, and can yield notable economic and environmental benefits.[9]

Microbial fuel cells are a method of wastewater treatment that uses microorganisms to convert solid waste in wastewater into electrical energy[10]. Currently, electrical energy is the most widely used clean energy in human society. MFCs can efficiently operate under ambient temperature conditions while processing organic waste. Moreover, MFCs do not require exhaust gas treatment since the primary gas produced is carbon dioxide. The development of microbial fuel cells and other renewable energy technologies demonstrates a global shift towards more sustainable and environmentally friendly energy solutions[11], [12]. With advancements in technology and improved cost-effectiveness, these energy sources will increasingly constitute a larger share of the future energy mix.[13] Government and international policy support will accelerate their development, particularly through regulations, financial incentives, and support for technological innovation. Furthermore, the widespread adoption of clean energy technologies will significantly reduce greenhouse gas emissions, promote economic diversification, and enhance energy security. In this context, MFCs, as an efficient and clean energy conversion technology, have high potential for widespread application in regions lacking electrical infrastructure, thereby increasing the diversity of our energy sources[14].

This review summarizes the developments in various components of microbial fuel cells to date, detailing how researchers have improved the performance and electricity generation capabilities of MFCs. The article also highlights the opportunities, challenges, and scalability issues that MFCs may face in future development.

2. MFC MECHANISM

A microbial fuel cell is a device that converts chemical energy into electrical energy. Its basic components include an anode chamber, a cathode chamber, a proton exchange membrane, electrodes, and an external circuit. The anode chamber contains microorganisms that decompose organic matter into smaller molecules, releasing electrons and protons in the process, which is an oxidation reaction. Electrons flow from the anode to the cathode through an external circuit, while protons flow to the cathode through the proton exchange membrane. In the cathode chamber, electrons and protons react with an electron acceptor (typically oxygen) in a reduction reaction.

In microbial fuel cells (MFCs), the transfer of electrons is accomplished by electroactive microorganisms. Researchers have identified three mechanisms of electron transfer in MFCs:

1.Direct electron transfer（DET）: DET refers to the direct contact between the outer membrane of electroactive bacteria and the anode surface, facilitated by conductive pili or nanowires[15], [16]. Electrons are transferred from the bacterial respiratory enzymes to the anode without any diffusible mediators.

2.Mediated electron transfer (MET): In this mechanism, electrons are shuttled between the bacterial cells and the anode via soluble redox mediators or shuttles[15], [17]. These mediators can be either exogenous (artificially added compounds like neutral red, methylene blue) or endogenous (naturally produced by bacteria like phenazines, flavins).

3.Direct interspecies electron transfer (DIET): This involves direct electron transfer between different microbial species via biological electrical connections like nanowires or cytochromes[17]. One species oxidizes the substrate and transfers electrons to another species, which then transfers them to the anode.

The relative contribution of each mechanism depends on factors like the microbial community composition, anode material and configuration, substrate type, and operating conditions[15], [16]. Direct electron transfer by electrochemically active biofilms on the anode surface is generally considered the most efficient mechanism for current generation in MFCs[16], [17].

3. OPTIMIZATION OF MFCs TYPES

In addition to traditional double chamber microbial fuel cells, some researchers are exploring ways to improve efficiency by altering the structure of MFCs. Structural changes directly impact the pathways, rates, and overall reaction kinetics of electron and proton transport within the cell. Researchers have also found that modifying the structure of MFCs can reduce the internal resistance, which in turn minimizes unnecessary power losses and enhances the overall efficiency of the cell. The following diagram (figure 1) illustrates some of the improved MFC design schemes proposed by these researchers[18], [19].

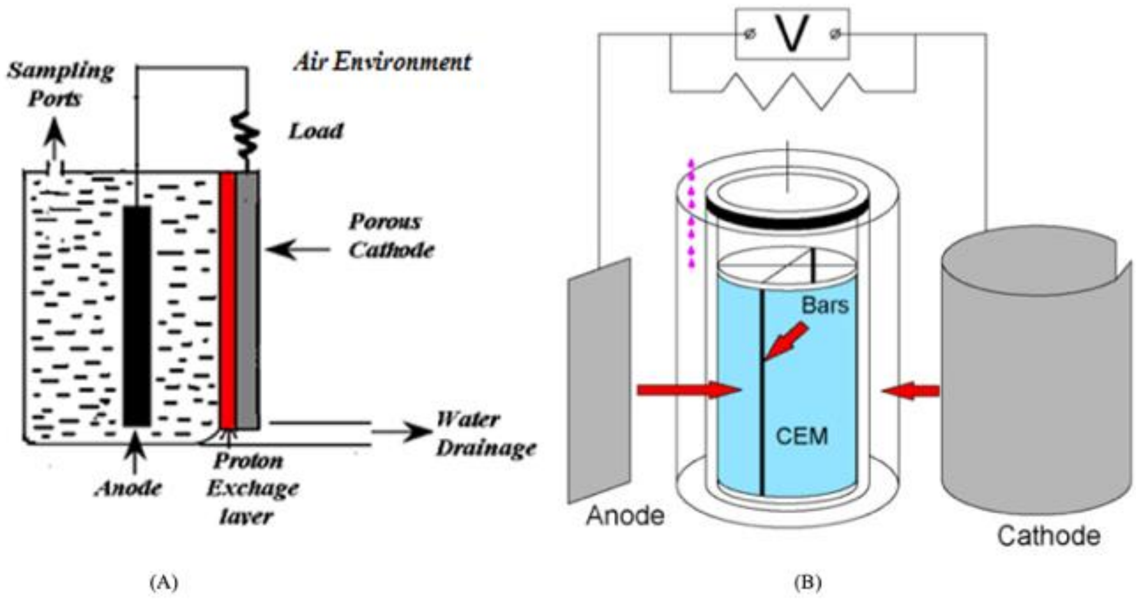

Figure 1 Schematic of (A) single chamber MFC and (B) bushing MFC (BMFC).

Researchers have employed various methods to reduce internal resistance in microbial fuel cells. For instance, some have omitted the proton exchange membrane, minimized the distance between the two electrodes as much as possible, and even added sodium chloride compounds to the solution to increase ion concentration, thereby lowering internal resistance.

4. ELETRODE MATERIAL

Microbial fuel cells rely on electrode materials that can effectively facilitate the transfer of electrons from the bacteria to the anode and promote the oxygen reduction reaction at the cathode. The choice of electrode material significantly impacts the performance and power output of MFCs. When researchers select electrode materials for microbial fuel cells, they primarily consider three aspects: conductivity, corrosion resistance, and cost.

1.Conductivity: High conductivity materials can reduce internal resistance, increase the electron transfer rate, and thus enhance the performance of MFCs. Common high conductivity materials include graphite, carbon cloth, platinum, and carbon nanotubes.

2.Corrosion Resistance: The electrodes of MFCs are typically immersed in solutions for extended periods, which are often highly corrosive. Therefore, the electrodes must resist corrosion and degradation over long-term use. Common materials with good corrosion resistance include titanium, stainless steel, and coated materials.

3.Cost: Cost is a practical factor that must be considered when choosing electrode materials, especially for large-scale applications. Common cost-effective materials include graphite, stainless steel, platinum, and carbon nanotubes.

Comprehensive Consideration: Graphite and carbon cloth offer a good balance between conductivity and cost. Stainless steel and titanium provide excellent corrosion resistance, with titanium being more expensive, while stainless steel is a more economical choice. Coated electrodes combine high conductivity and corrosion resistance but are more costly.

In practical research, the choice between conductivity, corrosion resistance, and cost depends on specific application needs. According to most research papers, carbon cloth is currently the optimal electrode material for MFCs in most situations, as it offers high conductivity, low cost, and relatively good corrosion resistance.

Currently, there have been some recent advancements in research on the electrodes of MFCs by certain researchers. focusing on improving efficiency, reducing costs, and enhancing the overall performance of these systems. Some key areas of improvement include:

1.Electrode Materials: Researchers have explored various materials to enhance the efficiency of MFC electrodes. Carbon-based materials like carbon cloth, carbon paper, and activated carbon fiber have been widely used due to their excellent conductivity and stability. Novel materials such as carbon nanotubes, graphene, and metal nanoparticles (e.g., gold and silver) have also been investigated to improve electron transfer and microbial adhesion on the electrode surface[20], [21].

2.Surface Modifications: Modifying the surface of electrodes to increase their biocompatibility and microbial adhesion has been a major focus. Techniques like nitric acid and ethylenediamine treatments have been applied to activated carbon fiber felts to enhance their performance. Such modifications have shown to increase the maximum power densities and shorten the start-up times for MFCs[20], [22].

3.Electrode Configurations: The design and configuration of electrodes play a crucial role in the efficiency of MFCs. High surface area and porous structures are essential for maximizing power output. Brush anodes made of carbon fibers and industrial brushes have demonstrated high power densities due to their large surface areas and effective microbial colonization[21]

4.Genetic Engineering: Advancements in genetic engineering have allowed for the manipulation of microorganisms to improve their electron transfer capabilities. By modifying the genetic pathways of bacteria such as Geobacter and Shewanella, researchers have been able to enhance their efficiency in electricity generation[20]

5. ANODE SIDE

In MFCs, the anode chamber typically contains sludge, which is the microbial electricity-generating side. The concept that the anode performance in microbial fuel cells is significantly influenced by electron conductivity and microbial adhesion has been explored in various studies. The review article by Banerjee et al. provides a comprehensive overview of the materials and designs of anodes in MFCs, emphasizing the importance of biocompatibility and conductivity for enhancing electron transfer and microbial biofilm formation. This review discusses multiple modification strategies to improve anode performance, highlighting how these factors are critical for efficient MFC operation[23].

In terms of improving electron conduction efficiency, researcher Chia-Ping Tseng discovered the use of self-doped polymers like CPE-K (carboxylated polyethylene) has been shown to enhance electronic conductivities of biofilms[24]. When added at concentrations up to 30 mg/mL, CPE-K significantly increased current densities compared to pure biofilms or pure CPE-K films. This is attributed to the interactions between ionic side chains and bridging counterions, which improve charge transport.

In terms of microbial adhesion, researcher Sabine Spiess discovered Modifying the surface of electrodes with positively charged materials like chitosan or ammonia can enhance microbial adhesion. Chitosan, a biopolymer with excellent biocompatibility and hydrophilicity, improves the interaction between microbes and electrodes[25].

Recent research has found that nZVI can simultaneously enhance electron conduction efficiency and increase microbial adhesion. In terms of electron conduction efficiency, Nabil et al[26] discovered that nZVI has good conductivity and can serve as an electron transfer medium, directly participating in the electron transfer process. It can provide more electron conduction paths between microbes and the anode, reducing the resistance to electron transfer and thus improving overall electron conduction efficiency. Additionally, Edwin et al[27] found that the surface of nZVI has high catalytic activity, which can promote redox reactions, thereby increasing the rate of electron generation and transfer efficiency.

In terms of increasing microbial adhesion, Feng et al[28] found that the nanoscale of nZVI provides a large specific surface area, offering more attachment sites, which aids in the adhesion and growth of microbes on the anode surface. Additionally, according to Tahseena et al[29], nZVI has good biocompatibility on its surface, promoting microbial adhesion and biofilm formation, thereby enhancing the performance of MFCs.

However, nZVI also exhibits direct toxicity to microbes.[30] The highly reactive surface of nZVI can cause oxidative damage to microbial cell membranes, compromising cell integrity and function, thus inhibiting microbial growth and activity. Hao et al[31] found that nZVI can produce reactive oxygen species (ROS), leading to oxidative stress responses within microbial cells, damaging DNA, proteins, and lipids, further affecting microbial survival and electricity generation. Despite nZVI's ability to promote initial microbial adhesion, its long-term presence may decrease biofilm stability. High concentrations of nZVI may lead to biofilm detachment and reduced microbial activity, thereby lowering MFC performance, as indicated in Shi et al[32].

To mitigate the impact of nZVI on microbes, Bensaida et al.[33] coated nZVI particles with magnesium hydroxide.

This coating reduces the reactivity of nZVI, minimizing direct contact and toxicity to microbes. The magnesium hydroxide layer also controls the release rate of iron ions, preventing rapid release that causes oxidative stress, thereby reducing harm to microbes. Magnesium hydroxide was chosen for its buffering capacity in water, stabilizing the pH of the solution, and protecting the microbial community. Additionally, magnesium hydroxide has good biocompatibility, aiding in microbial adhesion and growth, helping to form stable biofilms, and enhancing electron conduction efficiency.

6. CATHODE SIDE

In microbial fuel cells, the cathode accepts electrons and undergoes a reduction reaction. Currently, most microbial fuel cell cathodes react with oxygen in the reduction reaction. Many researchers are working to significantly improve the power output of microbial fuel cells by enhancing the oxygen reduction reaction (ORR). For example, some researchers have chosen to add noble metal catalysts such as platinum and palladium, which possess extremely high catalytic activity and can significantly increase ORR efficiency. However, the high cost of these noble metals limits their large-scale application.

Other researchers have used non-noble metal catalysts such as iron-nitrogen-carbon (Fe-N-C) and metal oxides (e.g., cobalt oxide and manganese oxide). These catalysts are more cost-effective and exhibit excellent performance in ORR. In addition to using catalytic methods, some researchers are enhancing the oxygen reduction reaction by using bio-cathodes.

Bacteria can directly catalyze the ORR at the cathode, reducing the overpotential losses and facilitating oxygen reduction. Certain bacteria like Sphingobacterium, Acinetobacter and Acidovorax have shown promising results as biocatalysts, achieving current densities up to 2.2 A/m^2. Microalgae can also induce the ORR and generate electricity in the cathode chamber of MFCs through a biocatalytic process[39], [40].

Oxygen reduction reaction is not the only option studied by researchers. As shown in Table 1, we can see the power densities and cathode electrolyte compositions for oxygen reduction reaction and other different reduction reactions.

7. CONCLUSION

In recent years, microbial fuel cells have garnered increasing attention from researchers, leading to significant advancements in MFC technology. Researchers have developed new conductive materials (such as graphene and carbon nanotubes) and modified materials (such as conductive polymers) to improve electron conduction efficiency and microbial adhesion capabilities. They have also optimized electrode structures (such as three-dimensional porous structures) to increase the surface area for microbial growth and electron transport paths. Additionally, by adjusting operational conditions such as pH, temperature, and nutrients, and introducing new electrolyte solutions, the overall performance and electrochemical efficiency of MFCs have been enhanced.

However, MFCs are currently still at the laboratory scale. The transition from laboratory to practical application faces challenges in terms of technical performance stability and cost reduction. Future research directions can be pursued in the areas of technology, materials, and application fields.

Technology:

- Explore new three-dimensional structures and nanomaterial electrodes to improve electron conduction and microbial adhesion.
- Develop smart MFC systems with real-time monitoring and automatic adjustment to optimize operating conditions.

Materials:

Table 1 Power densities and cathode electrolyte compositions for different reduction reactions

Types of Reduction Reactions	Composition of Electrolyte Solution	Power Density of Electricity Generation	Reference
Oxygen Reduction Reaction	An aqueous solution containing oxygen, which provides oxygen through the air aeration system.	$1.27 W/m^2$	[25]
Nitrate Reduction Reaction	The cathode chamber uses 0.722 g/L potassium nitrate solution as the electrolyte solution.	$574.3 mW/m^3$	[34]
Iron Reduction Reaction	Ferrous sulfate ($FeSO_4 \cdot H_2O$) was also added to the experiment to provide a source of iron ions.	$5.11 W/m^3$	[35]
Sulfate Reduction Reaction	Copper sulfate solution with cathode electrolyte solution of 2 g/L	$5.5 W/m^2$	[36]
Permanganate Reduction Reaction	potassium permanganate ($KMnO_4$) solution.	$0.69 W/m^2$	[37]
Reduction Reaction of Organic Compounds	High alkaline solution extracted from urine by electroosmosis	$15.3 W/m^3$	[38]

- Search for and develop new catalysts to enhance the electrochemical reaction efficiency of anodes and cathodes.
- Develop more biocompatible materials to promote microbial growth and biofilm formation.

Application Fields:

- Expand the application of MFCs in industrial and urban wastewater treatment to achieve dual goals of resource recovery and energy production.
- Consider integrating MFCs into distributed energy systems to provide sustainable energy for remote and off-grid communities.

Through these efforts, MFC technology is expected to achieve higher performance and economic feasibility, driving its practical application forward.

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