Microbial Fuel Cells: Technological Advances in Wastewater Treatment and Energy Recovery, and Prospects for Scale-up

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Abstract: Currently, many regions worldwide are facing dual pressures of water scarcity and energy transition, making the search for efficient and low-carbon wastewater treatment technologies particularly urgent. Driven by this demand, Microbial Fuel Cells (MFCs), a green bioelectrochemical technology, have garnered increasing research attention due to their ability to integrate wastewater purification with electricity recovery. However, their practical application is hindered by challenges such as relatively low energy conversion efficiency and power output. This paper provides a detailed review of recent research progress in MFCs, with a systematic examination of system configuration designs (including dual-chamber, single-chamber, up-flow, and stacked configurations), innovations in core components (anode, cathode, and membrane materials), and emerging coupled systems (e.g., MFC-constructed wetlands, MFC-membrane bioreactors, and MFC-microbial electrolysis cells). Key findings from representative studies are highlighted: dual-chamber MFCs have achieved a maximum power density of 6.2 W/m³ in dye wastewater treatment; single-chamber MFCs incorporating TiO_2 photoanodes reached a current density of 4571.43 mA/m²; up-flow MFCs demonstrated a COD removal rate of 95.5% for azo dye wastewater; and stacked MFCs with series-parallel hybrid connections yielded a peak power density of 2.451 W/m³. Recent material innovations-such as ternary transition metal sulfides and MXene-based composites-have enhanced anode performance, boosting power output by up to 54.4% compared to conventional carbon-based anodes. Modified clay-based membranes have also been developed as low-cost alternatives to Nafion, achieving power densities of 2.17 W/m³ at significantly reduced cost. Future research directions are proposed, aiming to improve MFC performance, enhance energy recovery from various wastewaters, and facilitate the commercialization and large-scale application of MFC technology.

Keywords: Microbial Fuel Cell; Wastewater Treatment; Energy Recovery; System Configuration; Electrode Materials; Coupled Processes

1. Introduction

Environmental pollution and the energy crisis are intertwined, profoundly constraining global economic activities and societal progress. The long-term and extensive reliance on traditional fossil fuels such as coal and oil, while driving industrialization, has inevitably led to severe air and water pollution. Facing this complex situation, the exploration and utilization of clean renewable energy sources such as solar, wind, and biomass have become a core focus for the international community.

Water pollution control is one of the most urgent issues among various environmental concerns. However, most current mainstream wastewater treatment technologies follow a linear "purification-disposal-discharge" model: although pollutants are removed, a significant amount of chemical energy contained in the wastewater is converted into useless thermal energy or excess sludge, failing to achieve effective resource recovery and reuse[1].This model involves relatively complex processes, high energy consumption, and its substantial indirect greenhouse gas emissions contradict global "carbon reduction" goals.

Is it possible to find a feasible path that genuinely combines pollution control with energy recovery needs? The rise of microbial fuel cell (MFC) technology provides a new approach to this challenging concept. Its core principle utilizes the metabolic activities of electroactive microorganisms to efficiently degrade organic pollutants and reduce carbon emissions while avoiding secondary pollution, simultaneously directly converting the chemical energy stored in pollutants into electricity. It is precisely this inherent synergistic characteristic of "turning waste into treasure" that gives MFCs significant and attractive application potential under the "Dual Carbon" strategy.

The advantages of MFCs extend beyond this. They possess characteristics such as wide fuel source availability, mild operating conditions, relatively high pollutant removal efficiency, and low excess sludge production. Existing research has shown that MFCs have demonstrated good treatment potential in various wastewater scenarios, from domestic sewage and food wastewater to industrial wastewater containing chromium, ammonia nitrogen, and complex dyes, adapting to diverse and complex water quality conditions[2].Currently, pollutants discharged into the environment are becoming increasingly complex in composition, and interactions between different pollutants are becoming more prominent-for example, the global concern in recent years over the discharge of wastewater containing radioactive nuclides such as tritium and uranium, which poses significant threats to marine ecosystems and long-term human health. Traditional water treatment methods are often inefficient and energy-intensive when dealing with such pollution. Therefore, the development of deep water purification technologies that combine efficiency and safety is becoming increasingly necessary[3, 4]. Relying on their unique bioelectrochemical degradation pathways, MFCs are demonstrating important research value in treating such emerging or recalcitrant pollutants, consistently attracting extensive research from scholars worldwide.

Based on the current needs in the field, this paper aims to review the latest research and application progress in MFC technology from multiple perspectives, focusing on analyzing key breakthroughs in system configurations and core materials, discussing the synergistic enhancement mechanisms arising from coupling MFCs with other processes, and objectively examining core challenges such as economic viability and stability faced by this technology on its path to scaling-up.

2. Advances in MFC System Design and Engineering

The core value of MFCs lies in utilizing a unique class of functional microorganisms to integrate wastewater purification and energy recovery. Microorganisms attached to the anode release electrons and protons during their metabolic degradation of organic pollutants; electrons travel through an external circuit to the cathode to generate current, while protons migrate through a selective exchange membrane to the cathode, where they ultimately combine with oxygen to complete the electrochemical reaction-it is this series of synergistic actions that achieves the direct conversion of chemical energy into electrical energy. Among these, reactor configuration design plays a key role in this process and has become a research focus. This section will overview traditional single/double-chamber configurations and current research hotspots-stacked and up-flow configurations.

2.1 Dual-chamber MFC

The dual-chamber MFC is the most typical system configuration in current MFC research and application. The system usually consists of separate anode and cathode chambers, physically separated by a proton exchange membrane (PEM). The anode chamber houses an anode electrode, whose surface is colonized by electroactive anaerobic microbial communities; the cathode chamber is equipped with a cathode electrode and corresponding catalytic materials. The core function of the PEM is to prevent oxygen diffusion from the cathode chamber to the anode chamber, thereby maintaining a strict anaerobic environment within the anode chamber-this is crucial for the normal growth and metabolism of anaerobic microorganisms and the efficient decomposition of organics in wastewater[5]. Correspondingly, the cathode chamber can independently maintain a stable oxygen-rich environment, providing suitable conditions for the ongoing oxygen reduction reaction. This dual-chamber isolated configuration allows for precise regulation of anaerobic conditions in the anode zone, significantly improving the degradation efficiency of complex organic wastewater pollutants. At the same time, the complete separation between the two chambers of anode and cathode effectively prevents undesired direct contact between oxidants and substrates within the system, minimizing the side reactions risk (as shown in Figure 1) [6]. Dual-chamber MFCs have conducted extensive practical exploration in the treatment and resource recovery of high-concentration industrial wastewater. For example, Karuppiah et al. constructed a dual-chamber MFC system for treating complex dye wastewater, achieving a maximum power density of 6.2 W/m^3, demonstrating stable potential for treating actual industrial wastewater[7].Raychaudhuri and Behera operated a dual-chamber MFC using rice processing wastewater as the substrate and found that acidic pretreatment of the wastewater significantly enhanced both pollutant removal and electricity generation[8].These results indicate the feasibility of this technology for industrial-scale application.

Although dual-chamber MFCs continue to achieve technological breakthroughs in controlled laboratory environments, they still face many obstacles in practical engineering applications. Particularly, the cathode chamber requires continuous aeration, leading to higher material and operational costs, and the expensive PEM required by the system further limits its large-scale application. In recent years, researchers have explored various PEM alternatives suitable for dual-chamber MFCs, including anion exchange membranes, cation exchange membranes, bipolar membranes, salt bridges, and other functional materials with macroporous filtration structures[9-12].In addition, single-chamber configuration MFCs, which completely eliminate the PEM, have gradually become a widely researched direction.

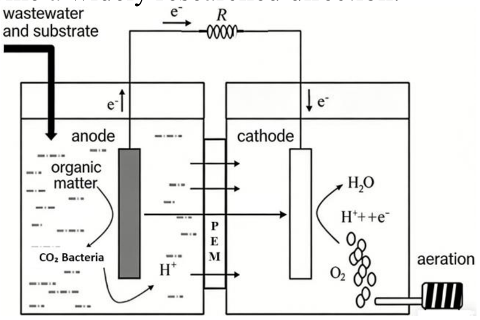

Figure 1. Working Principle of a Dual-Chamber MFC.

2.2 Single-chamber MFC

The most prominent distinction between single-chamber MFCs and traditional dual-chamber MFCs lies in the absence of core components such as PEM in the single-chamber configuration (specific working principle is illustrated in Figure 2), which keeps the overall fabrication cost relatively low. In such a single-chamber design, both the anode and cathode are housed within the same reaction chamber, allowing protons to migrate directly from the anode region to the cathode surface. This shortens the transfer pathway while significantly reducing the internal resistance of the system, ultimately enhancing its current output capacity [13]. The structure of the single-chamber design is generally not overly complex and does not require elaborate control systems, making it suitable for many practical application scenarios. Due to its simple and straightforward construction, single-chamber MFCs perform particularly well in space-constrained environments or situations requiring rapid deployment. Furthermore, stacking multiple units is more convenient, as there is no need for additional complex isolation or control devices. By eliminating the costly proton exchange membrane, overall expenses are further reduced, giving the single-chamber configuration a significant competitive advantage in system integration and multi-layer stacking applications. However, placing both electrodes in the same chamber also introduces potential issues: oxygen can more easily diffuse into the anode region, possibly triggering undesirable side reactions. Over prolonged operation, this may lead to gradual degradation of system performance. Coupled with relatively low energy recovery efficiency and certain design limitations, single-chamber MFCs still face considerable challenges in achieving large-scale practical implementation [14].

Addressing existing problems, researchers are attempting to improve single-chamber MFC configurations by incorporating design advantages from other bioreactors, aiming to retain their advantages of simple structure and low cost while improving operational stability and overall efficiency. For example, by utilizing the photocatalytic activity of semiconductor catalysts or coupling with membrane bioreactors to reduce the occurrence and impact of side reactions. Researchers like Lee coupled the traditional anode with the semiconductor catalyst TiO_2, successfully constructing a solar-driven MFC nanotube array (TNT type) photoanode for single-chamber wastewater treatment. This system generated more electricity while degrading Methylene Blue (MB) dye, achieving a maximum power density of 9.58 W/m^3 (Estimated) and a current density of 4571.43

mA/m^2[15],significantly outperforming traditional configuration MFCs.

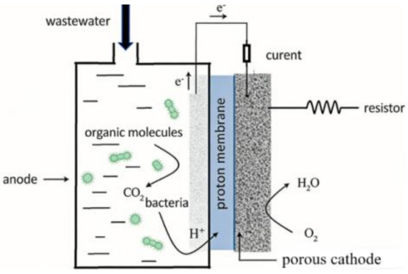

Figure 2. Working Principle of a Single-chamber MFC.

2.3 Up-flow MFC

The up-flow MFC was first successfully constructed by He and his team in 2005[16].Its design characteristic is that the wastewater to be treated enters from the bottom of the reactor and exits from the top, with the cathode chamber under continuous aeration and the anode and cathode connected by external wires. Based on this framework, scholars like Zafar further proposed an anaerobic up-flow filtration type MFC configuration in 2023[17]. In this new configuration, solid particles in the incoming liquid mostly settle at the bottom of the reactor, and only the preliminarily separated filtrate flows at the top, alleviating the issue of floc accumulation during the operation of single-chamber MFC devices. This up-flow structure allows the reaction substrate to continuously pass upward from the bottom through the core anode area, leading to more sufficient contact between the microorganisms attached to the anode surface and the wastewater, significantly prolonging their interaction time. Consequently, the organic degradation efficiency and the overall electricity generation performance of the system show significant improvement.

In the practical application of up-flow single-chamber membrane-less MFCs (whose working principle is shown in Figure 3), their potential for treating complex, non-biodegradable industrial wastewater is being clearly demonstrated through rigorous laboratory tests. The team of Sun used such a reactor for continuous operation over 140 days on wastewater containing the azo dye Acid Black 1 (AB1), with the entire system showing relatively stable operation during long-term operation[18].The researchers found that when the AB1 concentration was controlled at 25 mg/L, the system achieved a chemical oxygen demand (COD) removal rate of 95.5%, while the -N=N- groups and naphthalene structures in the dye molecule were almost completely removed. This result intuitively demonstrates the practical role of the up-flow reactor structure in accelerating pollutant decomposition and transformation, particularly in mitigating internal sludge deposition and enhancing mass transfer efficiency, which can bring tangible benefits to practical engineering applications. However, the researchers also observed that AB1, acting as an electron acceptor during the reaction, competed with the reactor's cathode structure for electron resources. Therefore, as the dye concentration in the wastewater increased, the system's output voltage and power density showed a clear declining trend. This phenomenon made the researchers realize that in real engineering applications, further improvement in electron transfer pathway design and reaction environment control is needed to achieve a more harmonious state between wastewater purification effectiveness and system power output. Overall, this work, through rigorous experimentation, clearly confirmed the practical feasibility of up-flow MFCs for treating complex, recalcitrant dye wastewater. Subsequent work on structural design adjustments and operational parameter optimization for similar reaction systems can draw specific reference from these accumulated experimental data, and more in-depth research can continue in the direction of energy-oriented treatment of complex, recalcitrant organic wastewater.

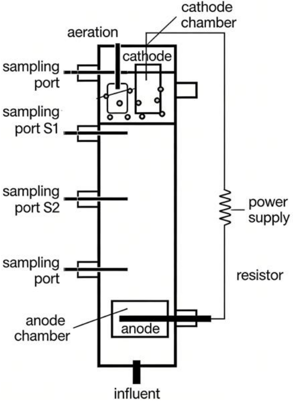

Figure 3. Working Principle of An Up-flow Single-chamber Membrane-less MFC[18].

2.4 Stacked MFC

In current MFC research, enhancing power generation capacity and pollutant removal efficiency remains a key focus, but the power output of a single MFC unit is still insufficient to meet practical application demands[19].Using oxygen as the electron acceptor, its theoretical open-circuit voltage typically does not exceed 1.14 V, and in practical operation, the voltage may even drop below 0.8 V[20],showing a significant gap compared to the energy output of traditional chemical fuel cells. Therefore, connecting multiple MFC units in series or parallel stacks (as shown in Figure 4) has become a key approach to increasing the system's total output voltage and power. In the design and optimization of MFC stack systems, the interconnection method between units directly affects the overall electrical output and pollutant removal performance, providing an important basis for enhancing the practicality of stacked MFCs. One study compared the effects of series, parallel, and hybrid connection modes on the performance of three continuous-flow MFCs[21].It found that under certain operating cost conditions, the series configuration could achieve a relatively high power density (up to 0.81 W/m^3) with good cost-effectiveness. Furthermore, Minutillo et al. compared four different configurations of microbial fuel cells (MFCs). The results showed that the configuration in which every two MFCs were connected in series and then linked in parallel (see Figure 5) achieved the highest power density of 2.451 W/m^3, which was significantly higher than the other connection modes. [22].

It is worth noting that simply increasing the number of electrodes within a single reactor has a limited effect on power enhancement, with a power density of only 0.071 W/m^3[22],far below that of multi-unit stacked systems. This indicates that reasonable unit stacking and connection optimization can more effectively improve the overall output performance of MFCs than simply scaling up the electrode size within a single reactor, providing a reference direction for the future modular design of MFC systems in practical engineering.

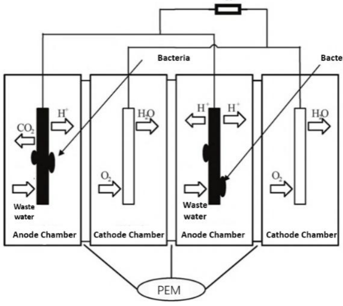

Figure 4. Working Principle of a Stacked MFC.

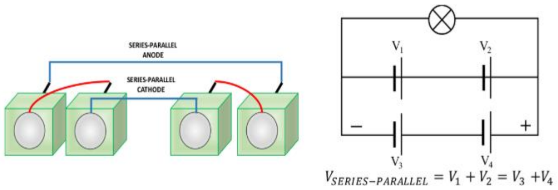

Figure 5. Experimental System by Minutillo et al.[22]

3. Innovations in Core Components

3.1 Anode Materials

In an MFC system, the anode chamber typically contains organic substrates, electroactive microbial communities, and the anode electrode. The choice of anode material affects the overall system cost and directly relates to its electrochemical performance. Current anode materials mainly fall into these categories: first, traditional carbon electrode materials such as graphite rods, carbon cloth, and graphite fiber brushes, which are widely used due to their good conductivity and compatibility with microorganisms[23]; second, metal compounds and their composites, such as iron oxides, titanium oxides, tin oxides, etc.; third, conductive polymers such as carbon nanomaterials like graphene and bio-based polymers[24-26].

Modification operations on the surface of traditional carbon-based electrode materials, such as ammonia treatment, heat treatment, acid treatment, and electrochemical treatment, can further enhance MFC performance. These methods aim to increase bacterial adhesion and accelerate electron transfer to the anode surface. For example, after applying ammonia treatment modification to carbon cloth and using it in an MFC, the startup time was shortened and the power density increased by 20%[27].However, the enhancement magnitude of such methods on MFC power generation performance is not substantial. They do not fundamentally change the inherent properties of the material, remaining at the level of surface modification of the anode material and failing to address the root cause, thereby limiting the space for further performance enhancement. Therefore, recent research has utilized the aforementioned metal compounds, their composites, and conductive polymer materials to modify anode materials or use them directly as electrode materials to pursue performance breakthroughs[28].

Guo et al. successfully synthesized

low-crystallinity ternary transition metal Co-Fe-Ni sulfide material using a facile one-pot solvothermal strategy and employed it as a high-performance MFC anode. During wastewater purification relying on an *Escherichia coli* strain, it generated relatively more electricity. Compared to traditional carbon-based anode materials, the MFC anode developed in this experiment exhibited 4.89W/m^3 (Estimated) power output density, a relatively higher figure. Furthermore, its performance was 8.4% higher than that of its binary sulfide counterparts, demonstrating excellent overall performance[29].Yang et al. developed a novel capacitive bio-electrocatalyst material using a two-dimensional nanomaterial, MXene. When this composite material was uniformly coated on a carbon felt substrate and used as an MFC anode material, the system startup time was significantly shortened, and the anode exhibited a high charge storage capacity of 2747 mC/cm^2, mitigating fluctuations in system output power. This MFC ultimately achieved a maximum power density of 6.01 W/m^3, representing a 54.4% performance improvement compared to the control group. The researchers further revealed that the anode surface was specifically enriched with an electroactive genus, *Desulfuromonas*, known for its electricity-producing capability, verifying from a microbial ecology perspective the strong affinity and selectivity of this anode material's interface for efficient electrogenic microbial strains[30].

3.2 Cathode Materials

The cathode is the core functional site for the oxygen reduction reaction (ORR) within an MFC. The material choice for this key component directly determines the upper limit of the system's power output and profoundly influences the specific path towards large-scale practical application. Platinum-based electrodes, relying on their extremely prominent ORR catalytic efficiency, have been regarded as the performance benchmark for such electrode materials over decades of research and application. However, in real-world complex application scenarios, they face significant limitations: relatively high preparation costs and the finite nature of natural resource reserves. These primarily present insurmountable economic barriers to the large-scale popularization of the technology. Moreover, in the complex and variable actual operating environment of air-cathode bio-cathodes, platinum catalysts have very low tolerance to various toxic substances. Common components in wastewater, such as sulfides and chloride ions, can easily cause irreversible deactivation of the catalyst's active sites, leading to a continuous, slow decline in catalytic performance[31].Therefore, developing non-platinum or low-platinum cathode materials that simultaneously possess relatively high catalytic activity, excellent environmental stability, and not excessively high preparation costs has become one of the core research directions crucial for the broader and more mature application of MFC technology.

In recent years, non-precious metal catalysts have been extensively applied within MFC systems due to their diverse raw material sources and relatively low cost. Among these, MnO_2 and TiO_2 are currently the relatively high-frequency research subjects for MFC cathode-side catalysts[32].Additionally, transition metal macrocyclic compounds and conductive polymers also exhibit stable chemical activity under specific operating conditions[33, 34].The demetalation utility of such materials and their relatively good catalytic characteristics for oxygen reduction give them considerable research value in the field of cathode materials.

3.3 Membrane Materials

The proton exchange membrane (PEM), as a key component of dual-chamber MFCs, serves the core function of constructing a selective ion channel, allowing protons to migrate smoothly between the electrodes and thereby maintaining charge balance. Currently, perfluorosulfonic acid membranes (e.g., Nafion NF-117) are the most widely used membrane materials. Additionally, other separation methods like salt bridges, anion/cation exchange membranes, and porous filter membranes are also under active development. Nafion membranes have high proton transfer efficiency, but the commercial promotion of such materials has long been hindered by relatively high and fluctuating costs. Market analysts mention that Nafion membrane prices have shown significant fluctuations over the past decade, exhibiting an overall upward trend; the latest statistics indicate its unit price has climbed above $1500 per square meter[35], representing a major economic obstacle to the large-scale application of MFC technology. This situation has also prompted researchers to actively explore alternative separation methods with more prominent cost advantages.

Dhanda et al. designed and prepared a composite membrane based on natural clay, incorporated with sulfonated titanium nanotubes (s-TNT) and montmorillonite (MMT). The introduction of s-TNT constructed efficient proton transport channels within the clay skeleton: sulfonic acid groups can act as proton carriers, while the titanium nanotube structure enhances the membrane's mechanical stability and water retention, helping to inhibit clay layer swelling. The resulting direct effects are relatively prominent. The membrane with the optimal composition (containing 10% s-TNT) achieved a relatively high ion transport number of 0.85 and a low internal resistance of 88.75 Ω in an MFC. Compared to the unmodified pure clay membrane, its power density increased to 2.17 W/m^3 (Estimated),a 2.62-fold increase, and its coulombic efficiency reached 26.71%[36].Bipolar membranes, leveraging their unique ion regulation capabilities, adjust the MFC reaction environment and improve the efficiency of specific processes. Their core mechanism lies in separating and stabilizing the pH of the electrode regions. For instance, in heavy metal wastewater treatment scenarios, bipolar membranes can maintain suitable pH conditions in the cathode area, significantly improving the reduction and removal rate of hexavalent chromium while enhancing system power generation performance. However, in bioelectrocatalytic hydrogen production processes, although such membranes can help maintain a high pH environment in the cathode chamber favorable for hydrogen evolution, their relatively large internal resistance limits current output and hydrogen generation rates[10].The dual-chamber salt bridge MFC studied by Lee et al. used a low-cost agar-electrolyte salt bridge (e.g., using 3M NaCl and 12% agar) to replace the expensive PEM. This constructed system demonstrated clear application potential in degrading organic wastewater while generating energy by adjusting key system parameters and selecting suitable electrode materials. For specific wastewater like tofu wastewater, its COD removal rate could exceed 95%. Although limited by the relatively high internal resistance of the salt bridge itself, its power density cannot yet match that of high-end membrane reactors, the prominent cost advantages, ease of maintenance, and integrated functionality of this technical route offer a promising and experimentally verified alternative for MFC applications in decentralized wastewater treatment scenarios, especially where electricity and funds are relatively limited[15].

4. Coupled Systems based on MFC

Although MFCs show considerable application promise from a technological potential perspective, their current power generation capacity and removal efficiency for recalcitrant pollutants are insufficient to support their large-scale application in various practical scenarios. Therefore, combining MFCs with other mature technologies for water treatment or energy recovery to build systems with coupled or integrated functionalities has become a core research direction for breaking through existing performance bottlenecks and achieving efficiency enhancement. The following sections will introduce three specific coupled systems: MFC-Constructed Wetlands (CW-MFC), MFC-Membrane Bioreactors (MBR-MFC), and MFC-Microbial Electrolysis Cells (MFC-MEC).

4.1 MFC-Constructed Wetland (CW-MFC)

Constructed wetlands (CWs) represent a green technology that simulates the ecological processes of natural wetlands. Within them, vegetation layers consisting of emergent and submerged plants interact with diverse microbial communities and various filling media to create a microenvironment characterized by alternating aerobic and anaerobic zones. This inherent feature aligns well with the functional requirement of separating the anode and cathode chambers in microbial fuel cells (MFCs), thereby facilitating the integration of the two technologies and leading to the development of the Constructed Wetland-Microbial Fuel Cell (CW-MFC) system (see Figure 6) [37]. In this system, the anode is embedded within the anaerobic substrate layer at the bottom of the wetland, where it enriches electroactive bacteria capable of degrading organic matter and generating electrons. The cathode is placed in the aerobic zone near the upper water layer or plant roots, utilizing dissolved oxygen in water or atmospheric oxygen to complete the reduction reaction. By integrating the electrode system into the constructed wetland’s media bed, the system achieves simultaneous wastewater purification and electricity recovery. Although structurally more complex than conventional constructed wetlands, it fully leverages the oxygen-transporting function of plant roots and the microbial enrichment capacity of wetlands, enabling the dual goals of pollutant removal and energy recovery. Thus, CW-MFC is not merely a combination of two technologies; rather, it represents an organic fusion of the ecological purification mechanisms of constructed wetlands and the bioelectrochemical power generation principles of MFCs. Building on the established engineering applications of constructed wetlands and the naturally occurring redox gradients within them, such integrated systems also hold potential for cost control during construction. They further open new research pathways for developing low-energy, sustainable decentralized wastewater treatment and energy recovery technologies[38].

Early experiments and explorations by researchers have clearly verified the technical feasibility of such integrated systems. In 2012, Yadav et al. constructed the first CW-MFC, which achieved power output on the order of tens of milliwatts per square meter while treating relatively high-concentration dye wastewater[39].As related research became more detailed, the configuration designs of such systems gradually diversified, evolving into various operational modes such as upflow, downflow, and upflow-hybrid. Among these, the upflow CW-MFC, which performs well, has received considerable attention in the industry due to its effective way of coordinating the contradiction between "anaerobic electricity production" and "aerobic reduction"[40]. In this specific design framework, the anode is buried deep within the dense substrate layer at the wetland bottom, aiming to utilize the rich organic matter in the influent to nourish the electricity-producing microbial community. The cathode is distributed in the wetland surface layer or areas dense with plant roots, ensuring full and continuous contact with air or dissolved oxygen in the water. When the wastewater to be treated is slowly injected from the system bottom, oxidation reactions first occur in the bottom anaerobic zone, releasing energy-carrying electrons. The water then gradually flows upward to the aerobic zone to complete subsequent reduction reactions. This orderly bottom-to-top flow path not only meticulously simulates but also reinforces the natural material cycling process in wetlands. More importantly, it helps maintain a stable redox potential difference between the bottom anaerobic zone and the upper aerobic zone, thereby continuously driving electron flow and generating usable electricity. Therefore, the upflow design not only improves the stepwise degradation process of pollutants but also fundamentally enhances the system's electricity generation capacity and operational stability.

The path of CW-MFC technology towards practical application is mainly constrained by three major bottlenecks: technological maturity, economic viability, and energy output efficiency[41, 42].As an emerging interdisciplinary technology, its engineering experience is scarce, and the long-term stability of system operation needs verification. Simultaneously, the cost of electrode materials and the integrated system makes its construction and maintenance expenses higher than traditional wetland processes, and its economic advantages have not yet materialized. The most fundamental constraint is that the internal electron recovery rate and energy conversion efficiency of the system are still at relatively low levels, and the limited power output is difficult to meet the demands of scaled-up applications. These factors together constitute key challenges that urgently need to be overcome for the development of this technology.

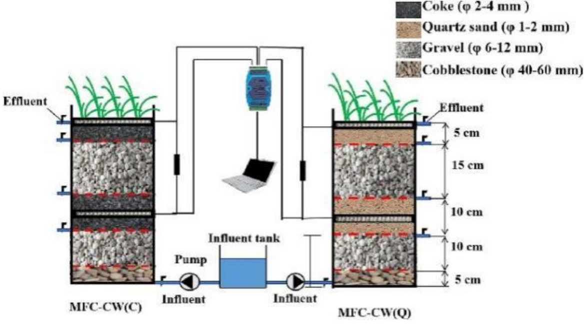

Figure 6. Schematic Diagram of a CW-MFC Working System[38].

4.2 MFC-Membrane Bioreactor (MBR-MFC)

Membrane Bioreactors (MBR) for water treatment, operating on a model combining efficient biological treatment processes with precise membrane separation technology, show relatively prominent advantages in treatment efficiency and space utilization. However, membrane fouling and high energy consumption pose obstacles to their further promotion[43].In a complementary manner, Microbial Fuel Cell (MFC) technology, capable of recovering usable energy directly from various complex wastewaters, can provide additional electrical energy output to the entire water treatment operation system, potentially compensating for part of the energy consumption generated during the aeration and membrane filtration processes in MBR operation. In terms of membrane fouling control, the electrons produced by the MFC anode reaction are directionally transmitted via an external closed circuit. This not only enhances the efficiency of the electron utilization pathway but the accompanying weak electric field has also been proven to help reduce pollutant deposition on the membrane surface, thereby alleviating a major bottleneck in the core operation of MBRs[43, 44]. This synergistic effect allows the system to move towards energy self-sufficiency or net energy production while strengthening pollutant degradation.

Cao et al. constructed a set of equipment consisting of a double-anode MFC serially connected to a biofilm electrode reactor, specifically designed for treating the azo dye Reactive Red. In the specific operational logic of this device, the MFC, along with the bioelectrochemical electrons generated during operation, were collectively delivered to the subsequent connected biofilm reactor to promote further reductive degradation of the dye. Relevant test data showed that this coupled device increased the removal rate of Reactive Red by approximately 42% while achieving a peak power density of 0.169 W/m³, demonstrating synergy between energy production and enhanced treatment[45]。Another study on an MBR-MFC coupled system indicated that the operational parameters of the device have a decisive impact on its overall efficiency. Adjusting the mixed liquor recirculation ratio can significantly improve the hydraulic conditions and microbial community distribution within the reactor. As the recirculation ratio gradually increased, the device's power generation efficiency was noticeably enhanced, achieving a maximum output voltage of 0.55 V and a power density of 33.01 W/m³[46]. This result suggests that engineering-based regulation methods can play a role in improving the comprehensive efficiency of such coupled devices.

Although specific observations have been drawn from related research work, MBR-MFCs still face numerous challenges to be overcome. One is the relatively high procurement cost of membrane and electrode materials, leading to not insignificant daily operating expenses, which in turn further increases the overall construction and long-term operation and maintenance costs. Additionally, both MBR and MFC technologies involve a certain level of technical complexity, coupled with significant daily operation and maintenance management difficulty, making the actual deployment of such coupled systems more challenging[47].

4.3 MFC-Microbial Electrolysis Cell (MFC-MEC)

Microbial Electrolysis Cells (MECs), as a technology capable of converting organic matter in wastewater into energy products like hydrogen by applying an external voltage[48], are complementary in principle to MFCs. Integrating the two to form an MEC-MFC coupled system holds promise for simultaneously improving energy recovery efficiency and pollutant removal effectiveness. In this synergistic system, the MFC can utilize part of the hydrogen produced by the MEC for power generation, while the current generated by the MFC can also provide partial electrical support for MEC operation, thereby achieving internal energy circulation and enhancement[49]. Furthermore, researchers have utilized the electric field generated by MECs to directly act on MFCs. A recent study constructed such a coupled system, applying parallel or opposing external electric fields via the MEC to regulate and accelerate the extracellular electron transfer process on the MFC anode surface based on the principle of electric field superposition. The research results showed that, regardless of the electric field direction, the applied external field could significantly promote the formation of the MFC anode biofilm and enhance its electrochemical activity, ultimately more than doubling the coupled system's power density compared to a standalone MFC (increases of 117.8% and 108.4%, respectively)[50]. This case indicates that beyond simple material and energy exchange, actively regulating interfacial reactions through electrochemical means is a key direction for unlocking the performance potential of MFC-MEC coupled systems. Moreover, this system can effectively recover methane in addition to hydrogen production, enhancing the level of resource recovery.

Similar to the two coupled systems mentioned above, the MFC-MEC system also faces a series of currently difficult-to-break-through problems.

The main two aspects are: maturity-related technical limitations in stability and efficiency, and over-sensitivity to environmental influences due to the dependence of both MFC and MEC efficiency on microbial activity[19].

5. Conclusion and Future Outlook

Wastewater, as an underutilized resource, exhibits tremendous application potential. MFCs, as a green technology capable of converting the chemical energy in wastewater into electricity, possess enormous development prospects. To date, researchers exploring this field have made significant progress in MFC system configurations, core components, and coupled systems. However, factors such as low energy output, poor stability, and high manufacturing costs still constrain the possibility of MFCs moving from the laboratory to large-scale application. Future advancements by scientists in these areas, the development and implementation of new optimization strategies and hybrid bioelectrochemical systems, as well as circular economy approaches, may be key to driving the wider adoption and success of MFCs on an industrial scale.

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