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Research advances and performance enhancement of microbial fuel cell technology in organic wastewater treatment

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Article info

Abstract

Microbial fuel cells (MFCs) employ microbial communities as biocatalysts, where organic substrates are oxidized and the resulting electron–proton flows are harnessed to both degrade contaminants and produce electrical energy. Optimization studies indicate that a Pt-Fe/C composite catalyst is employed at the anode, along with graphite felt as the cathode, while modifications such as MWNT modification or ammonia pretreatment are applied at the anode. The MFC operates effectively within a pH range of 6.0 to 7.0 and is capable of treating various types of wastewater. In the denitrification system, the removal efficiency of nitrate nitrogen reaches 91.35%, and the Cr(VI) removal rate at Ana-B cathodes is 97.05%; this coupling technology addresses existing limitations. Microbial fuel cells offer significant environmental and energy benefits. Future advancements in MFCs should prioritize the development of low-cost electrodes for practical engineering applications.

Keywords: Microbial fuel cell, organic wastewater treatment, electron transfer mechanism, electrode material optimization, coupling technology, efficiency optimization

1. Introduction

Wastewater with different kinds of organic substances (fatty acids, carbohydrates, etc.) and heavy metals (chromium, copper, etc.) have seriously polluted the environment. Chemical oxidation is commonly used to treat wastewater, in which the oxidant decomposes organic matter into harmless small molecules. Its advantages are that the method is highly efficient and can treat recalcant organic matter, but the cost of the oxidant and the problem of secondary pollution should also be considered. Adsorption is also commonly used. The adsorbent uses its porous structure and surface activity to adsorb the pollutant. Activated carbon can remove organic matter and heavy metals, zeolite can remove ammonia nitrogen and heavy metals at low cost, and biochar can both adsorb and degrade. However, its application needs to select the appropriate adsorbent and determine the optimal parameters according to the composition of the wastewater and the concentration of the pollutant. It also suffers from a low contaminant-removal efficiency due to the restricted adsorption capacity of the sorbent, and the saturation of the material may further lead to potential secondary pollution. In addition, the cost and difficulty of large-scale application of some highly efficient adsorbents and the low adsorption efficiency of adsorption for low concentration pollutants. Compared with these two, MFCs are more economical and environmentally friendly. It treats organic compounds as the energy source and transforms their chemical energy into electricity via bioelectrochemical processes, where the redox potential difference established between the anode and cathode

serves as the driving force for power generation. At the anode, microorganisms oxidize the organic substrates, releasing electrons and protons. The electrons are delivered to the cathode through the external circuit, while the protons migrate through the medium or membrane. At the cathode, these electrons participate in a catalyzed reduction reaction, thereby completing the overall redox cycle. This review summarizes the principle and development of wastewater treatment to provide technical basis for the application of organic wastewater treatment.

2. Microbial fuel cells

Microbial fuel cells are systems designed to convert the metabolic processes of microorganisms into electrical energy while simultaneously treating wastewater. The fundamental principles of MFCs are illustrated in Fig. 1. ① Bio-oxidation of substrates: In the anode chamber, microorganisms utilize organic substances for energy, releasing electrons, protons (H^+), and carbon dioxide (CO_2). ② Electron and proton transport: Electrons reach the anode through direct microbial transfer or with the assistance of mediators, whereas protons migrate toward the cathode either across an ion-exchange membrane or through the internal environment of the MFC. ③ Cathodic reactions: The electron acceptor present in the cathode compartment receives incoming electrons and reacts with protons to form water. ④ Current production: The movement of electrons between the anode and cathode through the external circuit gives rise to an electric current.

Cathodic and anodic reactions proceed with oxygen serving as the terminal electron acceptor and sodium acetate acting as the electron-donating substrate.

cathode: $O_2+4H^++4e^-\rightarrow 2H_2O$

anode: $CH_3COO^-+H_2O\rightarrow HCO_3^-+H^++e^-$

Overall reaction formula: $CH_3COO^-+2O_2=HCO_3+H^+$

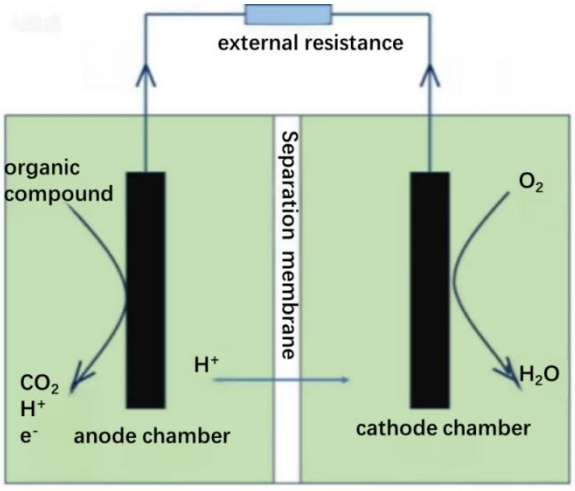

Figure 1. Schematic diagram of the classic dual-chamber MFC principle

2.1 Electron Transport Mechanism

1. Direct electron transfer mechanism

Direct electron transfer is the most efficient way of electron transfer. Its fundamental mechanism relies on microorganisms interacting directly with extracellular electron acceptors and channeling electrons via outer-membrane proteins, thereby transforming the chemical energy stored in organic substrates into electrical energy.

2. Indirect electron transfer mechanism

Microorganisms transfer electrons to electrodes via electron shuttles (ES), which can connect bacterial metabolism with the anode and improve transfer efficiency. Endogenous ES is generated naturally during microbial metabolism and is environmentally benign; however, its secretion level is relatively low, resulting in limited overall efficiency; exogenous ES is produced by externally added chemical substances, which can quickly improve efficiency, but requires regular replenishment, and some are toxic or increase costs.

2.2 Key Factors Influencing the Performance of MFCs

1. Electrode

The efficiency of the cathode reaction is crucial to battery performance, depending on the kinetics of the final electron acceptor reduction reaction, and can be classified as biological or non-biological based on the catalyst. The anode is the core of power generation efficiency, providing a habitat for microbial growth and determining electron-proton transfer; therefore, the material selection must have optimized chemical durability, good conductivity, and a large specific surface area.

Ying-Yue Chang et al. hydrothermally synthesized Pt/C and Pt-M/C (M=Fe, Co, Ni) cathode catalysts for use in dual-chamber MFC treatment of synthetic culture medium and molasses wastewater. Pt-M/C showed better catalytic activity than Pt/C, while Pt-Fe/C showed the best activity, increasing the maximum power density of MFC by 31% without affecting COD removal. This provides a basis for the development of low-cost and high-efficiency MFC catalysts [1].

Bruce Logan et al. fabricated a graphite brush anode by winding graphite fibers around a titanium wire core for use in air cathode MFCs. This anode enabled a peak power density of 2400 mW/m^2 in a cubic MFC, lowered the internal resistance to 8 Ω, and showed strong resistance to biofouling. This design provides an efficient and feasible anode solution for the large-scale application of MFCs [2].

2、pH

The pH environment is a key determinant of microbial physiological activity, and consequently exerts a significant influence on the electricity-producing performance of MFCs that rely on electrogenic microbes.

Chi-Wen Lin and colleagues utilized Cu(II) as an electron shuttle and implemented response surface methodology (RSM) to investigate how various microbial fuel cell (MFC) operating conditions relate to the efficiency of Cr(VI) removal [3].

S. Veer Raghavulu et al. used mixed bacterial communities as anode biocatalysts and employed a two-chamber MFC to treat chemical wastewater under different anode pH (6, 7, 8) and ferricyanide/aerated catholyte conditions. The results showed that acidic anodes produced the best electricity, neutral anodes were optimal for substrate degradation, and ferricyanide catholyte was conducive to electricity generation. This study provides a basis for optimizing MFC efficiency [4].

2.3 Basic Structure of Microbial Fuel Cells

(1) H-type dual-chamber MFC

The dual-chamber MFC is an improved MFC where the anode and cathode are placed in two separate containers (Figure 2). An ion exchange membrane separates the anode and cathode chambers, improving system stability and efficiency. Its advantages include isolating the two electrode reactions and reducing side reactions, but the ion exchange membrane is prone to clogging, leading to a decrease in power generation efficiency in the later stages.

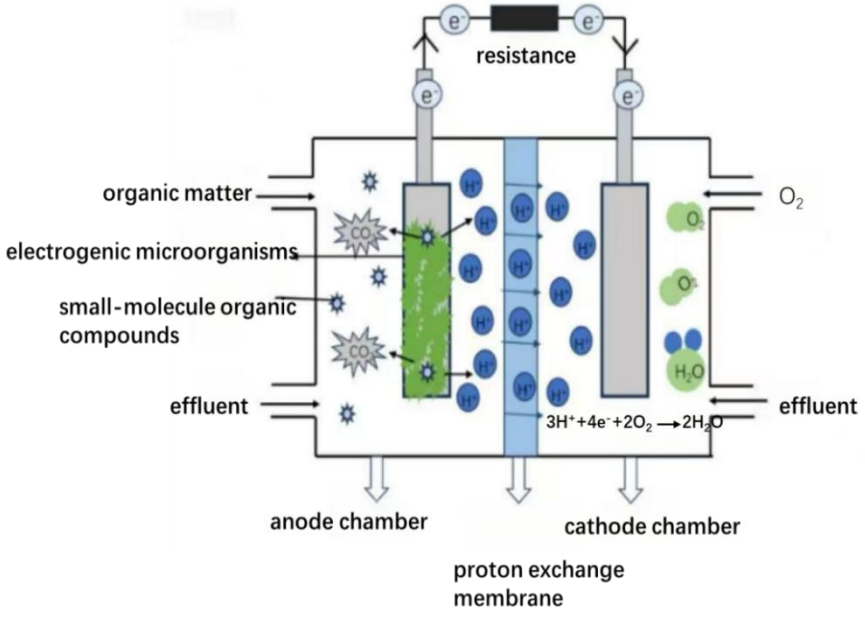

Figure 2. H type dual-chamber MFC

(2) Single-chamber MFC with an air cathode

Single-chamber MFCs employ an air-exposed cathode similar to that used in two -chamber configurations, but they eliminate both the ion-exchange membrane and the separate cathode compartment (see Figure 3). In this configuration, oxygen from the surrounding air functions as the terminal electron acceptor. The design is compact, and its energy conversion efficiency surpasses that of various battery types. Nevertheless, due to the proximity of the electrodes, there is a potential for oxygen to migrate from the cathode to the anode, which disrupts the anaerobic conditions necessary for the anode, ultimately diminishing microbial activity and leading to a reduction in power generation efficiency.

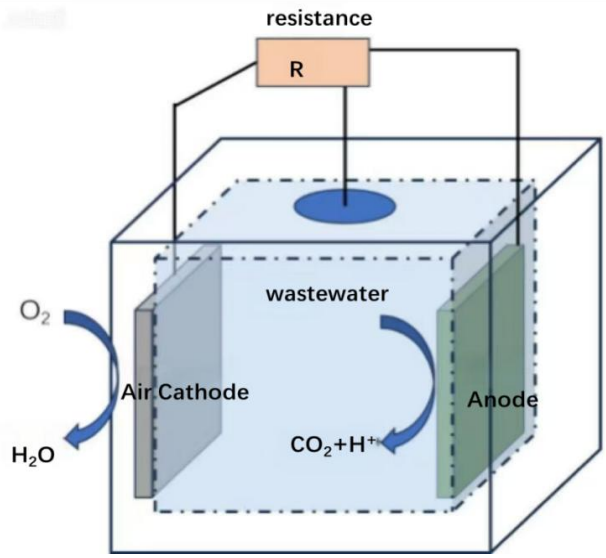

Figure 3. Air-cathode single-chamber MFC

(3) MFC battery pack

Building up battery packs to achieve cumulative power generation performance is the simplest and most direct way, which can immediately improve the performance of MFC. However, since the cost of each battery pack is different, this method is not suitable for every type of MFC. Moreover, series and parallel connections may also produce negative effects such as reverse voltage and reverse polarity.

3. Applications of microbial fuel cells

3.1 Nitrogen and phosphorus removal using microbial fuel cells

The removal of nitrogen and phosphorus from municipal wastewater is a critical task in environmental management. Surface water and domestic sewage in China are typically marked by low organic carbon content alongside elevated nitrogen and phosphorus levels. Insufficient organic matter leads to a lack of electrons in denitrification, affecting nitrogen removal efficiency. Anthropogenic nitrogen pollution accumulates rapidly, damaging ecosystems and harming health; untreated wastewater discharged directly will lead to eutrophication. Furthermore, phosphorus

is an essential element for life, and the Earth's phosphate reserves may be depleted within 50 years, with shortages impacting food production. Therefore, research on wastewater nitrogen and phosphorus removal and phosphorus recovery is of great significance.

Jakub Drewnowski et al. used a two-chamber MFC to investigate the effect of nitrate on its performance: 0-4.0 ppm nitrate did not affect the current density; the current density decreased when it exceeded 6.0 ppm; when it exceeded 4 ppm and persisted, the voltage dropped by about 0.013 mA/m² for every 1 ppm increase in concentration, and the maximum denitrification rate of the bacterial community was about 60 mg$NO_3^-\cdot L^{-1}\cdot h^{-1}$. This study provides parameter support for scenarios such as nitrate-containing wastewater treatmen [5].

Lian-gang Hou et al. established a coupled system that combined an MFC with microbially driven denitrification to treat nitrogen-containing wastewater. Their findings indicated that the MFC produced a peak voltage of 0.246 V during a single operational cycle, and the integrated system achieved an overall nitrate removal efficiency of 91.35%. This work addressed the challenge of achieving effective denitrification in wastewater with a low carbon-to-nitrogen ratio, streamlining the treatment process and lowering operational costs, thereby offering a promising strategy for low-carbon wastewater remediation [6].

O. Ichihashi and co-workers used a single-chamber, air-cathode MFC—featuring a carbon-felt anode and a Pt/C-coated carbon-paper cathode—and inoculated it with paddy soil to treat swine wastewater. They reported a peak power density of 2.3 W/m², coupled with a COD removal efficiency ranging from 7% to 91%, a phosphorus removal efficiency between 70% and 82%, and a phosphorus recovery rate at the cathode of 27%. The precipitate formed was identified as struvite. Notably, there was no need for chemical pH modifications, and both power generation and phosphorus recovery occurred concurrently, thereby offering a novel approach to phosphorus recycling and cost-effective wastewater treatment [7].

Fabian Fischer et al. used MFC to reduce and digest ferric phosphate in sludge using electrons and protons produced by E. coli metabolism, mobilizing orthophosphate. Magnesium chloride and ammonia were then added to precipitate struvite, with a product purity of 90% and no toxic metals. This technology realizes decentralized phosphorus recovery and provides a new path for sludge resource utilization [8].

3.2 Microbial fuel cell treatment of dye wastewater

Dye wastewater has a serious impact on the environment because of its complex composition, high hazard and difficulty of degradation. With the rapid growth of the

dye industry, the amount of dye wastewater discharged into the environment is rising dramatically. Dye wastewater has become one of the three typical types of recalcitrant and highly hazardous wastewater. Many researchers have studied the treatment of dye wastewater. Microbial fuel cell (MFC) is a new electrochemical device, which can degrade and transform pollutants via microbial metabolism, and attracted much attention due to its two typical applications, wastewater treatment and energy recovery.

Xiangfeng Xie and colleagues devised a composite system using CW-MFC to address wastewater containing the X-3B azo dye at varying concentrations. The anodic section played a significant role, showing improved results in closed-loop degradation. At an external resistance of 2000Ω with a concentration of 100mg/L, the removal rate of COD reached 60.0%, while the decolorization achieved 85.8%. These findings demonstrate the method's potential for effectively treating high-strength wastewater [9].

Jian Sun and co-workers constructed a dual-chamber MFC equipped with an aerobic biocathode to decolorize wastewater containing the azo dye Reactive Brilliant Red X-3B. After 12 hours of operation, the system achieved a COD removal rate of 24.8%, and the power density generated from the decolorization solution increased from 50.74 μW to 213.93 mW/m². The decolorization by-product generated from the MFC can be further processed using Redox media. This study marks the first documentation of the MFC's capability to effectively treat azo dye wastewater and provide a reduction in treatment costs [10].

Zhou Fang use CW system to evaluate the fraction of azo dye ABRX3, and dye-related COD levels affect . Optimal performance was obtained at an HRT of 3 days, a COD concentration of 300 mg/L, and an ABRX3 ratio of 30% and a power density of 0.852 W/m³. These results offer valuable guidance for optimizing azo-dye [11].

3.3 Microbial fuel cell treatment of chromium-containing wastewater

Tanning, electroplating and dyeing industries produce huge amounts of chromium-containing wastewaters. Chromium exists in two forms: trivalent chromium [Gr(III)] and hexavalent chromium [Gr(VI)]. Gr(III) is an essential trace element for living beings. However, under natural conditions, Gr(III) can be transformed into Gr(VI) through oxidation by manganese-containing minerals or photo-oxidation. Gr(VI) is 100 times more toxic than Gr(III). It is highly mobile, hydrophilic and easily absorbed and accumulated in living bodies. Severe symptoms include nosebleeds, respiratory infection, skin rash, chromosomal aberration and lung cancer.

Hui Wang et al. explored the use of a dual-chamber MFC to treat Cr(VI)-contaminated wastewater. The system exhibited declines in maximum voltage, coulombic efficiency, and peak power density, whereas the Cr(VI) removal rate increased from 0.03 to 0.14 mg/(L·h). This study provides fundamental principles and references for low-energy, resource-recovering treatment of heavy-metal wastewater [12].

Xinglan Cui et al. employed Ana-B as the cathodic catalyst in an MFC system. At lower initial Cr(VI) concentrations, the removal performance markedly improved; for example, an initial concentration of 10 mg/L resulted in a maximum removal efficiency of 97.05%. Under acidic conditions (pH = 2), the peak removal rate reached 94.27%. The incorporation of Ana-B significantly enhanced Cr(VI) reduction efficiency, offering new perspectives and scientific support for environmental remediation of this pollutant [13].

Dolly M. Revelo et al. found that the P3 battery (Pastow River inoculum, glucose 0.05 mol/L) and the S3 battery (sulfide-containing sludge inoculum, glucose 0.05 mol/L) had highest Gr(VI) reduction rates, 86.3% and 70%, respectively. This study realized Cr(VI) reduction and power generation by a low-cost device. It provides basis for pollution remediation and low-cost energy devices [14].

3.4 Microbial fuel cell treatment of antibiotic wastewater

The extensive application of antibiotics has greatly prolonged human life span and greatly decreased the difficulty of treating infectious diseases due to the ease of use and fast effects of antibiotics. However, if the antibiotic-containing wastewater is not properly treated, it will cause severe pollution. Antibiotic wastewater will accumulate in the environment and then enter humans or animals through the food chain, promoting the emergence of highly drug-resistant bacteria, increasing the chance of infection and making clinical treatment more difficult; meanwhile, it will damage the structure of the natural environment microbial community, making the original ecosystem weak and unable to function normally.

Qing Wen et al. glucose and penicillin mixture or penicillin as fuel to treat synthetic penicillin wastewater. Using a mixed substrate of the system achieved a maximum power density of 101.2 W/m^3—approximately six times higher than when each component was supplied alone—and reached a penicillin degradation efficiency of 98% within 24 hours. This demonstrates a feasible approach for simultaneous antibiotic wastewater degradation and electricity generation [15].

Brim Stevy Ondon et al. employed a single-chamber MFC to treat wastewater containing norfloxacin (NFLX). The system demonstrated strong tolerance to NFLX concentrations up to 128 mg/L, achieving a maximum NFLX degradation efficiency

of 65.5% and a COD removal rate of 94.5%. At the same time, it was capable of power generation, reaching a peak power density of 700 mW/m². The abundance of antibiotic-resistance genes produced was significantly lower than that observed in conventional wastewater treatment plants, indicating that this approach offers a promising alternative for antibiotic-contaminated wastewater treatment [16].

Tunc Catal et al. used air-cathode single-chamber MFC as the core, and combined with LC-MS/MS and density functional theory calculations, to monitor the neomycin sulfate containing wastewater. The MFC can partially degrade the antibiotic (the degradation rate exceeds 88% at 20 mg/L), and the power generation performance is linearly suppressed with the concentration increase. It has been confirmed that the MFC can sensitively detect the neomycin sulfate in wastewater, and provides a new way for antibiotic wastewater sensing [17].

4. Microbial fuel cell coupling technology

4.1CW---MFC Technology

CWs are control and engineered wetland systems that mimic the natural wetland ecosystem processes through the engineered and designed wetland system. Treatment of wastewater by CWs through microbial degradation, sedimentation and filtration.

Chunxia Mu et al. designed an upflow CW-MFC packed with different filler materials to treat wastewater containing Cr(VI). Among the tested media, the unit filled with volcanic rock showed the best performance, achieving 99.0% Cr(VI) removal, an output voltage of 0.595 V, and a maximum power density of 0.462 W/m³. These results indicate that volcanic rock is an optimal and cost-effective filler for CW -MFCs in heavy-metal wastewater remediation [18].

Meixue Dai et al.Constructed CW and CW-MFC for SMX-containing wastewater treatment for 70 days. The TN, NH_4^+-N and SMX removal of CW-MFC were 6.87, 21.07 and 11.05% higher than that of CW, and the maximum power density was 7.428 mW/m². In addition, the sulfonamide resistance gene abundance of CW-MFC was lower than that of CW. This work provides an efficient and low-risk technology for treating antibiotic wastewater [19].

Cong-Yun Zhu et al.Constructed CW-MFC for nitrogen-containing wastewater treatment by dividing the wastewater into different zones (R1) and directly inoculating with AGS. R1 could obtain high removal of COD (85%), Org-N to NH_3-N conversion (80%), NO_3^--N to gaseous nitrogen conversion (90%), and nitrification rate (94%) at aeration rate of 100 mL/min, and AGS was also more stable. This work provides an efficient solution for treating high-load nitrogen wastewater [20].

4.2 PEC---MFC Coupling Technology

In order to overcome the limitation of photoelectron-hole recombination in photocatalysis process, photoelectrocatalysis（PEC） technology has been developed. PEC technology integrates electrocatalysis （EC） and photocatalysis （PC） to enhance the removal efficiency of pollution control. MFC can offer low voltage needed for photoelectrocatalysis, and the energy consumption of PEC technology is reduced, and the treatment efficiency is improved.

Xizi Long et al. constructed a coupled MFC–PEC system connected in parallel for the treatment of azo-dye wastewater. In the MFC alone, the COD removal efficiency reached 56% and the decolorization rate was 85%. When integrated with the PEC unit, these values were reduced to 25% and 12%, respectively, while the PEC enhanced the MFC's maximum current output by 14.2%. The combined system ultimately achieved thorough dye decolorization and effective degradation of intermediate products, offering a novel strategy for dye-containing wastewater treatment [21].

Sergi Garcia-Segur et al. employed PEC technology using semiconductors（suc h as TiO_2） as photoanodes in combination with photocatalysis and electrolysis to remove organic pollutants such as dyes and chemicals from wastewater. The photoelectrolysis can effectively separate the electron-hole pairs, and the effect of its degradation is better than the two kinds of single process，providing a new idea for the treatment and industrial application of recalcant organic wastewater [22].

Xu Zhao et al. used Bi_2MoO_6 thin film electrodes as photoanodes to degrade triazine-containing azo dyes under visible light（λ>420 nm） by PEC technology. Due to the effect of hydroxyl radicals, the rate of the degradation of this technology is much higher than that of electro-oxidation and photocatalysis, and the electrode is stable. An effective solution for the treatment of visible light driven dyes wastewater has been found [23].

4.3 Electrical Fenton-MFC Coupling Technology

Electro-Fenton oxidation represents an innovative form of advanced oxidation technology that has evolved from traditional Fenton reactions. The underlying mechanism involves the electrons produced in the anode compartment traveling through an external circuit to the aerobic cathode, where hydrogen peroxide (H2O2) is synthesized. Following this, the Fe2+ introduced into the system gets reduced by these electrons, facilitating the breakdown of pollutants.

Jiaqi Lv et al. introduced PANI-Mn/CF composite anode into microbial fuel cell-driven electric Fenton process, and the power density of microbial fuel cell-driven electric Fenton process was enhanced from 5.49 times to the original CF anode, and the ohmic resistance was reduced to 7.17 Ω; the TCOD removal rate of anode sludge

was 37.14% and tetracycline hydrochloride removal rate of cathode was 93.03% within 10 h. System bottleneck was broken through and the recalcitrant pollutants were efficiently removed [24].

Huanhuan Zhao et al. constructed an MFC-Fenton coupling system. After 6 months, the herbicide mesotrione in anolyte was degraded, and the generated electricity promoted the in-situ generation of H_2O_2 in the cathode. When the process was optimized, the anolyte degradation rate was 0.83 mg/（L·h), and the cathode Fenton oxidation rate was 1.39 mg/（L·h), and it could remove a variety of pollutants. An efficient and sustainable treatment system for recalcitrant pesticide wastewater was provided [25].

Lei Fu et al. constructed in-situ H_2O_2-producing MFC-Fenton system to treat amaranth red azo dye wastewater. conventional Fenton (1 mmol/LFe^{2+}) could remove 82.59% of the color within 1 h; the electrochemical Fenton (0.5 mmol/LFe^{3+}) could reach a decolorization rate of 76.43%, with the maximum power density of 28.3 W/m^3, using potassium ferricyanide cathode system. A new way for the green treatment of azo dye wastewater was provided [26].

4.4 MEC---MFC Coupling Technology

Microbial electrolyzers is a process that consumes electrical energy. Coupling MFCs with MECs, the electrical energy from MFCs is used to power MECs by using electrical energy. The electricity is mainly produced by wastewater to obtain hydrogen or methane by MECs.

Yan Li et al. proposed a heavy-metal wastewater treatment approach in which Cr(VI) and Fe(III) functioned as cathodic electron acceptors in an MFC system. Their results showed that increasing the concentrations of these ions enhanced the electrical output: the maximum power densities reached 658.34 mW/m^2 at 50 mg/L Fe(III) and 419.31 mW/m^2 at 10 mg/L Cr(VI), with Fe(III) demonstrating superior conversion performance. Nonetheless, coulombic efficiency decreased as concentrations rose. This work offers a new pathway for the remediation of wastewater containing heavy metals [27].

Yang Li et al. developed an integrated MFC–MEC system for azo-dye wastewater treatment. Compared with a standalone MFC, the coupled configuration enhanced decolorization efficiency by 36.5–75.28%. Increasing the acetic-acid concentration at the anode promoted dye removal, whereas variations in catholyte pH (7.0–10.3) showed minimal influence. The study also theoretically verified that the short-circuit current generated by the MFC should exceed that of the MEC. These findings provide a cost-effective and efficient strategy for azo-dye wastewater remediation [28].

Min Sun et al. established an MEC–MFC hybrid system for hydrogen production using acetic acid as the carbon source. By regulating MEC power input—either through adjusting the series load resistance or by adding/removing auxiliary MFC units in series—the hydrogen generation rate reached 2.9 mL/(L·d) at a resistance of 10 Ω and increased to 14.54 mL/(L·d) when three MFCs were connected in series. In contrast, parallel connections offered no performance improvement. This work demonstrates a controllable and efficient approach for producing hydrogen from organic waste streams [29].

6. Conclusion

MFCs can treat organic wastewater and regenerate electricity at the same time. The principle of MFC is that microorganisms use the catalytic reaction to degrade pollutants and obtain electricity by oxidizing the substrate and transferring the electrons. The key to the improvement of the efficiency lays in the development of electrode materials. The cathode uses Pt-Fe/C composite catalyst; the anode uses carbon nanotube to reduce resistance and resistance. The use of carbon materials lays the foundation for the large-scale preparation of the above two electrodes. The neutral environment is conducive to the stable operation. MFC has the following advantages in the treatment of different wastewater: the removal rate of nitrate in low C/N ratio wastewater is more than 91%; 90% of pure phosphorus resource is recovered; the de-colorization rate of dye wastewater is 95.6%; the removal rate of Cr(VI) in chromium-containing wastewater is 97%; the degradation rate of antibiotic is more than 85% and the resistance gene is removed. Coupling technology expands the application field of MFC technology: the Cr(VI) removal rate of CW-MFC is further improved to 99%, the removal rate of various pollutants of MFC-electro-Fenton is more than 90%, and the removal rate of hydrogen produced by MFC-MEC is more than 90%. Although MFC has the above advantages, there are still challenges in large-scale preparation of electrode materials. In the future, we should continue to optimize materials and processes, promote technological integration and accelerate the transfer from laboratory to engineering.

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