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Wastewater Treatment using Microbial Fuel Cells

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Abstract: *Microbial fuel cells (MFCs) are emerging as an innovative bioelectrochemical technology for sustainable wastewater treatment, offering the dual benefit of degrading organic pollutants while simultaneously generating electricity. By harnessing the metabolic processes of electroactive microbes, MFCs convert biodegradable substrates into electrical energy through oxidation reactions. This approach presents an attractive alternative to traditional wastewater treatment methods, which often rely on energy-intensive operations and contribute substantially to greenhouse gas emissions. Recent progress in MFC technology—including advancements in electrode materials, reactor design optimization, and improved microbial communities—has led to enhanced power output and higher efficiencies in removing chemical oxygen demand (COD). Beyond the elimination of organic contaminants, MFCs also hold promise for the remediation of nutrients and heavy metals, increasing their environmental utility. Life cycle assessments and energy recovery analyses reveal that MFCs can function with minimal external power, making them suitable for decentralized wastewater treatment in both urban and rural environments. The incorporation of separated waste streams and hybrid systems further improves their operational adaptability. Although challenges remain in scaling up, reducing costs, and ensuring long-term performance, MFCs support circular economy principles and offer a sustainable route to energy-positive wastewater treatment.*

Keywords: *Microbial fuel cells*

I. INTRODUCTION

The increasing global demand for clean water, driven by population growth, urban expansion, and industrial development, results in the generation of approximately 380 billion cubic meters of wastewater annually.[20]Traditional wastewater treatment technologies, including activated sludge and chemical precipitation, are highly energy-consuming—requiring between 0.6 and 1.0 kWh per kilogram of chemical oxygen demand (COD) removed—and produce large volumes of sludge that pose disposal difficulties. These conventional methods contribute notably to climate change, accounting for 3 to 5 percent of worldwide greenhouse gas emissions.[18] A significant portion of energy consumption in treatment plants stems from aeration processes, which alone represent 50 to 60 percent of the total energy use in activated sludge systems. [21] This highlights the urgent necessity for more sustainable treatment alternatives that reduce environmental impacts and operational expenses.[17] Furthermore, inadequate wastewater treatment remains a critical concern, with approximately 80 percent of global wastewater released without sufficient processing, adversely affecting ecosystems and public health.

Microbial fuel cells (MFCs) present an innovative, dual-function approach by simultaneously treating wastewater and producing electricity through the microbial oxidation of organic compounds. Electroactive bacteria such as *Geobacter sulfurreducens* and *Shewanella oneidensis* facilitate electron generation by oxidizing substrates, which then flow through an external circuit to deliver electrical power.[5]Studies demonstrate that MFCs can remove 70 to 95 percent of COD and yield power densities ranging from 200 to 2000 mW/m² when treating diverse wastewater types, including municipal, brewery, and dairy effluents. This bioelectrochemical technology supports the principles of a circular economy, converting waste into a valuable resource. Currently, the widespread commercialization of microbial fuel cells (MFCs) faces several significant challenges, such as limited efficiency and high operational and maintenance expenses. Their practical use across various applications remains constrained by system instability, difficulties in scaling up, competing microbial processes, and the consequently restricted power output. Efforts to implement MFC

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technology for wastewater treatment are particularly hampered by these obstacles and require further investigation. Notably, many promising results achieved at laboratory or pilot scales have yet to be successfully replicated at larger, practical scales, highlighting the need for deeper insights into the progress and barriers of this technology. Although rapid developments in MFC research have led to an array of comprehensive reviews—covering topics including organic biomass resources, system configurations, resource recovery, operational stability, reproducibility, and the conversion of waste to energy—there is still more to be understood. Building upon previous research, the current review aims to highlight the versatile applications and different types of MFCs in both wastewater treatment and sustainable resource recovery. This analysis gives special emphasis to operational principles and the critical factors that influence the scalability of MFC systems, while also offering a detailed discussion of their types, processes, real-world uses, existing hurdles, recent innovations, and potential future developments in the context of wastewater management.[22-26]

The underlying mechanism of MFCs relies on bioelectrochemistry, where microbial catabolism couples with electrochemical reactions to degrade complex organic matter. This process reduces the need for external energy inputs and limits sludge formation compared to conventional aerobic systems.[1] The electron transfer driving electricity generation is governed by the Gibbs free energy change (ΔG) associated with substrate oxidation. For instance, acetate oxidation ($\Delta G° = -847.6$ kJ/mol) releases ample energy to transfer electrons to the anode effectively.[9] In addition to wastewater treatment, MFCs have the potential to recover electrical energy, offsetting treatment costs by approximately 0.664 kWh per cubic meter of wastewater.

Given their low energy requirements and capacity for decentralized operation, MFCs are particularly well-suited for resource-limited settings, addressing local wastewater pollution challenges effectively. This review aims to (1) comprehensively present the current state of MFC technology, (2) analyze recent design and operational improvements, (3) examine economic, environmental, and scalability aspects, and (4) discuss the key challenges and future research pathways. By integrating waste-derived materials and novel system configurations, MFCs offer a sustainable wastewater treatment option applicable to both rural and industrial contexts.

II. LITERATURE REVIEW

Conventional Wastewater Treatment Methods

Traditional wastewater treatment approaches encompass physical methods such as sedimentation and filtration, chemical treatments including coagulation and disinfection, and biological processes like activated sludge and anaerobic digestion. Activated sludge systems depend heavily on aerobic microorganisms to break down organic matter, but this requires extensive aeration, which consumes between 0.6 to 1.0 kWh per kilogram of chemical oxygen demand (COD).[18] Anaerobic digestion, while capable of producing biogas, often necessitates further processing for effective energy recovery. Chemical treatment techniques, on the other hand, may generate secondary pollutants that pose additional environmental hazards.[17] These conventional treatment strategies also lead to the generation of large amounts of sludge, with global production estimated between 10 and 20 million tons annually, resulting in significant expenses related to sludge management and disposal. [20]Due to the considerable energy demand and environmental impacts associated with these methods, exploring more sustainable options such as microbial fuel cells (MFCs) becomes essential.[2]

Microbial Ecology in MFCs

Microbial fuel cells (MFCs) represent an emerging and promising technology capable of addressing both energy generation and environmental sustainability challenges. MFCs are notable for their ability to produce biohydrogen, function as biosensors, and act as in situ power supplies, making them valuable for bioremediation and wastewater treatment applications. Their use in wastewater treatment is supported by several advantages, such as converting energy derived directly from organic substrates into electricity, producing regulated activated sludge, maintaining effective operation even at low temperatures, eliminating the need for gas treatment or energy input for aeration, and being suitable for regions with limited access to conventional electrical infrastructure.

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The energy output from MFCs is primarily determined by their structural design, the physical separation between electrodes, electrode materials, the properties and surface area of the proton exchange membrane (PEM), the selection of electron mediators, the type of substrate processed, the specific microorganisms used, and external operational conditions. Various MFC configurations exist, including single-chamber, dual-chamber, and modular stacked systems. The proton exchange membrane, often made from materials such as Nafion, agar, or cellophane, is central to MFC operation; its surface area relative to the electrodes significantly influences power generation.[29]

Electron mediators are crucial for transferring electrons from microbial cells to the electrodes, thus boosting power density. Natural intracellular mediators include NADPH, NADH, and cytochromes, while synthetic mediators, such as thionine, methylene blue, meldola blue, neutral red, and hydroxy-1,4-naphthoquinone, may also be used—although their practical applications are limited by toxicity concerns. Recent findings underline the importance of direct electron transfer from microbial cells to the anode, which enhances both system stability and coulombic efficiency (CE). CE refers to the proportion of electrons generated in the system that is recovered as electrical current, a value influenced by microbial species, substrate type, wastewater characteristics, reactor design, and experimental conditions.[30]

Electroactive microorganisms like *Geobacter sulfurreducens* and *Shewanella oneidensis* enable extracellular electron transfer (EET) through two primary pathways: direct and mediated mechanisms. [4]The direct route involves conductive structures such as pili or nanowires that establish physical contact between outer membrane cytochromes and the anode surface. In contrast, the mediated pathway utilizes soluble electron carriers, including redox-active compounds like flavins, to shuttle electrons across greater distances. Utilizing mixed microbial communities sourced from environments such as wastewater or soil improves the degradation of complex substrates, including polysaccharides and proteins, due to synergistic interactions among diverse species. [15]Cutting-edge synthetic biology approaches have focused on genetically modifying microbes to upregulate genes involved in EET, resulting in a 15 to 20 percent increase in power output. Additionally, factors such as the nature of the substrate, pH levels, and electrode characteristics shape the composition of the microbial community, with anaerobic conditions typically promoting the predominance of *Geobacter* species.[6]

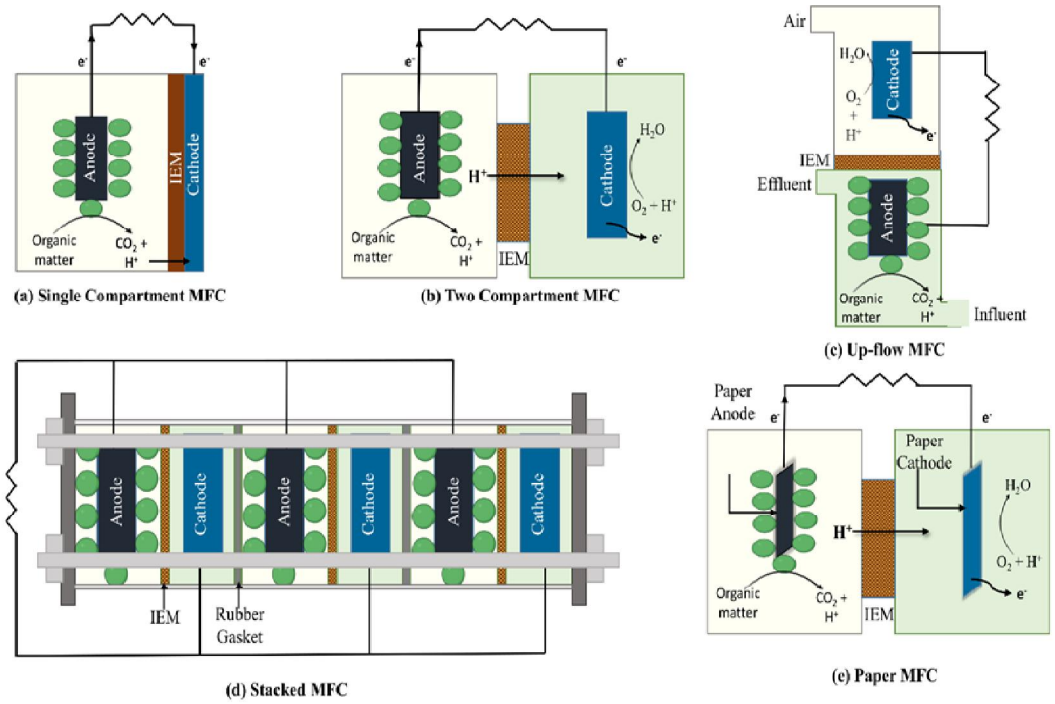

Figure 1. Different types of MFCs (IEM: ion exchange membrane).

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Microbial fuel cells (MFCs) are categorized based on factors such as the presence or absence of separate anode and cathode chambers, the configuration of electrode assemblies, and whether they use a proton exchange membrane (PEM) or a salt bridge. One common type is the single-compartment MFC, which consists of a single anode chamber with the cathode exposed to the environment. This design eliminates the need for an oxygen supply, making these MFCs simpler and more cost-effective. They can operate in batch or continuous modes and are relatively easy to scale up. For instance, a single-chamber MFC has been constructed using non-conductive polycarbonate plates secured with screws and bolts. The anode typically uses porous carbon paper, while the cathode is made of carbon cloth coated with a platinum catalyst. Nafion membrane often serves as the PEM, and copper wiring connects the electrodes to the external circuitry. Additionally, the use of ceramic materials in MFCs has shown promise by offering an economical alternative for ion exchange, creating a naturally stable environment for bacterial activity and enhancing energy conversion efficiency.[31]

This type of microbial fuel cell (MFC) features two distinct chambers, one for the anode and the other for the cathode, which are separated by either a proton exchange membrane (PEM) or a salt bridge. The anode chamber contains the specific microbes, their growth medium, and the anode electrode, while the cathode chamber houses the catholyte—typically freshwater or buffer solutions—alongside the cathode electrode and an oxygen supply. Electrodes in this two-compartment design are commonly made from materials such as stainless steel mesh, copper, graphite, carbon paper, or carbon and graphite fiber brushes. To maintain anaerobic conditions in the anode compartment, a continuous nitrogen flow might be necessary in some setups. Constructing this MFC type often involves using two borosilicate glass bottles connected by a clamp system and a glass bridge, with a Nafion PEM serving as the separator between chambers. Carbon paper acts as the electrode material for both anode and cathode, with the cathode typically enhanced with platinum as a catalyst. However, due to the high cost of platinum, alternative catalysts such as palladium-copper alloys, manganese oxides, or activated carbon combined with nickel are also employed. Microbial cultures for these systems can be grown in mineral salt medium (MSM) and stored at 4°C for later use.[32]

Energy scarcity and water pollution are critical global issues, and microbial fuel cell (MFC) technology offers a potential partial solution to these problems. The effectiveness of MFCs in generating electricity depends on a complex interplay of biological, physicochemical, electrochemical, and operational factors. Biological influences include the types, quantities, and enzymatic activities of the microorganisms present, with energy losses at the anode often resulting from decreased microbial electrochemical activity and anode overpotential. Among physicochemical and electrochemical factors are the nature and accessible surface area of electrodes, resistance within the electrolyte, proton transport efficiency through the proton exchange membrane (PEM), the rate of reduction reactions at the cathode, and the external resistance applied between electrodes. Operational parameters such as the organic loading rate, substrate type, and concentration also critically impact performance. The interdependent relationships among these variables make optimizing MFC performance challenging; for example, substrate conversion rates are influenced by the amount of electroactive bacteria, mass transfer dynamics, bacterial growth rates, organic substrate loading per unit biomass, proton transport efficiency across membranes, and the overall cell potential.[33]

A major electrochemical parameter affecting MFC operation is internal resistance, which can be broken down into ohmic resistance (arising from the electrodes, membrane, and electrolyte), charge transfer resistance, and diffusion resistance at the electrode-electrolyte interfaces. The surface area of the PEM relative to that of the electrodes plays a significant role: if the PEM area is smaller, it increases internal resistance and reduces power output. Furthermore, minimizing the physical distance between the anode and cathode is vital for reducing internal resistance and optimizing design. From a cost and performance standpoint, the PEM is especially important in double-chamber MFCs, influencing both efficiency and maintenance expenses. Although many studies utilize commercial Nafion membranes, these are sensitive to wastewater constituents like ammonium, which can impair performance. Alternative membranes such as Ultrex™, a cation exchange membrane, offer greater stability but come with higher resistance and reduced ion selectivity. Carbon paper separators have shown promise in lowering internal resistance and cost, yet their long-term durability data is limited. Ceramic materials have emerged as cost-effective and stable substitutes for traditional membranes, providing a favorable environment for the growth of exoelectrogenic bacteria and improving power output

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and treatment effectiveness. However, challenges such as the evaporation of anolyte remain significant and require further research to optimize membranes and materials for enhanced MFC efficiency and economic viability.

Microbial Desalination Cells (MDCs) represent an innovative electrochemical technology that converts chemical energy into electricity by utilizing fuels like biofuel, biomass, or hydrogen. Unlike conventional fuel cells, MDCs use naturally occurring microorganisms or proteins as biocatalysts at their anodes and cathodes, enabling efficient electrocatalytic reactions under moderate temperature and pH conditions. Introduced by Cao and colleagues, MDCs integrate microbial fuel cell (MFC) technology with electrodialysis to facilitate energy-efficient desalination and water treatment. These systems have garnered growing attention in sustainable energy and water purification research due to their potential to reduce energy consumption and capital costs through optimized material selection, reactor design, and biochemical mechanisms aimed at improving power output. A main challenge for MDCs is the relatively low potential from cathodic oxygen reduction reactions, which limits desalination efficiency when processing seawater. To overcome this, recent studies have employed machine learning techniques to better understand and enhance ion transport across ion exchange membranes within MDCs. [34]As pretreatment units for reverse osmosis (RO), MDCs can significantly lower energy demands and mitigate membrane fouling, making them valuable in water treatment chains. The technology exploits exoelectrogenic bacteria that oxidize organic compounds in wastewater, releasing electrons that generate a potential difference between electrodes. Structurally, MDCs consist of three key components: an anode, a cathode, and a central desalination section comprising cation and anion exchange membranes. Research has developed various MDC configurations to address water and wastewater challenges, focusing on improving electron transfer through advanced electrode materials to enhance both desalination and treatment efficiency. Compared to traditional desalination methods like RO, which consume roughly 3 kWh per cubic meter of seawater, MDCs operate without external energy input by deriving bioelectricity from organic waste. [35]This dual functionality of treating wastewater while producing sustainable energy positions MDCs as eco-friendly and cost-effective alternatives. Performance studies have reported desalination efficiencies exceeding 90% for both brackish and seawater, with desalination rates between 0.17 and 1.5 liters per square meter per hour. Additionally, MDCs offer reduced operational costs, making them especially suitable for resource-constrained settings. Nevertheless, issues such as membrane fouling and challenges related to scaling up for industrial applications continue to require further research and development.[36]

Electrode Material Advancements

Electrode materials play a vital role in the overall efficiency of microbial fuel cells (MFCs) by affecting microbial attachment, electron transport, and the economic viability of the system. [3]Carbon-based materials such as graphite felt and carbon cloth are commonly used as anodes due to their high surface area, typically ranging from 500 to 1000 m^2/g, and excellent compatibility with microbial communities. Cathode performance is often enhanced through the use of catalysts like platinum, manganese dioxide, or biochar, which accelerate the oxygen reduction reaction (ORR).[13]

The choice of electrode material significantly impacts both the cost and efficiency of microbial fuel cells (MFCs). Selecting an ideal electrode involves considering factors such as microbial adsorption capacity, electrochemical properties, and electron transfer capabilities.[37] Key attributes for MFC electrodes include robust mechanical strength, excellent electrical conductivity, a large surface area, and biocompatibility. Typically, MFC electrodes are made from non-corrosive metals or carbon-based materials.[38] To enhance the power output of MFCs, optimizing the electrode material is crucial, as it directly influences the processes of electron release, transfer, and acceptance between microorganisms and the electrode surface. Additionally, the electrode's function—whether serving as an anode or cathode—plays an important role in its overall performance.[40]

Recent advancements in electrode technology include the following innovations:

- Graphene-Based Electrodes: Utilizing graphene improves electrical conductivity and surface area, resulting in a 20–30% increase in power output.[7]
- Iron-Doped Carbon Materials: The incorporation of iron oxides helps reduce internal resistance within the MFC, thereby facilitating more efficient electron transfer.[19]

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- Biochar Cathodes: Produced from agricultural residues, biochar offers a cost-effective cathode alternative, reducing expenses by 50 to 70% compared to traditional platinum catalysts.[14]

Recent developments in electrode materials have greatly improved the performance of microbial fuel cells (MFCs) used in wastewater treatment by enhancing power generation, promoting microbial attachment, and optimizing electron transfer between bacteria and electrodes. Notable progress includes:

- **Anode surface modification:** Techniques such as heat treatment, acid treatment, and electrochemical oxidation have increased the anode's surface area and introduced functional groups that enhance electrical connectivity and support biofilm growth.
- **Incorporation of metals and metal oxides:** Modifications of anodes with materials like manganese dioxide (MnO2), palladium (Pd), iron oxide (Fe3O4), cobalt oxide, and zero-valent iron have resulted in improved electricity output and higher power densities—sometimes exceeding 800 mW/m²—although excessive metal loading can negatively affect performance.
- **Enhancements using carbon nanomaterials:** Adding graphene oxide (GO), carbon nanotubes (CNTs), and nitrogen-doped carbon nanorods to carbon-based anodes has significantly increased power output (up to 3.6 times) and coulombic efficiency by enlarging surface area, boosting biocompatibility, and supporting microbial colonization.
- **Use of conductive polymer composites:** Employing conductive polymers such as polydopamine and polyaniline (PANI), alone or combined with carbon materials, improves biofilm development and electron transfer, thereby enhancing the electrochemical activity of MFCs.
- **Advanced cathode catalysts:** While platinum-based catalysts have been the standard for facilitating oxygen reduction and increasing power output, their expense and limited stability have prompted the development of alternatives. New cathode materials include metal nanocomposites (e.g., copper, manganese oxides), metal-organic frameworks containing iron or nickel, and composites with carbon nanomaterials, some achieving power densities in the range of hundreds of mW/m² to over 16 W/m².
- **Focus on cost and scale-up:** Ceramic materials have emerged as affordable and stable substitutes for conventional proton exchange membranes and separators, offering a conducive environment for the growth of electroactive bacteria and improving overall energy conversion efficiency.

Various characterization methods are employed to analyze the properties of microbial fuel cell (MFC) components:

- **Scanning Electron Microscopy (SEM)** is used to examine the biofilm's structure and electrode surface morphology, ensuring consistent microbial coverage.
- **X-ray Diffraction (XRD)** helps identify crystalline phases within catalysts, such as the specific iron oxide peaks observed at 33.2° and 35.6°.
- **Fourier Transform Infrared Spectroscopy (FTIR)** detects key functional groups like carbonyl (C=O) and hydroxyl (O-H) on electrode surfaces.
- **Brunauer-Emmett-Teller (BET) Analysis** measures the specific surface area (typically 500–1000 m²/g for carbon-based electrodes) and analyzes pore size distribution.
- **Electrochemical Impedance Spectroscopy (EIS)** assesses the charge transfer resistance, where lower resistance values correlate with improved electron transfer efficiency.[3]

Silica used for zeolite Y synthesis was extracted from rice husk ash collected from the SPM rice mill in Rourkela, India. Various chemicals, including sodium hydroxide pellets, sodium aluminate (NaAlO2), nitric acid (HNO3), and hydrochloric acid (HCl, 35%), were sourced from Merck, India, while ferric nitrate (Fe(NO3)3·9H2O) was procured from Sigma-Aldrich, India. Arsenate (As(V)) solutions were prepared using Na2HAsO4·7H2O obtained from HiMedia, India. Fresh working concentrations of As(V) were daily prepared by diluting stock solutions with 0.5% HNO3 and deionized water. The pH of the arsenate solutions was measured using a pH/ORP meter (HANNA instrument) with 0.1 M HNO3 and 0.1 M NaOH as reference solutions. Initial and equilibrium concentrations of As(V) were determined using inductively coupled plasma optical emission spectrometry (ICP-OES) (Thermo Scientific iCAP 7000 Series). The surface charge of NaY and IMZY zeolites was evaluated through zeta potential measurements using a Malvern

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Zetasizer; 5 mg of zeolite was dispersed in 50 mL of 1 mmol/L NaCl and sonicated for 30 minutes. Chemical composition of NaY, IMZY, and CZY samples was analyzed using X-ray fluorescence (XRF) with the XGT2700 model. Crystalline phases of all samples were identified by X-ray diffraction (XRD) using a Rigaku ULTIMA-IV instrument with Cu Kα radiation at 40 kV and 40 mA, scanning from 5° to 60° with a step size of 0.02°. Transmission electron microscopy (TEM) on a FEI TECHNAI F30 G2 S-TWIN operating at 200 kV provided insights into crystal size and morphology for NaY, IMZY, and CZY. Surface morphology and elemental composition were examined by field emission scanning electron microscopy with energy dispersive X-ray spectroscopy (FESEM-EDX) using a Nova Nano SEM/FEI setup. Fourier transform infrared spectroscopy (FTIR) was performed on RHA, NaY, IMZY, and CZY to identify the structural bonds, particularly after arsenate adsorption, using standard KBr pellets over the range of 4000–400 cm−1, with a PerkinElmer instrument. Surface characteristics such as specific surface area, total pore volume, and average pore diameter of NaY, IMZY, and CZY were determined by BET analysis using a Quantachrome AUTOSORB-1 system.

III. WASTEWATER TREATMENT PERFORMANCE AND BIOELECTRICITY GENERATION

Experimental Setup

All chemicals used in this study were of analytical or biochemical grade and sourced from Sigma-Aldrich. Unless otherwise specified, experiments were carried out under anaerobic conditions at room temperature, approximately 22 °C. Spectrophotometric analyses were conducted using a Hach DR 3900 spectrophotometer (Düsseldorf, Germany). Bio-electrochemical measurements employed a three-electrode setup (AUTOLAB PGSTAT101, Metrohm Autolab, Utrecht, The Netherlands), comprising a working electrode, counter electrode, and Ag/AgCl reference electrode (saturated KCl, 0.210 V vs. SHE, Metrohm Autolab). The microbial fuel cell system used throughout the experiments was a two-chamber cylindrical reactor constructed from PVC components. The anodic chamber had an inner diameter of 4.5 cm and length of 3 cm, while the cathodic chamber measured 4.5 cm in diameter and 1.5 cm in length. A Nafion® 242 membrane (Sigma-Aldrich, Saint Louis, MO, USA) with a 0.5 cm diameter served as the separator between the two compartments. The working volumes were 70 cm^3 for the anode and 20 cm^3 for the cathode. Both electrodes consisted of circular carbon cloth plates measuring 4 cm in diameter, positioned 3 cm apart, and connected externally with varying resistances depending on the experimental requirements. For the operation of the microbial fuel cell (MFC), a microbial culture possessing specific electrogenic properties was required. The electrogenic bacteria utilized in this study were isolated from bottom sediment samples collected from the Yasna Polyana dam located in the Burgas region of Bulgaria. The inoculum consisted of a mixed microbial community including Bacillus sp., Bacillus mycoides, Brevibacterium frigoritolerans, Brevundimonas vesicularis, Arthrobacter sp., and Viridibacillus arenosi.

Regarding cultivation, the sediment samples were initially transferred into a rich liquid culture medium (as described in section 2.1). After incubating for 72 hours at temperatures ranging from 14 to 18 °C, the resulting biomass was harvested, washed, and then resuspended in a fresh medium of similar composition, except that 80 mM acetate was used instead of glucose. This cell suspension, with a concentration of approximately 10^7 colony-forming units per cubic centimeter (CFU/cm^3), served as the anolyte, which was introduced into the anode chamber of the MFC. The system was then operated under standard conditions, with periodic replacement of the anolyte to promote biofilm development.

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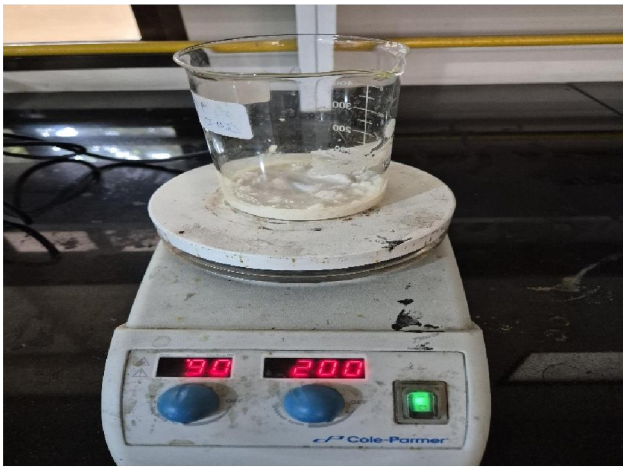
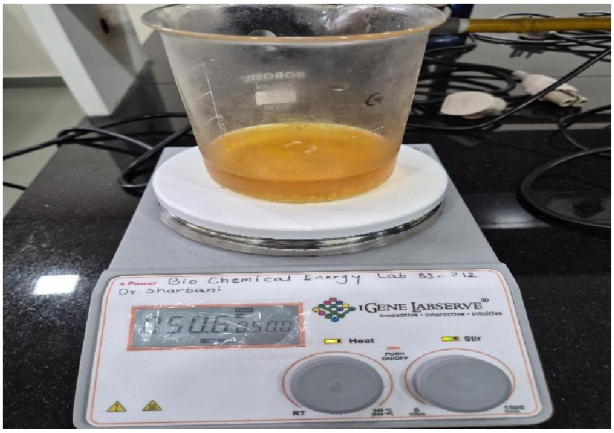
system was then operated under standard conditions, with periodic replacement of the anolyte to promote biofilm development.

The performance of microbial fuel cells (MFCs) is assessed by treating either synthetic or actual wastewater sources—such as municipal, brewery, or dairy effluents—using batch or continuous-flow reactor configurations. Key evaluation parameters include the percentage of chemical oxygen demand (COD) removal, power density measured in milliwatts per square meter (mW/m²), and coulombic efficiency (CE) expressed as a percentage.[4]



Experimental conditions are carefully controlled, including pH, temperature, dissolved oxygen levels, and organic loading rate (OLR). Electrodes are connected through external circuits with resistors typically ranging from 100 to 1000 ohms, allowing power output to be calculated based on the equation $P = I^2R$, where P represents power, I is the current, and R is the resistance.[4]

Performance Metrics



Microbial fuel cells (MFCs) have demonstrated promising wastewater treatment capabilities, achieving chemical oxygen demand (COD) removal efficiencies ranging from 70% to 95%, alongside power densities between 200 and 2000 mW per square meter. These performance indicators are comparable to traditional treatment methods while providing the added benefit of simultaneous energy recovery. Various wastewater types exhibit different outcomes: municipal wastewater shows COD removal of 70–80% with power densities around 200–300 mW/m²; brewery effluents achieve up to 94.6% COD reduction and produce power densities near 1680 mW per cubic meter; dairy wastewater treatment reaches 90% COD removal and a power density of approximately 621 mW/m²; tannery wastewater records 88% COD removal with a power density close to 544 mW/m²; swine wastewater attains 85% COD

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removal with power density near 664 mW per cubic meter; and textile wastewater treatment results in 82% COD removal coupled with 450 mW/m² power density. This data underscores the versatility and effectiveness of MFC systems across diverse wastewater streams.

The impact of various operational parameters, including solution pH, adsorbent dosage, sonication duration, and initial As(V) concentration, was examined to determine the optimal conditions for maximum arsenate adsorption by zeolite adsorbents. A sono-assisted adsorption method was employed to accelerate As(V) removal onto NaY zeolite, IMZY, and CZY. In a comparative analysis of conventional versus sono-assisted adsorption, the sonication time, adsorbent amount, and initial arsenate concentration were maintained at 90 minutes, 0.5 g/L, and 50 mg/L, respectively. As shown in Figure 9a, the highest arsenate removal efficiency of 99.9% was achieved with IMZY using ultrasound-assisted adsorption, attributed to the stronger positive surface charge of the modified NaY zeolite compared to other adsorbents. Additionally, the ultrasonic method reached equilibrium rapidly in just 30 minutes with IMZY, while the traditional approach took 75 minutes to remove only 66.1% of As(V). Consequently, this straightforward and efficient sonoadsorption technique was selected for subsequent experiments. Supporting this approach, earlier studies have reported effective contaminant removal from water using various adsorbents such as goethite, α-MnO2, goethite/α-MnO2 composites, activated carbon, wheat bran ash, natural clay, and nanozeolite X. The ultrasonic treatment improves mass transfer rates through physical effects like intense shear forces, microstreaming, turbulence, microjetting, and acoustic waves, while also enhancing adsorbent porosity by bubble cavitation. This cavitation effect exposes additional active sites on the zeolite, increasing arsenate affinity. Furthermore, ultrasonic irradiation promotes the movement of arsenate particles toward these highly active sites within the adsorbent, boosting removal efficiency.

Kinetics and Mechanisms

The bio electrochemical process in microbial fuel cells consists of oxidation at the anode and reduction at the cathode. Substrate degradation is typically described using Monod kinetics, where the rate of substrate consumption depends on the substrate concentration, biomass concentration, the maximum specific substrate utilization rate, and the half-saturation constant. The adsorption of pollutants onto surfaces follows the Langmuir isotherm model, which relates the amount adsorbed to the maximum adsorption capacity and the equilibrium concentration through a specific constant. Additionally, the rate of electron transfer is often characterized by pseudo-second-order kinetics. These models collectively provide a framework for understanding the mechanisms and rates involved in microbial fuel cell operation, with extracellular electron transfer (EET) pathways illustrating the microbial electron movement during the process[19]

Reusability and Stability

The practical use and commercial viability of microbial fuel cells (MFCs) in wastewater treatment heavily depend on their reusability and operational stability. These aspects are mainly influenced by the robustness of the microbial communities, the durability of electrode materials, membrane performance, and the stability of biofilm growth on electrodes. MFC systems with resilient electrogenic biofilms tend to sustain consistent performance across multiple operational cycles and wastewater inputs.

Long-lasting stability is closely linked to the choice of materials — durable, biocompatible electrodes (usually carbon-based or modified with stable composites) and membranes that resist fouling (such as ceramic alternatives to Nafion) help maintain steady electricity production and pollutant removal during repeated operations.

Efficient biofilm formation and maintenance are essential for effective electron transfer and contaminant degradation, but variability in substrate or environmental factors can impact MFC stability over time.

Studies demonstrate that MFCs can operate repeatedly for extended periods while retaining electricity generation and treatment efficiency. Nonetheless, issues such as membrane fouling, electrode deterioration, and shifts in microbial populations present challenges that require further refinement.

Strategies to enhance reusability include improving reactor design to lower internal resistance, performing regular maintenance like membrane cleaning or replacement, and sustaining electrogenic microbial communities despite varying wastewater characteristics.

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Although promising, commercial deployment remains limited as long-term stability and reusability under real wastewater conditions need more thorough demonstration to address cost and efficiency concerns.

Overall, recent research indicates that MFCs show encouraging potential for repeated use and operational stability in wastewater treatment, especially with advancements in materials and system design, but further work is needed to overcome persistent challenges like fouling, material degradation, and microbial ecology changes to enable reliable, scalable solutions.

The long-term stability of microbial fuel cells (MFCs) is essential for their practical implementation. Pilot-scale experiments have demonstrated reliable operation over periods ranging from six to twelve months, although issues such as electrode fouling caused by non-electroactive biofilms and membrane deterioration remain significant challenges.[7] One extended study lasting 400 days reported consistent chemical oxygen demand (COD) removal efficiencies of 65–70%, highlighting the system's durability. The behavior of biofilms in MFCs typically follows a growth and decay pattern: an initial colonization phase during the first 30 days, leading to a steady-state performance period, and eventually a decline due to fouling effects. This dynamic can be mathematically described by the equation $dX/dt = \mu X - k_a X$, where μ represents the microbial growth rate and k_a denotes the decay rate.[8]

Sustainability Benefits

Microbial fuel cells (MFCs) contribute to the reduction of greenhouse gas emissions primarily by decreasing the energy required for aeration, with a potential energy recovery of approximately 0.664 kWh per cubic meter of wastewater treated.[9] They transform organic waste into valuable resources, supporting the principles of a circular economy. Life cycle assessment studies indicate that MFCs produce a carbon footprint 20 to 30 percent lower than conventional activated sludge treatment processes. [17]Additionally, the use of waste-derived materials such as biochar-based cathodes, made from agricultural byproducts, further enhances the environmental sustainability and cost-effectiveness of MFC systems.[3]

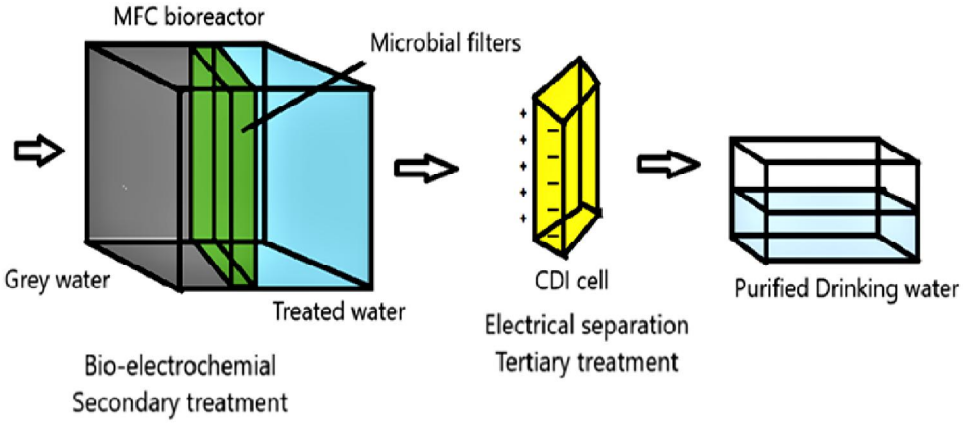

Figure 5. Green chemistry approaches for wastewater treatment through MFC system.

Challenges

Microbial fuel cells (MFCs) face several significant challenges that hinder their large-scale application. The power output remains relatively low, with power densities between 200 and 2000 mW/m², which is insufficient to meet substantial energy demands. High costs are another major barrier, primarily due to expensive components such as membranes, catalysts, and electrode materials. Biofouling caused by non-electroactive biofilms on electrodes reduces system efficiency over time, complicating long-term operation. Furthermore, scaling up MFCs presents engineering difficulties, as increases in system size do not proportionally enhance power generation or treatment capacity, restricting practical deployment on a large scale. These limitations demand ongoing research into cost-effective

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materials, improved designs, and biofouling mitigation to enable wider commercialization of MFC technology. Numerous studies indicate that microbial fuel cell (MFC) technologies offer an environmentally friendly approach to generating electricity while simultaneously removing contaminants from various wastewater sources. Despite these benefits, MFCs face notable challenges, particularly in terms of economic feasibility and the development of designs that maximize performance. As a result, MFCs have not emerged as major contenders in the renewable energy or wastewater treatment sectors. Nevertheless, under specific conditions, MFCs can achieve net positive energy generation by directly converting the chemical energy present in organic and inorganic waste materials into electrical energy through biological processes. This direct energy conversion allows MFCs to efficiently adapt to treating a diverse array of chemical substrates at varying concentrations. Furthermore, MFC technology provides valuable opportunities for researchers to investigate the electrochemical, biochemical, microbial, and surface interactions under controlled circumstances, which has contributed positively to the field. Much of the current research is directed toward understanding how various factors, such as material properties, chemical composition, and types of feedstock, influence MFC performance. This approach facilitates a deeper comprehension of the potential challenges that must be addressed for the successful large-scale application of MFC systems.[27] To facilitate the commercial viability of microbial fuel cell (MFC) technology, it is essential to address the high operational expenses and improve the currently limited power output. When compared to the conventional activated sludge systems commonly used for domestic wastewater treatment, MFCs exhibit capital costs approximately thirty times higher. This elevated expense is primarily attributed to the use of high-priced components such as electrodes, catalysts, current collectors, and separators. Within MFC systems, bacteria are capable of transferring electrons to the anode with a resulting negative anode potential of about 0.2 V, while protons are released into the solution. Among available cathode oxidants, oxygen and air are the most effective, each offering a theoretical maximum potential of 0.805 V, though platinum-based cathodes typically deliver a maximal potential of +0.3 V. Under optimal conditions—where internal resistance is minimal or microbial kinetics are ideal—the upper limit of achievable power density in MFCs is estimated between 17 to 19 W/m². However, actual power output tends to be significantly lower due to a range of factors, including suboptimal solution conditions, high internal resistances, limited substrate degradability, and the complex behavior of biofilms. One strategy for boosting current and voltage output involves configuring multiple MFC units in either parallel or series. Parallel circuits generally increase both current and power density, and often result in a noticeably higher coulombic efficiency compared to series arrangements. Series connections, on the other hand, can be used to elevate overall voltage, a feature that is more challenging to implement in chemical fuel cells because of the special influence of the external circuit on microbial communities. The issue of voltage reversal in series-stacked MFCs, along with its effects on system performance, presents an important area for future exploration. Another possible method to attain higher voltage involves charging capacitors with parallel-connected MFCs before discharging them in series, yet this approach also leads to greater financial and energy costs. Reducing both operational and capital costs, while optimizing power generation, remains crucial for achieving the widespread adoption and commercial success of MFC technology.[28]

IV. CONCLUSION

Microbial fuel cells (MFCs) present a promising and eco-friendly approach to wastewater treatment, capable of removing 70 to 95% of chemical oxygen demand (COD) while generating power densities ranging from 200 to 2000 mW/m². Progress in electrode materials, microbial community management, and reactor configurations has significantly advanced the technology's practicality. Techniques such as ultrasound application and system hybridization further enhance treatment efficiency and energy recovery. By lowering energy requirements and transforming waste streams into useful resources, MFCs support sustainable management of water and energy resources on a global scale. Ongoing technological improvements coupled with supportive policies are essential to facilitate their widespread adoption and integration into conventional wastewater treatment infrastructures.

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