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REVIEW ARTICLE

Microbial fuel cells: A sustainable approach for environmental remediation and green energy generation

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Abstract

Microbial fuel cells (MFCs) are an innovative, eco-friendly bioelectrochemical technology that simultaneously treats wastewater and generates renewable electricity by harnessing the metabolic activity of electroactive microbes. This review surveys advancements in MFC research from 2015 to 2025, highlighting key performance metrics, including power densities that typically range from 100 to 2000 mW/m^2 and chemical oxygen demand (COD) removal efficiencies between 60 % and 90 % across various organic substrates. MFCs generally consist of an anode chamber, where electrogenic bacteria oxidize organic matter, a cathode chamber that facilitates oxygen reduction and a proton exchange membrane (PEM) separating these compartments. Both pure cultures and mixed microbial communities play vital roles, with electrogenic microbes such as *Geobacter sulfurreducens*, *Shewanella oneidensis* and *Pseudomonas aeruginosa* being particularly important for electricity production. The technology effectively degrades a wide range of pollutants, including heavy metals (HMs), dyes, pharmaceuticals and nutrients, while utilizing waste streams such as domestic wastewater, industrial effluent, agricultural runoff and sludge to generate bioelectricity. Recent advances focus on improving electrode materials, exploring membrane alternatives and optimizing reactor designs to enhance electron transfer efficiency, increase power output and reduce costs. Despite challenges such as low power density, technical complexity, high material costs and scalability limitations, MFCs align with global sustainability goals, particularly the United Nations Sustainable Development Goals (SDGs) 6 and 7, offering potential for decentralized wastewater treatment and clean energy generation. Future research should prioritize interdisciplinary collaboration, policy support and industry engagement to bridge current gaps and advance the commercial deployment of MFC technology.

Keywords: bioelectrochemical systems; electroactive microorganisms; environmental remediation; microbial fuel cells; wastewater treatment

Introduction

Fossil fuels, including coal, oil and natural gas, are currently the most widespread sources of energy worldwide. When extracted and burned, they contribute to environmental waste, resource depletion, greenhouse gas emissions, global warming and climate change. Awareness of the modern energy crisis is vital due to the exhaustion of fossil fuels, increasing energy demands driven by population growth and the inequitable distribution of energy (1). Industrial effluents, municipal waste and agricultural runoff release large amounts of organic and inorganic pollutants into the environment, particularly into water bodies. This pollution leads to water quality degradation, loss of biodiversity and serious risks to human and ecosystem health. Traditional wastewater treatment systems are often energy-intensive and may be ineffective against emerging pollutants. For example, conventional wastewater treatment plants typically consume 0.5 to 1.0 kWh of energy per cubic meter of wastewater treated, contributing significantly to operational costs and associated carbon emissions (2). This evidence underscores the pressing need to balance growing energy demands with environmental protection and effective waste management. Thus, there is a pressing need for innovative, integrated technologies that can simultaneously address energy generation and pollution mitigation in a sustainable manner.

The rising global demand for clean energy and increased concern over environmental pollutants have intensified efforts to develop innovative, green and sustainable technologies. One promising development is the Microbial fuel cells (MFC), a versatile system capable of environmental remediation and clean energy production. These challenges, energy insecurity and ecological pollution, necessitate robust combined solutions and MFCs offer a promising approach (3).

MFCs can generate electricity, treat waste and remove pollutants through natural microbial metabolic processes, providing an eco-friendly option that aligns with international goals to reduce carbon emissions, conserve energy and protect the environment. As bio-electrochemical systems, MFCs use microorganisms to convert organic substances into electricity. Unlike other technologies, this method provides a sustainable approach to generating power while treating wastewater and removing pollutants, making it highly attractive for environmental applications. Their main advantage is collecting electrons produced during microbial respiration and transferring them to an electrode, resulting in an electric current (4).

Compared to other emerging technologies, such as Microbial Electrolysis Cells (MEC), which produce hydrogen gas but require external electrical input and the broader class of bioelectrochemical systems (BESs), MFCs uniquely generate electricity directly without extra energy input while simultaneously treating wastewater. This capability makes MFCs particularly valuable for remote or off-grid applications where energy recovery and waste treatment must be combined efficiently (5, 6).

Compared to traditional fuel cells, MFCs do not require harsh conditions or costly catalysts and they utilize biodegradable waste as an energy source, reducing both costs and environmental impact. In environmental cleanup, MFCs effectively degrade organic pollutants, lower chemical oxygen demand (COD) and can address HMs and other contaminants in industrial and municipal wastewater. Additionally, the modest electricity they produce can power low-energy devices, especially in remote or off-grid areas (7).

This review provides an overview of the principles, components, microbial communities, substrates and technological advances related to MFCs. It also examines their potential for wastewater treatment, pollutant removal and sustainable energy generation, considering ongoing challenges, limitations and future research directions. MFCs represent a promising convergence of biotechnology, environmental science and renewable energy, as the world moves toward a future focused on sustainable technology use.

Need for sustainable and dual-purpose technologies

The need to address global challenges such as increasing energy shortages, climate change and environmental pollution calls for replacing traditional, resource-intensive technologies with sustainable and multifunctional solutions. Conventional energy generation, especially those relying on fossil fuels, significantly contributes to greenhouse gas emissions and imposes high costs on natural ecosystems and human health. Conversely, environmental remediation efforts, like wastewater treatment, often consume considerable energy and economic resources, further burdening the environment (8). This paradox of requiring more energy while aiming for a cleaner environment has prompted a shift towards technologies capable of achieving multiple goals.

Sustainable and dual-purpose technologies are designed to solve two or more critical issues simultaneously; for example, renewable energy production that also helps reduce environmental pollution. Successful examples include anaerobic digesters that produce biogas while stabilizing organic waste and pilot-scale MFC systems treating municipal wastewater while generating electricity to power on-site sensors or lighting. These technologies exemplify circular economy principles where waste acts as a resource rather than a disposal problem (9).

Such innovations are essential for reducing dependence on finite resources, lowering resource consumption and minimizing environmental impact, thereby fostering both ecological and economic sustainability. They can convert organic waste-commonly found in industrial, municipal or agricultural effluents—into clean electrical energy while functioning as effective biological wastewater treatment systems (10). Microbial fuel cells, which harness the metabolic processes of microorganisms as their energy source, address these challenges with low energy input and minimal emissions. They turn environmental liabilities into valuable resources, aligning with the global shift toward a circular economy where waste becomes a source of energy rather than disposal. These integrated systems are essential to develop and implement, especially in light of global sustainability objectives such as the United Nations Sustainable Development Goals (SDGs), specifically SDG 6 (Clean Water and Sanitation) and SDG 7 (Affordable and Clean Energy) (11).

Recent studies position MFCs within a broader spectrum of renewable and decentralized treatment technologies. Although their power densities (typically up to a few watts per square meter under optimized pilot conditions) remain lower than those of utility-scale solar or wind systems, MFCs offer distinct multifunctionality. Unlike conventional renewables, they simultaneously treat wastewater and recover energy, enabling decentralized, off-grid applications where pollution mitigation and low-power generation are jointly required. This integration of treatment, energy recovery and resource reclamation makes MFCs particularly valuable for sustainable infrastructure and hybrid systems focused on co-benefits rather than peak power output (12, 13).

Microbial Fuel Cells (MFCs)

MFCs are simpler versions of fuel cells and their working principle relies on certain types of microorganisms, specifically electrogenic or exoelectrogenic bacteria, to transfer electrons produced by the metabolism of organic materials to an electrode. A typical MFC consists of two chambers: an anode chamber and a cathode chamber, separated by a PEM (14). In anaerobic conditions within the anode chamber, bacteria break down organic material (such as glucose, wastewater or other biodegradable substances). As a result of respiration, electrons and protons are produced. The electrons travel, either directly, via mediators or through nanowires, to the anode electrode and then flow through an external electrical circuit to the cathode, generating electricity. Simultaneously, protons move through the PEM to the cathode chamber, where they react with electrons and a terminal electron acceptor, usually oxygen, to form water. This seamless process of biodegradation, coupled with electricity generation, makes MFCs unique. They are efficient, sustainable and clean, benefiting the community by treating waste while producing renewable energy. The performance of an MFC depends on several factors, including the microbial strain, the substrate used, the electrode composition and the reactor design (15).

Basic structure and components of MFCs

MFC consists of three essential parts, namely the anode, the cathode and the PEM that separates the anode and the cathode. Fig. 1 depicts the schematic representation of electron flow and microbial interactions within an MFC system.

Anode: An anode is an anaerobic chamber where the bioelectrochemical reaction starts. Here, the electrogenic microorganisms oxidize organic substances through respiration, transferring electrons outside their cells to the electrode, leaving electrons and protons as byproducts (16). To effectively trap such electrons, the anode is made from highly conductive, non-toxic and non-corrosive materials, such as carbon cloth, carbon felt, graphite

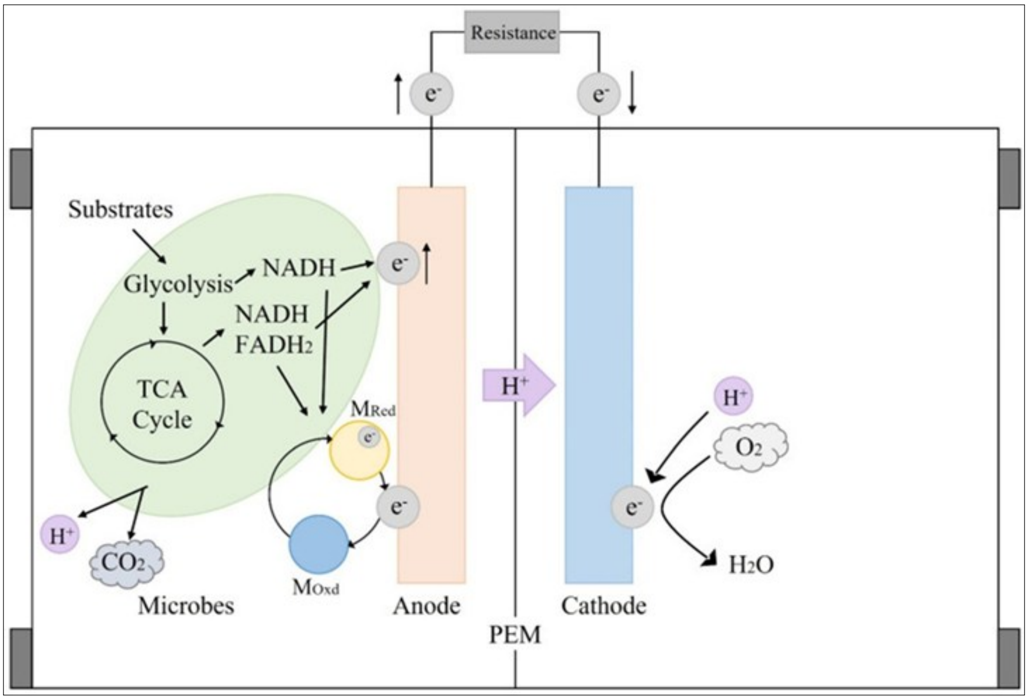

Fig. 1. Schematic representation of electron transfer in a Microbial Fuel Cell.

Organic substrates are oxidized by electrogenic microbes at the anode through metabolic pathways such as glycolysis and the tricarboxylic acid (TCA) cycle, generating reducing equivalents (NADH, $FADH_2$). Electrons are transferred to the anode either directly or via redox mediators and flow through an external circuit to the cathode, producing electricity. Protons (H^+) migrate through the proton exchange membrane (PEM) to the cathode, where they combine with electrons and oxygen to form water. This coupled bioelectrochemical process enables simultaneous wastewater treatment and energy recovery.

rods or carbon paper. A high surface area of these materials is selected due to dense microbial biofilm formation and a high rate of electron transfer between the microbial cells and the electrode surface. This is a natural interface between the biological and electrical components of the system, controlled by the biofilm, which is a complex formation of microbial communities effectively attached to the anode. The electrons released in the oxidation process by microbes travel along the external circuit between the anode and the cathode to produce a current that can be utilised (17).

Cathode: The cathode, the aerobic compartment of the MFC, serves as the final electron acceptor, where electrons produced at the anode are transferred through the external circuit and then undergo a reduction reaction. Cathode materials, such as manganese dioxide, activated carbon, carbon nanotubes and other conductive composites, are low-cost and effectively conduct the oxygen reduction reaction (ORR) with high productivity and efficiency (18). The presence of a catalyst coating on the cathode enhances the reaction dynamics, enhancing the power density and energy production of the MFC. The electrical efficiency and sustainability of the system depend on the successful output of the cathode, as it directly contributes to electrical activity and the overall sustainability of the system (19).

A typical MFC consists of two chambers: an anode chamber and a cathode chamber, separated by a PEM (14). The schematic representation of a dual-chamber MFC, showing microbial oxidation, electron flow through the external circuit and cathodic oxygen reduction, is illustrated in Fig. 2a.

Proton exchange membrane (PEM): PEM, a semi-permeable cation exchange membrane dividing the cathode and anode chambers, permits the protons (H^+ ions) produced on the anode to enter the cathode compartment, meanwhile preventing transmission of oxygen, metal ions and other unwanted molecules, keeping a chemical and electrochemical separation between the two chambers in a dual-chamber MFC. This restricted passage is necessary to maintain the redox conditions of the anode and cathode separate, which is fundamental to sustaining cell potentials and facilitating the transport of electrons between the anode and cathode via the outer circuit (20). Nafion, a perfluorinated polymer with high proton conductivity, mechanical stability and chemical stability, is used in the manufacture of PEMs. Nafion, being costly and susceptible to fouling, prompted the current research to find alternatives that are less expensive, more durable and more environmentally friendly, such as the assembly of bio-based membranes, ceramic composites and membrane-less configurations. The internal resistance of the MFC is susceptible to the performance of the PEM, which influences the voltage output and system lifetime. Thus, to increase the overall functionality and the cost-efficiency of MFCs, it is critical to optimize membrane characteristics, i.e. their selectivity towards different ions, degree of hydration and thickness (21).

Typical dimensions for MFC reactors vary widely, depending on the application scale, ranging from small laboratory volumes (10-1000 mL) to pilot or field units, which scale up to several litres. Electrode surface areas commonly span from 10 to over 500 cm^2 in research setups, influencing power density and microbial colonization (14).

Membrane alternatives to Nafion have been extensively explored to reduce cost and fouling issues. Ceramic membranes offer high durability and chemical resistance, while bio-based membranes provide environmental friendliness. Membrane-less configurations eliminate membrane costs but may reduce efficiency due to oxygen crossover. Each alternative presents trade-offs in proton conductivity, mechanical stability and long-term operational costs (22).

Cost analyses indicate that Nafion membranes remain the most expensive component, estimated at approximately $1000 per square meter, which limits their use in large-scale applications. Carbon-based electrodes, such as carbon cloth and felt, are relatively inexpensive and effective; however, overall system costs require optimization for commercial viability (23).

Mechanism of electron transfer in MFCs

The principle behind the MFC operation is the extracellular electron transfer (EET) mechanism. It engages how effectively chemical energy is transformed into electrical energy due to the usage of electrogenic microorganisms or exoelectrogens, which can pass on the electrons, formed as a result of organic substrates breaking down to a solid electrode (anode), whereby this can be directed through an external circuit, thus producing electricity (24). Different electron transfer routes, including direct, mediated and nanowire-based mechanisms, are illustrated in Fig. 2b. MFCs have three primary mechanisms that result in the transfer of electrons:

Direct electron transfer: The direct electron transfer (DET), in which electrons are transferred between microbial cells and the anode without using any medium carrier. This direct contact involves outer membrane cytochromes (such as OmcZ, OmcS) and nanowires or conductive pili, which are common in microorganisms such as *Geobacter sulfurreducens* and *Shewanella oneidensis* (25). This method is considered highly efficient; however, it requires the cells to be near the electrode. Therefore, it is essential to modify the surface area and roughness of the electrodes to promote dense biofilm growth and favourable direct contact.

Mediated electron transfer: In mediated electron transfer (MET), microorganisms utilize redox mediators, or electron-shuttling compounds, which can be endogenous (produced naturally by the microbes, such as flavins or quinones) or exogenous (methylene blue, neutral red, or humic acids, added artificially). These mediators transfer electrons between the microbial cells and the electrode surface. Such redox-active molecules can undergo oxidation and reduction, gaining electrons through microbial metabolic networks and depositing them at the anode (26). Although MET can enhance electron transfer rates in some systems, it also presents challenges, including toxicity, costs and long-term instability, particularly when synthetic mediators are used.

Nanowire-based or long-range electron transfer: This process is a form of DET, but it occurs over longer distances than direct contact between cells and electrodes. Some electrogenic bacteria like *Geobacter* and *Shewanella* produce conductive extracellular protrusions called bacterial nanowires (nanostructures made of proteins, usually pilin proteins and cytochromes) that can conduct electrons like metallic wires. These nanowires enable intercellular electron transfer over many micrometers (27).

This discovery has altered the understanding of electron transfer in MFCs by demonstrating that cells physically separated from the electrode can still contribute to current flow through these biological conductors. Extended electron transfer facilitates the formation of denser and more productive biofilms, thereby increasing the power output capacity of MFCs.

Electron transfer efficiencies differ by mechanism: DET via outer membrane cytochromes and nanowires achieves higher coulombic efficiencies (up to 80 %) compared to MET, where synthetic mediators may introduce losses and toxicity. Nanowire-based transfer enhances biofilm conductivity and power output, improving overall electron flux (28).

Significance of electron transfer in MFCs' performance

Electron transfer processes are central in evaluating the general performance and the effectiveness of MFCs. Power density output is one of the most important parameters affected by electron transfer, revealing the quantity of electrical power produced per square meter or volume (29). This efficient electron transfer will provide a stable and continuous supply of electrons from microbial cell metabolism to the electrode, directly improving power. Additionally, it affects the inner resistance of the MFC system. Poor or slow electron transfer augments internal resistance, thus lowering voltage output and energy conversion efficiency. Moreover, the stability of biofilm, that is, the structure and the activity of the microbial community growing on the anode, is closely linked to the mode and rate of electron transfer (30).

There is persistence of electron flux and good microbial activity on the biofilm, which should be well and electroactive. The efficiency of the microbial degradation of organic material (including wastewater or industrial effluents) is also determined by the rate of substrate utilization. The products of faster and more efficient electron transfer are a more effective result of substrate breakdown, leading to improved pollutant removal and efficient energy recovery. Research to address these performance parameters has been ongoing in the field, with a focus on enhancing electron transfer routes using MFCs. One of these involves genetically engineering microbial strains to transfer more electrons extracellularly, thereby interacting more effectively with the anode surface (31).

The other possible option is the production of a nanostructure electrode, which will have a large surface area available to the microbes and accelerate the transfer of electrons. Moreover, it is observed that composite materials are used, which facilitate rapid redox reactions and enable the adhesion of microbes to electrode surfaces; these materials comprise a combination of conductive polymers, carbon-based nanomaterials and metal oxides (26). In combination, these innovations aim to address the existing constraints of MFC technology and pave the way for its large-scale adoption in sustainable energy applications and the broader environment.

Types of MFC Configurations

Design and configuration have a significant impact on the performance and applicability of MFCs. A number of these MFC configurations have emerged over the years, offering improved energy output, enhanced substrate utilization and increased scalability to suit real-life applications. The most frequently used ones are the single-chamber MFC, the dual-chamber MFC and the stacked MFC systems (32). Representative applications of MFCs in environmental remediation, including wastewater treatment, HM removal, biosensing and bioelectricity generation, are depicted in Fig. 2c.

Single-chamber MFC: Single-chamber MFCs are one of the simplified and cost-effective configurations of MFC systems developed, where the cathode and anode are located in the same compartment, also known as an air-cathode. It does not require a separate cathode chamber and PEM, as in the case of dual-chamber systems, which further reduces material needs and maintenance requirements. The cathode is usually mounted on the external side of the chamber and is typically exposed to atmospheric oxygen as an external electron acceptor in the ORR (33).

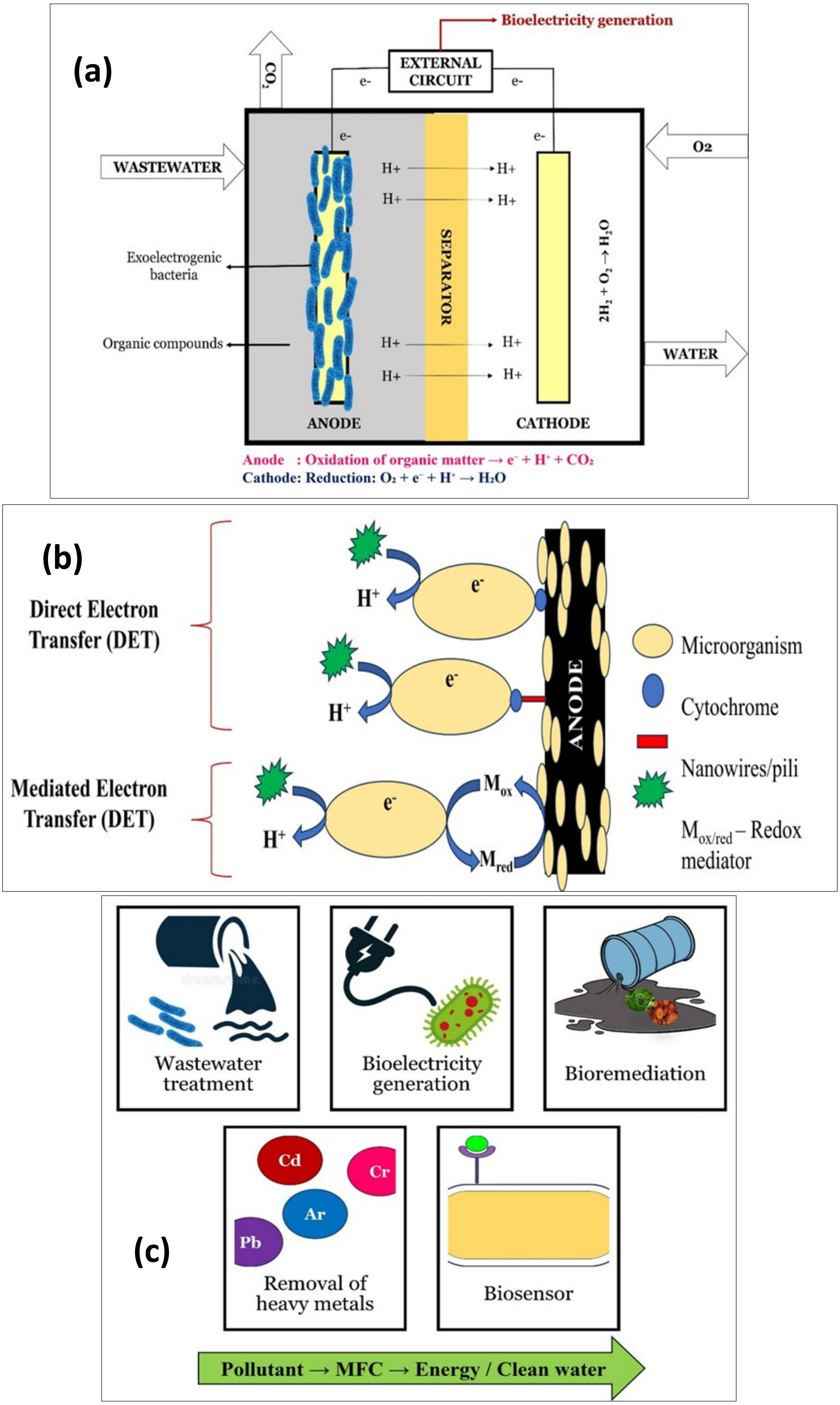

Fig. 2. Schematic overview of microbial fuel cell applications and mechanisms. (a) Representation of a dual-chamber MFC showing microbial oxidation of organic matter at the anode, electron transfer through an external circuit, proton migration through a separator and oxygen reduction at the cathode. (b) Electron transfer mechanisms in exoelectrogenic bacteria illustrating both direct electron transfer (DET) through cytochromes and nanowires and mediated electron transfer (MET) via redox shuttles. (c) Environmental applications of MFCs including wastewater treatment, bioremediation, heavy metal removal, biosensing and bioelectricity generation.

This arrangement is particularly well-suited for wastewater treatment, especially where compactness, low energy consumption and economic viability are required. Single-chamber MFCs have low internal resistance and a simple architecture, making them easy to operate and are therefore suitable for remote or decentralized systems, such as low-power environmental sensors or rural energy applications. A significant difficulty with such an arrangement, however, is the uncontrolled diffusion of oxygen between the cathode and the anode chamber. Electrogenic microbes in the anode are highly active in an anaerobic environment; thus, oxygen intrusion may hinder their activities, resulting in a low electron generation efficiency (34). Notwithstanding this drawback, the practicality and versatility of the single-chamber MFCs still make them a busy field of research and actual application.

Dual-chamber MFCs: The typical and well-researched MFC dual-chamber MFC contains two distinct sections: The anode chamber, in which organic substances get oxidized by microorganisms in anaerobic conditions and the cathode chamber, where the reduction of the electrons mostly occurs in an aerobic environment. A PEM separates the two compartments, necessitating the transfer of protons to the cathode side while preventing the movement of oxygen and other gases to maintain the required anaerobic environment in the anode chamber (35).

This geometry provides more experimental control and is thus especially appropriate for small-scale studies in bioelectrochemical research and for investigating the mechanistic details of microbial electron transfer and redox reactions. The use of various media and conditions in the two half-cells is also possible due to the separation of the chambers, contributing to the system's versatility. Membrane use necessitates additional costs and complexity for the system and can suffer from membrane fouling or proton flux limitations over time. Additionally, the electrodes are physically separated and therefore, the increase in internal resistance may result in reduced power outputs compared to single-chamber systems (32). Nevertheless, despite their disadvantages, dual-chamber MFCs continue to serve as a reference benchmark for microbial and electrochemical performance in controlled environments.

Stacked MFCs: Stacked MFCs, also known as modular MFC systems, are designed to enhance energy production by connecting multiple MFCs in series to increase voltage or in parallel to increase total current output, depending on the required output. Such modularity enables larger systems to be scaled up to support the energy requirements of household wastewater treatment, battery charging and powering wireless sensor networks (36).

A significant challenge in this system is voltage reversal, where some cells in the stack may act as energy consumers. This is due to the unequal distribution of load, the availability of the substrate and the activity of microbes in individual cells. Moreover, changes in pH gradients and ion accumulation across the connected units may lead to variations in performance within a unit. The electric inefficiencies, as well as the mismatching of internal resistance, further decrease the overall effectiveness of the stack (37). To overcome these concerns, scholars are working on new stacking schemes, such as configurations with no membranes, multiple-cathode systems and designs with fluidically interconnected multiple elements, which are construction and cost-effective. When properly balanced electrically and hydraulically, the stacked MFCs demonstrate considerable potential to become a practical and scalable renewable energy source, particularly in decentralized or resource-constrained areas (38).

Scaling considerations vary by configuration. Single-chamber MFCs offer a simpler design, lower material costs and better scalability with simpler maintenance; however, they suffer from oxygen diffusion affecting the anaerobic anode. Dual-chamber MFCs provide controlled electrochemical environments that are ideal for mechanistic studies, but they face challenges related to membrane fouling and scaling costs. Stacked MFCs enable modular scaling by electrically connecting multiple units but require careful load balancing to avoid voltage reversal and ensure stable operation (22, 39).

Hybrid configurations that combine features of different designs are emerging. Examples include membrane-less cathode designs in dual-chamber systems and integrating MFCs with anaerobic digestion or MEC to enhance energy recovery and waste treatment efficiency. Such hybrids aim to overcome the limitations of individual systems and improve cost-effectiveness and performance (5, 9).

Microorganisms used in MFCs

The microorganisms employed in MFCs, commonly referred to as electrogenic or exoelectrogenic bacteria, are considered the backbone of the system for producing electricity because they break down organic substrates during their metabolism and transfer electrons to the anode through the EET mechanism (40). Its substrate range, environmental tolerance and the mechanism of electron transfer are key factors in determining the efficiency and dependability of MFCs in actual use. The isolation of exotic strains, growing in optimal conditions and the advancement of superior quality electroactive bacteria (EAB) that can withstand various and harsh environments are current areas of research under investigation and this becomes imperative for subsequent generations of sustainable bio-electrochemical systems. MFCs have two broad microbial community types: pure cultures and mixed microbial consortia. The pure cultures, such as *Geobacter sulfurreducens*, *Shewanella oneidensis*, *Pseudomonas aeruginosa* and *Rhodoferax ferrireducens*, have been the easiest to investigate because they have well-defined systems of electron transfer and also exhibit predictable behavior when grown in the laboratory (41).

Several bacterial genera have been extensively researched and recognized to be good exoelectrogens within MFCs. Three of the most studied and most visible genera include *Shewanella*, *Geobacter* and *Pseudomonas*, which have each demonstrated distinctive roles in the efficiency and flexibility of MFC systems. Beyond classical electrogens such as *Geobacter*, *Shewanella* and *Pseudomonas*, recent studies have focused on extremophilic and genetically engineered microorganisms capable of operating under saline, acidic, or low-temperature conditions. Synthetic-biology approaches have enhanced electron transfer, broadened substrate utilization and improved stress tolerance (42, 43). Engineered microbial consortia combining fermentative and electrogenic species further optimize the conversion of complex substrates, increasing Coulombic efficiency and system resilience under variable field conditions. These strategies collectively expand the operational envelope and robustness of MFCs for real-world applications (44, 45). Key exoelectrogenic microorganisms and their characteristics were listed in Table 1.

Table 1. Key exoelectrogenic microorganisms and their characteristics

Microorganism	Electron Transfer Mechanism	Substrate Preference	Key Features	Applications	References
Geobacter sulfurreducens	Direct (via nanowires, cytochromes)	Acetate, ethanol, organic acids	Forms highly conductive biofilms; efficient electron transfer	Wastewater treatment, energy generation	(46)
Shewanella oneidensis	Direct & Mediated (flavins)	Lactate, pyruvate and amino acids	Facultative anaerobe; secretes redox mediators	Microbial Fuel Cells, biosensors, bioremediation	(47)
Pseudomonas aeruginosa	Mediated (phenazines)	Glucose, glycerol	Produces electron-shuttling compounds (phenazines)	Biosensing, medical and environmental Microbial	(48)
Desulfuromonas acetoxidans	Direct	Acetate, ethanol	Anaerobic; similar to Geobacter; uses sulfur as an	Anaerobic bioelectrochemical systems	(49)
Clostridium butyricum	Indirect	Carbohydrates, sugars	Fermentative; forms hydrogen as a by-product	Hydrogen production, Microbial Fuel Cells	(50)
Rhodoferax ferrireducens	Direct	Glucose, pyruvate	Psychrotolerant; capable of electricity generation at low temperatures	Cold-environment Microbial Fuel Cells	(51)

***Shewanella oneidensis*:** *Shewanella oneidensis*, a facultative anaerobic bacterium with higher metabolic flexibility, enables it to thrive in both aerobic and anaerobic conditions. It also exhibits both MET and DET (52). It utilizes endogenous redox-active molecules, such as flavins (e.g. riboflavin and flavin mononucleotide, or FMN), as electron shuttles in MET. These mediators enable bacteria to access electrons within their cells and transfer them to the electrode surface, even in the absence of direct physical contact. It also contains cytochromes in the outer membrane, such as MtrC and OmcA, which promote DET by interacting with, for example, metal oxides or electrode surfaces. The flexibility and reliability of *Shewanella* as a laboratory MFC model organism, due to its dual modes of electron transfer, make it a flexible and reliable model organism (53). Biofilms of *Shewanella* are generally thinner and electrically non-conductive compared to *Geobacter*, resulting in different current densities. Nevertheless, its strength and capability to grow in a variety of environmental conditions qualify it as an effective biosensor candidate and demand in short-term power production arenas.

***Geobacter sulfurreducens*:** *Geobacter sulfurreducens*, a strict anaerobe, is regarded as the gold standard of exoelectrogens due to its high DET capacities, making it favorable in the anaerobic conditions of the anode chambers in MFCs (54). The conductive pili or bacterial nanowires physically connect the bacterial cells to the electrode surface, enabling long-range electronic transport. *Geobacter* also expresses a variety of outer membrane cytochromes (e.g., OmcZ, OmcS) to act as the conductor between the intracellular metabolism and various surfaces. The structures enable *Geobacter* to establish dense, thick and highly conducting biofilms, which lead to high current densities and power outputs maintained in MFCs (55) utilizes simple organic compounds such as acetate and ethanol; hence, it is an ideal candidate for wastewater-fed MFCs. *Geobacter sulfurreducens* is a valuable choice due to its predictability and performance and it has become a common choice in mechanistic studies, electrochemical studies and attempts to genetically optimize MFC performance.

***Pseudomonas aeruginosa*:** *Pseudomonas aeruginosa* is an environmentally and metabolically versatile bacterium whose well-known capacity to thrive in non-ideal environments and its capability to degrade a wide variety of organic materials, including those in industrial wastewater, make it of particular interest. It employs MET by producing the phenazine compounds along with pyocyanin and phenazine-1-carboxamide (56). These phenazines act as natural redox mediators, allowing the transfer of electrons within the cell to the anode surface. This ability renders *Pseudomonas* particularly valuable in systems where colonization of the electrodes is less important or in systems where electron transfer must occur across greater distances within the biofilm. Additionally, it is a robust biofilm former, thereby promoting greater persistence on electrode surfaces and extending surface areas to facilitate electron transfer (57). Additionally, *Pseudomonas* is superior to *Geobacter* in terms of substrate flexibility, environmental robustness and cost-effectiveness, making it an excellent candidate for non-sterile, real-life MFC applications, such as industrial effluent treatment or bio-electrochemical sensing.

***Rhodoferax ferrireducens*:** *Rhodoferax ferrireducens* is a psychrotolerant exoelectrogen, making it suitable for MFC operation under cold conditions, such as in the polar region, refrigerated wastewater systems, or during snowy weather. It can directly transfer electrons, unlike the external mediators of *Shewanella* or *Geobacter* and readily metabolizes substances such as glucose or pyruvate (58). Being less well-studied than *Shewanella* or *Geobacter*, *Rhodoferax* has nevertheless demonstrated the ability to form stable biofilms, generating a moderate amount of power, which promises niche-MFC applications where temperature sensitivity limits the number of usable MFCs.

***Desulfuromonas acetoxidans*:** *Desulfuromonas acetoxidans* is an obligate anaerobic bacterium whose metabolic similarities are similar to those of *Geobacter*. It is also characterized by oxidizing acetate and other short-chain fatty acids and reducing sulfur compounds or electrodes as terminal electron acceptors. It utilizes DET through outer membrane cytochromes, making it a candidate for anaerobic BESs (49). Due to its high Coulombic efficiency and strong attachment to electrode surfaces, it is considered a promising candidate for exploration in sulfur-laden wastewater or industry anaerobic digesters coupled to MFCs.

***Clostridium butyricum*:** *Clostridium butyricum* is a fermentative anaerobe and it is most notable for producing hydrogen gas as a metabolic end product. Although it does not strictly transfer extracellular electrons, it is essential as a supplement to hybrid systems in MFCs. Other ways H_2 generated by *Clostridium* can be utilized include oxidation using other hydrogen-utilizing bacteria within the MFCs or direct use of hydrogen in a coupled catalytic electrode, resulting in electricity. It can also be used to break down complex carbohydrates into fermentable sugars, which are then further broken down into simpler molecules. Thus, it is applicable in synthetic consortia or two-stage MFC systems, where the production of electricity follows the fermentation process (59).

Substrates utilized in MFCs

Substrates are a crucial factor in determining the efficiency and functionality of MFCs, as they provide the primary driver of vital microbial energy production, which ultimately leads to electricity production. The type, composition and biodegradability of substrate directly affect the power density, Coulombic efficiency and the overall performance of the MFC system. The large variety of substrates researched for MFCs can be divided into synthetic and waste-based cases (60).

In laboratory work, it is usual to employ synthetic substrates (acetate, glucose, lactate and ethanol) whose chemical composition is precise and which are highly biodegradable. Acetate is the most common model substrate due to its simple structure and direct utilization by a wide range of electrogenic bacteria, such as *Geobacter sulfurreducens*. Other carbohydrates and glucose are also utilized, especially in cases where mixed microbial consortia are being studied, as they facilitate the growth of fermentative bacteria that can degrade complex organics into simpler ones, which exoelectrogens can utilize (61).

Real waste substrates are of more interest in real-world applications because they are readily available, inexpensive and environmentally relevant. These include domestic sewage, farm waste, food leachates, brewery waste and industrial waste, all of which contain organic contaminants. Wastewater not only supplies the carbon and energy materials needed for microbial growth but also helps clean up the environment by removing contaminants, including COD, nitrogen and even HMs. Electricity generation and pollutant degradation are two key benefits that render MFCs an attractive approach to addressing waste-to-energy issues sustainably (62).

Real wastewater is complex, comprising a mixture of biodegradable and recalcitrant compounds, suspended solids and toxic substances that can affect microbial activity and reduce MFC performance. This challenge is addressed through substrate pre-treatment, the use of an adaptive microbial community and system optimization strategies. Additionally, research is shifting toward making MFCs compatible with other biotechnologies, such as anaerobic digesters or enzymatic hydrolysis, to enhance substrate degradation and energy recovery (63).

Furthermore, selecting the right substrate for the MFC setup should strike a balance between microbial compatibility, energy output, accessibility and process goals. As the field advances, there is growing interest in utilizing unconventional and high-strength organic wastes as feedstock, which could significantly lower waste disposal costs and boost renewable bioelectricity production. Ongoing research on new substrates and their effects on microbial dynamics, electron transfer efficiency and system stability will be crucial for the commercial viability of MFC technology (64).

Organic and inorganic waste streams utilized in MFCs

The organic and inorganic waste generated from agricultural, domestic and industrial sources can be effectively utilized in MFC systems, converting it into bioenergy (65). Table 2 presents some examples of organic and inorganic waste streams used in MFCs.

Agricultural waste streams: Organic agricultural wastes include animal manure, crop residue, agricultural runoff and silage leachate, which contain high levels of biodegradable materials like cellulose, starch, proteins, fats and volatile fatty acids. MFCs host microorganisms that can efficiently break down these compounds and release electrons in the process. Agricultural organic waste is readily available and inexpensive, making it an ideal resource for decentralized MFC applications in rural areas, particularly for generating sustainable energy and treating waste on-site. Farming practices may also lead to the discharge of inorganic pollutants due to the widespread use of synthetic fertilizers and pesticides, causing water pollution, which specially designed MFCs could help address. Certain microbes can utilize these compounds either as electron acceptors or through nitrification and denitrification, enabling both electricity generation and nutrient removal (68).

The composition of agricultural waste streams varies seasonally, impacting their suitability and energetics in MFCs. For instance, during summer, the volatile solid and carbon content of organic waste is highest, whereas rainfall increases moisture, diluting organics in winter. These variations must be accounted for in substrate selection and pretreatment strategies to ensure process consistency and performance (72, 73).

Domestic waste streams: Localized sources, such as domestic wastewater, kitchen waste and sewage, contain abundant organic materials, including carbohydrates, lipids and proteins. These are easily digested by the microbial communities in MFCs, supporting various exoelectrogens, including *Geobacter* and *Shewanella*. Domestic waste is readily available at low cost. It is thus widely used in laboratory-scale and pilot-scale MFCs, especially at wastewater treatment and bioenergy recovery facilities in urban areas. Inorganic substances in small quantities-such as chloride, sulfate, phosphate and trace metals-may also come from cleaning products, detergents and corroded plumbing. Although these levels are lower than those in industrial waste, they can still impact microbial activity and MFC performance. Properly designed MFCs can stabilize these inorganic compounds, enable power generation while also removing organic pollutants (66).

Table 2. Examples of organic and inorganic waste streams utilized in microbial fuel cells

Source Type	Waste Stream	Waste Nature	Key Components	MFC Benefits	References
Domestic	Municipal wastewater, kitchen waste	Organic	Carbohydrates, proteins, fats and acetate	High biodegradability, widely available, low cost	(66)
Industrial	Brewery wastewater, textile effluent	Organic/Inorganic	Ethanol, dyes, phenols, sulfates, nitrates	Energy recovery, pollutant degradation	(67)
Agricultural	Animal manure, crop residues, silage	Organic	Cellulose, starch, lignin, ammonia	Suitable for rural MFC systems, fertilizer by-products	(68)
Mining	Acid mine drainage	Inorganic	Heavy metals (Fe, Cu, Zn), sulfates	Metal recovery, water detoxification	(69)
Electroplating	Metal-rich wastewater	Inorganic	Cr, Ni and Cu ions	Electricity generation and toxic metal reduction	(70)
Food Processing	Dairy effluent, fruit pulp wastewater	Organic	Lactose, fatty acids, pectin	Readily fermentable; supports high microbial activity	(71)

Industrial waste streams: The food processing, pulp and paper industries, breweries and pharmaceuticals sectors discharge effluents rich in organic pollutants, including ethanol, sugars, fats, dyes and phenols. These wastes are generally intense and complex, requiring a robust microbial community to break them down. MFCs are promising for converting challenging organic wastes from industries into electricity, thereby reducing COD and treating effluent before discharge (74).

The mining, electroplating, metal finishing and fertilizer industries generate wastewater containing HM wastes, such as chromium (Cr), copper (Cu), lead (Pb) and zinc (Zn), as well as nitrates, sulfates and ammonia. Although these compounds are not biodegradable, specialized microbes (e.g. sulfate-reducing bacteria, metal-tolerant species) can harness their redox potential by generating bioelectricity and recovering metals. This makes MFCs an emerging technology for industrial effluent treatment, offering the added benefit of energy savings (75).

The combination of organic and inorganic waste streams generated in households, industry and agriculture presents a promising path toward sustainable waste management, energy recovery and environmental cleanup with MFCs. While organic wastes promote microbial metabolism, inorganic streams facilitate bioremediation through redox reactions. MFCs can be adapted for various environmental and energy applications by tailoring microbial communities and designs to specific waste characteristics. This aligns with the concept of transforming waste into resources within the circular economy model (76).

Substrate pretreatment methods

Substrate pretreatment plays a vital role in enhancing the biodegradability and energy recovery potential of complex organic wastes used in MFCs. Various strategies are employed to improve substrate accessibility and microbial utilization. Physical methods, such as grinding, milling and ultrasonication, reduce particle size and increase surface area. In contrast, chemical pretreatments-including alkaline or acid hydrolysis, oxidative agents and ionic liquids-disrupt lignin-cellulose complexes, releasing fermentable sugars. Physicochemical techniques, such as steam explosion and ammonia fiber explosion (AFEX), further modify the substrate structure to facilitate microbial degradation. Biological pretreatment, employing fungi, bacteria, or specific enzymes, selectively decomposes lignocellulosic barriers, thereby enhancing substrate conversion and electron transfer efficiency (77, 78).

Pretreatment of agricultural and domestic wastes notably improves both biodegradability and power generation in MFCs. Among chemical options, alkali pretreatment using sodium hydroxide (NaOH), potassium hydroxide (KOH), or calcium hydroxide ($Ca(OH)_2$) is particularly effective in delignifying biomass, increasing the internal surface area and enhancing sugar yield, which collectively improve electron recovery. For instance, the NaOH treatment of rice straw resulted in a nearly fourfold increase in power density compared to untreated straw in solid-phase MFCs (44). Additionally, maintaining a balanced nutrient composition is essential for optimal microbial activity and electricity generation. A C: N:P ratio of approximately 20–30:1:1 is generally considered ideal; deviations from this range can result in nutrient imbalances that suppress microbial metabolism and energy conversion efficiency (73, 79).

Use of toxic compounds, wastewater and sludge as feedstock

Due to its versatile and eco-friendly uses, one of the most promising applications of the MFCs in the future is the treatment and use of toxic materials, wastewater and sludge to generate energy while remediating waste. This dual-purpose characteristic of MFCs is what has made this technology unique since they not only generate renewable electricity but also address some of the most recalcitrant waste streams that cause pollution (80).

Toxic compounds as feedstock: The use of MFCs in treating harmful and stubborn substances marks a significant advancement in green environmental technology. Most industrial and urban effluents contain hazardous substances such as phenols, chlorinated hydrocarbons, synthetic dyes, antibiotics, pesticides and HMs, which are resistant to breakdown and pose risks to both human health and the environment. Because these substances decompose slowly and can harm common microbes, traditional biological treatment methods often struggle to remove them effectively. However, some electrogenic bacteria, whether naturally occurring or genetically modified, exhibit exceptional metabolic abilities that enable MFCs to degrade and detoxify these pollutants (32).

Pseudomonas putida and *Geobacter metallireducens*, among other electroactive microbes, have been demonstrated to break down phenolic compounds and other aromatic hydrocarbons commonly found in the petrochemical and dye industries. They oxidize toxic substances and, in the process, transfer the generated electrons to the MFC's anode, producing bioelectricity as a byproduct of toxin bioremediation. At the same time, HMs such as hexavalent Cr^{6+}, Cu^{2+} and Zn^{2+}, commonly found in wastewater from electroplating, mining and tanning industries, can be effectively reduced at the MFC's cathode. These metal ions also serve as terminal electron acceptors, completing the electrochemical circuit while being reduced to less toxic or elemental forms (81).

The ability of MFCs to perform this dual function-oxidizing toxic organic pollutants at the anode and reducing HMs at the cathode-positions them as advanced tools for wastewater treatment, simultaneously generating energy. They can clean waste streams and generate electricity simultaneously. This technology offers new opportunities for pollution control, particularly in highly industrialized sectors such as fabric dyeing, pharmaceuticals, petroleum refining and metallurgy-industries known for their energy -intensive treatment processes that are often poorly managed. Future research can enhance this capability, improve the engineering of resilient microbial communities and develop electrode materials that are more robust and adaptable, thereby advancing the commercial viability of MFCs for treating toxic and complex waste streams (82).

Wastewater as feedstock: Municipal, agricultural and industrial wastewater are ideal and environmentally sustainable fuel sources for MFCs because they contain high levels of biodegradable organic materials, including sugars, lipids, proteins, amino acids and volatile fatty acids. The electroactive bacteria metabolize these organic substances within the MFC's anode chamber, acting as electron donors in microbial respiration. The free electrons are then transferred to the anode and pass through an external circuit, generating electricity. One of the main advantages of using wastewater as a substrate is its abundant availability at no cost and its continuous production in urban and rural areas. Additionally, it eliminates the need for artificial or synthetic materials as a substrate, making the process both economically and environmentally sustainable (80).

Reusing wastewater in MFCs to treat it while generating energy is a significant environmental benefit. MFCs can completely remove both COD and BOD, which are key indicators of water pollutant levels. By reducing COD and BOD, MFCs help prevent eutrophication of natural water bodies and lessen the load on traditional wastewater treatment facilities. The electricity produced is usually modest in small-scale setups but sufficient to power low-energy electronic devices, such as LEDs, environmental sensors, wireless transmitters, or small battery systems. This power can be scaled up in larger configurations or through series or parallel stacks of MFCs, which can potentially be integrated with microgrids to meet local energy needs (83).

Moreover, wastewater-powered MFCs are especially attractive for decentralized and off-grid sanitation systems, especially in rural areas and developing countries where access to conventional energy and wastewater or sewerage treatment is limited. In these settings, pilot MFCs have demonstrated not only the technical feasibility of the technology but also its potential to help achieve energy independence, protect the environment and improve public health. Further advancements in reactor design, electrode materials (including the optimization of engineered microbial communities) and ongoing research are likely to enhance the practicality of wastewater-based MFCs, especially as a sustainable, dual-purpose solution for energy and sanitation management (84).

Sludge as feedstock: The waste treatment by-products remaining after typical conventional wastewater treatment include activated sludge and anaerobic sludge, which have not been fully utilized as energy sources in MFCs. Such sludges are rich in microbial biomass and contain various complex organic compounds like proteins, lipids, polysaccharides and refractory organics. Sludge represents a potential renewable energy source because these components serve as high-energy substrates in MFCs to support electrogenic bacteria. Since sludge has a higher organic loading rate compared to common synthetic substrates or weak wastewater, proper handling of such sludge loading can lead to significant power generation and waste removal (85).

However, applying sludge in MFCs presents several technical challenges. Sludge is inherently heterogeneous, highly viscous and often contains high solids content, which can limit mass transfer, hinder electron diffusion and reduce the accessibility of organic matter to microbes. Exoelectrogens' physical characteristics can also impede their ability to metabolize energy-rich compounds efficiently. To overcome these limitations, pretreatment processes are typically used to increase the biodegradability and solubility of sludge organic materials. Effective treatment methods include ultrasonication, alkali hydrolysis, thermal treatment and enzymatic digestion, which help break down complex molecules, release intracellular material and boost electron production from sludge (86).

Beyond power generation, there are multiple environmental and operational benefits to using sludge in MFCs. It helps reduce sludge volume, thereby lowering the burdens of handling, transportation and disposal. It also improves sludge dewatering, simplifying downstream processing such as composting or incineration. Notably, MFCs can partially offset the energy needs of the entire treatment process, potentially making wastewater treatment plants energy-neutral or even energy-positive. Overall, integrating MFCs with activated and anaerobic sludge treatment provides a practical solution for renewable energy generation while supporting waste minimization, resource recovery and sustainable wastewater management (87). Further advancements in sludge pretreatment, reactor design and biofilm development will be essential for increasing the scalability and efficiency of sludge-fed MFC systems in both urban and industrial settings as the technology evolves.

Bioaugmentation and emerging applications

Bioaugmentation involves introducing specialized or genetically engineered microbial strains capable of degrading recalcitrant pollutants, thereby improving the treatment efficiency and energy recovery of MFCs. This strategy strengthens microbial communities with specific metabolic traits such as phenol degradation, dye decolorization, or HM reduction. Its success depends on careful selection of microbial consortia, optimization of environmental parameters (e.g. pH and temperature) and monitoring of microbial survival and activity to ensure long-term stability and performance (88-90).

Recent advances have focused on developing microbial consortia with enhanced electron transfer efficiency and tolerance to toxic environments. For instance, pilot-scale MFCs treating dye industry effluents supplemented with *Pseudomonas putida* and *Geobacter metallireducens* achieved substantial degradation of aromatic hydrocarbons and HM removal, while concurrently generating electricity to power auxiliary onsite sensors-demonstrating the scalability and robustness of bioaugmented systems in real-world operations (90-92).

There is also growing interest in extending MFC applications to the remediation of emerging contaminants such as microplastics. Recent studies have reported the effective removal of microplastics at concentrations ranging from 25 to 400 mg/L, accompanied by reductions in COD and enhanced power output. Innovative integrations-such as magnetic separation coupled with MFCs-have achieved up to 93 % removal efficiency for small microplastic particles, highlighting the potential of MFC-based systems for addressing modern pollution challenges (93, 94).

Applications in environmental remediation

MFCs are becoming potent environmental biotechnology tools because, in addition to producing electricity, they can degrade, detoxify, or remove a very diverse range of environmentally harmful substances. This has resulted in great appeal for many environmental cleanup efforts due to their versatility (95). A schematic overview of the diverse environmental and bioenergy applications of MFC systems, including wastewater treatment, lignocellulosic biomass conversion, biohydrogen and bioethanol production, bioplastics and platform chemical synthesis and metal recovery, is illustrated in Fig. 3.

Wastewater treatment (COD/BOD reduction): The treatment of wastewater is one of the leading and long-established environmental applications of MFCs, specifically for minimizing COD and BOD. These two parameters are crucial indicators of water pollution, indicating the quantity of organic materials in a particular sample of wastewater. COD is the amount of oxygen required to oxidize all the organic matter in the water completely. At the same time, BOD is the amount of oxygen needed by aerobic microorganisms to break down organic pollutants. Using COD can also reveal that there are dangerous levels of COD and BOD in untreated water or water that is not as clean as it should be and this can be disastrous to any aquatic life (96).

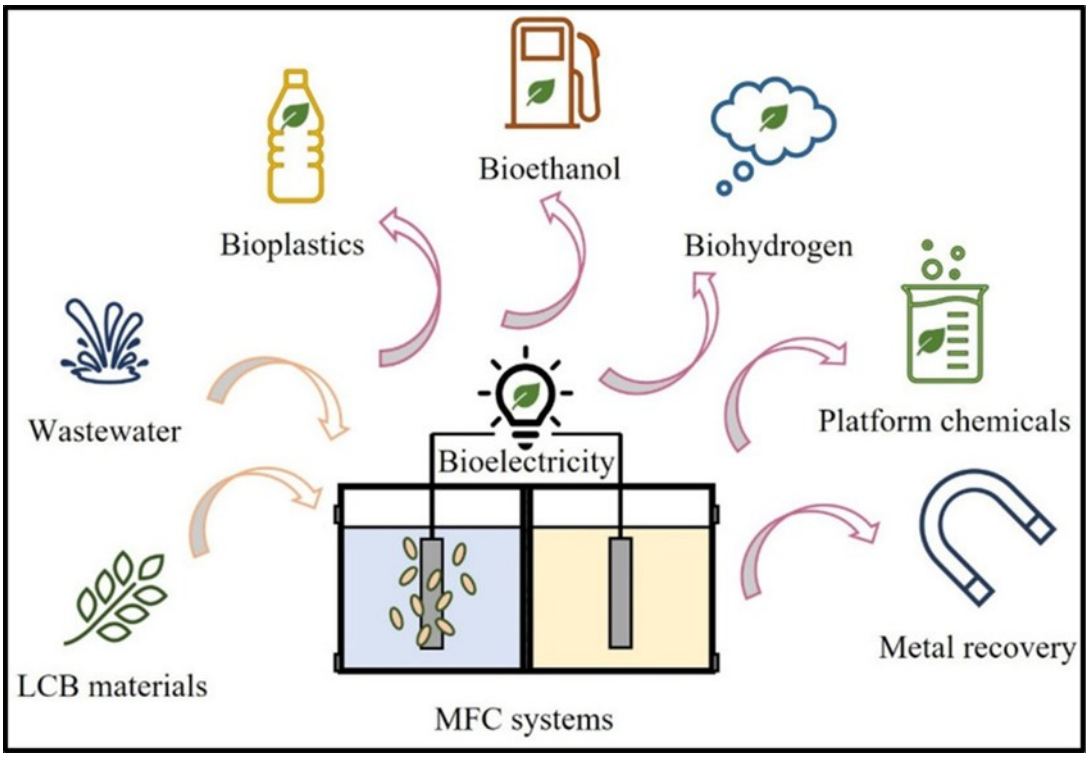

Fig. 3. Versatile applications of microbial fuel cell systems for bioelectricity and bioproducts.

Versatile applications of microbial fuel cell systems for integrated bioelectricity generation and bioproduct synthesis. MFCs can process diverse substrates such as wastewater and lignocellulosic biomass to produce bioplastics, bioethanol, biohydrogen and platform chemicals, alongside metal recovery and nutrient reuse, demonstrating their potential in sustainable bioenergy and circular bioeconomy frameworks.

Wastewater in the MFCs serves as a substrate or source of organic matter, which, when supplied to the electroactive microorganisms present in the anode chamber, facilitates the metabolism of these organisms. The organic compounds are oxidized by these microbes under anaerobic conditions, releasing electrons and protons as by-products of the metabolism. These electrons move down an external circuit and produce electricity. The protons cross a membrane (which may or may not be present) and enter the cathode chamber, where they react with oxygen to give water. This process not only produces bioelectricity but also degrades organic pollutants, thus efficiently reducing the level of CODs and BODs in the treated effluent (64).

Scores of laboratories and pilot-scale investigations have documented that MFCs can achieve COD removals of 60 % to 90 % based on reactor design, microbial consortium, substrate and detention time. The BOD removals are also substantial, with up to 80 % (and more) BOD removals and have made MFCs a competitive substitute for the traditional aerobic treatment systems (like activated sludge processes). Notably, achieving this does not require mechanical aeration, which is one of the most energy-intensive parts of traditional wastewater treatment. That is why MFC technology is exceptionally economical in non-grid, decentralized and rural wastewater treatment systems, where energy efficiency and low maintenance are paramount (97).

Additionally, the low sludge quantity associated with MFCs will further enhance their environmental effectiveness in this regard by reducing the burden of sludge management and disposal. The fact that MFCs can efficiently remove COD/BOD and recover energy makes MFCs one of the emerging wastewater treatment technologies that align with the principles of sustainability, resource recovery and environmental management (98).

A pilot-scale MFC treating sulfide-rich pineapple processing wastewater reported a 99 % COD removal, 97 % sulfide removal and stable current density of up to 88 mA/m^2 over several months, with practical guidelines developed for industrial up-scaling. These results surpass or match conventional processes while providing direct energy recovery (99). Fig. 4 illustrates the COD removal efficiency of MFCs for the different wastewater types analyzed.

Heavy metal removal and recovery: One of the most critical areas where MFCs can be of use in environmental remediation is the removal of HMs. These HMs include Cr^{6+}, Cu^{2+}, Pb^{2+}, nickel (Ni^{2+}), cadmium (Cd^{2+}) and Zn^{2+}. Although they have low toxicity levels, they are considered non-biodegradable pollutants that persist in ecosystems and accumulate in the food chain, posing serious health hazards and risks to both human health and biodiversity. Chemical-based treatment techniques, like chemical precipitation, ion exchange and membrane filtration, are known to be costly, energy-intensive and hazardous, producing secondary waste (102).

The solution is an ecologically sound and innovative MFC that enables electrochemical reduction of HM ions at the cathode. An MFC setup involves electrogenic microbes that oxidize organic materials (e.g. wastewater or sludge) into electrons and protons at the anode. These electrons move through an external circuit to the cathode, where they are used to reduce HM ions contained in the solution. To illustrate, the highly toxic and carcinogenic hexavalent Cr^{6+} may be reduced to trivalent Cr^{3+}, which is less malignant and more stable. Likewise, it is possible to deposit the Cu^{2+} as Cu^0 by reducing the Cu ions on the cathode surface, so that we can not only recover the resources but also detoxify (103). A field study using MFC reactors for mining effluents achieved 85 %-90 % removal for Cr and Cu ions and enabled simultaneous resource recovery. The system was operable off-grid, further lowering both operational and energy costs (104). Representative performance data highlighting removal

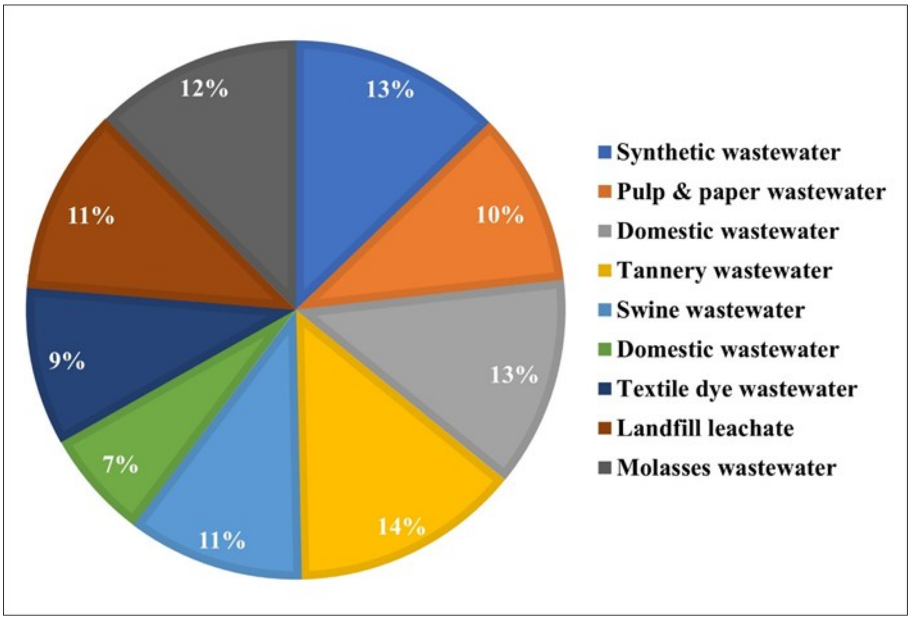

Fig. 4. COD removal efficiency of microbial fuel cells across different wastewater types.

The figure summarizes average COD removal efficiencies reported for various wastewater types treated using MFCs, including synthetic, pulp and paper, domestic, tannery, swine, textile dye, landfill leachate and molasses wastewater. (Data compiled from (14, 83, 100, 101)).

efficiencies and corresponding power densities for multiple HMs (Pb^{2+}, Cu^{2+}, Ag^{+}, Cr^{6+}, Ni^{2+}, Co^{2+}, Cd^{2+}) are summarized in Fig. 5, demonstrating the dual functionality of MFCs in bioelectricity generation and contaminant removal.

Such a reduction of metals not only eliminates the emission of toxic substances but also enables the recovery of valuable metals, transforming waste into a valuable resource. It operates at ambient temperatures and does not require a chemical reagent or any electrical input, making it especially suited for very low-cost, environmentally friendly operation in isolated or decentralized settings. Moreover, MFCs can be developed to selectively remove and recover specific metals based on their redox potential in complex waste streams (82).

Besides the cathodic reduction, the anode chamber can also play an indirect role in HM detoxification, sulfide release, or pH alteration, which facilitates metal formation. The flexibility and versatility of MFCs consequently make them very useful in the management of multi-metal effluents, particularly those from the electroplating industry, which is involved in the production of batteries, mining and electronic waste recycling. Briefly, the use of MFCs to remove HMs is a win-win situation, as it leads to environmental protection by removing a harmful pollutant and, consequently, enhances its economic value through the recovery of the metals. MFCs will continue to become an integral part of sustainable industrial wastewater treatment technologies as electrode materials, microbial community development and reactor designs advance (75).

Degradation of organic pollutants (dyes, hydrocarbons, pharmaceuticals): Water decontamination is a crucial function of MFCs, given the constant increase in concerns about water contamination from both industrial and municipal activities. Synthetic dyes, pharmaceuticals, petroleum hydrocarbons and other organic pollutants are also frequently found in surface waters, ground waters and wastewater effluents. These pollutants tend to

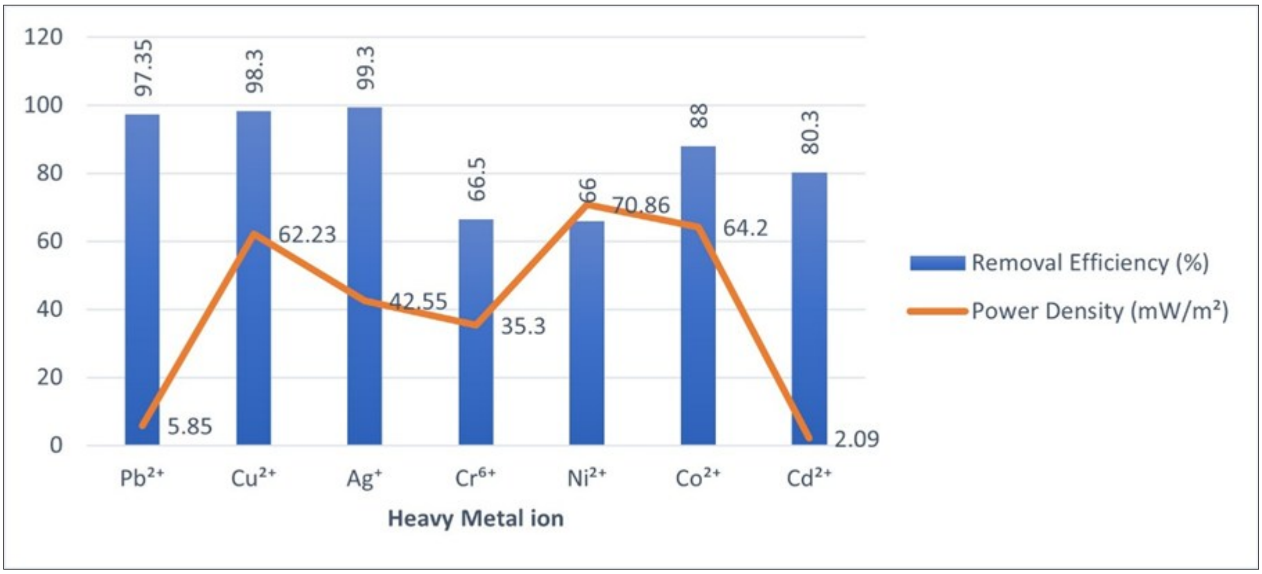

Fig. 5. Performance of microbial fuel cells in heavy metal bioremediation.

Removal efficiencies (%) and corresponding power densities (mW/m^2) for various heavy metals (Pb^{2+}, Cu^{2+}, Ag^{+}, Cr^{6+}, Ni^{2+}, Co^{2+}, Cd^{2+}) demonstrate the dual function of MFCs in simultaneous bioelectricity generation and contaminant removal. (Data compiled from (26, 105-110)).

be toxic, carcinogenic and persistent, posing a challenge to conventional biological treatment, which is highly hazardous to both the ecosystem and human health (32). These MFCs offer a relatively ecologically friendly and modern process for biodegrading these intricate pollutants through the synthesis of microbial metabolism and bioelectrochemical reactions. In an MFC, the electrogenic bacteria oxidize organic compounds at the anode, degrading them into simpler and less harmful molecules and discharge electrons and protons. The anode traps these electrons and, through an external circuit, transfers them to the cathode, with which electricity is produced. Mineralization, or the transformation of toxic organic substances, also occurs during this process, making MFCs highly efficient in treating recalcitrant pollutants (111).

A well-known application is the treatment of synthetic dyes in the textile and leather industries. Dyes such as methyl orange, Congo red, crystal violet and reactive black 5 are not only aesthetically polluting; they are also toxic and non-biodegradable in aerobic conditions. MFCs, mainly when operated in anaerobic or facultative anaerobic conditions, have been shown to decolorize azo dyes by microbial action, resulting in a substantial decline in colour intensity and chemical toxicity. The resulting electricity is also generated during the degradation process, adding value to the treatment process (112).

Hydrocarbons such as benzene, toluene, ethylbenzene, xylene (BTEX) and polycyclic aromatic hydrocarbons (PAHs), which are standard components of petroleum products, have also been effectively utilized in the biodegradation process using MFCs. They are chemically stable and are incredibly recalcitrant in the traditional wastewater treatment plants because they are hydrophobic. In MFCs, specially developed microbial consortia with the ability to degrade hydrocarbons anaerobically synergistically interact with electrogens to degrade such pollutants, allowing the flow of electrons to be utilized for energy generation. This renders MFCs suitable for use in industrial effluent treatment and the treatment of oil spills, oil-contaminated soils and sediments (113).

The degradation of pharmaceutical and personal care products (PPCPs) represents a significant area of application. Ibuprofen, naproxen, diclofenac, antibiotics (e.g. sulfamethoxazole, amoxicillin) and hormones such as estradiol and testosterone are prevalent compounds retained in wastewater due to their incomplete removal in conventional wastewater treatment facilities. Preferably in the presence of enriched populations of specialised microbes or bio-electrocatalysts, MFCs have been found to transform or fully mineralise a wide range of such substances. MFCs can also aid in curbing the extension of antibiotic-resistant bacteria and genes, thereby reducing the risk of new health hazards, by lowering exposure to sub-lethal dosages of antibiotics (114).

To demonstrate this, a study involving an MFC used to treat hospital wastewater found that more than 80 % of ibuprofen and acetaminophen were broken down within 72 hrs of exposure, along with the production of power (115). For textile wastewater, a 2024 case study using a cheese whey-fed MFC achieved 97.1 % *in situ* decolorization of methylene blue within 18 hrs and continuous-mode operation consistently achieved >74 % decolorization depending on retention time. Other studies using MFCs confirm dye removal rates of over 75 % for various azo and vat dyes, with stable electricity output. In another experiment, it was further revealed that the total decolorization of methyl orange in textile dye wastewater occurred without any change in the current output (116, 117).

These results open up a new prospect for MFCs, being not only sources of energy but also efficient bioreactors that can help address some of the most recalcitrant organic pollutants in our environment. To conclude, MFCs are an environmentally friendly and versatile technology in the degradation of synthetic dyes, hydrocarbons and pharmaceutical product residues. They represent a practical option for future wastewater treatment and environmental sustainability since they can generate carbon-free energy while cleaning up pollution in the environment (7).

Nutrient removal (nitrogen and phosphorus): Eutrophication also occurs in aquatic ecosystems when excess nitrogen and phosphorus cause algal blooms that deplete aquatic life of oxygen, leading to the failure of marine ecosystems. This is a result of agricultural runoff, sewage release and fertilizer use, thereby increasing the presence of nutrients in water bodies. The MFCs have been shown to eliminate these nutrients via the bioelectrochemical pathways. As an example, the viability of ammonium (NH_4^+) oxidation at the anode and nitrate (NO_3^-) as a terminal electron acceptor at the cathode, which can be reduced to nitrogen gas (N_2), will be demonstrated. More sophisticated MFCs will even precipitate phosphates as struvite (magnesium ammonium phosphate) and it can be reused as a fertilizer. Pilot-scale MFC processing swine wastewater demonstrated up to 85 % nitrogen and 90 % phosphorus removal, supporting nutrient recovery as struvite and making effluent suitable for irrigation (118). The aspect of nutrient removal incorporated in MFCs enables a closed-loop of nutrient recycling, energy recovery and efficient farming, which is why it is associated with rural environments where wastewater treatment and precision farming are applicable. Such advantages render MFCs a progressive solution to the nutrient imbalance issue and water quality problem faced by the whole world (118, 119). Integrated CW–MFC systems have reached pilot demonstration, improving pollutant removal while producing auxiliary power. A 2023 pilot CW-MFC study reported enhanced electricity generation and improved nutrient removal compared with CW alone, illustrating a viable pathway for field deployment in decentralized sanitation projects (120).

Soil and sediment remediation: The addition of water-based MFCs, particularly those of the sediment microbial fuel cell (SMFC) type, is emerging as a method of *in-situ* remediation of polluted soils and sediments. Sediments contaminated with petroleum spills, PAHs and chlorinated compounds are considered challenging to remediate due to the high cost and difficulty of excavation-based methods. SMFCs utilize the natural microbial population existing in sediment to break down these chronic pollutants. The anode is inserted into the polluted sediment and as half of the bioelectrochemical gradient is formed, the other half is put in the overlying water or soil layer. SMFCs enable the controlled and constant destruction of pollutants through microbial oxidation at the anode electrode, while electron conduction to the cathode occurs without interference with the ecological environment. They are also very low-maintenance and operate passively, making them highly appealing for the long-term clean-up of remote, submerged, or ecologically sensitive sites (102, 121).

Across laboratory and pilot scales, MFCs have demonstrated COD removal efficiencies of 80 %-95 % , BOD reductions of 75 %-90 % and power densities typically ranging from 0.5 to 2.0 W m^{-2}, depending on the substrate and configuration. These quantitative ranges substantiate qualitative claims of effective pollutant degradation and bioelectricity generation, confirming the suitability of MFCs for simultaneous treatment and energy recovery (122, 123).

MFCs as environmental biosensors: MFCs are rapidly advancing as flexible environmental biosensors. Their innovative method of producing measurable electrical signals linked to microbial metabolism shows that these devices are not only a creative way to generate bioenergy but also act as platforms for near-real-time environmental quality monitoring. Their biosensing ability depends on the principle that electrical outputs (voltage or current) change proportionally with the amount of biodegradable organic compounds or pollutants in the sample being monitored (although this understanding is consensus-based). Assuming that electroactive microbes exist in the anode chamber that metabolize these pollutants proportionally, changes in microbial activity can influence the electrical signals, indicating shifts in microbial respiration, electron transfer efficiency and interactions among various biogeochemical processes (124).

The multifunctional nature of MFCs allows them to operate as self-powered sensors, capable of continuous in situ monitoring without external energy, making them ideal for remote, distributed, low-resource environments. Additionally, MFC biosensors have demonstrated sensitivity to a wide range of analytes, including organic pollutants such as BOD and COD, HMs and emerging contaminants like pharmaceuticals and pesticides. This sensitivity has been enhanced by recent advances in miniaturization and wireless data collection, which have improved their integration into environmental monitoring networks (125).

As environmental biosensors, MFCs present a sustainable, cost-effective and real-time alternative to traditional laboratory analyses, supporting innovative efforts in environmental management, pollution control and public health. MFC-based biosensors can measure numerous critical water quality parameters, enabling comprehensive assessment and management of water quality. These biosensors can analyze parameters such as BOD, COD, pH, conductivity and toxicity (126).

MFCs detect BOD by measuring the electrical output generated by microbial oxidation of biodegradable organic matter. The voltage or current produced by these reactions directly correlates with BOD levels. MFCs enable real-time measurement of organic pollution in wastewater. Similarly, COD can also be monitored with MFCs, which respond to the total oxidizable organic and inorganic substances in the sample. This provides a faster alternative to traditional COD testing, which often requires extensive labour and chemicals (127).

The pH level influences electron transfer efficiency and microbial activity in MFCs. MFC systems can monitor pH by detecting changes in electrical output, as pH fluctuations impact system performance. Conductivity affects internal resistance and overall MFC function by reflecting the ionic strength of water. Biosensors can estimate conductivity indirectly by measuring shifts in electrical output, which helps determine dissolved ions and salinity. Toxic chemicals, such as pesticides or HMs, inhibit microbial activity and reduce the electrical signals produced by MFCs. Therefore, MFC biosensors can serve as toxicity sensors to identify harmful pollutants and evaluate their impact on water quality (128).

Recent advances and innovations

Over the past few years, MFCs have undergone significant technological advancements, with scientists and engineers tackling major challenges related to low-power discharge, scalability, affordability and system stability. These breakthroughs and technologies span a wide range of research areas, including material science, microbiology, reactor design, hybrid technologies and digital integration-aiming to bring MFCs closer to practical applications in green energy generation, environmental cleanup and sustainable waste management (87).

One notable area of innovation is the development of high-performance electrode materials. Surfaces of advanced materials, such as graphene, carbon nanotubes (CNTs), metal-organic frameworks (MOFs) and doped carbon composites, have been engineered to enhance surface area, conductivity and microbial compatibility. These materials facilitate faster and more effective electron transfer, resulting in high power and current densities. Additionally, electrode bio-functionalization with redox mediators, nanoparticles and microbial enzymes is being researched to enable DET between microbes and electrodes, further enhancing performance (129).

On the microbial front, advances in synthetic biology and genetic engineering have led to the development of engineered electrogenic strains with enhanced metabolic pathways and electron-shuttling capabilities. Researchers are also optimizing mixed microbial consortia to boost system resilience, substrate versatility and pollutant degradation. Studies focus on quorum sensing, co-culture engineering and extremophiles to maintain stable operation under various environmental conditions (130).

In reactor design, innovations include modular, scalable and membrane-less MFCs. These designs minimize internal resistance, simplify repairs and are economically scalable for urban and rural deployment. Examples include paper-based biosensing MFCs, stacked configurations to increase power output and miniaturized versions such as wearable MFCs for biomedical use. Additionally, 3D printing techniques are being utilized to produce more precise and customized MFC components (131).

Another key development involves integrating hybrid energy systems and digital technologies with MFCs. There is a growing trend to connect MFCs with solar, wind and battery storage systems to create multi-source renewable energy platforms. Real-time monitoring and automation, enabled by artificial intelligence (AI) and the internet of things (IoT), are used to optimize system performance, detect faults and predict maintenance needs (132).

Ultimately, in terms of sustainability, MFCs are being increasingly considered for applications beyond wastewater treatment. These include bioremediation of HMs and emerging contaminants, desalination, resource recovery (such as nutrients and metals) and self-powered biosensors for assessing environmental pollution. Overall, the evolving landscape showcases a multidisciplinary community effort to transform innovative ideas into efficient, scalable and versatile platforms that can address some of the world's most pressing energy and environmental challenges. Future advancements are expected to bridge the gap between laboratory research and real-world field implementation, expanding the role of bioelectrochemical solutions in sustainability (133).

Novel materials (nano-electrodes, carbon-based composites): Innovation in the field of novel electrode materials and their utilisation is one of the most radical directions of MFC technology. The primary experimental factors influencing the electrical performance, stability and scalability of MFC systems are the composition, surface structure and conductivity of the electrodes, as these are the primary interfaces through which microbe interaction and electron transfer occur. Initial investigations have utilized conventional materials such as graphite rods and carbon cloth. Still, recent investigations have increasingly focused on nano-engineered electrodes and carbon-based composites, which exhibit improved electrical, physical and biological performance (134). Recent electrode-material research has focused on metal-free carbon composites, doped graphene and conductive-polymer hybrids, which combine high surface area with enhanced oxygen-reduction kinetics. Comparative analyses reveal that these advanced electrodes can deliver 20 %–40 % higher power densities than traditional carbon cloth, while reducing the cost per square meter by up to 50 %. Long-term durability testing under real wastewater conditions indicates stable performance for more than six months of continuous operation, suggesting feasible transition to field-scale production (135, 136). Table 3 represents the comparison of novel electrode materials used in MFCs.

Nano-electrodes: Nano-electrodes form an advanced technology in fabricating superior MFCs. They are nanomaterials (synthesized or engineered at a scale of 1 to 100 nanometers) where physical and chemical properties vary drastically from those of the bulk. The high ratio of surface area to volume is one of the most significant benefits of nano-electrodes, as it presents a spacious surface for microbes to attach and form thick biofilms. This is of particular interest in MFCs, in which the process of electron transfer between microbial cells and the electrode surface is limiting to power production. The special nanoscale morphology of these materials also enables close interfacial contact of the electroactive bacteria and the electrode, therefore allowing them to perform the role of DET without mediators (143).

Some of the nano-material electrodes are CNTs, graphene, zinc oxide (ZnO) nanowires and titanium dioxide (TiO_2) nanoparticles. They have not only high conductivity, which favours an adequate flow of electrons, but also are mechanically stable and compatible with long-term interaction with microbes. An example is the use of multi-walled carbon nanotubes (MWCNTs) grafted onto anode surfaces, resulting in a nano-textured bio-interface with a significantly increased ability to obtain electrons when the species used was *Geobacter sulfurreducens*. The activation energy required in redox reactions also decreases at these advanced interfaces, resulting in high current and power density, as well as improved system performance (144).

Carbon-based composites: Hybrid composites are made from carbon-based materials and are formed by combining carbon structures (such as graphite, activated carbon, or carbon black) with conductive polymers, metal oxides, or natural binders to create multifunctional electrodes. These composites aim to address the limitations of single materials, which may include low mechanical strength, poor conductivity, or limited microbial compatibility. They are designed to enhance electron transfer rates, ensure chemical stability and remain affordable, making them especially attractive for large-scale MFC implementations (145).

The most popular are graphene oxide-polyaniline composites, which can function as both an anode and a cathode due to their combination of graphene's high conductivity and the electron-rich structure of polyaniline, resulting in excellent performance. Similarly, carbon black polymer blends have been reported to promote robust microbial growth while also enhancing conductivity. These composites often contain functional groups (e.g. carboxyl, hydroxyl, or amine) that facilitate ion exchange and microbial adhesion, which are essential for continuous operation and high electron transfer. Carbon-based composites are also emerging as effective, low-cost alternatives to platinum-based catalysts, particularly on the cathode side and they are environmentally friendly (146).

Activated carbon, carbon aerogels and metal-free doped carbons (such as nitrogen-doped graphene) are shown to be highly active catalysts for the ORR, a crucial terminal reaction in most MFCs. These materials are more sustainable and less expensive, providing resistance to catalyst poisoning and fouling, which extends electrode lifespan and enhances reliability. For example, nitrogen-doped graphene cathodes have demonstrated outstanding performance in enhancing ORR kinetics, while maintaining low material and fabrication costs, which facilitates the establishment of affordable MFC systems (147).

Table 3. Comparison of novel electrode materials in microbial fuel cells

Electrode Type	Material / Composite	Key Advantages	Typical Applications	Performance Metrics	References
Nano-electrode	Multi-Walled Carbon Nanotubes	High conductivity, large surface area promote dense biofilm formation	Anode surface modification	Current Density: ~1500-2000 mA/m²; Power: ~2-4 W/m²	(137)
Nano-electrode	Graphene / Graphene Oxide	Excellent electrical properties, strong microbial adhesion	Both anode and cathode	Power Density: up to 5 W/m²	(111)
Carbon composite	Activated Carbon + Conducting Polymer (e.g., Polyaniline)	Cost-effective, good catalytic activity, stable under harsh conditions	Cathode replacement for Pt	ORR efficiency close to platinum (~80 %-90 %)	(138)
Carbon-metal oxide hybrid	CNTs + MnO_2 or TiO_2	Enhanced catalytic surface for oxygen reduction, corrosion-resistant	Cathode catalysts	Power Output Increase: 30 % -50 % over traditional materials	(139)
Biofunctionalized electrode	Carbon felt + redox mediators (e.g., flavins)	Facilitates mediated electron transfer, better microbial communication	Anode for mixed-culture systems	Higher start-up rates, enhanced stability	(139)
Metal-free catalyst	Nitrogen-Doped Graphene	High ORR activity, low cost, durable	Cathode	Power Density: ~3.5-5 W/m²	(140)
Natural material-based	Biochar or Coconut Shell-Derived Carbon	Eco-friendly, cheap, sustainable, moderate conductivity	Anode or cathode in rural/off-grid systems	Power Density: ~0.5-1 W/m²	(141)
3D-structured electrode	Carbon foam, porous graphite scaffolds	High porosity and better mass transport promote thick biofilm growth	Advanced reactor designs	Power enhancement: up to 2× over flat electrodes	(142)

Recent techno-economic and manufacturing studies highlight that advanced carbon materials (graphene derivatives, doped carbons, CNT composites) offer substantial performance gains but require careful life-cycle and scale-manufacturing analysis: scalable electrochemical exfoliation and other up-scalable GO/ graphene routes have reduced material cost trajectories and demonstrated production methods amenable to pilot-scale electrode manufacture, improving the practical cost–performance ratio of nano-engineered anodes and cathodes (148, 149). Durability data are emerging: nitrogen-doped carbons and hybrid carbon–polymer composites show improved ORR stability vs. Pt in lab tests and earlier field simulations, but long-term aging (fouling, biofilm corrosion, mechanical fatigue) remains underreported; recent accelerated-aging tests indicate that doped carbon cathodes retain >80 % activity after hundreds of operational hours under realistic wastewater conditions, suggesting promising lifetime improvements but underscoring the need for multi-month pilot durability data before industrial adoption (135, 150). Preliminary LCA work shows that replacing Pt catalysts with metal-free doped carbons or carbon composites materially reduces global warming potential and toxicity hotspots associated with mining and catalyst processing; however, electrode fabrication (exfoliation, chemical functionalization) can add upstream impacts-so cradle-to-gate LCAs and comparison with conventional materials are essential to confirm net environmental benefits (151, 152).

Functionalization and surface engineering

Surface functionalization and engineering approaches are also crucial for optimizing the electrode-microbe interface in MFCs, in conjunction with the proper selection of electrode materials. These modifications are crucial for enhancing hydrophilicity, facilitating microbial attachment, improving electron mobility and promoting biofilm formation, particularly in systems comprising mixed microbial consortia. Fictionalization enhances the binding capacity of electroactive bacteria to the electrode and their reactivity, which is vital for direct or MET (153).

Common surface modifications include treatment with acids or bases to generate functional groups, such as carboxyl (COOH) or hydroxyl (OH), plasma exposure to increase surface roughness and hydrophilicity and coating with nanoparticles to provide catalytic activity or alter electrochemical behavior. For instance, electrodes can be coated with metal oxides, such as manganese dioxide (MnO_2) or iron (II, III) oxide (Fe_3O_4), to enhance the redox potential and facilitate microbial electron transfer. These surface modifications not only improve biocompatibility but also reduce start-up times and enhance the stability of microbial communities, particularly in long-term and high-load MFCs. This approach is particularly useful in mixed-culture MFCs, where a diverse array of microorganisms with varying electrochemical capabilities coexist. Surface functionalization helps balance competition among microbial species, promoting the growth of electroactive strains and ensuring more reliable energy production, even under fluctuating substrate conditions or environmental influences (154).

Surface functionalization (e.g. MnO_2, Fe_3O_4 coatings, conductive polymer grafting) improves microbial adhesion and ORR kinetics. When implemented using scalable coating methods (such as spray coating or roll-to-roll deposition), the marginal cost per square meter can be substantially reduced-pilot studies demonstrate that structured surface coatings of rGO or NiOx can be produced at a pilot scale with favorable economics compared to lab-scale deposition methods (155).

Hybrid systems and scale-up efforts

The maturity of technology has led to the development of MFC prototypes in real-world settings, moving beyond laboratory conditions and emphasizing hybrid systems and scaling up. This research aims to overcome current limitations, including low power, material costs and operational challenges, while also creating new capabilities for multifunctional energy and wastewater treatment platforms. Plans for hybridization and scaling are necessary to transition MFCs from conceptual research to commercially viable, established technologies with global applicability as sustainable solutions (55).

Hybrid systems: In MFCs, the concept of hybrid systems involves coupling MFCs with other renewable technologies or treatment methods to create multi-functional systems that are more energy-efficient, operationally efficient and environmentally friendly. These combinations aim to balance the seasonal variability of solar or wind energy and maximize resource recovery, leading to improved overall performance indicators (156).

An example of a hybrid system is the integration of MFCs with photovoltaic (solar) panels. Solar energy supplies power to operate other components, such as pumps, sensors, or MECs, which follow the MFC phase. Such setups can sustain themselves even in off-grid or rural locations. Another common hybrid configuration pairs MFCs with anaerobic digesters, which treat high-solid organic wastes and produce methane; the liquid effluent then leaves the MFC to generate electricity and clean water (157). Integration of MFCs with constructed wetlands (CW-MFCs) and sediment-based systems has demonstrated strong potential for scalable environmental applications. These hybrid systems combine phytoremediation and sediment microbial activity with electrode-based energy capture, enabling the simultaneous removal of pollutants and the generation of low-level electricity. Pilot-scale demonstrations have reported enhanced nutrient degradation and sustained power output sufficient to operate sensors or auxiliary treatment units under outdoor conditions, underscoring their suitability for decentralized wastewater management in peri-urban and rural settings (120, 158).

These systems are particularly useful in agro-industrial and municipal waste treatment facilities, as they maximize energy recovery from diverse waste streams. Additionally, the low-voltage electricity generated by MFCs can be stored and distributed via capacitor banks and battery systems, supporting intermittent or peak-load applications, such as environmental sensors or disaster lighting. The potential for real-time biosensing, automatic fault detection and feedback control further enhances the appeal of hybrid systems for use in innovative grid systems and environmental monitoring stations in remote areas (159). Meta-analyses of pilot and pilot-scale MFC/BES projects show that although reported current densities vary widely across wastewater types and climates, consistent design principles (electrode area: reactor volume ratios, flow regime control and modular stacking) enable predictable scale-up; recent systematic reviews identify repeatable pilot successes (CW-MFC pilot plants, agro-industry effluent pilots) and provide design guidelines for reducing internal resistance and oxygen intrusion for larger units (160).

Scale-up efforts: The process of transitioning MFC systems from small laboratory prototypes to larger-scale systems suitable for field or industrial applications is highly complex and essential for commercialization. The aim is to maintain or enhance system performance (e.g. power density, pollutant removal efficiency and stability) while ensuring economic viability, durability and ease of maintenance. Overall, the increased reactor volume and electrode surface area required for scale-up present significant challenges, which can lead to increased internal resistance or decreased mass transfer efficiency (68).

Common issues in large-scale systems include oxygen intrusion, pH imbalance and uneven substrate distribution, which may lead to microbial stratification and lower electron recovery. To address these issues, scientists have developed stacked MFC arrays, where multiple cells are connected in series (to increase voltage) or in parallel (to boost current). Modular expansion is also achievable by adding extra units and overcoming site limitations through the use of stacked designs. Another factor in scaling up is the cost of materials-particularly electrodes, membranes and catalysts (161).

Expensive materials, such as platinum cathodes and Nafion membranes, are being replaced with low-cost alternatives, including activated carbon, biochar and natural polymer membranes (e.g. chitosan, agar). Advances like 3D printing of electrode structures, membrane-less designs and common electrodes have also lowered costs and simplified designs. Pilot MFC systems already deployed in various settings, including wastewater treatment plants, aquaculture farms and constructed wetlands, demonstrate promising results in achieving energy neutrality and reducing environmental impact. Some systems can treat hundreds of liters of wastewater daily and power sensors, data loggers, or communication modules in real-time (162). Recent techno-economic analyses stress that membranes (for example, perfluorinated polymer membranes such as *Nafion*) and catalysts are dominant cost drivers; substitution with ceramic or bio-based membranes and metal-free cathodes can reduce capital and life-cycle impacts. Comparative life-cycle assessment (LCA) studies of bioelectrochemical systems (BES) and MFC technologies reveal potential reductions in global warming potential (GWP) compared to conventional activated-sludge wastewater treatment, particularly when energy recovery and nutrient recycling, such as magnesium ammonium phosphate (commonly known as struvite), are considered. However, outcomes are highly scenario-dependent-sensitivity to electrode lifetime, membrane replacement frequency and system electricity credit determines whether a MFC system is net beneficial in a given context (151, 152, 163).

Challenges and limitations

Although the technology and environmental enrichment potential of MFCs are promising, their large-scale deployment and commercial use are still limited by several technical, economic and operational challenges. These issues affect the systems' efficiency, durability and cost-effectiveness, making it essential to address them through interdisciplinary research and innovation. The main concerns can be summarized into three key areas: power output and electron efficiency, electrode honeycombing and membrane costs and flexibility, durability and operational stability (123).

Low power output and efficiency: One of the main drawbacks of MFCs is their relatively low power density compared to traditional energy sources, such as batteries or fuel cells. Most laboratory-scale MFCs produce between a few milliwatts and a few watts per square meter, which is only sufficient for low-power uses such as sensors or LED lights. This low output results from limitations in electron efficiency, slow kinetics at the cathodes and internal resistance caused by materials used in the system, such as the electrolyte, membrane and spacing between electrodes (164).

Additionally, the energy conversion efficiency, which measures the ratio of electrical energy produced to the chemical energy in the substrate, is generally relatively low, often less than 20 %-30 %. Factors like surface degradation of substrates, overpotentials at the electrodes and mass transfer limitations also impact overall performance. Although recent advances in nanostructured electrodes, biocatalysts and reactor design modifications have shown promise, current power levels still restrict the practical use of MFCs for generating medium to large-scale energy (165).

Electrode fouling and membrane cost: Biofouling and electrode degradation reduce the long-term stable performance of MFCs, especially in natural wastewater environments. Over time, electron pathways can become clogged with non-electroactive microbial communities, organic matter and inorganic precipitates that deposit on the anode and cathode surfaces, decreasing catalytic efficiency and hindering oxygen diffusion. This results in lower system output and necessitates frequent cleaning or replacement, thereby increasing operational costs (166).

Additionally, components like PEMs, often made from expensive materials such as Nafion, pose a significant cost barrier to commercial adoption. These membranes are crucial for separating the anode and cathode chambers, transferring protons and preventing oxygen and other pollutants from crossing. However, they tend to clog, chemically degrade and lose sensitivity over time, especially when exposed to harsh or fluctuating wastewater compositions. Although new membrane-free or alternative membrane systems (e.g., natural polymers like chitosan, or clay-based materials) are being developed at lower costs, they are still in the early stages of optimization. Currently, they do not match the performance of standard commercially available membranes (167).

Operational scalability and maintenance: Scaling up MFC systems from lab to industrial sizes involves numerous engineering and logistical challenges. The primary issue is the nonlinear increase in performance as size expands, particularly when reactor volume or electrode area increases; power output does not grow proportionally. This is due to uneven substrate distribution, biofilm layering and increased resistance in larger systems. Additionally, maintaining stable and consistent microbial activity on a large anode surface is challenging and in mixed microbial communities, environmental shifts or competition can alter community characteristics (168).

Designing flow channels, managing hydraulic retention times and shaping reactors become more complicated at larger scales. Understanding how scaling impacts performance is crucial to avoid problems such as short-circuiting, dead zones, or excessive head losses. Practically, this means systems must be resilient, self-sustaining and low-maintenance, especially in rural, off-grid, or developing regions. However, they are less suitable for uncontrolled environments because they require constant monitoring, pH adjustments, membrane cleaning and the management of biofilms. Integrating real-time monitoring with IoT and AI provides a solution, but it also adds costs and complexity that must be balanced with performance gains (169).

Prospects and research trends

With the increasing global focus on developing sustainable technologies, MFCs are gradually being recognized as a promising solution to address many urgent issues at the intersection of energy, environmental impacts and waste management. Although current limitations in power generation, scalability and cost-effectiveness still exist, ongoing research continues to transform MFCs from experimental to potentially practical technology. Looking ahead, a structured research and development roadmap is essential to accelerate the transition of MFCs from laboratory prototypes to commercial, field-scale systems. Recent strategic analyses propose three developmental phases: (a) short-term (1-3 years) optimization of electrode materials, reactor miniaturization and cost benchmarking; (b) medium-term (3-7 years) pilot-plant validation in industrial and municipal wastewater streams with integrated LCA and techno-economic assessments; and (c) long-term (7-15 years) establishment of modular, decentralized treatment networks linked to smart-grid infrastructure for energy recovery and monitoring (170, 171).

Market analyses indicate that microbial fuel-cell technologies could achieve a global market valuation of approximately USD 543 million by 2035, driven by increasing demand for decentralized wastewater-to-energy systems and supportive policy frameworks. Cost declines are expected from scalable manufacturing of carbon-based electrodes and bio-derived membranes, which-if realized-could reduce capital expenditure by an estimated 30 %-40 % relative to current laboratory materials and accelerate pilot-to-market pathways (170).

The future integration of MFCs with renewable energy infrastructures represents a promising breakthrough scenario. Coupling MFC modules with photovoltaic (PV) panels or small-scale wind systems enables the creation of hybrid microgrids that can balance intermittent renewable supply with continuous, low-power outputs from waste-derived bioelectrochemical generation. Smart-grid integration, supported by IoT-enabled sensors and low-power MFC biosensors, enables real-time monitoring, predictive maintenance and data-driven optimization of distributed BESs. Recent work on grid-connected MFC control and on low-power sensor-grade MFC electrode improvements demonstrates the technical feasibility of these hybrid and digitally enabled scenarios (171, 172).

From a policy and sustainability perspective, alignment with the United Nations SDGs (SDG 6: Clean water and sanitation; SDG 7: Affordable and clean energy) remains critical. LCA that account for energy recovery and nutrient recycling (for example, struvite recovery) show that MFC/BES configurations can reduce net greenhouse-gas footprints relative to conventional activated-sludge wastewater treatment under favourable scenarios (e.g., long electrode lifetimes and high energy credit). Therefore, regulatory recognition (performance benchmarks for power density, COD removal and life-cycle greenhouse-gas emissions) and market mechanisms (for example, carbon-credit or green-technology certification pathways) are essential enablers for accelerating the commercialization of MFC technologies (151, 173).

To operationalize these prospects, we recommend: (a) coordinated pilot networks that publish standardized performance datasets to enable cross-study LCA and techno-economic meta-analyses; (b) prioritizing long-duration durability testing of electrodes and membranes under realistic wastewater conditions; (c) funding public–private demonstration projects that couple MFC pilots with PV or battery storage to test hybrid microgrid use cases; and (d) engagement with policy-makers to co-develop certification/measurement standards so that MFC installations can access sustainability finance and potential carbon-credit markets (151, 170, 173). These steps will help move MFC research beyond “promising prototypes” to resilient, regulated and economically viable field systems that contribute to circular wastewater management and distributed low-carbon energy services.

Advances in microbial biotechnology, synthetic biology and techno-economic assessments are shaping the future development of MFCs. These interdisciplinary efforts aim to improve efficiency, functionality and commercial viability. The following are the major fields expected to define the future of MFC research and application (174).

Genetic engineering of microbes for enhanced performance: Genetic engineering of electroactive microorganisms is a key future direction, as it can enhance their electron transfer capabilities, substrate variety and resistance to environmental stresses. Additionally, *Geobacter sulfurreducens* and *Shewanella oneidensis* are naturally occurring fermenters with impressive extracellular electron-sharing abilities, but their metabolic pathways are not optimized for efficient large-scale electricity production. Researchers can now modify relevant metabolic features using advanced genome editing techniques (e.g. CRISPR-Cas9, transposon mutagenesis and plasmid-based gene expression systems) to increase redox protein levels, boost biofilm formation and improve tolerance to toxic wastewater (175).

By combining in vitro approaches with *in silico* computational design, engineered strains can be programmed to produce electron shuttles, develop denser and more conductive biofilms, or co-metabolize multiple waste streams, thereby increasing their resilience in real-world conditions. Furthermore, synthetic pathways can enable bacteria to utilize non-natural or complex substrates as feedstocks, greatly expanding the range of materials usable in MFC applications. These genetic modifications have the potential to significantly increase electron recovery efficiency, current density and system lifespan, thereby making MFCs more commercially viable and environmentally sustainable (176).

Use of synthetic biology: In addition to traditional genetic engineering, the emerging field of synthetic biology is revolutionizing microbial system design and control in MFCs. Synthetic biology involves assembling artificial genetic circuits, engineering enzymes and creating modular microbial consortia capable of performing complex, programmable functions within a bioelectrochemical system. Researchers are currently developing so-called designer microbes that can respond dynamically to changing environmental conditions, self-repair broken pathways and even communicate using quorum sensing (177).

These functional properties can be utilized to assemble synthetic consortia-multi-species microbial communities where each species plays a specific role in waste oxidation, electron transfer, or pollutant detection. For example, one species may be adapted to degrade long-chain hydrocarbons, while another is optimized for electron transfer to the electrode. Additionally, utilizing synthetic biology enables the development of bio-sensing MFCs, where engineered microbes produce a measurable electrical signal upon encountering specific contaminants, such as HMs, pharmaceuticals, or pathogens. The dual role of MFCs in decentralized water treatment and environmental monitoring has the potential to revolutionize these fields (178).

Techno-economic feasibility and life cycle assessment (LCA)

To make MFCs commercially viable, it is essential to assess their techno-economic feasibility and environmental sustainability through a comprehensive cost-benefit analysis. These analyses help identify cost bottlenecks, optimize system design and guide decisions on large-scale deployment. Techno-economic analysis (TEA) evaluates capital costs, operating expenses, materials used, system lifespan and return on investment (ROI). Recent TEA studies indicate that membrane costs, electrode materials and system complexity are key factors contributing to the high costs associated with MFCs. As a result, developing membrane-less systems, low-cost biochar electrodes, or modular designs is gaining interest, as they offer potential cost savings (179).

Environmental impact is assessed through life cycle analysis (LCA), which considers the entire lifespan of MFCs-from material extraction and construction to waste management and decommissioning. LCA studies have compared MFCs to conventional wastewater treatment and energy systems, finding that MFCs can produce lower greenhouse gas emissions, achieve a neutral energy balance and enable nutrient recycling. However, these benefits must be balanced against concerns such as material scarcity, system longevity and effluent quality standards. Comparing TEA and LCA provides a comprehensive understanding of system performance and helps policymakers, investors and engineers make informed decisions about the future deployment of MFC technology (152).

Failure analysis and lessons learned

Despite numerous laboratory-scale and pilot demonstrations, several recurring failure modes and technical bottlenecks have hindered the large-scale commercialization of MFCs. Key challenges commonly reported include: (a) persistently low power density and high internal resistance, which limit net energy recovery in scaled reactors; (b) membrane fouling, electrode corrosion and catalyst degradation that cause long-term performance decline; (c) voltage reversal and stack imbalance during multi-cell operation due to uneven substrate distribution and electrochemical heterogeneity; and (d) operational instability arising from biofilm detachment, toxic shocks in real wastewater matrices and the need for frequent maintenance. These failure modes have been documented across recent laboratory and pilot. Practical lessons learned emphasize the selection of robust and low-cost electrode and membrane materials, the adoption of electronic control systems to prevent voltage reversal, pretreatment of complex waste streams and the incorporation of design elements that facilitate maintenance and durability testing. Furthermore, transparent reporting of unsuccessful trials and negative outcomes is crucial for accelerating learning, guiding engineering optimization and de-risking future scale-up initiatives.

Conclusion

MFCs represent an innovative environmental remediation technology that unites sustainability with renewable energy generation. By harnessing the metabolic activity of electrogenic microorganisms, they convert biodegradable and harmful wastes into electrical energy-offering an eco-friendly alternative to conventional treatment and energy systems. Their versatility allows efficient purification of diverse waste streams, including municipal, industrial and agricultural effluents, as well as those contaminated with HMs and pharmaceuticals. Recent studies have achieved reductions of up to 90 % in COD and 80 % in BOD, with power densities of nearly 2 W m^{-2} under optimized pilot-scale conditions. Integration with constructed wetlands and other hybrid systems has enhanced nutrient recovery, achieving a conversion rate of more than 85 % of waste phosphorus into magnesium ammonium phosphate (struvite). Advances in electrode materials, proton-exchange membranes, microbial engineering and reactor design have steadily improved power output and energy recovery. Typical Coulombic efficiencies range from 40 % to 75 %, with current densities of 1-3 A m^{-2} and overall energy recovery approaching 60 % of theoretical maxima. Although current outputs remain modest, these levels already meet the needs of many low-power applications and the modularity of MFCs supports scalable deployment. Key barriers remain-particularly high material costs, internal resistance, membrane fouling and long-term operational stability-but pilot demonstrations worldwide indicate growing technical maturity. Wastewater-treatment MFCs have reached technology-readiness levels 6-7, while micro-MFC sensors for environmental monitoring are approaching commercial viability at levels 8-9. Policy support, public-private partnerships and standardized performance benchmarks for power density, pollutant removal and greenhouse-gas mitigation will be critical for widespread adoption. Establishing clear certification and incentive frameworks can further integrate MFCs into sustainability and carbon-credit programs. In summary, MFCs provide a practical route for transforming organic waste into clean energy while reducing pollution and resource loss. With continuing improvements targeting power outputs above 5 W m^{-2}, greater than 90 % COD removal and electrode lifetimes exceeding 24 months, MFCs are poised to evolve from laboratory prototypes into commercially viable, circular economy solutions that advance global goals for clean water and renewable energy.

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Authors' contributions

SMHK contributed to writing the original draft, visualization, formal analysis, data curation and conceptualization. TK contributed to reviewing and editing, supervision, resources, formal analysis. AB, MS, PR, GV contributed to the formal analysis and review of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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