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Microbial fuel cells as a sustainable nexus of wastewater treatment and bioelectricity generation: Advances, challenges, and future directions in a circular bioeconomy

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ABSTRACT

Microbial Fuel Cells (MFCs) have emerged as a promising technology for wastewater treatment and bioelectricity generation, offering a sustainable solution to energy and environmental challenges. Recent advancements in MFC systems, particularly in material design and microbial optimization, have significantly improved power densities and efficiency. MFCs have demonstrated chemical oxygen demand (COD) removal efficiencies of up to 97%, with power densities ranging from 0.1 W/m^2 to 23 W/m^2, depending on substrate type and system configuration. Despite these advances, challenges such as high capital costs and limited energy recovery efficiency hinder large-scale adoption. The integration of Internet of Things (IoT) and machine learning for system optimization, alongside hybrid MFC systems combining solar and wind energy, has enhanced operational efficiency by up to 20% in some cases. This review presents a comprehensive overview of these breakthroughs, highlighting the environmental, economic, and policy considerations crucial for scaling MFC technology. It also identifies key areas for future research, including improvements in electrode material durability and microbial community stability, which are vital for achieving long-term operational reliability and economic viability in real-world applications.

1. Introduction

The climate change and environmental safety action with the growing increase in wastewater pollution globally are part of the complex challenges that face the present and future generations of humankinds [1] The evidence of security risks arising from these challenges Globally is clear in many ways almost to everyone [2]. With the growing world population and quest for the improvement of the living standard of human beings on the planet, the environment is always affected negatively in so many ways, most especially through accumulation of waste from various sources such as livestock production [3]. Petrochemicals [4], pharmaceuticals [5] agriculture [6]. Solid waste which constitute large percentage of the municipal wastes has increasingly been dumped of in an open space creating serious environmental problems is projected to increase by 50% in this year [3]. Waste from food left over and agriculture are part of the major sources through which toxic substances accumulated in the environment [7]. The increasing high energy demand and inevitable exhaustion of fossils together with the pollution caused by its usage has necessitated research for the development of more sustainable methods for environmental decontamination [8].

1.1. Brief on MFC basics and significance

Microbial fuel cells are simple technology that utilizes the metabolic activity of microorganisms to oxidize the pollutants present in the wastewater thereby releasing electrons for the generation of bioelectricity and simultaneously treating the wastewater [9]. This technology is considered as an alternative in solving the energy and environmental crisis faces Globally [10] the technology provides a clean

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renewable energy [11] and remedies the environment by converting the waste to useful and valuable products [12]. Microalgae-bacterial fuel cell utilizes the mutual relationship between bacteria and microalgae in which the electrogenic bacteria provide the required carbon dioxide for the microalgae photosynthesis and in return the algae provide oxygen to the bacteria needed for its metabolic functions and hence a mutual benefit [13]. The developmental history about the microbial fuel cell can be traced to the 1960 interest of National Aeronautics and Space Administration (NASA) of generating electric current from waste materials and the development of an alternative source of energy due to the 1970s and 80s oil crisis [14]. Other reasons that made the advent of MFC significantly contribute to its adoption and conducting research about it are bioeconomy [15,16] renewable energy generation and lower cost [11,17].

Reducing the ability of the MFC is also another advantage that made it excellent candidate for sustainable environmental remediation [18–20]. Microbial fuel cells, despite their promising applications in several fields, are still bench-top technology this is due to some persistent challenges such as high cost of proton exchange membrane, electrode materials the pillars on which the efficiency of the MFC depends on, and mass transfer limitations between component of the MFC [21–23].

1.2. Wastewater and sustainable-energy nexus

The two most essential ingredients that are requisite for the continuous and improving living standard on Earth are energy and water [24]. The usage of energy accounts for 60% of the greenhouse gas emission [25,26] a major environmental pollution leading to Global warming [27,28] the major source of energy currently utilized is exhaustible fossil fuel [29]. Energy is said to be non-destructible but can only be converted from one form to another [30]. Wastewaters contain a lot of organic matter the chemical energy of which can be converted to electrical energy by the metabolic action of microorganisms [31]. This idea began when in 1911 utilization of microorganisms in the generation of energy was suggested by a British Botanist Michael Crisse Potter [32] who generate electrical current from the cell cultures of *Escherichia Coli and Saccharomyces*. MFC not only degrade the waste and generate electric current but in doing so it simultaneously treat the wastewater and free it from the contamination [33], several research studies has demonstrated that the performance and efficiency of the MFC largely depends on the particularly electrode's conductivity and roughness [34], biocompatibility [30] and specific surface area [35], charge resistance and active surface area of the electrodes [36], other parameters that affect the functions and the efficiency of MFC are the proton exchange membrane and substrate [37]. Numerous pieces of research have been conducted and reported in literature and are still ongoing in search of the solutions and how to improve the above-mentioned properties and overcome the challenges.

1.3. comparative analysis of energy consumption and environmental impact between microbial fuel cell (MFC) technology and traditional wastewater treatment methods

Microbial fuel cells (MFCs) utilize the metabolic activities of microorganisms to degrade organic pollutants in wastewater, converting chemical energy into electrical energy. This dual functionality makes MFCs a promising alternative to conventional wastewater treatment methods. Traditional wastewater treatment processes, such as activated sludge, biological nutrient removal (BNR), and constructed wetlands, are widely used for effluent treatment but often have high energy demands and environmental impacts.

1.3.1. Energy consumption in wastewater treatment

Energy consumption is a critical factor when evaluating the sustainability of wastewater treatment methods. Traditional treatment processes, particularly those based on aerobic treatment such as activated sludge, are energy-intensive, primarily due to the need for aeration. Aeration accounts for up to 60% of the total energy consumption in conventional biological treatment systems. In contrast, MFCs offer the potential to generate energy while treating wastewater, which could reduce the overall energy footprint of wastewater treatment systems [38].

1.3.2. Traditional wastewater treatment: energy consumption

1.3.2.1. Activated sludge process. The activated sludge process is the most widely used biological treatment method. This process involves the aeration of wastewater to promote the growth of microorganisms that degrade organic matter. However, the high energy demand for aeration is a significant drawback. The energy consumption of an activated sludge system can range from 0.4 to 1.5 kWh per cubic meter of treated wastewater, depending on the size of the treatment plant and the degree of aeration required. This high energy demand contributes to the overall carbon footprint of wastewater treatment facilities [39].

1.3.2.2. Biological Nutrient Removal (BNR). BNR processes, which are designed to remove nitrogen and phosphorus from wastewater, also require significant energy input. The energy consumption of BNR systems is influenced by the aeration needs for nitrification, denitrification, and phosphorus removal. The energy consumption for BNR systems can exceed 1.5 kWh per cubic meter of wastewater, further increasing operational costs and environmental impacts [40].

1.3.2.3. Constructed Wetlands. Constructed wetlands are a low-energy alternative for wastewater treatment, relying on natural filtration processes. While the energy consumption of constructed wetlands is generally lower than that of activated sludge systems, they require land and may have limited capacity for high-strength wastewater. The energy consumption of constructed wetlands is minimal, primarily limited to pumping and aerating the water in some designs [29].

1.3.3. MFC technology: energy consumption

MFC technology offers the unique advantage of energy recovery from wastewater, which can significantly reduce the energy consumption of the treatment process. MFCs generate electricity as organic matter is degraded by microorganisms, which can offset the energy demands of the treatment system [41].

Previous studies have often approached MFCs through the lens of individual components such as materials or electrochemistry, while this article advances the field by adopting a system-level perspective, which highlights the interconnected nature of MFCs as a unit of wastewater treatment, bioelectricity generators, and circular bioeconomy enablers. This article synthesizes comprehensive recent advancements in microbial fuel cell (MFC) technologies, particularly focusing on the integration of MFCs with wastewater treatment. The article contributes to closing critical knowledge gaps and shaping the future trajectory of MFC technology, by addressing both technical and non-technical barriers to the large-scale deployment of microbial fuel cells (see Table 1).

2. Biological and electrochemical mechanisms

2.1. Electron transfer pathway

This is one of the pivotal factors that determine the functions and efficiency of an MFCs set up, the electrons are generated by the microorganism's degradation of organic matter, these electrons must be transported to the anode for the generation of electricity, the transfer of these electrons to anode can be either i) directly or through ii) mediated transfer method. The direct electron transfer is carried out through a conductive pili or nanowires these two special structures facilitate the

Table 1
Below gives a comparative analysis of energy consumption and environmental impacts between MFC technology and traditional wastewater treatment methods.

Parameter	Traditional Wastewater Treatment	MFC Technology	Reference
Energy Consumption	High, especially for aeration in activated sludge systems (0.4–1.5 kWh/m^3)	Low, with energy recovery potential (0.2 kWh/m^3)	[38,39]
Greenhouse Gas Emission	High, due to energy-intensive processes (0.3–1.5 kg $CO2/m^3$)	Low, with potential for carbon-neutral operations	[40,41]
Chemical Use	High, including coagulants, flocculants, and disinfectants	Minimal, no need for chemicals in the treatment process	[46]
Sludge Production	High, requiring disposal or further treatment	Minimal, reducing the need for waste disposal	[48]
Sustainability	Limited, resource-intensive with significant environmental impact	High, utilizes organic waste and produces renewable energy	[2,42]

process and thus rapidly reaches the anode directly and transfer the electron within short period of time, this will enhance the generation of current density, power density and the coulombic efficiency [38–40]. While in a situation the direct electron transfer is not possible the bacteria release a redox active compounds which act as electrons shuttles, diffuse and reaches the anode to transfer the electrons, this is also effective but unlike in direct transfer, this may take time to diffuse through the medium and transfer the electron in addition to the possibility of being degraded in the cause of its function [41-43].–

Fig. 1 shows the electrons transport pathways in a microbial fuel cell while Table 2 shows a summary of typical substrates in the anodic and cathodic compartments of an MFC. The electrons transfer by the microbial community is influenced by several factors such as the microorganisms involved, the substrate's nature and the type of electrode [44]. Varying electrons transfer abilities are exhibited by various types of microorganisms, the nature of the anode material significantly influence the efficiency of electrons transfer, its biocompatibility, electrical conductivity and surface area all affect the electrons transfer efficiency for instance utilization of biomaterials as anodes have been reported to increase the surface area of the anode electrode which significantly provide large surface area for the bacterial attachment and subsequently this will enhance the microbial transfer of electrons and thus electricity generation and overall system efficiency [45,46]. The efficiency of MFC directly depends on the rate of electron transfer, high rate of electron transfer ultimately leads to the increase in the energy generation and overall efficiency of the system [47].

Table 2
Electrochemical reactions in the anodic and cathodic chambers of an MFC using typical substrates.

Substrate	Anodic reaction	Cathodic reaction
Acetate	$CH_3\ COO^- + 4H_2O \rightarrow 2HCO_3^- + 9H^+ + 8e^-$	$O_2 + 8e^- + 8H^+ \rightarrow 4H_2O$
Glucose	$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^-$	$24H^+ + 24e^- \rightarrow 6O_2 + 12H_2O$
Butyrate	$C_4H_8O_2 + 2H_2O \rightarrow 2C_2H_4O_2 + 4H^+ + 4e^-$	$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$
Glycerol	$C_3H_8O_3 + 6H_2O \rightarrow 3HCO_3^- + 17H^+ + 14e^-$	$2O_2 + +14H^+ \rightarrow 14H_2O$
Malate	$C_4H_5O_5^- + 7H_2O \rightarrow 4H_2CO_3 + 11H^+ + 12e^-$	$3O_2 + 12e^- + 12H^+ \rightarrow 6H_2O$
Citrate	$C_6H_5O_7^{3-} + 11H_2O \rightarrow 6H_2CO_3 + 15H^+ + 18e^-$	$3O_2 + 18e^- + 18H^+ \rightarrow 9H_2O$
Acetic acid	$C_2H_4O_2^{3-} + 2H_2O \rightarrow 2CO_2 + 8H^+ + 8e^-$	$2O_2 + 8e^- + 8H^+ \rightarrow 4H_2O$

Some electrogens possess excellent ability to transfer electrons generated directly to the anode surface, this ability is fundamental in the

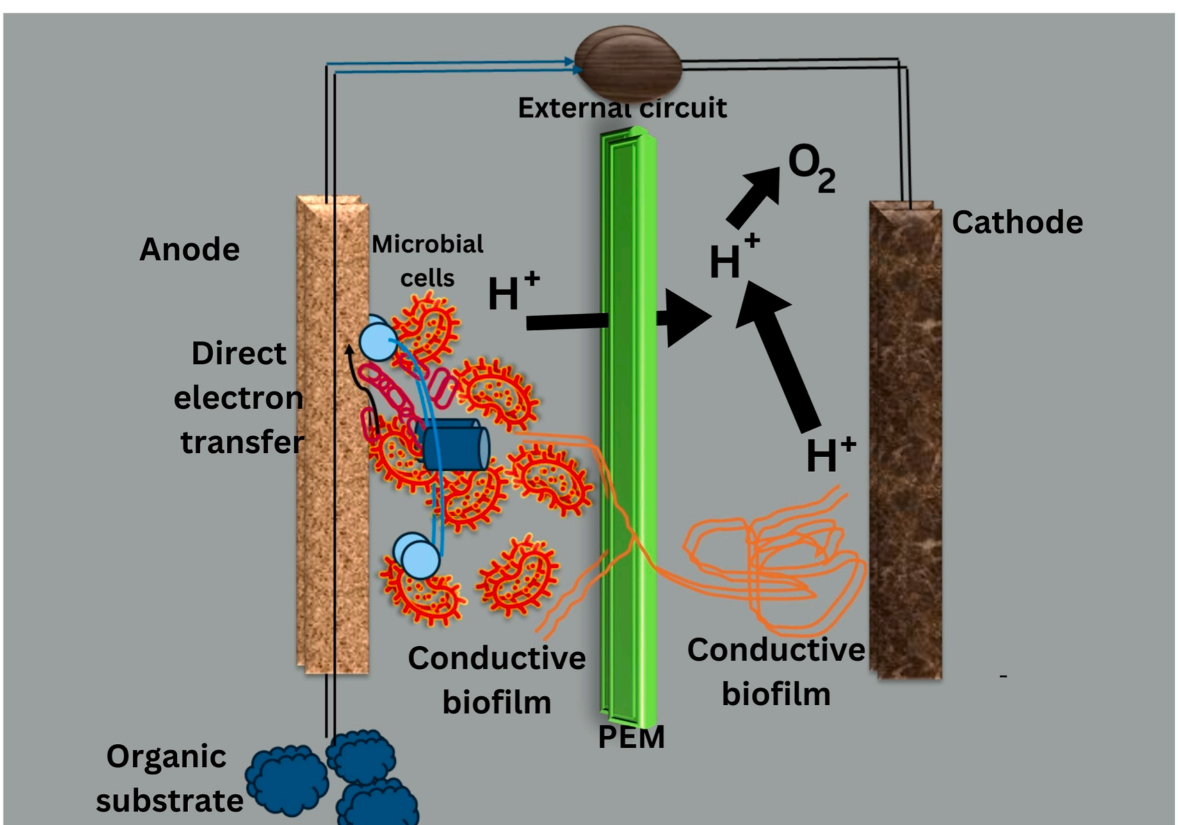

Fig. 1. Electron transport pathways in Microbial fuel cell.

enhancement of MFCs energy outputs and overall functional maximizations, this ability is usually facilitated by special structures often redox-active proteins also known as cytochromes that exist within the cell walls of these microorganisms cytochromes plays major role in electrons transfer chain and redox catalysis [59].

Nanowires are electrically conductive appendages possessed by other microorganisms which in addition to cytochromes can be used in the transfer of electrons to the anode, these nanowire has an additional advantage of being able to transfer electrons to the anode even when the cell is not directly attached to the anode surface, this can greatly enhance the energy output and the overall efficiency of the system because the active surface of the anode is increased and more colonies can thrive in the medium environment even when some microbial cells are not in close proximity with the anode material [60,61].

2.2. Roles of microbial communities

An electrically active bacteria are natural microorganisms that have the ability to generate electrical energy through their metabolic activities by converting the chemical energy in the organic matter to electrical energy, these microorganism's applications have only been recently exploited after a British Professor at Durham University published his work in 1911 [62] in which 0.3-0.5V was generated from a set up involving platinum electrode, yeast and bacterial suspension in a liquid medium. Several research has shown that there is no single dominant species in the microbial communities that are responsible for the production of electricity in the microbial fuel cell [63,64]. Various species of microbial organisms were found to be responsible and capable in the generation of electricity, the microbe's specific species are jointly formed by a combination of the substrate, its pH, available nitrogen and dissolved oxygen, temperature and humidity, electron donors and acceptors [44,65,66] (see Table 3). The role of microbial communities in energy production using microbial fuel cells is essentially dependent on the electron transfer ability of the electrically active bacteria, the electrons are generated because of metabolic activity of the bacteria on the organic matter, these electrons have to be transported to the anode for the utilization and generation of electric current [54]. There are various routes by which electrons can be transported to the anode. The mechanisms through which electrons transfer occurred have been discussed in section (2.1) of this paper.

2.2.1. Factors affecting the roles of microbial communities in an MFC

The functions microbial community in the microbial fuel cells are affected by the environmental features such as pH, conductivity, oxygen level, temperature, ion present, contaminant types and concentration [59,67]. To overcome the challenges posed by these factors certain measures are employed which include adjustments of pH, temperature and moisture, addition of external nutrient or co-metabolic substrate (glucose, vitamins or pyruvate), cathodic aeration and manipulating environmental conductivity of the media etc. These physical manipulations can directly influence the functions of the microbial community in the pollutant's decontamination and electricity generation [68,62].

a) pH

This is an essential factor that has great influence on the performance of the microbial fuel cell, in fact change in pH can affect several parameters such ions concentration, biofilm formation and membrane potential. The anodic pH does affect the metabolic rate of the microorganisms for the substrate and therefore the proton and electron concentrations are subsequently determined by the pH level in the anode chamber. Tremouli et al. (2017) reported the investigation of pH effect on the microbial fuel cell performance using various anodic pH ranges (6, 6.5, 7, 7.5, 8, 8.5 and 9) the maximum voltage output of 109 mV and coulombic efficiency of 25% were observed at pH 7, the maximum power density of 50.6 mW/m^2 was obtained at pH 9 [69]. Halim et al. (2021) Investigated the effect of various pH (6 – 10) levels in municipal wastewater on the performance of microbial fuel cell, maximum power density of (1459.02 mW m^{-2}), current density (1288.9 mA m^{-2}), voltage (1132 mV) and chemical oxygen demand (COD) removal 94% as well as coulombic efficiency (41.7%) were reported to have been achieved at pH 8 [70]. A lower and upper pH of 5 and 9 respectively were used by Bagchi and Behera 2021, in which the highest open circuit voltage (OCV) of 801 mV and power density of 3.03 W/m^3 were achieved at pH 9 on 28th day of the continuous operation [71].

Table 3
Summary of selected reported works in literature on studies of some microorganisms in MFCs.

Microbe(s) studied	pH	Temperature (°C)	Electrode material/ catalyst	Reference
Shewanella putrefaciens, *Geobacter sulfurreducens*	7.0-8.0	30	Carbon paper anode, air cathode	[49]
Geobacter sulfurreducens, *Shewanella oneidensis*	7.0	30	Carbon cloth anodes, graphite cathodes	[50]
Mixture of *Geobacter*, *Pseudomonas* and *Aeromonas*	pH 7.6	37°C	Carbon cloth	[51]
Shewanella oneidensis, *Geobacter sulfurreducens*, *Escherichia coli*	7.0	30	Porous carbon felt anodes, graphite cathodes	[52]
Geobacter sulfurreducens, *Shewanella oneidensis*, *Rhodopseudomonas palustris*, *Shewanella putrefaciens*	7.0	30	Carbon fiber, graphite electrodes	[53]
Geobacter sulfurreducens, *Desulfovibrio desulfuricans*, *Pelobacter carbinolicus*	7.0-8.0	25-30	Graphite electrodes	[54]
Methanosarcina barkeri, *Geobacter sulfurreducens*, *Pelobacter carbinolicus*	7.0	25	Gold electrodes, carbon cloth anodes	[55]
Geobacter sulfurreducens, *Desulfovibrio desulfuricans*	6.5-7.0	25	Carbon electrodes, graphite cathodes	[56]
Pseudomonas aeruginosa	Not specified	Room temperature	Air-cathode microbial fuel cell	[57]
Geobacter sp., *Pseudomonas*, *Aeromonas*	7.0	30	Carbon anode with applied voltage	[51]
Geobacteraceae, *Desulfobulbus*, *Methanosaeta*	7.0	30	Graphite felt anodes	[58]

b) Temperature

Temperature is one of the key factors that influence the growth and function of microorganisms. Altering the temperature have a direct effect on the activity of the microbial community, the temperature ranges 30°C – 40°C were reported by many researchers to be the optimum range in which the microorganisms can lives and function well [72]. Increase in temperature within this normal range always increases the rate of microbial degradation of the substrate and subsequently increases the electricity generation output of the system [73]. The effect of temperature was investigated by many researchers, some are; Adelaja et al. (2015) reported the investigation on the effect of salinity, redox mediators and temperature on anaerobic biodegradation of petroleum hydrocarbons in microbial fuel cells, the result obtained in their research shows that optimum reactor performance at 40°C was 1.15 mW/m^2 maximum power density, 89.1% COD removal and a degradation efficiency of 97.10% [74]. Larrosa-Guerrero et al. (2010) reported the effect of temperature on the performance of microbial fuel cells and their results show that at temperature of 4 °C 58% final COD removal and 15.1 mWm^{-2} maximum power while at 35 °C 94% final COD removal and 174.0 mWm^{-2} maximum power were obtained respectively [75].

c) Conductivity

The anode serves as a source of electrons for the electrons acceptors in the system. The conductivity promotes the rate of the microorganism's degradation activity on the substrates; this will improve the electron transport efficiency and enhance energy and overall function of the microbial community and thus increase in the systems efficiency [76]. It was reported by Li et al., 2016 that salinity and conductivity amendment of soil enhanced the bio electrochemical degradation of petroleum hydrocarbons they rinsed the polluted soil, and added carbon fiber to it, this action results in enhancement of the charge output by 110% and increase in the maximum current densities from 81 to 304 mAm^{-2} as well as the enhancement in the degradation rate of hydrocarbon by 484%, especially the high molecular weight fractions (C28–C36 of n-alkanes and 4–6 rings of PAHs) [77]. Gu et al. (2017) investigated the effects of electrolyte conductivity on power generation in bio-electrochemical systems and found out the maximum current density (0.73 mA/cm^2) was generated using an analyte solution with a conductivity of 14.93 $\pm$ 0.02 ms/cm, this value was four times greater than the minimum current density (0.13 mA/cm^2), generated using a solution with a conductivity of 2.61 $\pm$ 0.04 ms/cm [78].

3. Material and design innovations

MFC set up is simple and inexpensive as virtually all locally materials can be utilized to set it up, it consist of anode and cathode separated by a proton exchange membrane (PEM) which usually is a Nafion [79]. Electrons and protons are generated from anode by the action of microorganisms on the organic matter in order to generate energy, the electrons will pass to the cathode and reduced the electron acceptor which usually is oxygen because it satisfied the criteria of being abundantly rich, non-toxic to the biofilm community, biocompatible and unaffected by the actions of other substrates present in the system [80]. MFC can be constructed using several materials, it can be a single chamber cell or double chamber. In the single chamber both anode and cathode are systematically placed in one container containing the medium thereby eliminating the usage of proton exchange membrane [53,55], the size of which vary greatly from 250 ml to 2L for the laboratory set up depending on the application. Several substances have been employed as an electrode in the fabrication of MFC, some of which are carbon cloth, graphite rod, carbon felt, platinum, magnesium oxide, graphite oxide and carbon brush [31]. The construction of MFC is determined by the types of application it's going to be employed for example, an MFC intended to produce biofuel will prioritize the formation of large volume biomass.

3.1. Electrode materials, membrane types

Electrodes (anode and cathode): These are fundamentals elements of MFC on which the formation and development of biofilm depend on, energy generation and quantity generated is also affected by the properties of the electrodes employed in the MFC's construction [81]. The materials usually utilized as electrodes particularly are metallic such as (stainless steel and copper sheet), carbonaceous materials such as (carbon paper, carbon rods and carbon brush). This is because carbon rods has high conductivity and chemical stability, large specific surface area and corrosion resistance possessed by carbon paper and stainless steel respectively [33]. The electrogenic bacteria in the anode is responsible for the degradation of the organic matter present in the waste [82], in doing so, electrons and protons are released into the medium and subsequently the proton passed through the membrane and combine with the oxygen to form water while the electrons released will pass to reach the electron acceptor in the cathode and reduce it [83]. The electrode must be highly conductive with large specific surface area, biocompatible with less or no toxicity to the biofilm, anticorrosion and non-degradable materials, excellent mechanical strength, roughness and low resistance [84]. The traditional electrodes mentioned above, though possessed some excellent properties but have other limitations such as the brittleness of carbon paper, the high cost of stainless steel and the lack of sufficient electrochemical active sites for the enhancement of extracellular electron transfer (EET) processes between the electrode (anode) and the electrochemically active microorganisms in the system [85]. Several works have been reported on the development of modified hybrid electrodes with enhanced required properties, in this regard nanoparticles of metal oxides, graphene oxides coating and biomass has all been employed [22,86], we will discuss each of these subsequently in section (3.2) of this paper.

3.1.1. Anode

This is where the degradation of organic matter takes place by the action of electrogens which leads to the production of electrons. The generated electrons will pass through the external circuit, then pass through the membrane to reach the electron acceptor and reduce it and subsequently passed for bio energy generation. The materials utilized as anode in the MFC set up play a pivotal role in the biofilm development and its functions enhancement thereby significantly affects the bioenergy outputs, waste treatment and overall functions of the system. The anode material must possess properties such as excellent electric conductivity, biocompatibility, low resistance, corrosion resistance, durability, stability and low cost. The research for the modification of anode materials is still ongoing, some of the materials utilized in the improvement are nanoparticles, conductive polymers, biomass, biochar, metals catalyst and graphene oxide [87], this will be elaborated in the subsequent part of this paper (see Fig. 3).

3.1.2. Roles and properties of anode

Anode is one of the basic elements of MFC that play a very fundamental role in the performance and efficiency of the system. In fact, lack of anode with excellent properties is one of the bottlenecks that prevents the MFC's scale up, below are some of the basic roles and properties of anode in an MFC set up.

a) Flow of electrons and electrical conductivity: the anode must possess high electrical conductivity for good flow of electrons generated from the oxidation of organic matter by the bacteria. The anode's surface is where the bacteria reside and executes its oxidation activity. The materials employed as an anode must therefore have excellent electrical conductivity for the enhanced receiving and transport of electrons generated by the bacteria [88].
b) Biocompatibility and Biofilm development: the microorganism resides on the surface of anode intimately and thus a non-toxic, non-corrosive and biocompatible anode will go a long way in the enhancement of the biofilm development, metals such copper, nickel and iron are all susceptible to corrosion and hence toxic to the development of biofilm [89].
c) Stability and Durability: the mechanical strength of the anode material can help the material withstand prolong operation without any defects such as swelling and corrosion which usually occur when

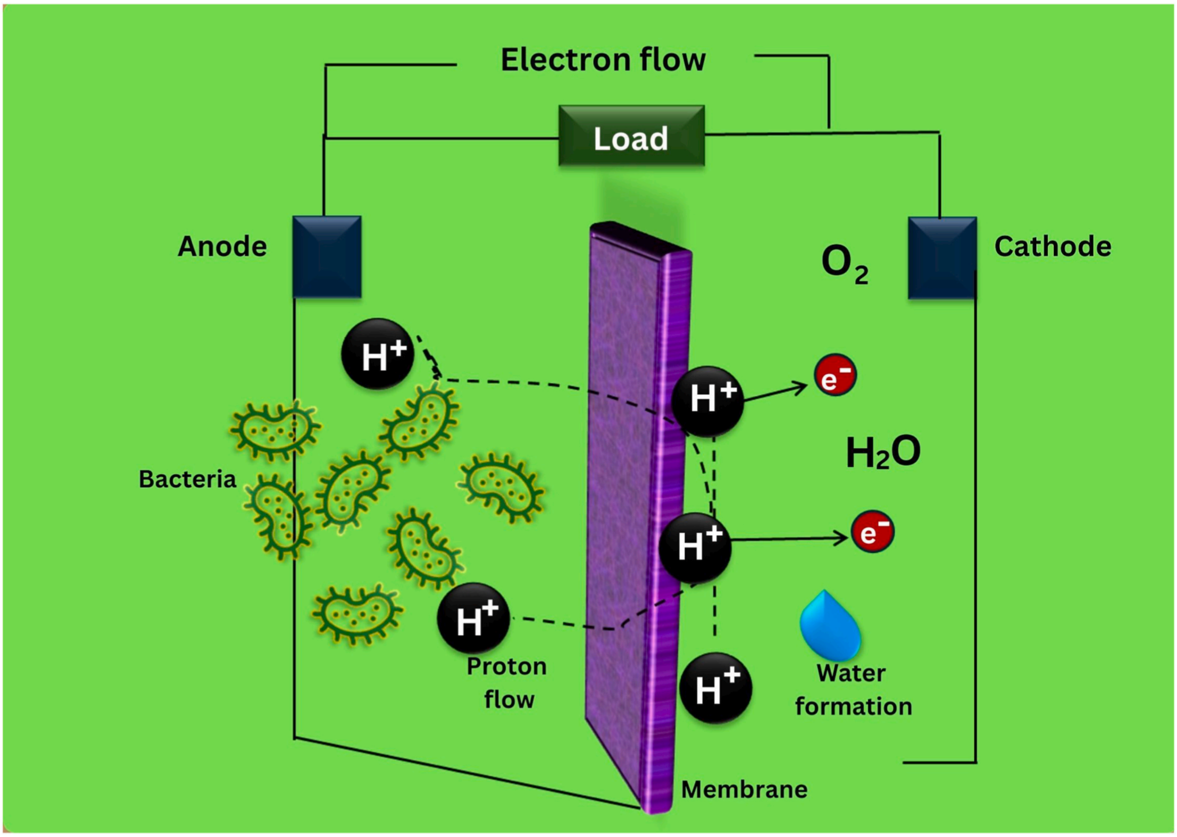

Fig. 2. Proton flows across membrane in MFC.

Fig. 3. Materials for anode modification.

microorganisms are introduced into the system, this usually arises due to bio incompatibility and chemical instability of the anode materials employed in the set up [90].

d) Cost and availability: the cost of the anode is important because it adds up to the total cost of the MFCs. Metals such as gold, silver and platinum are precious and expensive, natural carbon-based compounds such as biomass from plants, biochar and some metals nanoparticles are currently being explored and serve better with improved overall efficiency of the MFCs [72,74,76].

3.1.3. Cathode

This also like anode plays a vital role in the MFC's operational performance and efficiency, it is produced from several materials such as metals [91], conductive polymers [92], carbon-based materials [93]. After the oxidizing activity of the anode on the substrate, the cathode utilized the generated electrons to reduce the oxidant usually oxygen and complete the circuit. The thermodynamic and kinetics of the cathode reactions especially the oxygen reduction reaction (ORR) and mechanism of transport significantly contribute to the generation of power density, coulombic efficiency and stability for long term operation, while the anode received much attention for its modification and operational efficiency enhancement, the cathode is still paced with the challenges [94].

3.1.3.1. Types of membrane.

i Proton Exchange Membrane (PEM)

The most widely used membrane is Nafion, it is one of the basic components of MFC that determines its functions and performance efficiency [95]. It is the membrane that prevents the passage of oxygen and other substrates from the anode to the cathode [96]. The membrane selectively allowed the passage of protons from the anode to the cathode [97]. Excellent proton conductivity, high physical and chemical stability, low internal resistance and excellent energy recovery are all required properties for a good PEM [81,82]. Several research have been carried out and reported in trying to overcome the limitations PEM. Nanomaterials [83,84], biochar, conductive polymers and hydrogels have all been used in the modification of the PEM to enhance and improve its performance [81,82]. The functions and required features of a good membrane will be discussed in detail subsequently.

ii Cation Exchange Membranes (CEMs)

Cation exchange membranes selectively transport positive ions (protons or other cations). They help maintain electron-neutrality, reduce internal resistance, and improve coulombic efficiency. CEMs have been applied in both dual-chamber and single-chamber MFCs, providing moderate cost alternatives to Nafion while supporting efficient microbial growth [91,92].

iii Anion Exchange Membranes (AEMs)

Anion exchange membranes facilitate the transport of negative ions (OH^-, Cl^-) and are particularly useful in alkaline MFCs. AEMs can reduce pH gradients and mitigate biofouling compared to traditional PEMs, making them promise for long-term applications [94,95].

iv Ceramic and Clay-Based Membranes

Ceramic and clay membranes are gaining attention as low-cost, durable alternatives. They offer proton conductivity while preventing oxygen crossover and biofilm infiltration. Single-chamber ceramic MFCs demonstrate stability over extended operations and are suitable for wastewater treatment and energy recovery applications [96–98].

v Hybrid and Composite Membranes

Hybrid membranes, composed of polymers combined with inorganic fillers (e.g., agar-Nafion composites, graphene oxide), provide enhanced proton conductivity, reduced oxygen crossover, and improved mechanical and chemical stability. They are increasingly applied in pilot-scale MFCs due to their cost-effectiveness and durability [92,99].

vi Membrane-Free or Microfluidic MFCs

Recent studies have explored membrane-free MFCs and microfluidic configurations, where separation is achieved through laminar flow rather than physical membrane. These designs reduce internal resistance, simplify reactor construction, and allow high surface-area-to-volume ratios, but careful control of flow and substrate is critical [100–102].

3.1.4. Functions of membrane in an MFC

Proton exchange membrane is one of the basic elements of MFC and serves a fundamental function, it serves as a demarcation between the anolyte and catholyte and thus preventing their mixed up, while selectively allowing the passage of some specific ions and maintaining the stability of the system. Fig. 2shows the movement of proton across the membrane in an MFC. The type and properties of a membrane can influence energy generation, internal resistance and substrate overall utilization [103] (see Fig. 3).

Nafion and Sulfonated polyether ketone possessed excellent properties such as high proton conductivity and chemical stability which made them widely employed membrane in bio electrochemical systems, despite these properties they also suffers some disadvantages such as being too expensive, biofouling and sometimes proton leakage, this may lead to pH fluctuation in the system [104].

a) Exchange of ions; membrane is an essential element in an MFC set up and plays a vital role in maintaining a demarcation between the two electrodes and prevent mixing up which will lead to lower efficiency or even failure of the system, while simultaneously allowing the passage of selected ions from the anode to the cathode. Selective ion transportation is achieved using a specific type of membrane, for instance PEM for proton (H^+), CEM for cations (Na^+, Cu^{2+}, Fe^+) and AEM for anions (Cl^-, OH^-). Generally, this selective transportation is done through some phenomena such as diffusion, convection and electrostatic migration. Ion conductivity, water uptake and swelling properties determine the efficiency of membrane in this function [105,87].
b) Movement of electron: Typically, membrane plays a pivotal role in demarcating the anode and cathode chambers thus preventing the electrons generated due to microbial degradation of organic matter from reaching the cathode directly which can disrupt the system and affect its efficiency, instead the produced electrons are passed through external circuit and therefore enabling the controlled generation of electricity. The membrane ensures the chambers separation and the direct passage of electrons from through electrolyte to the cathode [106].
c) Substances cross over prevention: substances like oxygen can easily cross over to the other chamber, for example membrane prevent oxygen from reaching the anode chamber and thereby contaminate the anaerobic environment required for the bacterial oxidation of organic matter. Instead, it selectively allows specific ions to reach the designated chamber, this is critical in maintaining the restriction of movement of the undesirable substances and sustaining the operational functions of the system which will enhance its overall efficiency [103].

Overall enhancement of MFC performance: the basic function of the membrane is to demarcate between the positive (anode) and negative electrode (cathode), prevent the oxygen diffusion to the cathode and mixing electrolyte thereby maintaining the unique composition of the electrodes, this demarcation is essential in optimizing the performance of the MFC and maximizing the outputs of its energy generation and waste treatment therefore, enhancing the overall performance and efficiency of the system [107].

3.2. Recent breakthroughs in materials design and nanostructured systems

There are tons of reported works in literature done in the improvement of several elements in MFC. The basic elements on which the function of the MFC depend on are.

3.2.1. The electrodes

The electrode for the application in MFC needs must be highly conductive with large specific surface area, biocompatible and corrosion resistant, with less charge resistance and mass transfer supportive. Several works have been reported to modify the electrode. Table 4 below shows some of the reported works in literature (see Table 5).

3.2.2. Application of biochar in electrode modification

Biochar refers to the solid residue obtained by heating biomass in a low oxygen condition, the utilization of these materials for various applications in an MFCs set up is currently an active area of research [127], it have been utilized either directly as an electrode [128] or as coating to other materials for improved functions [115], in all cases there have been improved properties. There are several works reported in literature involving the utilization of this material as electrode, we will give a summary of some of the reported works found in literature in the subsequent part of this review.

3.2.3. Biochar preparation

The biomass is converted into biochar through a thermochemical graphitization [106,108], hydrothermal carbonization [109,110], gasification [129], torrefaction [112,113], mechanochemical and microwave pyrolysis [114,127], in a temperature range (200 – 1000^{o}C) [130–132]. Usually, the selection of a suitable method for the preparation of biochar is tailored to suit the desired characteristics of the product, because each of these methods have its own distinct properties and requirements [133] depending on the desired characteristic of the biochar material (see Table 5).

3.2.4. Application of nanoparticles in electrode modification

Nanoparticles are materials with particles size smaller than 100 nm, these materials are known for their large surface area, and since one of the basic requirements of electrode is enough surface area, nanoparticles covered this requirement. Several materials have been utilized to produce nanomaterials for electrode modification.

Table 5
Summary of some reported works on biochar modified electrodes.

Electrocatalyst/Modified Electrode		Biomass Source	Max power	References
Anode	Cathode			
	HT-PC-KOH	Digestate	1814 mW/m^2	[116]
$Fe_3C@C$		Sugarcane	2316 mW m^{-2}	[112]
K_2CO_3-BC700		Algal	1076W/m^2	[108]
SMFC-P10		Bamboo	19.7 mW/m^2	[117]
G-BC		Algal	6.8 W/m^3	[115]
CS/MWCN		Corn straw	2.68 Wm^{-2}	[118]
	Mn/Fe@WRC	Water mellon rind	399.3 mW/m^2	[119]
	G/BC	*Pinus resinosa* wood	2.67 Wm^{-2}kg^{-1}	[120]
	SC/CF	Odorous water sediment	219.44 mWm^{-2}	[121]
	CS/Cu	Coconut shell	47.04 mWm^{-2}	[122]
	BC	Bamboo	85.85 mW/m^2	[93]
	BC-CeO_2	Straw	343.21 mW/m^2	[123]
Fe-Mn/NSC		Human hair	14.6 W/m^3	[124]
MnO_2/CSC		Coconut shell	1.72 W/m^2	[125]
	HC-N + PY	Water hyacinth	1444 mW/m^2	[126]

a) Nanobiochar; the material biochar refers to the solid residue obtained by heating biomass in a low oxygen condition. The utilization of these materials for various applications in an MFCs set up is currently an active area of research, it has been utilized to produce nanoparticles for the modification of electrode. There are several methods of producing the nanobiochar the methods for the preparation of nanobiochar involve first converting the biomass into bulk biochar by pyrolysis, followed by size reduction through various techniques to obtain the nanobiochar in the desired size range. These stages will be discussed in detail below.
b) Size reduction: the production of the nanoparticle materials is achieved through various method but generally top-down method is the most widely employed technique [134], though the nanoparticle size traditionally formed in the process of bulk biochar preparation, but in limited yield, in order to obtain a high yield of the nanoparticle, sizes of the bulk material needs to be reduced, this is achieved through a grinding or milling [135].
c) Separation of nanobiochar from the bulk biochar: the two methods utilized in this stage are filtration using membrane and sedimentation using centrifugation, the latter is the most widely used. After the centrifugation the nanoparticles can be collected from the supernatant, while the larger particles settled as a separate layer of precipitate. The other method of using separation membrane gives more control of the particles sizes but is more expensive than the sedimentation method [116,136,137].

Table 4
Representative reported works on electrode modification.

CATALYST	COATINGS USED	OUTPUTS		REFERENCE
		Power Density	Pollutants Removal (%)	
MnO_2	Bamboo leaf	85.85 mW/m^2	84.0	[93]
K_2CO_3/BC	Algae	1076 W/m^2	950.12	[108]
ABC	Datura peels	584.2 mW/m^2	85.4	[109]
MFC-MIL 53(Fe)/BC	Banana peel Waste	142.2 ± 1.5 mW/m^2	93.8 ± 2.2	[110]
GO/TiO2	Orange feel	0.105 mW/m^2	87.25	[23]
B-Rgo	Activated carbon	411mWm^{-2}	78	[111]
Fe_3 C	Sugarcane	2316 mW/m^2	96	[112]
CS	Corncob straw	1556.34 mW/m^2	87.66	[113]
BC-400	Air dried corn stalk	108.05 mW/m^2	97.14	[114]
CF-CNT/HNO_3	CNT/HNO_3	59 mW/m^2	Not reported	[30]
SC(900)-FeS_2@MoS_2	Sodium alignate aerogel (SC)	1.88 W/m^2	90	[85]
HAB-GS	Harmful algae	6.8 W/m^3	Not reported	[115]

3.2.5. Metallic nanoparticles

Metallic nanoparticles were utilized in the modification of electrode materials for functional enhancement. Several works have been carried out and reported in the literature and this area is still an active area of research. Mehta et al. (2024) reported performance enhancement of MFC system with ecofriendly barium hexaferrite nanoparticles as electrode additive material, they reported 12.469 mW/m^2 and 116.420 mW/m^2 as maximum power and current densities respectively [138]. Modified anodes with Fe_2O_3@AuNPs/PANI nanocomposites was reported by Alalawy et al. (2023) to have been used in enhancing bioelectricity generation in seaweed-derived microbial fuel cells [139]. Yadav et al. (2024) reported a better energy generation using Tin oxide nanoparticles-coated cathode for the detection of aqueous urea using compost-based microbial fuel cell configuration [140]. Ahmed et a., (2025) utilized $CoFe_2O_4$@$NiMoO_4$ nanocomposite-modified carbon-felt bioanodes for high-efficiency microbial fuel cells [141]. Ag nanoparticles modified Co, N co-doped carbon nanosheets was used by Jiang et al. (2021) as bifunctional cathode catalyst to enhance performance of microbial fuel cells [142]. Iron nitride and iron carbide nanoparticles (Fe_3N-Fe_3C/CF) at different temperatures were utilized by Cheng et al. (2024) to modify an anode for the enhancement of microbial fuel cell performance [143]. Li et al. (2021) reported the utilization of Au and Cds nanoparticles on the surface of electrogens cells for the modification of photo-assisted bioanodes in microbial fuel cells using layer-by-layer assembly [144].

TiC@C–TiO_2 nanoparticles were synthesized by Dehghanian et al. (2025) as an emerging efficient structure for the modification of anode in high-power microbial fuel cells [145]. Mahmoodzadeh et al. (2025) successfully increases both the power and voltage generation of a microbial fuel cell using nickel nanoparticles modified carbon felt and graphite felt electrodes [146]. Yang et al. (2025) synthesized iron oxide nanoparticles for an improved bioenergy generation and biochemical oxygen demand degradation in a microbial fuel cell system [147]. Wang et al. (2025) reported the successful synthesis NiO/Fe_3O_4 as a bimetallic-modified capacitive anode in a microbial fuel cell for enhanced electricity generation and energy storage [31]. 1000 mW m^{-2} power density generation was reported by Jiang et al. (2024) using Cu/Co-NC@mS-T as bimetallic electrocatalysts for oxygen reduction reaction in microbial fuel cells [148].

3.2.6. Conductive polymers

Conductive polymers were also utilized in the modification of electrodes for enhance MFCs performance, preparation of polypyrrole/titanium nitride composite modified biochar and its application in microbial fuel cells was reported by Ref. [149]. Polyaniline was also utilized by Ref. [150] to produce a modified anodes for brewery waste treatment in microbial fuel cells. Wang et al. (2025) also published a work on Microalgae biocathode coupled polyvinyl alcohol proton exchange membrane for performance of recirculation honeycomb microbial fuel cells [128]. Polyaniline conducting matrix was coated by Tesfaye et al. (2025) with the Fe_3O_4 nanoparticles and utilized as graphite pencil anode for the enhancement of energy generation in microbial fuel cell system [151]. Mumtaz et al. (2024) fabricated a polyaniline modified anode that resulted in the increase of power generation and waste removal [152].

3.2.7. Carbon nanotubes

Altin and Uyar (2025) reported their work using multiwalled carbon nanotube to modify graphite (GF) and carbon felt (CF) electrode for the enhance treatment of horse manure and energy generation using microbial fuel cells [30]. Yu et al. (2024) reported the synthesis of CNT@Ti_3C_2TxMXene nanocomposite catalysts as anodes to improve the electricity production performance of microbial fuel cells [87]. Abbas and Ismail (2025) innovated the application of multiwalled carbon nanotubes as anode nanomodification using flaxseeds nanopowder as supportive material in microbial fuel cell for enhancing energy recovery [36]. Lascu et al. (2025) investigated the influence of polypyrole-derived carbon nanoparticles on the improved performance of the microbial fuel cell [153].

3.2.8. Graphene

Graphene was used by Mkilima et al., (2025b) in the modification of electrodes in dual chambered microbial fuel cell for wastewater treatment [154]. Fu et al. (2025) reported the application of graphene oxide hydrogel as anode in microbial fuel cell for carbamazepine degradation and energy [155]. Zeng and Zhang (2025) investigated the fabrication of MnO_2/GO as anode in microbial fuel cells for improved functions [156]. Ni-Doped Iron Oxide/GO nanoparticles by co-precipitation method were also synthesized by Benito-santiago et al. (2025) for improved oxygen reduction reaction (ORR) [157].

4. Integration of microbial fuel cell with wastewater treatment

Wastewater is a serious environmental concern that poses several threats to the environment and living organisms. Depending on their source, wastewater contains various pollutants such as heavy metals, hydrocarbons, dyes, pharmaceuticals and other toxic substances [158]. The conventional methods for the treatment of wastewater are inefficient, energy intensive and expensive, a viable alternative and sustainable method that can replace the conventional methods is microbial fuel cell, it is a simple technology that utilizes the metabolic activity of microorganisms to simultaneously treat the wastewater and generate electricity [159,117]. The microbial fuel cell significantly reduces the amount of energy required for the aeration of the sludge in conventional method, because it generates electric energy from the anaerobic digestion of the various organics present in the wastewater [160]. It was also reported that the wastewater contains 3 - 10 times the energy required for their treatment [161].

One of the advantages of the microbial fuel cell method in the treatment of wastewater is that it can be employed in treatment of wastewater from various sources such as petrochemicals [4], pharmaceuticals [153,154], textiles, chemicals [56,121,122], livestock [8], mining [162] and electronics industries. This is due to the unique ability of the various microorganisms present in the wastewater to degrade organic and inorganic compounds and generate electricity [163]. There are several published articles in the literature about the efficiency of microbial fuel cells in the treatment of wastewater, some of which reported over 90% removal of COD and 80% to 90% of both nitrogen and sulfur removal. We will discuss some of the reported work about the efficiency of MFC in section (5) of this paper.

4.1. Comparative analysis of approaches and methodologies in microbial fuel cell (MFC) research

Table 6 below presents a comparative analysis of various approaches and methodologies used in MFC research, with strengths and weaknesses of each method or approaches for deeper understanding of the various methods and approaches (see Table 7).

4.2. Microbial fuel cells performance metrics

The performance of microbial fuel cells technology involves analysis and evaluation of several parameters that are influenced by the complex roles of the biological, electrochemical and environmental factors. The accurate performance evaluation of an MFC technology requires combine analysis of its microbial activity, energy generation output and wastewater treatment efficiency. The key performance metrics of MFCs will be discussed in this section considering both their theoretical and practical relevance.

4.2.1. Power density

Power density is the most widely considered and reported metric of

Table 6
Comparative analysis of various approaches and methodologies used in MFC research.

Approach/ Methodology	Strengths	Weaknesses	References
Integration of MFCs in wastewater treatment systems for energy recovery	Demonstrates practical application in industrial wastewater treatment, showcasing MFCs' ability to generate power while purifying water	Limited scale-up results; high operational cost	[164]
Investigation of alternative low-cost electrode materials	Identifies cost-effective alternatives to precious metal electrodes, making MFCs more commercially feasible	Lacks long-term performance data and stability of alternative electrodes	[165]
Optimization of MFC performance with diverse microbial communities	Provides new insights into the role of microbial community structure in MFC performance	Focuses primarily on microbial composition, lacks integration with system optimization	[166]
Development of microbial fuel cell prototypes with variable configurations	Demonstrates scalability potential with various configurations of MFCs	Prototypes not tested under real-world conditions	[167]
Application of MFCs in agricultural waste-to-energy conversion	Strong focus on environmental sustainability by converting agricultural waste into power	Strong focus on environmental sustainability by converting agricultural waste into power	[168]
Focus on the integration of MFCs into industrial energy systems	Highlights potential integration into existing industrial systems for decentralized energy production	Highlights potential integration into existing industrial systems for decentralized energy production	[169]
Optimization of MFC configurations and power output	Strong focus on environmental sustainability by converting agricultural waste into power	Limited data on the scalability of the technology in large agricultural settings	[170]
Investigation of different anode-cathode configurations for MFC optimization	Demonstrates effective use of different configurations to improve MFC efficiency	Focuses mainly on configuration without addressing environmental impacts	[171]
Investigation into the scalability of MFCs using large-scale reactors	Highlights the scalability potential of MFCs using large-scale reactors	Lack of cost-benefit analysis and long-term operational feasibility	[172]
Study on hybrid MFCs combined with solar panels for enhanced power generation	Hybrid systems effectively enhance power generation capabilities	Complex integration system; potential issues with system reliability	[173]
Use of MFCs in environmental monitoring	MFCs can provide real-time monitoring of environmental pollutants, offering dual use for energy and environmental remediation	Lack of detailed integration with existing monitoring systems	[174]
Exploration of biofilm formation for enhancing MFC performance	Strong focus on microbial growth and biofilm formation to increase energy recovery	No focus on operational efficiency and energy output in practical scenarios	[175]

Table 7
Summary of the reported works on energy recovery and conversion efficiency.

Substrate/Waste Stream	Power/ Current Density	Normalized Energy Recovery ($kWh{\cdot}m^{-3}$)	Reference
Municipal wastewater	—	0.033 ± 0.005	[176]
Various systems	—	<1.0	[177]
Primary sludge/ wastewater	—	1.73 (operational); 3.23 (max)	[178]
Urine	—	0.747–0.825	[179]
Domestic wastewater (CW effluent)	—	0.001124	[180]
Municipal wastewater	—	1.14	[181]
Synthetic wastewater (algal-biochar anode)	0.86 mW	0.002–0.004	[7]
Brewery wastewater (dual-chamber MFC)	1.03 $W\ m^{-3}$	0.51	[182]
Food-waste leachate (meta-analysis)	15.15 $W\ m^{-3}$	0.30	[183]
Synthetic wastewater, air-cathode SC-MFC	1431 ± 80 $mW\ m^{-2}$	0.45	[184]
Domestic sewage (DW-MFC)	63 $mW\ m^{-2}$	0.55	[185]

an MFC. It serves as the measure of the electrical performance of an MFC system, it is simply expressed in milliwatts per meter square of an electrode (mW/m^2) or milliwatts per unit volume of the reactor (mW/m^3) [125,126]. The power density metric enables comparative evaluation of various MFC configurations and designs [195].

For consistency and comparability, the electrode area or reactor volume of the system is required to be standardized and thus, power density of a microbial fuel cell system of any study must be normalized by the unit surface area of the electrode or unit volume of the reactor [196].

Mathematically, power density is calculated by combining the voltage output (V) in power equation and the value of current (I) according to Ohm's law as follows.

$$P = V \text{ x } I \tag{i}$$

$$I = \frac{V}{R}\ (\text{Ohm's law}) \tag{ii}$$

$$\text{Combining equation i and ii will give; } P = \frac{V^2}{R} \tag{iii}$$

Where. P is power (W), V is voltage (V) and R is external resistance (Ω) [197].

4.2.2. *Coulombic efficiency*

Coulombic efficiency is a parameter used to evaluate the conversion of chemical energy into electrical energy [198]. It is the ratio of total coulombs transferred to the anode from the substrate relative to the possible maximum number of coulombs if all substrates produce current [183].

Mathematically.

$$CE = \frac{C_P}{C_V} \times 100\% \tag{iv}$$

where C_P is the total coulombs calculated by integrating the current over the time for substrate consumption (C) and C_T is the maximum possible coulombs of the substrate, the value of which is given by $C_T = V \text{ x } b \text{ x } A \text{ x } e \text{ x } mol_{substrate}$ (C). V is the volume of anode chamber (m^3), b is the number of moles of electrons produced by oxidation of substrate (b = 8 mol e^-/mol acetate), A is Avogadro's number (6.023×10^{23} molecules/mol), e is electron charge ($1.6\ 9\ 10^{-19}$ C/electron), and $mol_{substrate}$ is the moles of acetate oxidized by the microorganisms. CE shows the efficiency of the electricity conversion from substrate [195].

4.2.3. Chemical oxygen demand (COD)

Chemical oxygen demand is a metric for evaluating the performance of microbial fuel cells. It is one of the key parameters that measure the quantitative amount of oxygen required for the complete oxidation of the organic and inorganic pollutants present in the wastewater [197]. Usually chemical oxygen demand (COD) is determined through a closed reflux calorimetric method, it is the equivalent amount of oxygen used in oxidizing all oxidizable substances in the organic matter, the amount COD removal signifies the efficiency of the microbial fuel cells system in wastewater treatment, there are several works reported on COD removal efficiency ranging from 80% to 97% [143–145]. The percentage of chemical oxygen demand removed can be calculated using a formula below [199].

$$\%E_{COD} = \frac{COD_{in} - COD_{out}}{COD_{in}} \times 100\% \quad \text{v}$$

4.2.4. Case studies and pilot projects

The efficiency of the laboratory scale capacity of the microbial fuel cells despite some bottlenecks it faced have attracted interest in scaling up the technology. For the past decades several pilot scale projects of microbial fuel cells with various capacities have been applied in the treatment of real wastewater from various sources as reported in the literature. Some of the works reported are Dannys et al. (2016) reported achieving 107% operational energy requirement from 84L/hr scale-up in microbreweries wastewater treatment with 3000 mg/L chemical oxygen demand (COD) inlet. 91.9% and 26.4 kWh of chemical oxygen demand (COD) conversion and electricity generation were achieved respectively [200]. Rossi et al. (2022) also reported development of pilot scale air-cathode microbial fuel cells of 850 L (1400 L total liquid volume) for domestic wastewater treatment. 0.46 ± 0.35 W (0.043 Wm^{-2} normalized to the cross-sectional area of an anode) of power was generated with 1.54 ± 0.90 A of current and 9% coulombic efficiency was achieved. An ≈ 49 ± 15 % of the chemical oxygen demand (COD) was removed in the microbial fuel cell [201].

A 90L pilot scale microbial fuel cell was reported by Daong et al. (2015) for a two-stage wastewater treatment involving stage 1 of diluted wastewater and stage 2 the raw wastewater. 84.7% and 81.7% while 87.6% and 86.3% of COD and solid sediment removal efficiency were achieved at stage 1 and 2 respectively. 0.056 kWh/m^3 and 0.097 kWh/m^3 of energy sufficiently enough to operate the system were produced at stage 1 and 2 respectively [190]. Juarez et al. (2025) developed and employed a passive aerated membranelles microbial fuel cell (PAML-MFC) for the treatment of 1000L/day. The system operated for 10 months removing 60 to 80% of the 500 mg/L COD contained in real wastewater and the 10 individual units that made up of the system generated an average of 1 mW/m^3 [202].

5. Key numerical findings from previous microbial fuel cell (MFC) studies: quantitative comparisons of system performance, effectiveness, and efficiency

Over the years, numerous studies have evaluated MFC performance across various metrics, including power density, energy recovery efficiency, chemical oxygen demand (COD) removal, and cost-effectiveness. These quantitative findings provide valuable insights into the effectiveness and scalability of MFCs, especially in comparison to traditional wastewater treatment methods and other renewable energy technologies (see Fig. 4).

5.1. Energy recovery and conversion efficiency

The performance of the microbial fuel cells system depends on many factors including the wastewater stream/substrate and electrode types. The table below compiles representative studies on microbial fuel cells (MFCs) with numerical findings like energy recovery or conversion efficiency metrics. All normalized energy recovery (NER) values have

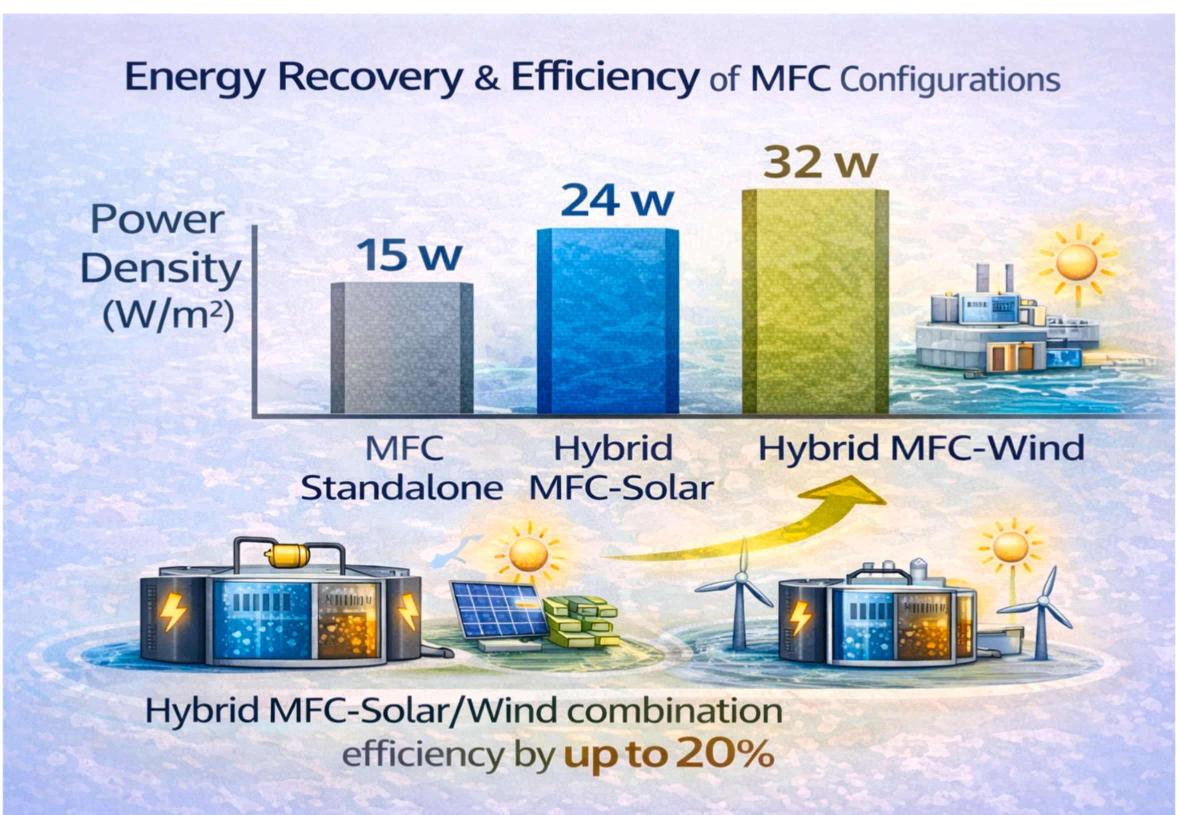

Fig. 4. Energy recovery and efficiency of different MFCs.

been standardized to kilowatt-hours per cubic meter ($kWh{\cdot}m^{-3}$) wherever possible. The Table 7 contained recent studies from 2014 to 2025, covering laboratories, pilots and field-scale systems.

Several MFC studies do not directly report normalized energy recovery (NER) in $kWh{\cdot}m^{-3}$. Instead, they often report power density ($mW{\cdot}m^{-2}$), Coulombic efficiency, or COD removal. Where essential data such as substrate loading, hydraulic retention time, or flow rate were absent, NER back-calculation was avoided to maintain methodological transparency and accuracy. Only explicitly reported or verifiable NER values were included. This aligns with PRISMA data transparency principles, emphasizing traceability of derived values to original data.

5.2. Challenges in viable energy output

Microbial fuel cells technology provides sustainable method of converting waste to energy through the activities of microorganisms. The technology scales up to produce sustainable, cost effective and sufficient energy is yet to be realized, despite a lot of research carried out for the practicability of this system. Some of the challenges bedeviling this technology's practical applications are thermodynamics constraint, materials and operational costs, reactor scale-up limitations, biological stability and system inefficiencies that impede viable energy output. We shall discuss some of these challenges briefly in this section.

5.2.1. Thermodynamic constraints

There is numerous research reported in the literature on optimization of reactor design and materials, but still microbial fuel cells are paced with the fundamental restriction due to thermodynamic imbalance such as energy losses that occur at various stages from the oxidation of the substrate and metabolic activity of the microorganisms to the electrons transport and electrode conductivity. It was for instance reported that in a glucose-fed microbial fuel cell system only 44% of energy can be recovered as generated electrical energy, this recovered percentage drops further when the system is applied for real wastewater treatment [157,158].

5.2.2. High operational and material costs

The economic viability is one of the fundamental bottleneck of the microbial fuel cell technology, the essential materials for the system design and its operation is too cost compared to the energy output harvesting, from proton exchange membrane (mostly Nafions) and aluminum catalyst to advanced electrode materials are highly expensive for scale-up application, the cost for the scale-up ranges from USD 735/m^3 to USD 36,000/m^3 [203]. The additional necessary requirements such as pumps, aeration, light source and reactor system further increase the high expensiveness of the system which outweighed its energy output [204,205].

5.2.3. Biological variability and operational stability

Environmental variability like fluctuation in temperature of the system immediate vicinity may affect the performance of the MFC. Instability of the microbial fuel cell for a long-time operation remains a fundamental constraint, biofouling, microbial community shifts and pH imbalances are some of the problems that significantly contribute to the reduction of energy output and the overall operational efficiency of the MFCs system. The inefficient performance of the proton exchange membrane in a dual chamber MFC design may often lead to the pH imbalance that results in acidification and alkalization of anode and cathode chambers respectively, which will subsequently affect microbial activity, applying buffer is directly increasing the cost and complexity of the system [161,206].

5.2.4. Technological innovations in microbial fuel cells are needed to improve energy output

Despite two decades of progress, most MFCs still deliver modest areal power densities, often orders of magnitude below fuel-cell and battery benchmarks, mainly due to (i) sluggish extracellular electron transfer (EET) at the anode, (ii) high ohmic and pH-gradient losses across the separator/electrolyte, and (iii) slow oxygen reduction at the cathode, by far the largest activation overpotential in air-cathode systems. State-of-the-art reviews converge on these same loss mechanisms and underline the need for materials and reactor innovations rather than incremental tweaks to feedstock or inoculum alone [207]. Some innovations like anode engineering to make electron export faster and denser to accelerate direct/mediated EET and increase electroactive surface area while maintaining biofilm integrity using nano scaffolds, biobased/low-cost carbons. Cathode catalysis to replace platinum and remove the biggest voltage penalty are all needed [199,208,209].

6. Scaling and smart systems

MFC represents a simple promising dual function technology that simultaneously treats wastewater and generates bioelectricity. Despite extensive research in the MFC, the technology is still crawling at laboratory scale yet to be employed in large-scale applications due to technical and economic hurdles. Modular design was employed in the scaling of this technology, and promising results were obtained in some of the reported literature.

6.1. Modular design for scaling

Modular design involves configuring multiple small units into stacks or networks. Some of the reported works in literature are.

Ge and He (2016) studied a 200L capacity modular designed MFC system consisting of 96 MFC modules. The system operated for 300 days and generated 200 mW power with 68%, and 75% ammonia nitrogen and chemical oxygen demand removal respectively, and 90% suspended solid in a local wastewater treatment plant for treating primary effluent [186]. He et al. (2016) design 2L volume modular scale MFC that achieved 400 ± 8 mW m^{-2} an average of 57% COD removal for 8 h [210]. Gajda et al. (2018) also reported achieving 245 mW of power density from a small scale modular multi-unit system [211]. Walter etl., (2020) reported to have generated 860 mW maximum power density from 15-module stacked MFC and 680 mW from 18-module stacked [212]. Mateo et al. (2018), generate 741.4 mW maximum power density from modular stacked development of 112 mini MFCs [213]. Dong et al. (2015) reported a 90L stackable pilot scale microbial fuel cell for the treatment of brewery wastewater and were able to achieve 87.6% COD removal and generate 0.097 kWh/m^3 [190].

Some of the challenges of MFC scale up are discussed below.

6.1.1. Decrease in power density with reactor size increase

One of the fundamental and consistent challenges faced by MFC scale-up is the decline in the quantity of power density as the size of reactor increases. This inverse relationship between the power density and the reactor size arises due to the extension in space between the electrode, increments in the internal resistance and limitation in the diffusion of the substrate [203].

6.1.2. Electrode and reactor configuration

Reported research in the literature indicated that linear enlargement of the electrodes does not have proportional power increment. Instead, cathode-specific surface area, which is defined as the total surface area of a cathode per unit mass or volume (m^2/g or m^2/cm^3) is the major factor for predicting the power output of the MFC than just the electrode size alone. This is because the larger specific surface area of the electrode provides more active sites for the reaction to take place, thereby improving the performance of the MFC and overall efficiency of the system [203]. The reactor configuration is also another challenge for MFC scaling, a comparison of air and liquid cathode in pilot scale research (>100L) air-cathode microbial fuel cell outperform liquid-catholyte configuration in both area and volumetric normalized power density [148,164,165].

6.2. Integration with IoT, machine learning and sensors

Integrating microbial fuel cells with Internet of Things (IoT) platform, sensing technologies and machine learning (ML) will offer exciting and promising potential such as self-powered devices that are capable of real time environmental monitoring and predictive control efficiency enhancements (see Fig. 5). In fact, integrating MFCs with these technologies has further enhanced the utilization of its application in several fields.

6.2.1. IoT powered by MFCs

Veerubhotla et al. (2019) developed internet of things powered by bacterial fuel cell on paper [214]. Costilla-Reyes et al. (2018) reported a power management system with maximum power extraction and health protection algorithm for multiple microbial fuel cells for IoT [215]. Nath et al. (2021) also reported to have integrated IoT/clod-based hardware with the developed microfluidic paper-based microbial fuel cell with the yield of maximum power density of f 15.4 mW/cm^2 [216]. De La Rosa et al. (2019) also developed plant microbial fuel cells-based energy harvester system for self-powered IoT that generated maximum power of 0.71 V, current density of 5 mAcm^{-2}, and a power density of 3.5 mWcm^{-2} [217].

6.2.2. Integration of MFC with machine learning and sensors

Panja and Meharia, (2024) reported the microbial fuel cell accurate performance prediction using machine learning [218]. Cai et al. (2019) reported to have achieved 92% accuracy to predict the feed substrate in microbial fuel cell by incorporating microbial fuel community data with machine learning technique [219]. Hess-Dunlop et al. (2024) developed a deep learning for the prediction of energy output of microbial fuel cells with 2.33% to 5.71% error [220]. Lesnik and Liu, (2017) employed Artificial Neural Network and developed a platform for predicting microbial fuel cell biofilm communities and bioreactor performance with an average percent error of Coulombic efficiency and COD removal rate predictions of 1.77% and 4.07%, respectively [221]. Du et al. (2022) utilize machine learning to develop a microbial electrochemical sensor for the quantification of multiple toxicants present in wastewater [222]. Atoche et al. (2023) investigated the capacity of the renewable energy of microalgae microbial fuel cell to power the GioT sensor nodes and the maximum power density generated was 80.10 mW/m^2 [223].

7. Limitations and challenges faced by MFC in real-world applications

The key limitations of microbial fuel cells (MFCs) technology fall into technical, operational, economic, and systemic categories. Power Density Issues were reported in most of the large-scale systems [177,214], power output was much lower than expected at lab scale, highlighting a key scalability issue in MFC technology. Operational Instability is also one of the issues, various systems struggled with fluctuations in performance due to substrate composition, biofilm development, and electrode deterioration, as demonstrated in multiple studies [224]. Cost and Complexity of Scaling were reported to be part of the challenges in scaling to pilot or real-world volumes, system configuration, energy recovery efficiency, and maintenance complexity, which were also mentioned as part of the challenges [225] (see Table 8).

7.1. Proposal for potential solutions to the challenges in scaling the applications of microbial fuel cells (MFCs) in real-world settings

While MFC technology has shown considerable success in laboratory and small-scale pilot studies, its implementation in large-scale, real-world settings remains limited. This proposal outlines potential solutions to these challengfaces and provides a roadmap for overcoming the

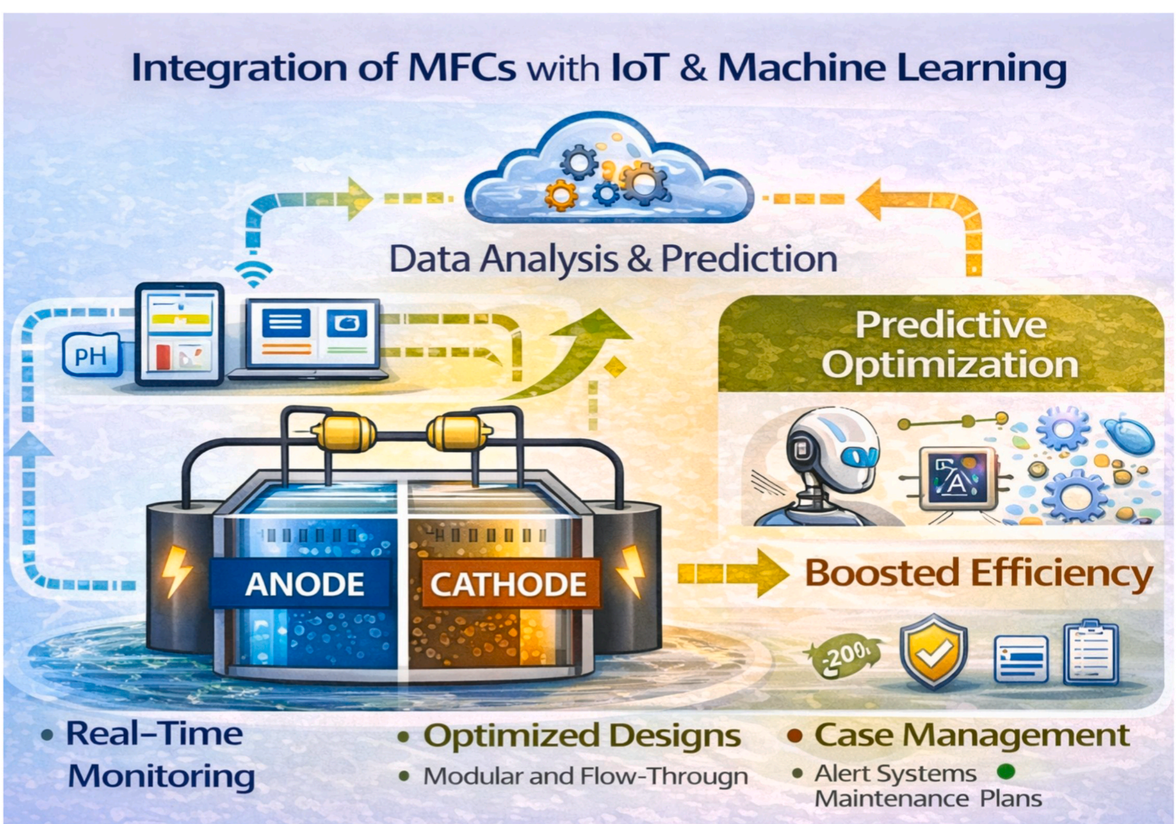

Fig. 5. MFCs integration with IoT and machine learning.

Table 8
Shows a summary of some selected publications on challenges faced by MFC technology in real-world pilot scale applications.

Reactor size	Wastewater Type	Power Outcome	COD Removal	Key Failure Issue	Reference
200 L	Municipal wastewater	200 mW	75%	Performance fluctuations due to wastewater quality, operational factors	[186]
45 L	Primary clarifier effluent	Stable power output at low COD	24% COD, 40% TSS, 28% Nitrogen	Reduced biogas production, energy gain from MFC offset energy losses	[187]
10 L	Brewery wastewater	23.0 V (open-circuit voltage)	>85% COD and NH_4-N removal	Cathode deterioration leading to performance loss; power recovery post-maintenance	[188]
1000 L	Municipal wastewater	0.42 to 3.64 W/m^3	70-90% COD removal	Significant fluctuations in performance due to wastewater quality and system operation	[189]
90 L	Brewery wastewater	8 to 19.1 W/m^3	87.6% COD removal	Performance affected by scaling-up issues, including reactor configuration	[190]
72 L	Artificial wastewater	50.9 W/m^3	97% COD removal	Substrate cross-conduction, inadequate configuration of multiple MFC modules	[176]
12 L (modules)	Urine	~12 W/m^3	~80% removal	Difficulty in maintaining high power density due to self-stratification issues	[191]
250 L	Domestic wastewater	0.47 W/m^3	~75% COD removal	High area-specific resistance limiting power, complexity in system scaling	[192]
20 L	Food processing wastewater	0.25 W/m^3	~70% COD removal	High internal resistance and fouling; poor scalability for large systems	[193]
850 L	Domestic wastewater	Power output (0.043 W m^{-2})	91% COD removal	Fluctuated performance, Low power output due to large and reactor configuration	[194]

barriers to the large-scale application of MFCs (see Fig. 6).

7.2. Key challenges in scaling MFCs

7.2.1. Low power density and energy recovery

One of the primary limitations of MFC technology is its relatively low power density, which hinders its ability to compete with other renewable energy sources like solar and wind. Scaling up MFCs to meet the energy demands of municipal wastewater treatment plants or industrial applications remains a significant challenge.

7.2.2. High initial and operational costs

The high capital investment required for MFC systems, especially for electrodes and materials, limits their feasibility for widespread adoption. Additionally, the operational costs, including maintenance of microbial communities and system monitoring, are substantial.

7.2.3. Limited system longevity and stability

The long-term stability and performance of MFC systems are still uncertain. Microbial communities in MFCs need to be carefully managed to maintain efficiency, and there are concerns regarding the degradation of materials, such as electrodes, over time.

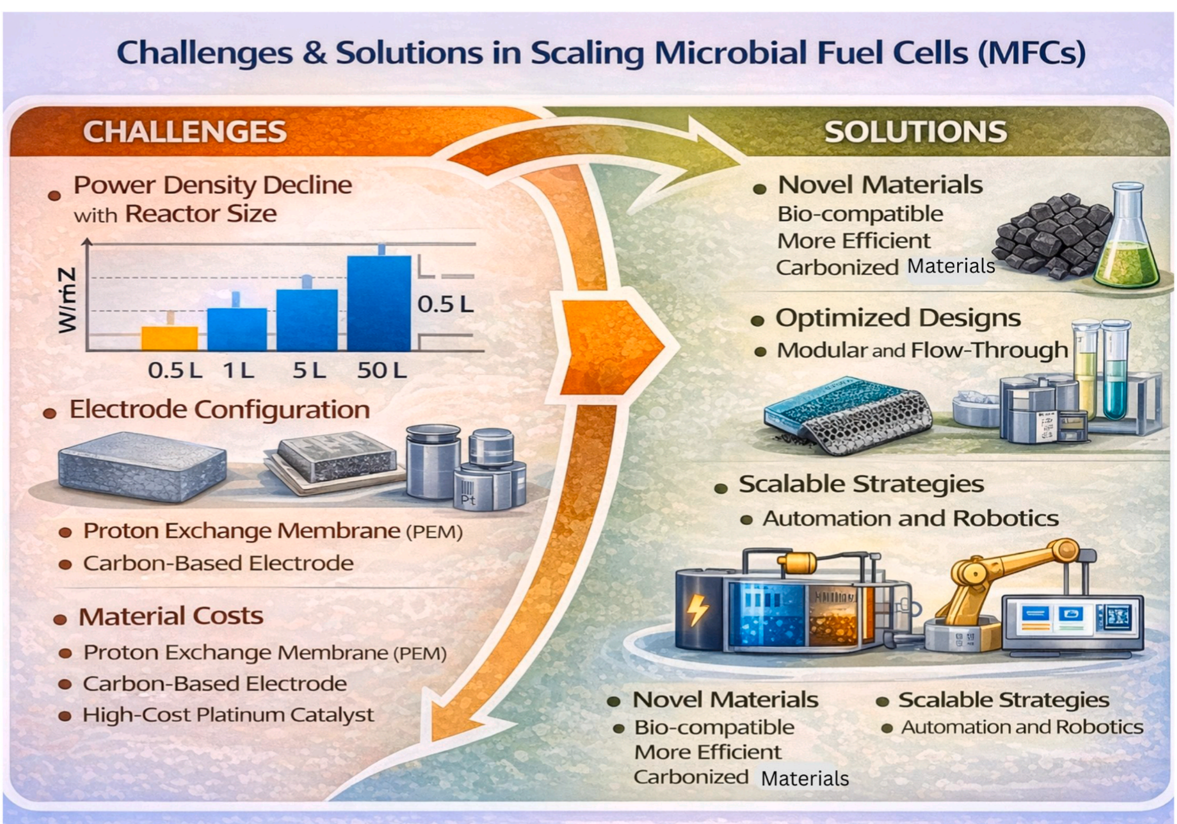

Fig. 6. MFCs scale-up challenges and solutions.

7.2.4. Scalability and infrastructure integration

While small-scale MFC systems have been successfully deployed, scaling these systems to treat the large volumes of wastewater in municipal plants or to produce significant amounts of electricity remains a complex task. Furthermore, integrating MFC systems into existing wastewater treatment infrastructure presents challenges in terms of both technical compatibility and cost.

7.2.5. Environmental impact of materials

The use of expensive materials such as platinum in MFC electrodes raises environmental and economic concerns. Although alternative materials like carbon-based electrodes have been developed, the overall environmental impact of materials used in MFCs requires further investigation.

7.3. Proposed solutions to overcome scaling challenges

Below are the detailed discussions of the proposed potential solutions to the above challenges faced by the scale-up implementation of microbial fuel cells.

7.3.1. Enhancing power density through system optimization

7.3.1.1. Microbial community engineering. One potential solution to increase the power density of MFCs is the optimization of microbial communities. By selecting or engineering microbes that are more efficient at transferring electrons or producing higher power outputs, the overall energy recovery of MFCs can be improved. Several research demonstrated that the application of certain microbial species and microbial consortia can enhance the power output of MFCs by improving electron transfer efficiency [46,226].

7.3.1.2. Electrode and Reactor design optimization. Improving the design of electrodes and reactors can also significantly enhance MFC power density. For example, the use of nanomaterials or the modification of electrode surface areas can improve electron transfer and increase the efficiency of MFCs. Cunkuan et al., (2024) found that the use of nanostructured electrodes in MFCs led to improved energy recovery, suggesting that future MFCs should integrate these advanced materials to enhance performance [227].

7.3.2. Reducing costs through material innovations

7.3.2.1. Development of low-cost electrodes. To address the high initial costs of MFC systems, one of the most promising approaches is the development of low-cost electrode materials. Carbon-based materials, such as activated carbon or graphite, offer a cost-effective alternative to platinum. Research by Zhang et al., (2025) and Das et al., (2025) highlighted the use of biomass as effective substitutes for platinum electrodes, providing a cheaper and more sustainable solution for MFCs [81,228].

7.3.3. Improving longevity and stability

7.3.3.1. Microbial community management. To ensure the long-term stability of MFC systems, it is essential to maintain a healthy microbial community that is resilient to environmental changes. Advances in microbial ecology and genetic engineering could allow for the creation of more robust microbial strains that are less prone to decline in performance over time. Xinxin et al., (2025) emphasized the need for advanced microbial monitoring and management systems to ensure stable operation in large-scale MFCs [229].

7.3.3.2. Electrode protection and maintenance. The degradation of electrodes over time is another major challenge. Using advanced materials, such as conductive polymers or carbon composites, can help protect electrodes from corrosion and improve their durability. Zhang et al., (2025) proposed the use of self-healing materials in MFC electrodes to extend their operational life [230].

7.4. Economic, environmental, and policy perspectives

7.4.1. critical evaluation of the economic feasibility and market readiness of microbial fuel cell (MFC) technology

7.4.1.1. Cost-effectiveness of MFC technology. The economic feasibility of MFC technology is predominantly influenced by the initial investment costs, operational costs, and long-term profitability. Initial investment costs primarily involve the construction of MFC systems, including the price of materials such as electrodes, proton exchange membranes, and the reactors. According to a study by Khan et al. (2024), the cost of electrodes, particularly those made from precious metals like platinum, significantly influences the overall cost of MFC systems [231]. Research indicates that a shift toward low-cost materials such as carbon-based electrodes or bio-based electrodes is essential for reducing capital costs [232].

Operational costs are driven by the maintenance of MFC systems, energy recovery rates, and the efficiency of the microbial communities involved. Energy recovery through MFCs remains relatively low compared to conventional energy sources such as solar or wind. However, recent advancements in optimizing microbial communities and electrode configurations have improved energy output, which could reduce the operational cost per kilowatt-hour over time. Zhang et al. (2025) demonstrated that integrating MFCs with waste treatment processes could offset operational costs, as these systems could simultaneously treat wastewater while generating power [108].

Despite these advancements, the scalability of MFC systems remains a significant cost barrier. The high capital investment required for large-scale installations and the complexity of maintaining microbial communities for optimal energy production are considerable challenges. In a market where cheaper and more efficient technologies are readily available, MFCs are yet to show strong economic viability on a commercial scale (see Fig. 7).

7.4.1.2. Market potential of MFCs. MFCs possess unique market potential, primarily in niche applications such as remote or off-grid power generation, waste treatment, and small-scale renewable energy systems. One promising area is the integration of MFCs in wastewater treatment plants, where they can serve dual functions of energy recovery and effluent purification. Unuofin et al., (2020) discussed the potential for integrating MFCs in industrial waste management, where they could contribute to decentralized power generation while reducing the environmental footprint of wastewater treatment processes [233].

Furthermore, as global interest in sustainable and renewable energy solutions grows, there is increasing demand for green technologies, particularly in sectors like agriculture, food production, and environmental remediation. MFCs offer potentially disruptive technology in these industries, as they can harness organic waste and provide a form of localized renewable energy. For instance, Du and Shao, (2022) highlighted the application of MFCs in agricultural waste management, where organic by-products can be converted into electrical power, contributing to the economic viability of rural areas [234].

However, the adoption of MFCs in the broader energy market faces significant hurdles. These include competition with well-established energy production technologies such as solar, wind, and hydroelectric power, all of which benefit from economies of scale and widespread infrastructure. Furthermore, the lack of supportive policies and financial incentives for MFC deployment limits their market penetration.

7.4.1.3. Market readiness and barriers to adoption. The market readiness

Fig. 7. Economic, environmental and policy considerations.

of MFC technology is constrained by several factors, including high production costs, scalability challenges, and technological limitations. While MFCs have demonstrated promise in laboratory settings and small-scale prototypes, scaling up these systems to industrial levels remains difficult. Petrovic and Hossain (2020) outlined that the integration of MFCs into existing energy systems, such as the national grid or industrial applications, would require significant modifications to both the technology and infrastructure [235].

Another key barrier is the lack of standardized designs and performance metrics for MFCs, which impedes their commercial acceptance. Without clearly defined standards for efficiency, cost-effectiveness, and reliability, it is difficult for potential investors and consumers to evaluate MFCs as a viable alternative to other renewable energy sources. Nawaz et al. (2020) emphasized that for MFCs to be competitive in the renewable energy market, standardized testing and performance protocols need to be established, along with government backing in the form of subsidies or tax incentives for green technologies [236].

Furthermore, market adoption is often influenced by the perception of technological maturity and risk. MFC technology, though promising, is still considered by many as experimental. For large-scale commercial adoption to occur, businesses and governments need to recognize MFCs as a reliable and scalable solution. As such, investments in further research and development, particularly in improving energy output and reducing production costs, are essential.

7.4.1.4. Techno-economic analysis. Analyzing the economic feasibility, environmental compatibility and policy applicability is important for the scale-up of the microbial fuel cells technology from lab to real World field. The fundamental economic hurdle faced by the scale-up of microbial fuel cells technology is the exorbitant capital cost, which is due to the expensive electrode materials, current collector, carrier materials and catalyst used [237]. The capital cost is still high despite utilization of some cheap materials for instance the most widely used membrane in the scale-up application is Ultrex membrane it also costs \$110 m^{-2} or even the carbon cloth materials considered relatively cheap and employed in some research, the capital cost still is approximately \$1.5 m^{-3} municipal wastewater [238,195].

7.4.1.5. Regulatory frameworks and sustainability indices. Microbial fuel cells (MFCs) are a game changer in the quest for the creation and maintaining a sustainable environment. MFC is not just a technology, it is a phenomenon that provides a viable alternative to the exhaustible fossil sources of energy that endanger the environment. The MFC works excellently in the treatment of wastewater and removes toxic substances in the percentage range from 60% to 90% [183,196–198] which is within the reclamation and reuse level of resources.

Life cycle assessment studies on microbial fuel cells recently conducted by Akinbuja et al. (2025) compared microalgae-assisted biotic cathode and abiotic graphite platinum/titanium (Pt-Ti) cathodes, it was reported in this research that replacing Pt-Ti cathode with graphite reduces global warming potential (GWP) by 99% [239]. Another comparative evaluation between the constructed wetland (CW), stand-alone microbial fuel cells (MFC) and hybrid CW-MFC revealed a significant environmental differential. The constructed wetland shows a substantial lower global warming potential (GWP) with only 142.26 kg CO_2-eq, while the stand-alone microbial fuel cell exhibited higher global warming potential of 2615 kg CO_2-eq. This revealed differential is largely due to the energy-intensive materials requirement of the stand-alone MFC such as catalysts, proton exchange membranes and electrodes. However, the hybrid CW-MFC exhibited lesser environmental burdens and higher performance efficiency [199,200,208,209].

Despite the compelling environmental sustainability promise exhibited by the microbial fuel cells, the policy regarding this technology remained fragmented and insufficient to support and encourage scale-up and commercialization [240]. MFC may be used as an essential instrument in the attainment of sustainable development goals. It contributes significantly to mitigating greenhouse gases and carbon dioxide sequestration. The current campaign of low carbon or decarbonization championed by some industrialized nations and environmental activists can recognize MFC as a potential technological instrument in their integrated mitigation strategies policy [205,201].

7.5. regulatory landscape and policy frameworks governing the implementation of microbial fuel cell (MFC) technology in wastewater treatment facilities

7.5.1. Regulatory frameworks governing MFC technology deployment

The regulatory framework governing the implementation of MFC technology in wastewater treatment facilities is multifaceted, involving several national and international regulatory bodies. These regulations typically fall into three major categories: environmental protection, health and safety, and energy generation.

7.5.1.1. Environmental Regulations. Wastewater treatment is subject to strict environmental regulations aimed at minimizing pollution and protecting water quality. Regulations such as the Clean Water Act (CWA) in the United States and the European Union's Water Framework Directive (WFD) set quality standards for wastewater effluent and mandate treatment processes to ensure the protection of aquatic ecosystems. MFC technology, as an alternative treatment method, must comply with these regulations, especially regarding the quality of treated effluent and the impact on receiving water bodies [241]. Moreover, MFCs need to meet environmental standards concerning the disposal of microbial waste and by-products, which could potentially introduce pollutants if not properly managed [41].

7.5.1.2. Health and safety Regulations. The deployment of MFC technology in wastewater treatment facilities also requires compliance with health and safety standards. Regulatory agencies such as the Occupational Safety and Health Administration (OSHA) in the U.S. and the Health and Safety Executive (HSE) in the U.K. are responsible for ensuring that MFC systems do not pose risks to workers operating or maintaining these systems. This includes safeguarding against biohazards, as MFCs often involve the cultivation of microbial communities that could potentially carry pathogens. Safety guidelines for handling microbial cultures, as well as the risks associated with chemical additives or electrodes used in MFC systems, are crucial in ensuring the safe deployment of MFCs [231,232].

7.5.1.3. Energy generation and grid integration. MFCs have the potential to generate electricity, which introduces additional regulatory concerns related to energy production. In many countries, electricity generation and distribution are heavily regulated, and MFC-generated electricity may need to comply with grid connection and power generation standards. For instance, regulations governing distributed energy generation, such as the Federal Energy Regulatory Commission (FERC) in the U.S. or the European Network of Transmission System Operators for Electricity (ENTSO-E), may impose requirements for the integration of MFC systems into national or regional power grids. This includes technical standards for energy output, voltage regulation, and the operation of MFC systems within existing energy infrastructures [242].

7.5.2. Regulatory challenges and compliance issues

Below are some barriers that can delay or prevent the large-scale adoption of MFCs, as stakeholders need to navigate complex regulatory processes to deploy these systems effectively.

7.5.2.1. Lack of standardized Regulations. One of the major challenges faced by MFC technology is the absence of standardized regulatory frameworks. While environmental and safety regulations are well-established for conventional wastewater treatment technologies, MFCs are still considered emerging technology. As a result, there is a lack of standardized testing procedures and performance metrics for MFC systems. This makes it difficult for regulators to assess whether MFCs meet the same regulatory criteria as traditional treatment methods. Without clear standards for efficiency, energy recovery, and effluent quality, MFCs are often subject to case-by-case approvals, which can slow down their adoption in the industry [243].

7.5.2.2. Interdisciplinary Regulatory gaps. The interdisciplinary nature of MFC technology presents a unique challenge in regulatory oversight. MFCs span multiple domains of regulation, including environmental protection, energy production, and industrial safety. As a result, existing regulatory bodies may not have the expertise or authority to regulate the full scope of MFC technology. For example, while the Environmental Protection Agency (EPA) in the U.S. may oversee the environmental aspects of MFC systems, the Federal Energy Regulatory Commission (FERC) may govern their energy production and integration into the grid. This lack of coordination between different regulatory agencies can lead to regulatory delays and confusion, impeding the widespread implementation of MFCs [244].

7.5.2.3. Uncertainty in Wastewater treatment efficacy. Regulatory agencies require assurance that any new wastewater treatment technology, including MFCs, will meet established water quality standards. However, the performance of MFC systems in large-scale operations has yet to be fully validated, particularly in comparison to conventional treatment methods. MFCs may not consistently achieve the same level of contaminant removal as traditional technologies, and the energy recovery may not be sufficient to justify the initial costs of deployment. Until comprehensive data on the long-term efficacy of MFC systems in real-world wastewater treatment scenarios becomes available, regulators may hesitate to approve these systems for widespread use [236,237].

7.5.2.4. Economic viability and cost-benefit analysis. Regulatory approval often depends on the cost-effectiveness of technology, particularly for publicly funded wastewater treatment plants. While MFCs offer potential energy savings, the high capital costs of MFC systems, especially those involving expensive electrode materials, pose a significant barrier to implementation. Governments and regulatory agencies must evaluate the long-term economic benefits of MFCs, including potential savings on energy costs and reductions in greenhouse gas emissions, against the high upfront investment required for MFC systems. Until there is conclusive evidence that MFCs can be economically competitive with conventional treatment technologies, regulatory approval and financial incentives may remain limited [245].

7.5.2.5. Monitoring and compliance Enforcement. Once MFCs are deployed, ensuring that they remain in compliance with environmental and health standards is crucial. Continuous monitoring of effluent quality, microbial safety, and energy production is required to ensure that MFC systems are performing as expected. However, regulatory agencies may lack the resources or expertise to effectively monitor MFC systems, particularly in decentralized or small-scale applications. This can result in difficulties in enforcing compliance and ensuring that MFC systems continue to meet regulatory requirements throughout their operational lifetime [243].

7.6. successful examples of interdisciplinary projects in MFCs

Several interdisciplinary collaborations in MFC research have successfully advanced technology and demonstrated its potential in wastewater treatment and renewable energy generation. Below are specific examples that showcase the power of combining knowledge from multiple fields.

7.6.1. The electrochemistry of microbial communities and energy recovery

A study conducted by Wang et al. (2015) focused on developing continuous stirred microbial electrochemical reactor through an interdisciplinary approach, integrating microbiology, electrochemistry, and materials science. The research demonstrated how combining the understanding of microbial communities (microbiological expertise) with the optimization of MFC materials (materials science) could significantly improve the power output of MFCs. The team explored the role of different microbial species in biofilm formation and how they affect electron transfer rates. By selecting the most suitable microbial consortia and using conductive materials for electrodes, the team achieved higher energy recovery and COD removal from organic wastewater [246].

7.6.2. Sustainable wastewater treatment with MFCs: the role of materials science

An example of interdisciplinary collaboration between environmental engineering and materials science is seen in the work by Zhang et al. (2025). The study focused on improving the performance of MFCs by developing novel electrode materials that were both cost-effective and efficient for wastewater treatment. Materials scientists and engineers developed carbon-based electrodes with enhanced surface areas and conductivity, while environmental engineers optimized reactor designs to maximize wastewater flow through the MFCs. The results demonstrated that these MFCs were highly effective at treating wastewater while producing electricity, reducing the need for external energy inputs. The success of this project underscores the value of integrating materials science and environmental engineering expertise to create systems that are both functional and sustainable [108].

7.6.3. Microbial fuel cells for agricultural waste management and energy recovery

In a study by Kumar et al. (2024), the integration of MFCs with agricultural waste management was explored in an interdisciplinary project combining agricultural science, environmental engineering, material science and microbial biotechnology. The research focused on converting agricultural waste products, such as wheat bran byproduct, into electricity using MFCs. The team optimized microbial fuel cell power generation while simultaneously treating organic waste using a biochar from synthesized from wheat byproduct [247]. The findings suggest that MFCs could serve as a sustainable technology for agricultural waste-to-energy conversion, providing farmers with a dual benefit of waste management and energy recovery. This project highlights the importance of cross-disciplinary expertise in addressing complex waste management challenges in agriculture.

8. Environmental implications of microbial fuel cell (MFC) technology: potential drawbacks and unintended consequences of widespread deployment in wastewater treatment plants

The microbial fuel cells innovation holds significant promise for both environmental sustainability and the development of decentralized energy systems. However, the widespread deployment of MFC technology in wastewater treatment plants (WWTPs) introduces a range of environmental implications, both positive and negative. While technology offers clear environmental benefits, it also presents several potential drawbacks and unintended consequences that must be carefully considered for its large-scale implementation.

8.1. Positive environmental implications

8.1.1. Energy recovery

MFCs can generate electricity from organic matter in wastewater, which could offset the energy requirements of WWTPs. This is particularly advantageous for energy-intensive processes like aeration in conventional activated sludge systems [248]. By producing clean, renewable energy, MFCs could help reduce the reliance on grid electricity, which is often derived from fossil fuels, and mitigate the carbon footprint of wastewater treatment.

8.1.2. Sustainable wastewater treatment

The treatment of wastewater through MFCs reduces the need for chemical additives and the production of harmful sludge, both of which are prevalent in conventional treatment methods [249]. MFCs also offer the potential for low-cost and low-energy wastewater treatment in remote areas where conventional infrastructure may be lacking.

8.1.3. Reduction in greenhouse gas emissions

Traditional wastewater treatment systems, particularly those that rely on aerobic processes, can release significant amounts of greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4). MFCs, by contrast, are more energy-efficient and may produce fewer greenhouse gases, contributing to the overall reduction of the environmental impact of wastewater treatment [250].

8.2. Potential environmental drawbacks and unintended consequences

8.2.1. Resource and material use

One of the significant challenges associated with MFCs is the use of materials for electrodes and membranes. Many early-stage MFCs have relied on expensive materials, such as platinum, for cathodes, which raise concerns about the environmental impact of sourcing and disposing of these materials. Platinum is a rare and non-renewable resource, and its extraction can lead to environmental degradation through mining practices [251]. Although researchers are working on developing cheaper and more sustainable materials, such as carbon-based electrodes, the environmental cost of producing and disposing of these materials remains a concern. Furthermore, the life-cycle impacts of MFC components, from production to disposal, need to be carefully evaluated to ensure that the benefits of energy generation do not outweigh the environmental costs of material use [252].

8.2.2. Microbial community management and environmental impact

The performance of MFCs is heavily influenced by the microbial communities used in the system. These communities are not static; they can evolve over time and adapt to the environmental conditions within the reactor. The introduction of non-native or genetically engineered microbial species into natural ecosystems could have unintended ecological consequences [253]. For example, if MFCs are deployed in open systems or areas with high biodiversity, the release of non-native microbes could disrupt local ecosystems, leading to potential ecological imbalances. Furthermore, the long-term stability and health of microbial communities in MFCs require continuous management and optimization, which may involve the use of chemicals or additives that could have unintended environmental impacts [254].

8.2.3. Production of toxic by-products

Although MFCs are designed to degrade organic pollutants in wastewater, the process may sometimes result in the production of toxic by-products, such as hydrogen sulfide (H_2S) or other volatile organic compounds (VOCs), depending on the microbial community composition and operational conditions. These by-products can pose environmental hazards if not properly managed. For instance, hydrogen sulfide is toxic to aquatic life and could be harmful if released into the surrounding environment [255]. Therefore, effective monitoring and control mechanisms are needed to ensure that the degradation process in MFCs does not produce harmful substances that could negatively impact ecosystems.

8.2.4. Waste management and long-term sustainability

While MFCs reduce the production of sludge compared to traditional treatment methods, they do not eliminate the need for waste management. The microbial communities in MFCs produce biomass that must be periodically harvested and processed, adding another layer of complexity to the overall waste management strategy. Furthermore, the longevity and sustainability of MFCs depend on the continuous supply of organic matter for microbial growth and energy generation. If the supply of organic waste is reduced or disrupted, the performance of the MFC system may degrade, requiring additional energy inputs or interventions to maintain the process [256].

8.3. social implications of microbial fuel cell (MFC) technology: community acceptance, stakeholder engagement, and public perception

8.3.1. Community acceptance of MFC technology

Several social factors contribute to the level of acceptance of MFC technology, including awareness, trust, perceived benefits, and concerns about risks.

8.3.1.1. Awareness and education. Community acceptance of MFC technology often begins with raising awareness and providing education about its benefits and potential. Educational outreach initiatives are essential to inform local communities about how MFCs work, their environmental benefits, and their role in sustainable energy generation and wastewater treatment. For instance, Aklin et al. (2018) found that communities with higher levels of knowledge about renewable energy technologies were more likely to accept and support their implementation [257]. In the case of MFCs, providing clear, accessible information about how technology addresses both waste treatment and energy needs can help foster positive perceptions among community members.

8.3.1.2. Trust in technology and institutions. Trust in technology and the institutions implementing it plays a significant role in community acceptance. The involvement of trusted local organizations, such as municipalities, universities, or non-governmental organizations (NGOs), can help to build credibility and legitimacy for MFC projects. Additionally, transparency in decision-making processes, clear communication about risks, and the demonstration of successful pilot projects can increase trust in the technology. A study by Kluskens et al., (2024) demonstrated that community trust in technology providers was a key determinant of the acceptance of innovative environmental technologies [258].

8.3.1.3. Perceived benefits. The perceived benefits of MFC technology, such as improved waste management, energy savings, and environmental sustainability, play a crucial role in determining community acceptance. Research by Batel, (2020) suggested that communities are more likely to embrace technologies that provide tangible local benefits, especially those that contribute to reducing environmental pollution and improving energy independence. For example, in rural or off-grid communities, MFCs that generate electricity while treating wastewater may be seen as a valuable resource that directly improves quality of life [259].

8.3.1.4. Media and communication. The way MFC technology is portrayed in the media can significantly influence public perception. Positive media coverage highlights the benefits of MFCs in addressing environmental pollution, reducing energy consumption, and promoting sustainability can enhance public support for technology. On the other hand, negative media reports that focus on potential risks or failures could undermine public confidence [260].

8.3.1.5. Cultural context and values. Cultural factors and societal values influence how the public perceives new technologies. In regions where environmental sustainability is highly valued, MFC technology may be viewed positively as a means of achieving green energy solutions and addressing wastewater management challenges. Conversely, in areas with low environmental awareness or where there is skepticism toward new technologies, MFCs may face resistance. Olajide, (2020) discuss how cultural factors can shape public attitudes toward renewable energy technologies, including MFCs [261].

8.4. Microbial fuel cells serve as alternative source of sustainable energy for circular bioeconomy

As energy demand rises globally and the pressure to decouple economic growth from fossil-fuel consumption intensifies, innovative technologies that integrate waste valorization, bioenergy generation, and circular economy principles are gaining prominence. MFCs is one such promising alternative. The paradigm of circular bioeconomy is characterized by resource loops, low waste, cascading use of biomass, and renewable feedstocks. MFCs can play vital multiple roles that align with circular bioeconomy goals such as.

- Waste valorization, converting organic residuals into electricity and bioproducts [262].
- Energy generation from low-grade biomass/waste, alleviating reliance on primary fossil energy and mitigating greenhouse gas emissions [263].
- Integration into biorefineries, as a module in which residual streams from bioprocessing (e.g., wastewater) are further treated and energy recovered, thus improving overall system efficiency [264].

8.5. Microbial fuel cells utilization requires collaborations within economy, environmental and regulatory policy

Microbial Fuel Cell (MFC) technology offers the promise of simultaneous wastewater (or organic waste) treatment and electricity generation, thus potentially contributing to circular economy solutions, resource recovery and decarbonization [263]. However, despite decades of laboratory research, translation into broad commercial or municipal deployment remains limited. One reason is that technical innovation alone does not guarantee real-world uptake: economic viability, environmental sustainability, and regulatory enabling frameworks all must align. As noted in broader fuel-cell reviews, the operational principle, environmental consequences and economic concerns must be considered together [265]. Thus, the thesis emerges that successful MFC deployment requires multi-stakeholder collaboration: engineers, technologists, water and energy utilities, economists, policy-makers and regulators must coordinate to overcome non-technical barriers.

8.5.1. Economic & business model considerations

Though MFCs can treat waste and generate energy, many studies emphasize that power densities are still relatively low and cost per kWh remains higher than many alternatives (e.g., anaerobic digestion + biogas, conventional fuel cells) [161]. Without supportive business models or subsidies, utilities or industries may not adopt MFCs unless they demonstrate clear revenue or cost-savings.

To strengthen economic viability, MFCs should be embedded in waste-to-resource flows e.g., nutrient recovery (P, N), coupling with biorefineries, or disposal cost reduction. Kurniawan et al. (2022) show MFCs treating P-laden wastewater while generating electricity [266]. This creates multiple value streams (treatment fee savings, energy and possibly recovered chemicals), which makes business proposals more robust.

8.5.2. Environmental & resource recovery dimensions

One of the key environmental rationales for MFCs is the coupling of waste treatment with energy production. Unuofin et al. (2023) emphasize that MFCs align with a circular bioeconomy by valorizing organic waste streams. From an environmental standpoint, this offers benefits, reduced organic loads in wastewater, lower greenhouse gas emissions (if displacing fossil energy), and the potential for nutrient recovery. These benefits must be quantified (LCA, carbon footprint) to attract policies support [263].

8.5.3. Regulatory and policy frameworks

Enabling regulation for waste-to-energy technologies, policy frameworks often segment waste-regulation, water regulation, and energy regulation into separate silos. MFCs bridge waste/water and energy sectors, so regulation must recognize their hybrid nature. As Ramadan (2017) discusses, policy design must accommodate emerging waste-to-energy technologies.

Regulatory gaps include (i) recognition of MFCs as renewable or low-carbon technologies, (ii) incentives for wastewater utilities that generate energy, (iii) permitting frameworks for novel bio electrochemical systems [161].

9. Future perspective of the MFC

The idea of utilizing the invisible microorganisms to simultaneously convert the chemical energy content of the organic matter present in the wastewater into electrical energy and treat the wastewater is undeniably enticing, but employing this lab-based enthusiasm into real-world application requires overcoming persistent technological and economic hurdles that have been the bottleneck of this fascinating technology to scale up.

9.1. Research gaps and interdisciplinary collaborations

Some of the research gaps in the MFCs technology are.

9.1.1. Scale-up complexities

Despite the enticing nature of the MFCs technology the scale-up remains fragmented and unpredictable the linear increase in size doesn't translate into power generation. Bottlenecks like ionic short circuit and cell-voltage reversal remain. Recent development by researchers suggested employing modular miniaturized designs connected in parallel or in series instead of large-scale units but this also introduces new challenge in system design and control.

9.1.2. Biofilm-electrode interactions and substrate stability

The interaction between the biofilm and electrode is fundamental in the performance of the microbial fuel cells, the instability of the organic substrate often affects the efficiency of long-term performance but still these relationships are virtually completely unexplored or not satisfactorily characterized.

9.1.3. Innovations in electrochemical integration

Employing novel electrical components such as supercapacitors in the enhancement of the operational performance of the MFCs has revealed a promising preliminary result but extensive exploration is required in that direction.

9.2. Interdisciplinary collaboration

The utilization of nanotechnology, particularly electrode design revealed materials upgrade as foundation to the development of the microbial fuel cells technology**,** Chakma et al. (2025) recently reported in their paper that employing nanomaterials significantly improve the performance of MFC, increases electrode active surface area thereby enhances electron transfer and improve cathode/anode properties [226]. However, despite this development, challenges such as inefficient extra cellular electron transfer (EET) and expensive materials for the electrode persist. An interdisciplinary collaboration between the nano chemists and genetic engineers can integrate nano structured materials and genetically modified electrogens to overcome the limitations in the MFC technology and enhance the power output and energy recovery efficiency [36,267,202] (see Fig. 7).

9.3. Vision for MFCs in the circular economy and net-zero goals

Microbial fuel cells have an enticing nexus with sustainability, the technology can treat wastewater, recover energy, remove pollutants and recover resources, these are fundamentals in circular economy in which wastes are considered inputs, not trash. Fig. 8 summarizes these fundamentals roles of MFC. The MFCs 100% fits into these essential values of circular economy while in net-zero core strategic mission any technology that provides an alternative source of energy and leads to the reduction in the emissions of greenhouse gases is held dearly and essential. Therefore, if MFCs could be scale-up it will go a long way in addressing the challenges of energy crises, circular economy and environmental pollution. Some of the recent literature reported promising results about the performance of microbial fuel cell in environmental remediation and resource recovery for instance Yang et al. (2025) reported excellent performance of a constructed wet land microbial fuel cell in pollutant removal, with the average removal efficiencies of COD, NH_4^+ -N and TP of 83.95%, 78.7s2% and 77.17%, respectively [268]. Mukimin and Vistanty, (2023) reported the removal of 4.35 kgm^{-3} of CO_2 from wastewater, 17.25 kgm^{-3} of methane (CH_4) emission reduction and 48.94% of chemical oxygen demand efficiency [269]. These and several results reported in the literature made the MFC a promising future technology with essential nexus in sustainability.

9.4. Conceptual contribution of this review

9.4.1. Bridging materials-process divide

The significant progress achieved in material innovation (e.g., biochar electrodes, nanomaterials catalysts, conductive polymers) has often been reported separate from the practical challenges of wastewater treatment (e.g., stability, fouling, variability). This article has effectively bridged that gap by discussing the integration of advanced materials with wastewater treatment performance metrics, such COD removal and normalized energy recovery. The article viewed material innovation as an enabler of robust, scalable wastewater treatment rather than an isolated technological advancement. By framing material innovations in the context of their ability to improve performance efficiency in wastewater, this article provides a more holistic understanding of how MFCs can evolve into functional wastewater treatment systems [223,226].

9.4.2. Unifying energy recovery and treatment efficiency metrics

The field of MFC research has often been divided using inconsistent performance metrics, with studies frequently focusing on power density without regard for how it integrates with wastewater treatment efficiency (e.g., COD removal, nutrient recovery). This article addresses this gap by considering multifaceted performance indicators: including power density, coulombic efficiency (CE), COD removal, and normalized energy recovery (kWh·m^{-3})—into a unified framework for evaluating MFCs. The integration of these diverse metrics allows for a more nuanced evaluation of MFC systems, helping to bridge the gap between lab-based metrics and real-world wastewater treatment goals. This approach provides the foundation for future techno-economic and life-cycle assessments of MFC systems and facilitates meaningful comparison with conventional wastewater treatment technologies [224,225].

9.4.3. Rebalancing system optimization: cathode limitations and long-term operation

While the majority of MFC research has focused on anode optimization, this review shifts attention to cathode limitations, particularly oxygen reduction reaction (ORR) kinetics and cathode durability in wastewater environments. By recognizing the cathode as a dominant voltage-loss mechanism, this review emphasizes the need for balanced optimization across both electrodes. In addition, the review incorporates long-term operational data, addressing biofouling, microbial drift, and membrane degradation—factors that are often overlooked in short-term

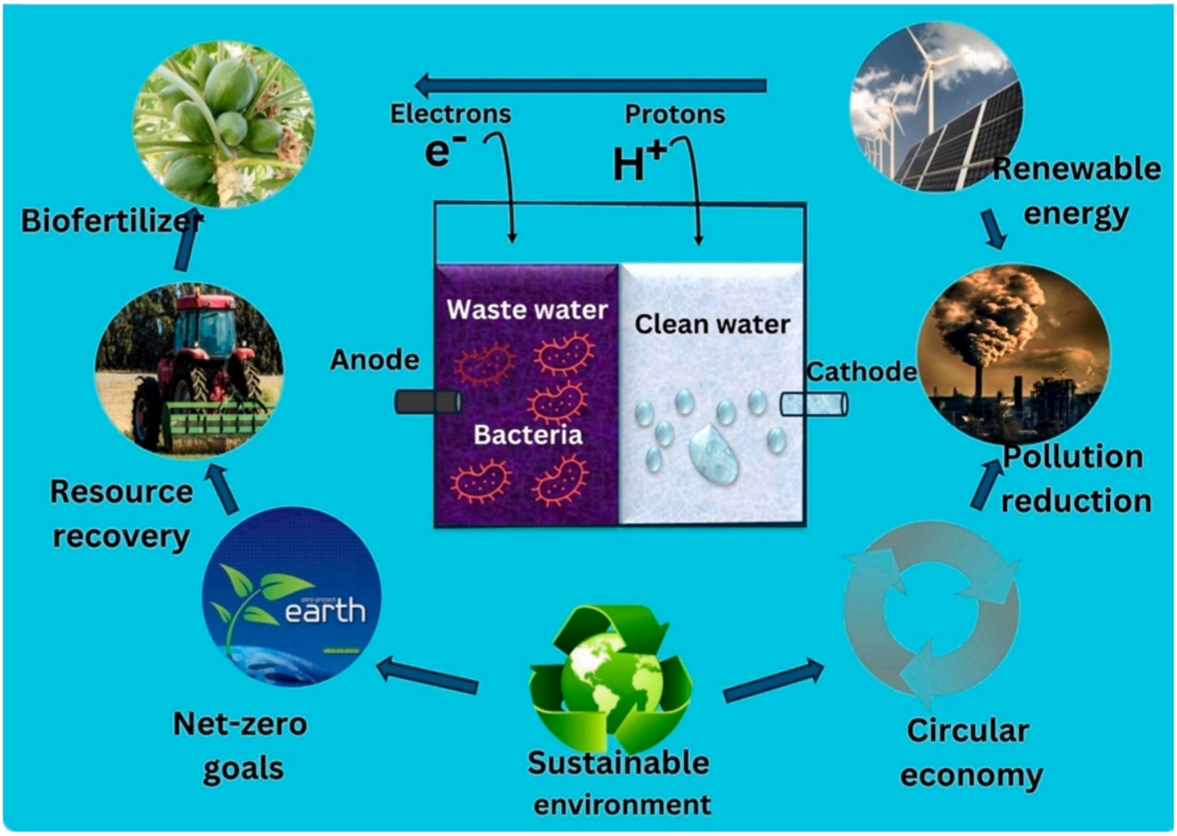

Fig. 8. Vision for microbial fuel cells in circular economy and net-zero goals.

studies but are critical for MFCs to function as reliable, long-duration systems for wastewater treatment. This focus on system longevity aligns with real-world requirements for MFCs to transition from experimental devices to stable, scalable technologies [187,188].

9.4.4. Positioning MFCs within smart, adaptive wastewater infrastructure

A key contribution of this article is its conceptual expansion of MFCs into the realm of smart wastewater systems. By integrating MFCs with Internet of Things (IoT) technologies, real-time sensors, and machine learning (ML) for adaptive control, this article positions MFCs not just as passive treatment units but as self-monitoring, self-optimizing systems. This integration is crucial for addressing wastewater variability, substrate fluctuation, and real-time performance prediction, enhancing the resilience and autonomous operation of MFCs in dynamic wastewater environments. By focusing on the potential for MFCs to function within intelligent water management systems, the article sets the stage for MFCs to play a key role in next-generation, data-driven wastewater infrastructure [270,189].

9.4.5. Embedding MFCs in the circular bioeconomy and policy landscape

The article conceptually elevates MFCs from niche bio electrochemical technologies to core components of a circular bioeconomy. By emphasizing waste valorization, greenhouse gas mitigation, and resource recovery, it aligns MFCs with the growing demand for sustainable, integrated waste-to-energy technologies. The article also tackles the policy and regulatory barriers to MFC adoption, recognizing the siloed nature of current regulations across water, waste, and energy sectors. By advocating for multi-stakeholder collaboration and policy integration, the review highlights the need for holistic regulatory frameworks that support the scalable deployment of MFC systems. These insights are crucial for overcoming the non-technical barriers that have limited MFC adoption in real-world applications [191,192].

9.4.6. Implications of data reproducibility and reliability in microbial fuel cell (MFC) research

Reproducibility in scientific research refers to the ability to achieve consistent results when experiments are repeated under the same conditions, while reliability pertains to the dependability of the data produced. In the context of MFC research, the reliability of data is crucial for the validation of experimental findings, optimization of MFC systems, and the eventual translation of laboratory results to large-scale applications.

9.4.7. Importance of reproducibility in MFC research

9.4.7.1. Validating scientific claims and advancing knowledge. Reproducibility is the cornerstone of scientific credibility. In MFC research, ensuring that results can be consistently reproduced allows researchers to validate their findings, confirm hypotheses, and establish reliable principles regarding the performance of MFC systems. Without reproducibility, the risk of advancing false or misleading claims increases, which could hinder the development of MFC technology.

According to Sara et al., (2019), the importance of reproducibility in bio electrochemical systems, including MFCs, cannot be overstated, as it forms the basis for understanding how MFCs function and optimize their performance [271]. For example, Wang et al., (2016) reported that variations in electrode material, microbial community, and reactor design could significantly affect power generation in MFCs. Therefore, reproducible results across different laboratories are necessary to ensure that MFC technology's potential is accurately assessed and understood [272].

9.4.7.2. Guiding design and engineering decisions. Reproducible experimental data provide critical feedback for designing more efficient MFC systems. Variations in performance caused by differing experimental protocols or environmental conditions need to be identified and controlled to draw meaningful comparisons between studies. Larrosa et al., (2009) noted that the consistency of MFC system designs across studies is essential for comparing performance metrics such as power density, efficiency, and energy recovery potential. Achieving reproducibility across different setups and scales allows researchers to identify optimal designs, materials, and operational conditions [273].

9.4.7.3. Ensuring Reliability for Real-World applications. The long-term deployment of MFC technology in real-world applications such as wastewater treatment plants or decentralized energy systems relies on the reliability of MFC systems under diverse operational conditions. Consistent and reproducible research results provide the foundation for building robust MFC systems that can maintain performance over time in various environmental and operational contexts. Leicester et al., (2023) highlighted that variability in microbial communities, substrate types, and operational factors must be rigorously controlled and reproducible to ensure that MFC systems are scalable and resilient in the field [274].

9.5. data quality assurance measures in MFC research

To achieve reproducibility and reliability in MFC research, several data quality assurance measures are essential. These measures help standardize experimental practices, reduce sources of variability, and ensure the accuracy and consistency of the data generated. Below are key quality assurance practices that are critical for improving data reliability in MFC research.

9.5.1. Standardization of experimental protocols

One of the most effective ways to enhance reproducibility is through the standardization of experimental protocols. Bird et al., (2025) emphasized the need for standardized procedures in MFC research, including consistent methods for electrode preparation, microbial inoculation, reactor configuration, and operational conditions (e.g., temperature, pH, substrate concentration). By adopting standardized practices, researchers can reduce experimental bias and ensure that results are comparable across different laboratories [275].

9.5.2. Clear reporting of experimental conditions

Transparent and comprehensive reporting of experimental conditions is crucial for ensuring data reproducibility. Sathya et al., (2022) emphasized the importance of publishing detailed information about experimental setups, including the materials used, reactor configurations, electrode specifications, microbial consortia, and environmental conditions. The more thoroughly these factors are reported, the easier it will be for other researchers to replicate the experiments and validate the results [39].

9.5.3. Use of control experiments and replicates

Control experiments and replicates are essential for identifying confounding variables and assessing the reliability of experimental results. Control groups, where MFCs are run under standard conditions or without the application of a specific treatment (e.g., different electrode materials or microbial communities), provide a baseline for comparison. Replicating experiments and using multiple independent trials can help detect inconsistencies and ensure that observed results are not due to chance or experimental errors [276].

9.5.4. Data validation and statistical analysis

Proper statistical analysis is critical for ensuring the robustness of MFC research findings. Researchers should use appropriate statistical methods to validate their results, such as regression analysis, hypothesis testing, and variance analysis. By conducting thorough statistical evaluations, researchers can quantify the uncertainty in their data and identify trends or patterns that might otherwise be overlooked. The data analysis should be rigorous, including uncertainty quantification, to improve the reliability and interpretability of results in MFC studies [277].

9.5.5. Long-term monitoring and performance testing

For MFC systems, long-term monitoring is crucial to evaluate the durability and reliability of microbial communities, electrode materials, and overall system performance. Long-term studies allow researchers to assess the stability of MFCs under real-world conditions and ensure that the results obtained in shorter experimental timelines are indicative of the system's performance over time. Ge et al., (2016) noted that conducting long-term performance testing is essential for identifying potential system failures, material degradation, or microbial community shifts that could affect the reliability of MFC systems [186].

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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