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Microbial Fuel Cells for Bioelectricity Generation: Current Innovations, Challenges, and Future Prospects

Shravan Kumar[1], Nakul Rajesh Shenode[2], Yashavant Jeph[3], Rasika Kudale[4]
[1]*Assistant Professor, Department of Biochemical Engineering, Harcourt Butler Technical University, Kanpur, Uttar Pradesh, India*
[2]*Assistant Professor, Swaminarayan Siddhanta Institute of Technology, Nagpur, Maharashtra, India*
[3]*Department of Biotechnology, Indian Institute of Technology, Hyderabad*
[4]*Department of Organon of Medicine and Homoeopathic Philosophy, Smt. Malini Kishore Sanghvi Homoeopathic Medical College and Hospital Miyagam Karjan, Vadodara Gujarat India*

Abstract: Microbial Fuel Cells (MFCs) have emerged as a compelling technological advancement that utilizes microbial metabolic processes to produce electricity from organic waste substrates. This review examines the latest advancements, prevailing challenges, and prospective developments of MFCs in relation to renewable energy generation and ecological sustainability. MFCs present a dual benefit by facilitating wastewater treatment while concurrently generating bioelectricity, thereby rendering them appealing for decentralized energy frameworks and waste management strategies. Recent progress in the fields of genetic engineering and synthetic biology has culminated in the development of optimized microbial strains and improved biofilm stability, which significantly enhances the efficiency of electron transfer. Innovations in electrode materials, including carbon nanotubes and graphene, have further augmented the performance metrics of these systems. Nevertheless, obstacles persist in augmenting power output, minimizing material costs, and scaling MFCs for larger industrial applications. This review also elucidates the environmental and economic implications of MFCs, particularly their capacity to mitigate carbon emissions and generate financial savings in the domain of wastewater treatment. Lastly, we delineate future research trajectories, concentrating on synthetic biology, hybrid renewable systems, and commercialization strategies that will catalyze the scalability and wider acceptance of MFC technology. The prospects for MFCs are indeed promising, providing innovative solutions to the pressing global challenges of energy production and waste management.
Keywords: Microbial fuel cells, Bioelectricity, Microbial Strain Optimization, Renewable energy, Sustainability

I. INTRODUCTION

The demand for sustainable and renewable energy technologies has reached critical levels as global energy consumption continues to rise, and the environmental impact of fossil fuels becomes untenable, additionally, the global waste management crisis has been exacerbated by rapid urbanization [1]. According to the World Bank, global municipal solid waste generation is expected to reach 3.4 billion tons by 2050, up from 2.01 billion tons in 2016 [2]. Concurrently, wastewater treatment facilities consume about 3-5% of global energy annually, with the U.S. alone using 30 terawatt-hours for wastewater treatment [3]. To tackle these issues microbial fuel cells (MFCs) offer a promising alternative by not only reducing the energy burden of wastewater treatment but also generating electricity in the process. MFCs represent an innovative bioelectrochemical system that exploits the metabolic processes of microorganisms to generate electricity [4]. The core principle of MFCs involves the oxidation of organic substrates by electrochemically active bacteria, which transfer electrons to an anode via extracellular electron transfer (EET) mechanisms [5]. This electron flow proceeds through an external circuit to a cathode, where reduction reactions, typically oxygen reduction occur. The system essentially mimics microbial respiration, but instead of reducing terminal electron acceptors within the cell (such as oxygen), the electrons are harvested to generate electrical current [6]. MFCs address two crucial global challenges simultaneously, energy production and waste management. The dual function of MFCs which is producing electricity from organic waste presents a paradigm shift in energy harvesting, as it allows for energy recovery from wastewater and other organic waste streams. This makes them particularly attractive for applications in decentralized wastewater treatment systems in both developed and developing regions [7].

In recent years, research has focused on improving the efficiency of electron transfer, with advances in electrode materials and microbial engineering significantly boosting power outputs [5]. While the current densities achieved by MFCs still lag behind conventional fuel cells, incremental innovations have raised power generation capacities, with laboratory-scale MFCs achieving up to 5–10 W/m² under optimal conditions [6]. Additionally, various exoelectrogenic bacteria, including *Geobacter sulfurreducens* and *Shewanella oneidensis*, have been identified as key players due to their robust electron transfer capabilities [8].

This review aims to provide an in-depth analysis of recent technological advancements in MFCs, focusing on innovations in microbial strains, biofilm formation, electrode materials, and reactor designs that have improved system efficiency. It will also explore the dual utility of MFCs in both energy generation and environmental remediation. Furthermore, this review will address the key challenges, such as scalability and economic feasibility, that need to be overcome to transition MFCs from laboratory settings to industrial-scale applications. Finally, the future potential of MFCs in the broader context of renewable energy and waste management will be explored, offering insight into how this technology could evolve to play a significant role in the global shift towards sustainable energy solutions.

II. WORKING PRINCIPLE OF MICROBIAL FUEL CELLS

Microbial Fuel Cells (MFCs) are bioelectrochemical devices that generate electricity through the microbial degradation of organic matter. The basic working of an MFC involves a two-chamber system (anodic and cathodic), separated by a proton exchange membrane (PEM) [4]. The anode chamber houses the microorganisms, while the cathode chamber facilitates the reduction reaction [9]. The overall process of MFCs can be broken down into three key steps, (i) Electron Transfer Mechanism, (ii) Anode Reaction, and (iii) Cathode Reaction.

A. Electron Transfer Mechanism

Microorganisms oxidize organic substrates, releasing electrons and protons. The electrons are transferred to the anode through a series of electron transfer processes, either directly by the microbes or through mediators (such as cytochromes or conductive pili). The protons migrate through the proton exchange membrane to the cathode chamber [10].

B. Anode Reaction

The oxidation of organic matter by exoelectrogenic bacteria generates electrons. At the anode, the electrons enter the external circuit to produce a flow of current [11]. The reaction occurring at the anode is articulated by equation (1).

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^- \qquad (1)$$

Here, glucose ($C_6H_{12}O_6$) represents the organic substrate, and the bacteria metabolize it, releasing protons and electrons.

C. Cathode Reaction

At the cathode, the electrons travel through the external circuit and combine with protons (which migrate across the PEM) and oxygen to form water [11]. The typical reaction at the cathode is articulated by equation (2).

$$6O_2 +2\ 4H^+ + 24e^- \rightarrow 12H_2O \qquad (2)$$

This reduction reaction occurs at the cathode, where oxygen serves as the electron acceptor.

D. Proton Exchange Membrane (PEM)

The PEM allows protons (H^+) to pass from the anode chamber to the cathode chamber while blocking the flow of electrons. The separation of protons and electrons creates a potential difference between the anode and cathode, which drives the flow of electrons through the external circuit, generating electricity [12].

E. Type of Microorganisms involved in MFCs

MFCs rely on exoelectrogenic microorganisms, which possess the unique ability to transfer electrons extracellularly to the anode. These microorganisms use various mechanisms, such as direct electron transfer (DET) via conductive pili or mediated electron transfer (MET) using redox-active compounds [13].

F. Key Microorganisms involved in MFCs

1) Geobacter sulfurreducens

Geobacter species use cytochromes, especially the outer membrane cytochrome *OmcS*, to transfer electrons directly to the anode. The conductive pili (also known as nanowires) facilitate this direct electron transfer [14]. This typical reaction can be articulated by equation (3).

$$\text{Acetate } (CH_3COO^-) + 4H_2O \rightarrow 2CO_2 + 7H^+ + 8e^- \qquad (3)$$

2) Shewanella oneidensis

Shewanella species are known for using both direct and mediated electron transfer mechanisms. They can secrete soluble electron shuttles like flavins, which transport electrons from the cells to the anode [15]. This typical reaction can be articulated by equation (4).

$$\text{Lactate } (C_3H_6O_3) + 4H_2O \rightarrow 3CO_2 + 12H^+ + 12e^- \qquad (4)$$

3) Escherichia coli

While not a typical exoelectrogen, *E. coli* can be genetically engineered to enhance electron transfer capabilities. It uses fermentation byproducts that can act as electron donors in the MFC setup [16]. A comparative analysis of various microorganisms, their electron transfer mechanisms, typical substrates, electron donors, and potential power output is elucidated in Table 1.

Table I. Comparative analysis of various microorganisms, their electron transfer mechanisms, typical substrates, electron donors, and potential power output

Microorganism	Electron Transfer Mechanism	Typical Substrate	Electron Donor	Power Output Potential
Geobacter sulfurreducens	Direct (cytochromes, nanowires)	Acetate	Electrons via nanowires	High
Shewanella oneidensis	Mediated (flavins)	Lactate	Electrons via flavins	Moderate
Escherichia coli	Engineered (DET/MET)	Glucose	Fermentation products	Variable (with engineering)

G. Types of electron Transfer Mechanisms

1) Direct Electron Transfer (DET)

In DET, the microbes make direct contact with the anode via conductive pili or nanowires. For example, *Geobacter* species use nanowires that allow direct electron flow from the bacteria to the anode surface [17].

2) Mediated Electron Transfer (MET)

In MET, microbes secrete soluble redox mediators (e.g., flavins, phenazines) that shuttle electrons from the microbial cells to the anode. *Shewanella oneidensis* is a prime example, as it releases flavins that facilitate electron transfer [17].

H. Electron Transfer Equation

The comprehensive reaction governing the oxidation of organic matter and the transference of electrons within microbial fuel cells (MFCs) can be articulated through the equation denoted as (5).

$$\text{Organic Substrate} + H_2O \rightarrow CO_2 + H^+ + e^- \text{ (Anode)} \qquad (5)$$

At the cathode, the relationship can be succinctly encapsulated by the equation (6).

$$O_2 + H^+ + e^- \rightarrow H_2O \text{ (Cathode)} \qquad (6)$$

III. RECENT ADVANCES IN MFC TECHNOLOGY

In recent years, significant advancements have been made to improve the efficiency, scalability, and application potential of Microbial Fuel Cells (MFCs). These breakthroughs, spanning areas such as microbial strain optimization, biofilm enhancement, nanomaterial-based electrodes, and cathode reactions, are helping to address the long-standing limitations of MFCs.

A. Advancement in Microbial Strain Optimization

Advancements in biotechnology, genetic engineering, and synthetic biology have opened new avenues for improving the performance of microorganisms in MFCs. Traditional exoelectrogenic bacteria like Geobacter sulfurreducens and Shewanella oneidensis are now being genetically modified to enhance their electron transfer capabilities and metabolic efficiency [18].

Researchers are focusing on overexpressing key electron transfer proteins such as cytochromes (OmcS in *Geobacter*) or engineering conductive pili to increase the electron flow to the anode [19]. Additionally, synthetic biology approaches have allowed for the creation of microbial consortia, where engineered strains can efficiently degrade complex organic substrates while simultaneously improving electron transfer rates [20]. These modified strains are designed to resist environmental fluctuations, increasing the operational stability of MFCs. Synthetic pathways are being integrated into microbial genomes to optimize energy extraction from diverse waste streams, including agricultural waste, industrial effluents, and even urine [21]. Synthetic biology also allows for the creation of tailor-made strains that can optimize biofilm formation, enhancing electron transport efficiency. According to Do et al., (2020), Escherichia coli has been engineered to express Geobacter's outer membrane cytochromes, significantly improving its electron transfer rates, even under anaerobic conditions [22].

B. Advancement in Biofilm Formation and Stability

Biofilm formation is critical for the efficient operation of MFCs, as it provides a dense network of microorganisms on the anode surface for continuous electron transfer. Recent advancements focus on optimizing biofilm conductivity and stability. Efforts have been made to develop biofilms with high electrical conductivity by incorporating conductive nanomaterials like carbon nanotubes (CNTs) and metal nanoparticles within the biofilm matrix [23]. These additions enhance the internal electron transfer rates across microbial communities, reducing the internal resistance of the MFC. The use of engineered materials like modified carbon fibers, graphene-coated anodes, or hydrogels has promoted more stable biofilm formation. These materials provide greater surface area and enhanced attachment sites for microbial colonization, which leads to better electron transfer efficiency [24]. Additionally, these materials contribute to higher tolerance against environmental stressors like pH shifts and temperature changes. According to Verma et al., (2021), biofilms integrated with CNTs exhibited a 50% increase in conductivity, resulting in a notable boost in the power density of MFCs [25].

C. Advancement in Nanomaterials and Electrode Design

Innovations in nanomaterials have significantly improved MFC efficiency, particularly in anode materials. The anode plays a crucial role in electron capture, and advances in electrode design have focused on materials that increase surface area, conductivity, and microbial affinity [26]. CNTs are being widely explored due to their exceptional conductivity, high surface area, and strong microbial attachment properties. Anodes coated with CNTs have demonstrated significant improvements in current density, as they facilitate more efficient electron transfer from microbes to the electrode surface [27]. Graphene, with its high conductivity and chemical stability, has also been used to design high-performance anodes. The large surface area provided by graphene sheets allows for more microbial attachment and higher rates of electron transfer. Furthermore, graphene's excellent mechanical properties enhance the long-term stability of MFC systems [28].

Conductive polymers like polyaniline (PANI) and polypyrrole (PPy) have shown promise as flexible, cost-effective anode materials. Their conductive nature and easy fabrication allow for scalable solutions in MFCs. These materials can be coated onto metal or carbon substrates to improve electron transfer efficiency and microbial colonization [29]. According to Buldini et al., (2019), graphene-based anodes in MFCs increased power output by 60% compared to traditional carbon cloth anodes, while CNT-enhanced electrodes achieved even higher electron transfer rates [30].

D. Advancement in Enhanced Cathode Reactions

The cathode reaction, typically involving the reduction of oxygen, often limits the overall efficiency of MFCs due to slow kinetics and the high cost of catalysts. Recent innovations have focused on improving cathode materials and reaction efficiency to lower system costs while improving output [31]. Traditional platinum-based catalysts, though highly effective, are expensive. Researchers have been exploring alternatives like transition metal catalysts (e.g., iron, cobalt, and manganese oxides) that can promote oxygen reduction reactions (ORR) at a fraction of the cost. Additionally, carbon-based catalysts doped with nitrogen, sulfur, or phosphorus have been shown to enhance ORR activity [32]. Carbon-based materials, such as carbon cloth and activated carbon, have emerged as sustainable alternatives for cathodes. When functionalized with nitrogen or metal nanoparticles, these cathodes can reduce the overpotential for oxygen reduction, increasing power generation efficiency.

These materials are not only cheaper but also more stable in long-term operations [33]. By improving oxygen diffusion and optimizing the surface properties of cathode materials, researchers have been able to significantly improve cathodic performance. Techniques such as coating cathodes with hydrophilic materials or introducing oxygen carriers can promote faster reduction reactions, thus enhancing the overall output of MFCs [34]. Recent work by Gurikar et al., (2021), using nitrogen-doped carbon cathodes reported a 45% increase in power density and a 30% reduction in material costs, offering a promising alternative to traditional platinum-based systems [35].

IV. APPLICATIONS OF MFCS

Microbial Fuel Cells (MFCs) hold a unique position in the renewable energy sector due to their ability to generate electricity while simultaneously treating waste. Their potential applications span multiple fields, ranging from environmental sustainability to decentralized energy systems.

A. MFCs in Wastewater Treatment

Microbial Fuel Cells (MFCs) offer a dual-purpose solution in wastewater treatment: the removal of contaminants and the simultaneous generation of electricity. MFCs operate by breaking down organic waste in wastewater, reducing chemical oxygen demand (COD) while producing bioelectricity. This makes them an attractive option for both energy recovery and sustainable water management [36]. Traditional wastewater treatment methods are energy-intensive, whereas MFCs leverage microbial activity to generate energy from the organic pollutants present in wastewater. This process can be integrated into existing treatment facilities to offset operational energy costs [37]. In China, a large-scale pilot project demonstrated the potential of MFCs in treating municipal wastewater. The MFC system was able to reduce COD by 85% while generating 0.6 W/m^2 of electricity. Similar pilot plants in the Netherlands and India have shown COD reductions of over 80% with energy recovery, making MFCs a sustainable alternative to traditional treatment methods [38].

B. Remote Power Generation with the help of MFCs

MFCs hold significant potential for small-scale, off-grid energy generation, especially in rural or remote areas where access to conventional energy sources is limited. Organic waste from agriculture, food processing, or even human waste can serve as fuel for MFCs, providing a sustainable energy source for decentralized power generation [39]. In areas without reliable grid electricity, MFCs can be used to power small-scale applications such as lighting, sensors, or low-energy electronic devices. They are particularly useful in remote regions where access to renewable resources (like solar or wind energy) may not be feasible year-round [40].

In Africa, researchers have explored the use of MFCs to provide power for basic needs such as charging mobile phones and lighting in rural communities. A small-scale MFC system utilizing agricultural waste was able to produce enough electricity to power LED lights for several hours a day [41]. MFCs can utilize locally available organic waste resources, reducing the need for expensive fuel transportation. Additionally, they offer a decentralized, low-maintenance solution suitable for regions lacking technical expertise for complex power systems [42].

C. Utilizing MFCs in Biosensors and Environmental Monitoring

MFCs can function as highly sensitive biosensors, detecting and responding to environmental pollutants by generating varying levels of electricity based on changes in their substrate (organic material). This has opened up new possibilities for using MFCs in environmental monitoring and early-warning systems [43].

MFCs can be designed to detect various pollutants in water, such as heavy metals, organic toxins, or nitrogenous compounds. When the concentration of these contaminants changes, it alters the microbial activity in the MFC, causing a measurable shift in electricity generation. This makes MFCs highly effective in monitoring water quality in real time [44]. In wastewater treatment plants, MFCs have been implemented as sensors to monitor the organic load (COD levels) of incoming water streams. This real-time monitoring allows for more responsive and efficient treatment processes [45].

A study from South Korea demonstrated the use of MFCs as biosensors to detect trace amounts of mercury in industrial wastewater. The MFC biosensor showed rapid response times, providing a cost-effective and eco-friendly method for continuous environmental monitoring [46]. MFC biosensors are self-powered, requiring no external energy sources, and their sensitivity to even low concentrations of pollutants makes them highly effective in detecting early signs of contamination [47].

The various applications of Microbial Fuel Cells (MFCs), which represent a significant area of research and technological development, are thoroughly examined and elaborated upon with the inclusion of recent, relevant examples that can be found in the detailed presentation of Table 3.

Table III. Applications of Microbial Fuel Cells (MFCs) with Recent Examples

Application	Description	Recent Examples	Impact/Outcome	References
Wastewater Treatment	MFCs treat wastewater by breaking down organic matter and generating electricity.	Wenling, China (2022): A full-scale MFC-based system treated domestic wastewater while producing electricity.	Generated 0.38 kWh/m³ of wastewater, with a 90% reduction in Chemical Oxygen Demand (COD).	[48]
		Spain (2021): An MFC-treated industrial wastewater from a brewery.	Achieved 70% COD removal and produced bioelectricity, reducing energy costs for wastewater treatment.	[49]
Remote/Off-Grid Power Generation	MFCs can generate electricity in off-grid locations using organic waste as a fuel.	India (2023): MFCs were deployed in rural areas to power small sensors and lighting systems using organic waste.	Provided decentralized power to remote communities, reducing reliance on traditional energy sources.	[50]
		Africa (2022): MFCs provided power to sensors monitoring wildlife habitats.	Enabled real-time data collection without the need for external power sources.	[51]
Biosensors and Environmental Monitoring	MFCs are used as biosensors to detect environmental pollutants and changes in water quality.	USA (2022): MFCs were used to monitor nitrate levels in agricultural runoff.	Detected nitrate concentration changes with high accuracy, enabling real-time monitoring of water quality.	[52]
		Germany (2021): MFCs were used as biosensors in wastewater treatment plants to detect toxic pollutants.	Improved the efficiency of pollutant detection, reducing treatment times and improving water quality.	[53]
Bioremediation of Contaminated Sites	MFCs can be applied to clean up contaminated soils and groundwater while generating electricity.	Japan (2020): MFCs were used in the remediation of soil contaminated with heavy metals.	Achieved successful removal of 60% of lead and other heavy metals while producing small amounts of electricity.	[54]
Desalination and Water Purification	MFCs help in desalinating water and treating saline wastewater.	South Korea (2023): An MFC desalination plant treated brackish water and produced electricity.	Reduced energy consumption by 30% compared to traditional desalination methods.	[55]

V. CURRENT CHALLENGES AND LIMITATIONS OF MFCS

Despite the promising potential of Microbial Fuel Cells (MFCs) for renewable energy generation and waste management, several key challenges and limitations hinder their widespread adoption, as discussed in Table 2.

Table II. Current challenges and limitations of microbial fuel cells that are hindering their widespread adoption

Challenge	Description	Impact	References
Power Output	The power density generated by MFCs is	This limitation restricts MFCs to niche	[56]

	currently low (ranging from 1 to 5 W/m²), making it insufficient for large-scale power generation.	applications, such as small-scale sensors or low-energy devices. The low output is largely due to inefficient electron transfer rates and limitations in microbial activity.	
Cost of Materials	MFCs rely on expensive materials such as proton exchange membranes (PEMs) and catalysts (e.g., platinum for cathode reactions). These components significantly increase the overall system cost.	High material costs make it challenging for MFCs to be cost-competitive with traditional energy technologies, limiting their commercial viability for widespread use. Efforts to develop cheaper alternatives like metal-free catalysts are ongoing.	[45]
Scalability	Scaling MFCs for industrial applications is difficult due to the complexity of microbial communities and the need for large surface areas for electrodes, increasing system size and cost.	Large-scale MFC systems would require extensive infrastructure and optimized microbial management. Current small-scale prototypes show promise, but transitioning to industrial scales faces economic and engineering barriers.	[57]
Long-term Stability and Efficiency	Maintaining consistent microbial activity over time is difficult, with biofilm degradation, microbial community shifts, and reduced efficiency. This leads to declining power generation and increased system maintenance.	Long-term performance can be affected by environmental factors (pH, temperature, nutrient availability), biofilm detachment, or electrode fouling. These issues reduce the reliability and scalability of MFCs for long-term applications.	[58]

Addressing these challenges is crucial for the future scalability and adoption of MFCs in industrial, environmental, and energy sectors. Researchers are actively seeking solutions through advances in materials science, microbial engineering, and system design to overcome these limitations and unlock the full potential of MFC technology.

VI. ENVIRONMENTAL AND ECONOMIC IMPACTS OF MFCS

Microbial Fuel Cells (MFCs) offer a dual-purpose approach to energy production by converting organic waste into electricity while reducing environmental pollutants. This sustainable energy technology has significant environmental and economic implications.

A. Carbon Footprint Reduction by MFCs

Microbial Fuel Cells (MFCs) offer a more sustainable approach to both energy generation and waste treatment compared to conventional methods, leading to a reduction in carbon emissions [59]. Traditional wastewater treatment methods, such as activated sludge systems, are energy-intensive and rely heavily on fossil fuel-based electricity, leading to significant CO_2 emissions. MFCs, on the other hand, generate electricity from organic waste, significantly lowering the carbon footprint by producing renewable bioelectricity. Studies suggest that MFCs could reduce CO_2 emissions by as much as 50% in wastewater treatment facilities by replacing conventional power sources [60].

Unlike anaerobic digestion, which generates methane (a potent greenhouse gas), MFCs do not produce methane as a byproduct. This makes MFCs environmentally favorable, as methane emissions from landfills and traditional biogas plants contribute substantially to global warming [61]. The energy generated by MFCs contributes to the global renewable energy mix, which helps reduce reliance on carbon-intensive energy sources like coal and natural gas. In pilot projects, MFCs have demonstrated the ability to treat wastewater while producing electricity with a fraction of the emissions produced by fossil fuel-powered treatment plants [62].

B. Economic Viability of MFCs

While MFC technology is still in its early stages, it has the potential to deliver significant economic benefits, particularly in sectors like wastewater treatment, remote power generation, and biosensing [63]. Wastewater treatment plants are among the largest energy consumers at the municipal level. MFCs offer an opportunity to offset these energy costs by producing electricity during the waste treatment process. Early studies show that MFCs could reduce operational costs by up to 20-30% by converting organic waste into bioelectricity, reducing both energy costs and sludge production [64].

MFCs can provide decentralized power generation solutions, particularly in rural or off-grid areas where access to conventional energy infrastructure is limited. Utilizing organic waste from agriculture, food processing, or even human waste, MFCs offer a low-cost alternative to expensive grid extensions or diesel generators [65]. Despite the current high cost of materials, ongoing research, and technological advancements, such as the use of cheaper catalysts and scalable designs, are gradually lowering the overall cost of MFC systems. The global market for MFCs is expected to grow as the technology matures and becomes more competitive with other renewable energy sources. The long-term economic viability of MFCs will likely depend on improvements in power output, material costs, and the ability to scale systems efficiently [66].

As the global push toward sustainable development increases, the market for renewable energy technologies, including MFCs, is expanding. The integration of MFCs into wastewater treatment plants, particularly in regions with high waste production and energy demand, could provide a cost-effective solution for meeting both energy and environmental targets [67]. Economic feasibility could be further enhanced with the support of government policies and incentives promoting renewable energy adoption and green waste management. Carbon credits, subsidies for clean energy projects, and R&D grants could make MFC projects more financially attractive [68].

VII. FUTURE PROSPECTS OF MFCS

Microbial Fuel Cells (MFCs) have shown significant potential in renewable energy and environmental sustainability. As research and development efforts continue, several prospects for MFCs are emerging, paving the way for enhanced energy generation, broader applications, and more efficient systems.

A. Synthetic Biology and Metabolic Engineering techniques for upgrading MFCs

Advances in synthetic biology and metabolic engineering hold significant potential for enhancing the efficiency and scalability of Microbial Fuel Cells (MFCs). Researchers are increasingly focused on engineering microorganisms with improved electron transfer capabilities and higher power outputs [69]. Synthetic biology allows for the customization of microbial metabolic pathways to improve electron transfer rates. For example, researchers are working on genetically modifying *Geobacter* and *Shewanella* species, key exoelectrogenic microorganisms, to increase their electron transfer capabilities. Synthetic biology could enable the creation of designer microbes that are more resilient, stable, and efficient in electricity generation [70].

By tweaking the metabolic pathways in these microorganisms, it is possible to optimize energy extraction from organic substrates. Techniques like CRISPR and other gene-editing tools are being explored to develop strains with enhanced biofilm formation, increased tolerance to harsh conditions, and better substrate utilization, leading to more efficient MFCs [42]. Another promising direction is engineering microbial consortia, where different species work together in a symbiotic relationship to maximize power generation. This approach can potentially overcome the limitations of single-species systems by combining the strengths of various microorganisms [71].

B. Integrating Hybrid Systems with MFCs

Integrating MFCs with other renewable energy technologies offers a promising pathway for improving efficiency and expanding the range of applications [72]. Combining MFCs with solar panels could allow for continuous power generation. During the day, solar energy can be harnessed to power systems, while MFCs can take over at night or during low-light conditions, using waste biomass or wastewater as a substrate for energy production [73]. In areas with access to wind energy, MFCs could provide a complementary energy source. Wind turbines can supply large amounts of energy during high-wind periods, while MFCs can offer a steady, low-power supply during periods of low wind or energy demand. Such hybrid systems can stabilize energy output, making them more reliable and economically feasible for off-grid and rural applications [74].

Pairing MFCs with battery storage technologies could help address one of the core limitations of MFCs, low power density. In this hybrid setup, MFC-generated electricity could be stored for later use, helping to smooth out fluctuations in power supply and meet real-time energy demands more effectively [75].

C. Scalability and Commercialization of MFCs

Scaling up MFC technology for commercial applications is critical for its broader adoption. Significant progress has been made in pilot projects, but several challenges remain [5]. Pilot projects worldwide are exploring the potential for scaling up MFCs for applications like wastewater treatment and decentralized power generation. For instance, some wastewater treatment facilities have successfully integrated MFCs to partially offset their energy costs, showcasing the technology’s real-world potential [76].

Ongoing research focuses on reducing the cost of key components like electrodes and proton exchange membranes (PEMs). Cheaper alternatives to expensive materials like platinum and Nafion are being explored, including graphene-based anodes, conductive polymers, and metal-free catalysts. These innovations are essential for making MFCs economically viable on a large scale [77]. To make MFCs commercially feasible, future research must address several challenges, including improving long-term stability, increasing power density, and reducing costs. Researchers are investigating the use of advanced materials for better biofilm adhesion, enhancing microbial stability, and optimizing reactor configurations for industrial-scale applications [78].

Government policies promoting clean energy and waste management could accelerate the commercialization of MFCs. Carbon credits, subsidies, and public-private partnerships for renewable energy projects can incentivize investment and help MFCs gain a foothold in the market [79].

VIII. CONCLUSION

Microbial Fuel Cells (MFCs) represent a revolutionary technology at the intersection of sustainable energy production and waste management. By leveraging the natural metabolic processes of microorganisms to convert organic waste into electricity, MFCs offer a dual benefit: renewable energy generation and environmental remediation. This review has explored the fundamental workings of MFCs, highlighted key advancements in microbial strain optimization, biofilm stability, and electrode materials, and discussed real-world applications such as wastewater treatment, remote power generation, and biosensors.

Despite significant progress, MFCs face challenges such as low power density, high material costs, scalability issues, and long-term stability. However, with ongoing advancements in synthetic biology, nanotechnology, and hybrid energy systems, MFCs hold immense potential for commercialization. Future research must focus on improving the efficiency and economic viability of MFCs, while policy support and market incentives can further accelerate their adoption.

As global efforts to reduce carbon emissions and promote renewable energy intensify, MFCs offer a promising solution for addressing both energy and environmental challenges. By turning waste into watts, MFCs represent an innovative and sustainable pathway toward a cleaner, greener future.

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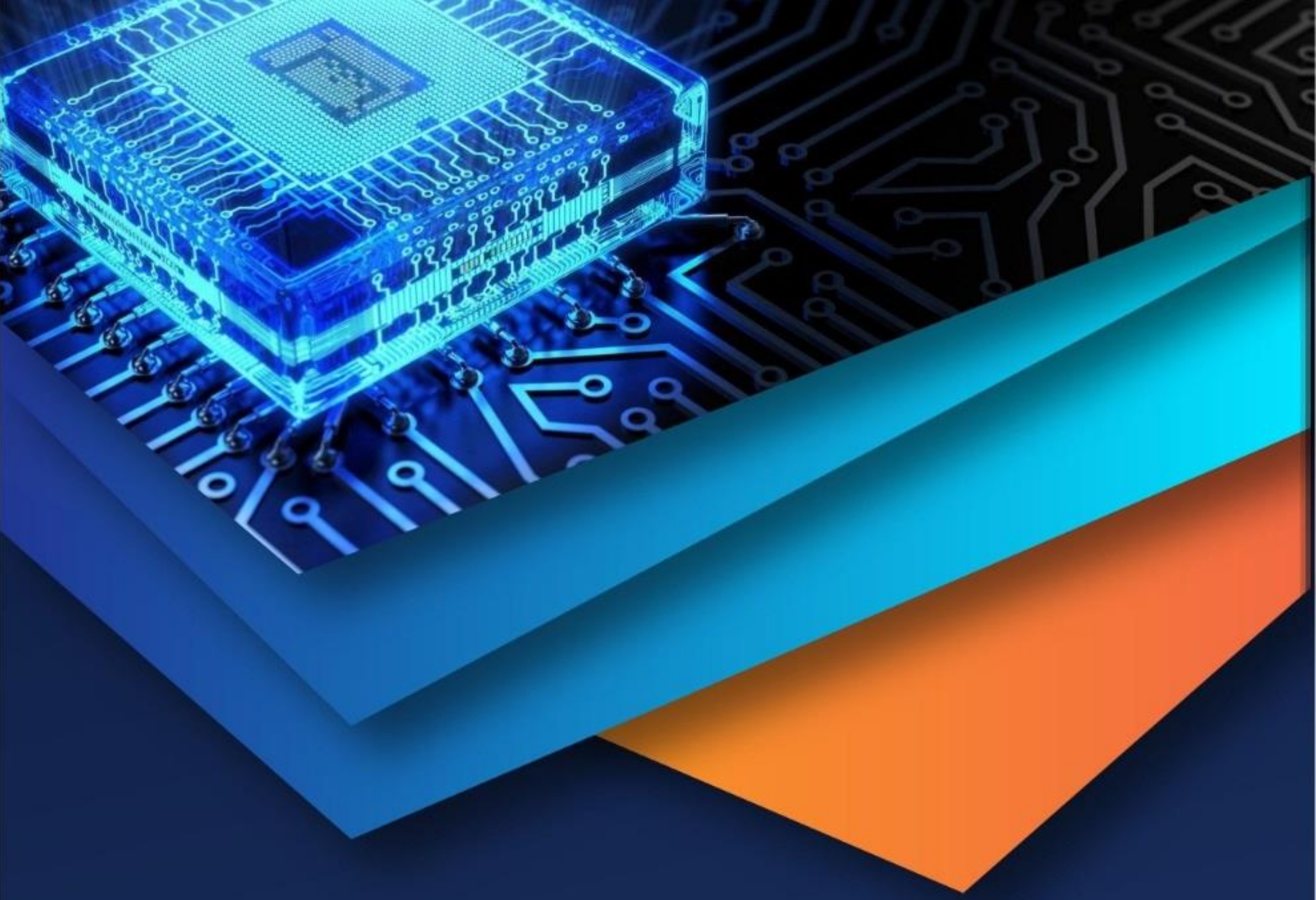

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