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Electrode Surface Modification Strategies for Enhanced Performance of Two-Chambered Microbial Fuel Cell: A Minireview

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ABSTRACT
Various advancements in microbial fuel cells (MFCs) have been proposed due to its sustainable method for the treatment of wastewater along with bioelectricity production. That has resulted in tremendous progress toward reducing global demand for energy and environmental problems caused by fossil fuel consumption. One of the key MFC input material that is considered as a main concern is electrode materials. They are critical for the performance of double-chambered microbial fuel cells (DC-MFC) and many other configurations. The aim of this paper is to discuss the effect of various electrode modifications on the efficiency of DC-MFCs. The principles of DC-MFC including anodic oxidation of substrate, reduction of oxygen in cathode chamber and proton exchange membrane mechanism were considered due to their importance in understanding strategies to optimize MFC performance. Different anode materials were modified to enhance biofilm formation, electron transfer kinetics as well as functionalization of electrode surfaces with conductive polymers, metal oxides, graphene derivatives and nanocomposite. Power and current densities were improved as well as significant reduction in chemical oxygen demand (COD) which showed pollutant removal capacity. This review also emphasizes scaling up of MFC involved considering surface area of electrode, biocompatibility, stability and cost effectiveness.

Keywords: Microbial Fuel Cell, Double-Chambered MFC, Anode electrode modification, Wastewater treatment

INTRODUCTION

Energy crisis and environmental contamination are two major problems ravaging economy particularly in developing countries (Ramesh *et al.*, 2025). Over utilization of fossil fuels is rapidly depleting it due to global competition for the resources. Solid and gas pollutant became rampant as a result of fossil fuels usage which adversely contribute to environmental pollution. Due to such challenges, the focus is now on developing alternative strategies particularly renewable energy to replace the conventional ones (Nosek *et al.*, 2020). Microbial fuel cell (MFC) is an electrochemical device that harnesses the chemical energy present in organic matter into electrical energy through microbial metabolic processes (Haruna *et al.*, 2024). MFC generate the electrical energy as biocatalyst feeds on the available substrate thereby treating the waste and other hazardous substances concurrently (Salisu *et al.*, 2023). MFC have emerged as area of research with particular interest in many sectors such as energy and environment due to potential in sustainability attributed by its high efficiency, low consumption of energy and protection of environment (Roy *et al.*, 2023). MFC research has reach advanced level recently but issues such low power output, high cost of construction materials and unstable operation limits its scale up. The elements that have great impact on MFC performance include microorganisms, electrodes and space between them, proton exchange membrane (PEM), substrate concentration, and external and internal resistance (Xia *et al.*, 2021). The most significant among all is electrodes which determine the cost and performance of the MFC. Electrode material and its design is the biggest hurdle to making MFC successful and scalable (Liu *et al.*, 2020).

Many researchers have shown interest on improving MFC performance through testing different material as electrode, shaping it to have various configurations (Pant *et al.*, 2010). In recent decades a large number of electrodes have been explored. Bacteria are employed as catalysts which transfer electrons to the surface of the electrode, these electrodes can be broadly categorized into two; chemical electrode (air cathode and aqueous air cathode) and bioelectrodes (anode and biocathode) (Ramesh *et al.*, 2025). Electrode materials employed in MFC have general and variable properties. They should be cheap, durable, have good electrical conductivity and chemical stability (Yaqoob *et al.*, 2020). Carbon and non-corrosive metals are the most used electrode that possesses afore mentioned general properties (Hussain *et al.*, 2022). Among various electrodes available each has certain requirements. To have excellent bio-catalytic properties, electrodes need to have high surface roughness, biocompatibility and smooth flow of electrons from bacteria to electrode surface. Bio-electrodes functions as conductor and attachment surface for bacteria (Roy *et al.*, 2023). Modification of electrode to improve bacterial adhesion and electron conductivity has become area of interest in MFC research (Gholami-Kermanshahi *et al.*, 2025). Air-cathode is made up of base material, binder, waterproof cover and catalyst, each of which has its unique properties and function. The base material serves as supporting material and current collector (Dakal *et al.*, 2025).

To prevent water loss in air-cathodes, hydrophobic coatings are attached and immobilization of catalyst on the substrate is conducted sometimes with binder (Santoro *et al.,* 2017). Activated carbon have been developed and used as air-cathode as it doesn't require catalyst which drastically lowers the cost of MFC (Santoro *et al.,* 2015). For aqueous air-cathode it requires base material, catalyst and binders. How electrodes are developed and basically arranged is a major concern affecting the performance and scalability of MFCs (Ramesh *et al.,* 2025). Based on this arrangement, electrodes are categorized into plane and three dimensional electrodes. An ideal bio-electrode configuration should be good current collector and provide a wide surface area for bacterial attachment (Xu *et al.,* 2025). Plane electrodes are mostly employed in air electrodes. Special configuration is required when air electrode contain a chemical catalyst in order to enable reduction of oxygen in reaction involving the catalyst, air and water (Xia *et al*., 2021). The purpose of this review is to examine how electrode modification affects the performance of two-chambered microbial fuel cell.

Fundamentals of Double-Chambered Microbial Fuel Cells (DC-MFCs)

A DC-MFC has two compartments known as anode and cathode separated by PEM or a salt bridge (Chakma *et al.,* 2025). The anode chamber operate anaerobically to prevent oxygen to acts as electron acceptor, electrogenic bacteria in this chamber decompose the available organic matter yielding CO_2, protons (H^+) and electrons (e^-). The PEM serve as a medium through which protons are transferred to cathode chamber while electrons are collected by the electrode material and move via external circuit to the cathode thereby generating an electrical current (Hindatu *et al*, 2017a; Borja-Maldonado & López Zavala, 2024). Water is formed in the cathode chamber due to reaction between electrons, protons and atmospheric oxygen which serves as electron acceptor (Santoro *et al*., 2017). The performance of MFC deeply depends on microbial population and electrode materials. Many research showed that mixed cultures yield higher current than pure cultures (Elangovan *et al.,* 2023).

MFC offer dual benefits as the waste are been removed, bioelectricity are generated through biochemical activities of the microorganisms (Hindatu *et al.,* 2017b). In the anode chamber microbes act as biocatalyst oxidizing different organic substrate such as acetate, glucose and wastewater. Oxidation of these substrate by the microbes releases CO_2 as byproduct which breaks down the chemical bonds in organic matter releasing free electrons (e-) and protons (H+) (Pant *et al.,* 2010). The anodic reaction in MFC utilizing glucose as substrate is shown in equation 1, whereas equation 2 demonstrates reduction reaction of an electron with atmospheric oxygen in cathode chamber (Inamuddin *et al.,* 2021). As the protons liberate to cathode chamber through PEM and electrons via an external circuit water is formed (Dileep *et al.,* 2023). Cathode chamber can use other materials such hexacyanoferrate or permanganate as acceptor apart from oxygen (Dakal *et al.,* 2025). The entire anodic and cathodic reactions are what lead to generation of useful electrical current and degradation of organic matter into CO_2 and water (Roy *et al.,* 2023).

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

$$O_2+4e^-+4H^+\rightarrow 2H_2O \quad (2)$$

The PEM partitioned the cathode and anode compartments in a DC-MFC. Protons released during oxidation of organic matter in the anode chamber are selectively transferred to the cathode through the PEM (Inamuddin *et al.,* 2021). Only anaerobic condition is required by electrogenic microbes to transfer electrons to anode electrode, the PEM prevent oxygen from crossing aerobic cathode to anode chamber. Therefore, the versatility of PEM is beyond proton transfer (Ramesh *et al.,* 2025). Crossover of substrate and other substances are significantly reduced by membrane which could have reduced the efficiency of the MFC system by preventing the flow of electrons between the electrodes (Pant *et al.,* 2010). Nafion is the most commonly PEM because of its high proton conductivity and low internal resistance but selecting right membrane is essential particularly when exploring other membranes due to their impact on overall power output and internal resistance of the cell (Yaqoob *et al.,* 2020).

MATERIALS AND METHODS

Electrode Materials Used in Microbial Fuel Cells

The main types of electrode material used in MFC include anode, cathode and filler materials. Appropriate electrode most be employed for MFC to function effectively in term of microbial attachment, electron transfer and electrochemical efficiency (Ramesh *et al.,* 2025). Many carbon based materials such as carbon paper, carbon felt, carbon fiber and composites base like carbon nanotubes have been used aiming to boost production of electricity (Hindatu *et al.,* 2017b). Real application of MFC technology requires increase in power output and decrease in material costs. Material used as cathode should have catalytic properties to enable reduction of oxygen (Nosek *et al*., 2020). Anode and cathode have different characteristics requirement but they possesses the following general characteristics:

Surface Area:

One of the important factors affecting power output in MFC is electrode surface area. The ohmic losses emanate in MFC as a result of electrode resistance. MFC efficiency can be enhanced and resistance be reduced by increasing electrode's surface area while maintaining the same volume. Electrode kinetics can be increased due to increase in surface area offering more reaction sites (Santoro *et al.,* 2015).

Electrical Conductivity:

The electrons released by electrogenic microbes pass through anode electrode to the external circuit. The materials that possesses excellent electrical conductivity lowers electron flow resistance. Interfacial impedance has to be low to enable electron transfer enhancement. The cathode should also have good ionic conductivity to enhance the triple phase boundary reaction (Jafary *et al.,* 2026).

Stability and Durability:

The anode and cathode materials may be degraded due to oxidation and reduction reaction in anode and cathode compartments of the cell. The electrode can be made more durable by roughing their surfaces, but could be prone to fouling which drastically reduce the long term performance of the cell. The electrodes need to be fabricated to withstand both acidic and alkaline environment and last long as well (Roy *et al.,* 2023).

Cost and Accessibility:

Most electrode materials are expensive which affect the capital cost of the MFCs. To make MFC viable for commercial purposes, the materials need to be readily available, inexpensive and sustainable. Platinum and many other metals are good electrode material but are very costly and don't last long. Non-expensive metals and composites have been used in place of precious metals in electrodes (Hosain *et al.,* 2025). Biocompatibility is another crucial aspect to enhance bacterial attachment to the surface of electrode thereby increasing its lifespan.

The Anode Material

The formation of biofilms and transfer of electrons from microbes to the electrodes depend on the anode material used. A number of materials have been used as anodes in MFC such as graphite rods and brushes, carbon cloth, carbon paper, carbon felt, and reticulated vitreous carbon because of their excellent electrical conductivity, high surface area, low cost, biocompatibility and chemical stability (Yaqoob *et al.,* 2020). A wide variety of anode materials used in MFC are listed in Table 1 along with their advantage and disadvantages. Allotropes of carbon such as carbon nanotubes (CNTs) have shown to be potential replacement for wide range of electrodes materials because of their outstanding electrical conductivity, catalytic qualities, biocompatibility and high surface area (Yu *et al.,* 2021; Hindatu *et al.*, 2017a). Ohmic resistance can be maintain at very low level by grafting CNTs on stainless steel mesh. The space between CNTs accommodate quite number of microbes. The least amount of amorphous carbon provides the highest charge interaction. In an attempt to fabricate highly conductive anode with large surface area, Choudhury *et al*. (2017) grafted CNTs on carbon cloth, they found an increase in maximum pore density by 250%.

Table 1: Different Materials used for MFC Anode with Their Advantage and Limitations

Anode material	Advantage	Disadvantage	Reference
Stainless steel	High conductivity, relatively cheaper, easy accessibility.	Low surface area, biocompatibility issues, corrosion.	(Pant *et al.*, 2011)
Graphite rod	High conductivity and chemical stability, relatively cheaper, easy accessibility.	Difficult to increase surface area.	(Nosek *et al.*, 2020)
Graphite fiber brush	High specific area and easy construction	Clogging	(Wei *et al.*, 2011)
Carbon cloth	Large relative porosity	Relatively expensive	(Savla *et al.*, 2020)
Carbon paper	Easy wire connection	fragile	(Mahalingam *et al.*, 2021)
Carbon felt	Large surface area	High resistance	(Dumitru & Scott, 2016)

RESULTS AND DISCUSSION

Surface Functionalization of Anodes

Carbon based materials such as pencil graphite electrodes (PGE), carbon cloth (CC), and carbon felt (CF) are some of the most widely used anodes in MFC due to their good electrical conductivity, biocompatibility as well as chemical stability. Surface reactivity restriction and hydrophobicity nature of these materials prevent biofilms development and slow down the kinetics of electron transfer (Gholami-Kermanshahi *et al.,* 2025; Tesfaye *et al.,* 2025). Transition metal oxides (TMOs) and conductive polymers have been extensively used by researchers to modify these electrode materials to get rid of restrictions problem (Eyoel *et al.,* 2025; Tesfaye *et al.,* 2025). In the study conducted by Eyoel *et al.* (2025), they used polyaniline-cobalt oxide (PANI-Co_3O_4) nanocomposite to modify surface of PGE. A maximum power density of 413.07 mW/m² and a current density of 2429.56 mA/m² were achieved which is higher than bare PGE by 6.78 times. In another study, the power density produced by PANI-coated Fe_3O_4 nanocomposite on a PGE was 424.51 mW/m² which is superior to unmodified graphite by 6 times (Tesfaye *et al.,* 2025). The increased in performance of these electrode was due to impact of high redox activity of the metal oxide nanoparticle which make more active sites available and drastically lower internal resistance (Eyoel *et al.,* 2025). Waste-derived materials have been combined with graphene derivatives to enhance MFC performance. Mkilima *et al.* (2025) used graphene-coated carbon cloth anodes in DC-MFC, they achieved 93.6% increase in power density from 405.6 mW/m² to 785.3 mW/m² and about 37.5% decrease in internal resistance. They also achieved a COD removal efficiency of 85.4%, along with the degradation of some drugs used as substrate such as acetaminophen (83.2%) and tetracycline (81.7%), as well as a nitrate removal rate of 83.2%. Enset corm-derived reduced graphene oxide (E-rGO) was used in combination with Fe_3O_4 to achieve cost-effectiveness. The power density of 39.77 mW/m² and a current density of 1171 mA/m² were achieved which is far better than when only E-rGO was used (Weldegrum *et al.,* 2025). Using the E-rGO/Fe_3O_4 composite as anode electrode, the efficiency of remediation of Cr (VI) and Pb (II) are 79.2% and 73.8% respectively.

Another novel modification approach was conducted by Włodarczyk & Włodarczyk, (2025), they coated the electrode with activated coconut carbon (ACC). The modified electrode produced a power density of 26 mW/m² which is higher than the electrode coated with only carbon paint (10 mW/m²). Singh *et al.* (2025) have conducted mechanical reinforcement technique by encircling a carbon veil with a woven carbon sleeve. The power generated with modified electrode (527.7 mW) tripled unmodified electrode (175.5 mW) and the long term structural integrity of the electrode was maintain for many months of operation. In an attempt to treat industrial wastewater with modified electrodes, Mumtaz *et al.* (2024) have used PANI-modified nickel foam (PANI@NF) anode for treatment of wastewater from leather tanneries, they achieved COD reduction by 80% and power density of 279.3 mW/m². According to this finding, the modification improves the bioelectrochemical performance of the cell which make it ideal way for deep treatment and energy recovery of complicated industrial and municipal wastewater. Nickel foam (Ni-foam) have a high electrical conductivity and its three dimensional open cellular structure make it to have large surface area for bacterial adhesion. Ni-foam has become excellent metallic substrate that outperforms conventional carbon materials (Gholami-Kermanshahi *et al.,* 2025). Ni-foams are hydrophobic in nature but research showed they can be made superhydrophilic by acid etching for 1 hour (Gholami-Kermanshahi *et al.,* 2025). The acid etched Ni-foam electrode yields a maximum power density of 708.0 mW/m^2, which is 3.8 times greater than that of unmodified Ni-foam electrodes. Gholami-Kermanshahi *et al.* (2024) also modified Ni-foam electrode by adding Ni–N and NH_3 functional groups which enhance bacterial attachment to the surface via N_2 plasma modification for 1 hour. The power density attained 247.1 mW/m² surpassing Ni rods (5.1 mW/m²) and graphite rods (29.5 mW/m²).

Graphene derivatives and specialized polymers are excellent substances used in electrode modification. Graphene coated carbon fabric anodes made by chemical vapor deposition can reduce internal resistance by 37.5% and enhance power density by 93.6%, to 785.3 mW/m² (Mkilima *et al.,* 2025). Hydrophilic treated graphene (HTG) plates was used by Borja-Maldonado & López Zavala, (2024) in medium size MFC reactor generating a power density of 32.05 mW/m² higher than that of control used by 32 times. The polyaniline nanofibers (PANInf) graphene electrode generate a power density of 1091 ± 5% mW/m² and a current density of 0.87 mA/cm² thereby producing a three-dimensional network that enhance electrostatic interactions between biocatalyst and electrode surface for efficient transfer of electrons (Ahmed & Kim, 2024). These changes give electroactive bacteria like *Shewanella* and *Geobacter* a more hospitable microenvironment, which improves substrate oxidation and speeds up electron transfer kinetics (Ahmed & Kim, 2024; Mkilima *et al.*, 2025). Upon modification of many non-conventional anode materials a significant efficacy in the treatment of particular harmful pollutants and wastewater treatment was observed (Singh *et al.*, 2025). These various modification techniques highlight how crucial it is to maximize the electrode-biofilm interface in order to accomplish both deep treatments of industrial wastewater and effective energy recovery at the same time (Gholami-Kermanshahi *et al.*, 2025; Mkilima *et al.*, 2025). The compiled results from the sources are shown in the following table.

Table 2: Summary of MFC Performance after Modification of the Anode Electrode

Microorganism Used	Carbon Source	Anode Material	Material for Anode Modification	Performance	Reference
Aeromonas hydrophila	LB broth	Nickel (Ni) foam	Acid etching (60 min)	708.0 mW/m^2	(Gholami-Kermanshahi *et al.*, 2025)
Aerobic sludge (mixed culture)	Acetate	Carbon cloth	Polyaniline nanofibers (PANInf)	1091 ± 5% mW/m^2; 0.87 mA/cm^2	(Ahmed & Kim, 2024)
Mixed consortium	Domestic wastewater	Hydrophilic-treated graphene (HTG)	Hydrophilic treatment / Surface sanding	32.05 mW/m^2; 69.8% COD removal	(Borja-Maldonado & López Zavala, 2024)
Aeromonas hydrophila	LB broth	Nickel (Ni) foam	N2 plasma modification (60 min)	247.1 mW/m^2	(Gholami-Kermanshahi *et al.*, 2024)
Raw activated sludge	Acetate, Tryptone, & Yeast extract	Carbon veil	Woven carbon sleeve reinforcement (wrapping)	527.7 mW max power (3-fold increase); improved biofilm retention	(Singh *et al.*, 2025)
Mixed culture	Molasses decoction (MDYP)	Glass plate + Carbon paint (CP)	Activated coconut carbon (ACC) grains	26 mW/m^2; 26.5% average COD reduction	(Włodarczyk & Włodarczyk, 2025)
Mixed sludge inoculum	Leather tannery wastewater	Nickel foam (NF) or Carbon felt (CF)	Polyaniline (PANI) in-situ deposition	279.3 mW/m^2 (with NF); 581.8 mA/m2; 80% COD reduction	(Mumtaz *et al.*, 2024)
Geobacter and *Shewanella*	Municipal & Pharma wastewater	Carbon cloth	Graphene coating (Chemical Vapor Deposition)	785.3 mW/m^2 (93.6% increase); 85.4% COD removal; 83.2% Nitrate removal	(Mkilima *et al.*, 2025)
Escherichia coli	Glucose	Pencil graphite electrode (PGE)	Biosynthesized Iron oxide (Fe_3O_4)/PANI nanocomposite	424.51 ± 6.86 mW/m^2; 2475.01 ± 1.23 mA/m^2; 645 mV OCV	(Tesfaye *et al.*, 2025)
Mixed culture (pond wastewater)	Sweet potato waste	Graphite rod	Enset corm biosynthetic reduced graphene oxide (E-rGO)/Fe_3O_4	39.77 mW/m^2; 1171 mA/m^2; 79.2% Cr (VI) & 73.8% Pb (II) removal	(Weldegrum *et al.*, 2025)

CONCLUSION

Electrode modification is an excellent strategy to enhance performance of DC-MFCs. This review showed that the efficiency of different anodes has been enhanced through functionalization, incorporation of nanocomposite, conductive polymer grafting, addition of graphene derivatives and treatment with metallic substrate. This enhancement was possible due to increased bacterial adhesion to electrode surface, electron transfer efficiency and other electrochemical activity. The modifications yield high power and current densities, reduction in internal resistance and wastewater treatment through COD removal. Despite these developments the issue of durability, material cost and scaling up hindrance still exist. Future research for optimizing anode electrodes should put more emphasis on developing low cost, environmentally friendly and long lasting materials.

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