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Eco-friendly fabrication principles of microbial fuel cells using nanotechnology principles for the sustainable energy production-A review

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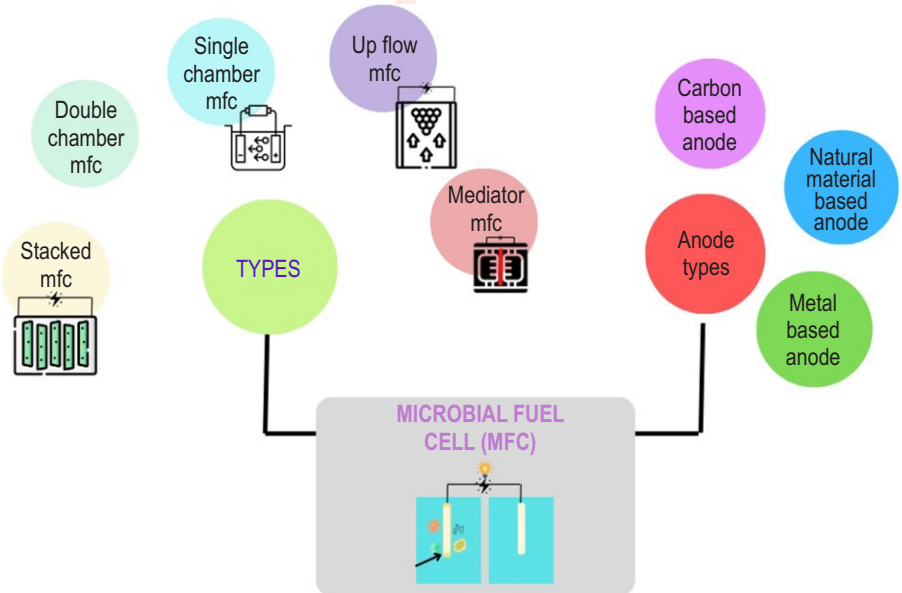
Abstract

A promising environmentally friendly bioenergy device called a microbial fuel cell (MFC) uses bacterial biofilms as biocatalysts to convert organic matter into power.Because MFCs provide potentially new prospects for sustainable energy production from biodegradable and reusable waste materials, their design and use have drawn significant attention. However, novel fabrication methods should be needed for an effective functioning of Microbial fuel cell. The present study explores the concepts of nanotechnology principles for MFC fabrication which can be used to enhance the performance of MFC. The integration of nanotechnology principles into MFC fabrication offers exciting prospects for advancing sustainable energy and environmental technologies. Methods for improving MFC performance by altering the conventional fabrication techniques of the components for rapid transfer of electrons, improved conductivity, corrosion resistance, biofilm adhesion and biocompatibility with nanotechnology principles has discussed.

Role of nanomaterials like nanoparticles, nano tubes and nanocomposites mainly polymeric nanocomposites in fabrication technology explored clearly. A further study will help in addressing the main challenge in scaling up MFCs, which is the external energy required to begin the circuit to extract energy and investigating the long-term impact of nanocomposite-based MFCs on ecosystems.Continued research and innovation in this field are essential for realizing the full potential of nanomaterial-based MFCs in practical applications.

Key words: Fabrication, Microbial fuel cells, Nanocomposites, Sustainable energy



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Introduction

Renewable energy has grown to be a significant component of the existing energy system and a key area for energy growth. Wind and solar energy are prime examples of renewable energy sources that have seen extensive development and widespread use. Clean, renewable energy has grown to be a significant component of the existing energy system and a key area for energy growth.The limitation on energy transmission has made energy the primary utility (Xiong and Zhang, 2017). Despite the widespread development and application of sustainable energy sources in order to accomplish effective environmental preservation and sustainable economic development, more work needs to be done in the development of renewable energy alternatives (Wang *et al.,* 2022). Experiments from literature offered a novel method of using high-value metal. In actuality, there are number of advantages to employing fuel cells as opposed to alternative energy sources, including the elimination of all emissions of gases that pollute the environment, such as CO, CO_2, NO and SO increased efficiency, and the lack of mobile parts, which reduces noise pollution (Al-Zaidi *et al.,* 2021).

It is evident that hydrogen and fuel cells can meet the growing demands of society and provide a workable answer for most energy-related areas (Lixin Fan *et al.,* 2021). Fuel cells, also known as electrochemical energy converters, are known for their high efficiency and low emissions of pollutants. They convert chemical energy into heat and electricity. Each FC cell is made up of two electrodes: anode, which is used for fuel oxidation, and cathode, used for oxidant reduction. An electrolyte that can conduct ions but not electrons separate the electrodes (Alberto Coralli *et al.,* 2018). There are various combinations of oxidant and fuel that can be employed. Air, chlorine, or chlorine dioxide might be the oxidants, while the fuel could be either methanol or diesel. In contrast, the majority of contemporary fuel cells are made of hydrogen and oxygen (Al-Zaidi *et al.,* 2021) (Fig. 1). This state-of-the-art assessment concentrates on current initiatives to create environmentally friendly nanomaterials for fuel cell components, particularly electrolyte membranes and electrodes. Additionally, the green methods for developing fuel cell materials are explained. The principles, characteristics, and importance of developing green nanomaterials for fuel electrolytes and cell electrodes are also explained (Kausar *et al.,* 2023).

Coatings that boost these materials conductivity or the capacity of microorganisms to stick to them, such as polyaniline-coated carbon felt, can be added to make them even better. Green polymers, nanomaterials, and green production techniques have been used in the design of fuel cell electrodes, catalysts, membranes, and other components. The fuel cell component's performance has increased with the use of innovative nanomaterials. In this sense, simple physical and chemical methods have been used to create polymeric materials and nanocomposites. There have been attempts to generate power utilizing traditional fuel cell techniques as well as renewable energy sources (Fadzli *et al.,* 2021).

Microbial fuel cell are an example of a bio-electrochemical process that uses electrons from bacterially catalyzed metabolic reactions to create electricity. A proton exchange membrane separates the cathodic and anodic chambers of a typical microbial fuel cell (Naha *et al.,* 2023). There are two types of microbial fuel cell: mediator and mediatorless. Microbes lacking active surface proteins that aid in electron transport to the anode electrode are found in mediator type microbial fuel cell. This type of bio-electrochemical fuel cell called a microbial fuel cell needs live bacteria to operate as a biocatalyst for the production of bioenergy in anodic chambers (Fadzli *et al.,* 2021). Use of microbial fuel cell for energy preservation and storage has been in use for a long period of time. The ability of the microbial fuel cell to create energy allowed it to quickly progress from an ecologically beneficial electrical device to a sustainable system (Fig. 2). An anode and a cathode electrode, which are typically separated by a proton exchange membrane and connected by a conductive wire, are needed for the microbial fuel cell to generate electrical current (Boas *et al.,* 2022).

The ability of electroactive bacteria, often referred to as exo electrogens, to transfer electrons extracellularly and directly to conductive materials without the need for mediators through anodic respiration is essential of Direct electron transfer mechanism (Mahmoud *et al.,* 2022). DET is not just found in bacteria; a variety of other microorganisms have also been identified as possible exo-electrogenic according to evidence of DET mechanism. The amount of electricity that may be produced by an MFC is limited by the problem of over-potentials, which prevent electron transfer from bacteria to the electrode and hence, lower the electric potential across microbial fuel cell. The electrical resistances of the electrodes, membranes, and electrolytes are also among these variables (Poon *et al.,* 2016).

With the use of external electrical current, it transfers electrons from reduced molecules created by microbial oxidation on the anode to oxidized compounds, such as oxygen on the cathode, to create an electric current. The search for an alternative clean and green energy technologies to meet the world's energy needs is becoming increasingly difficult given the rise in greenhouse gas emissions and socio-economic instability. The performance of microbial fuel cell depends on a number of variables, including the organic substrate, cathode, anode, and permeable exchange membrane. The performance of anodes and the reactions and interactions that occur therein are among the most crucial of all the components (Yaqoob *et al.,* 2021). The biggest obstacle is the organic substrate. Because the organic substrate did not give the bacterial population enough power, resulting in poor microbial fuel cell output, the lesser stability of the substrate may have affected remediation efficiency and energy generation. Future studies should focus on the long-term durability of organic substrates in microbial fuel cell for industrial use. The literature review indicates that no comparable data on the interaction of electrode-bacteria and electrode effect in the presence of various organic substrates in MFC is currently available (Fadzli *et al.,* 2021).

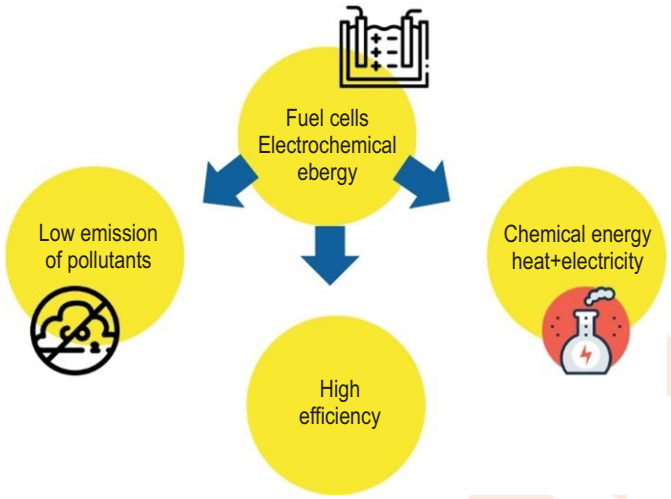

Fig.1: Features of fuel cells.

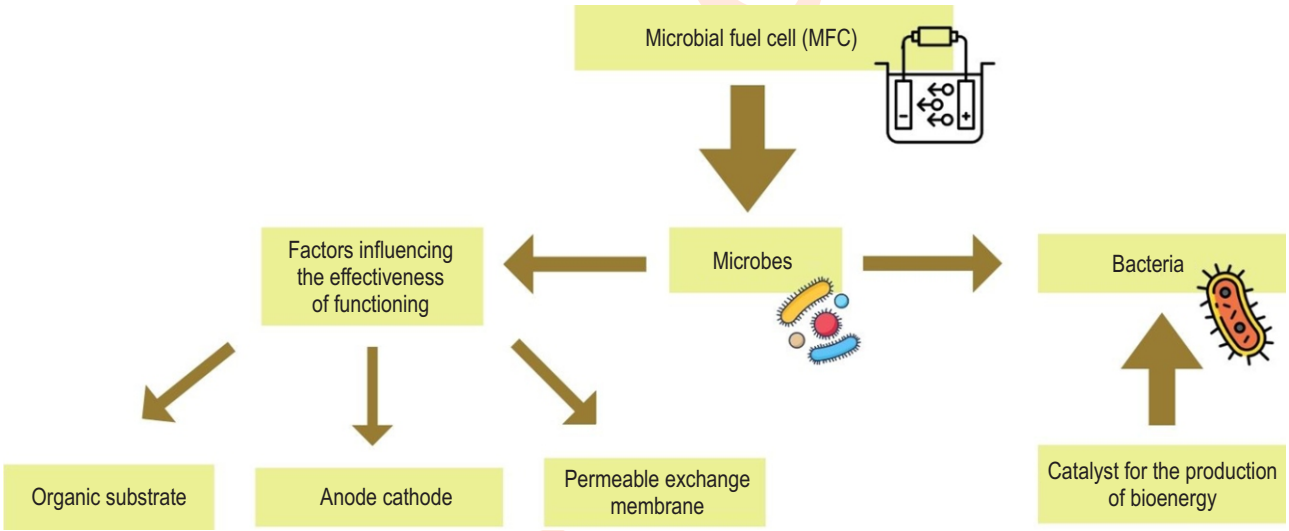

Fig.2: Properties of Microbial fuel cell (MFC).

Because of its distinct and obvious effects, nanotechnology has permeated every industry and contributed to many scientific advances in the fields of medicine, agriculture, etc. (Salem Salah Salem *et al.,* 2023). Nanotechnology offers numerous advantages in battery manufacturing, including reduced combustible electrode material, shorter battery life, and increased power accessibility. Nanoparticles on electrode surfaces increase the current flow, improving hybrid car efficiency and reducing battery weight (Fig. 3). Separating liquids from solid electrodes also prolongs battery lifespan and prevents low-level discharge (Kumaş and Akyüz, 2020). This research review explores and discuss the integration of nanotechnology principles in the fabrication of microbial fuel cells to enhance their performance.

Microbial fuel cells: A potential replacement for conventional fossil fuels is the microbial fuel cell. It offers enormous potential for managing waste, producing energy and valuing biomass (Wang *et al.,* 2022). Technology that uses catalytic activity of microorganisms to generate electrical energy from chemical energy is the Microbial Fuel Cell. The two electrodes (anode, cathode) that make up a typical MFC are separated by an agar salt bridge and linked via an external circuit. In Microbial Fuel Cell, a large range of substrates have been used. The MFC

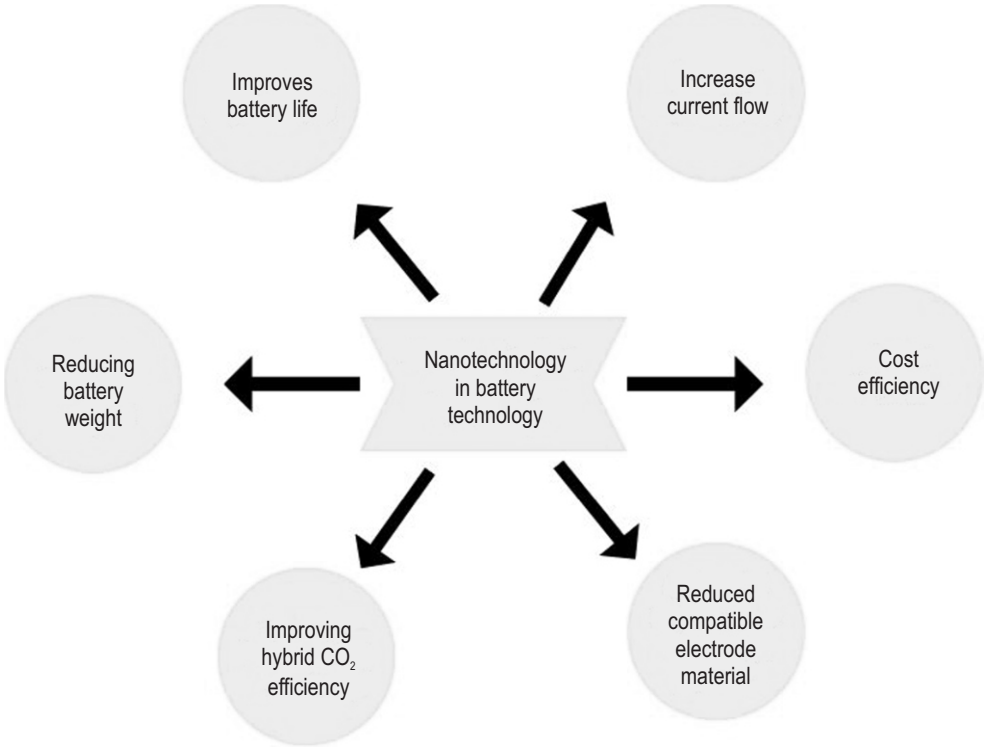

Fig. 3: Advantages of nanotechnology in battery technology.

performance, including the Coulombic efficiency, power density is influenced by substrates in addition to the integral composition of the bacterial community in the anode biofilm. Low molecular weight substrates, such as carbohydrates like glucose, xylose, fructose, sucrose, lactate and malate, inorganic compounds like sulfate and organic acids like acetate, butyrate, succinate, propionate, lactate, succinate, and malate, alcohols like methanol and ethanol are used as substrates during the development of this technology. Subsequently, complex substrates including chitin, pectin, molasses, starch, cellulose and dextran are also used (Chaturvedi and Verma, 2016). The architecture of microbial fuel cell, the spacing between electrodes, the electrode that is used, the proton exchange membrane, the mediators, the substrate, the microorganisms involved, and a few other external factors all have a major role in how much energy they produce. microbial fuel cell come in a variety of forms, such as stacked, double-chambered, and single-chambered models (Malik *et al.,* 2023).

Many microorganisms, including *Proteobacteria, Acidobacteria, Cytophagale* and *yeast strains* like *Saccharomyces cerevisiae, Hansenula anomala, Blastobotrys adeninivorans, Pseudopalaina polymorpha, Firmicutes* and *Candida melibiosica, adeninivorans* have the ability to transfer electrons produced by metabolism to generate electricity (Fozia Anjum *et al.,* 2023). These microbes, especially some species of bacteria, exhibit effective behaviour for the transfer of electrons via cytochrome pathways and proteins (Bazina *et al.,* 2023). Microbial fuel cell can be classified dual chambered and single chambered. Dual-chambered microbial fuel cell are those that have distinct cathodic and anodic chambers, as opposed to single-chambered microbial fuel cell, which have both cathode and anode in a single chamber. A single-chamber microbial fuel cell involves only the anodic chamber coupled with an air cathode to which the protons and electrons are transferred. The traditional microbial fuel cell design, known as the dual-chambered microbial fuel cell design, has two chambers that are divided by an ion exchange membrane. These are currently limited to use in laboratories and are normally operated in batch mode, however, they can also operate continuously.

Types of MFC: There are various types of MFC's based on the chamber and electrodes present. Double-chamber MFCs, using two bottles separated by PEM, are simple designs used for remote sensing due to their design defining catholyte choice a single chambered mfc form which houses electrodes in the same chamber, separated by PEM, and allows placement near or far, making it cost-effective and more powerful than double-chamber MFCs. Mediator microbial fuel cell Electrochemical inactivity characterizes the majority of microbial cells. Mediators including neutral red, methyl blue, humic acid, methyl viologen, and thionine help move electrons from microbial cells to the electrode. The majority of mediators on the market are pricy and harmful

(Kumar *et al.,* 2017). The upflow MFC has a cylinder-like form. At the bottom of the MFC anode is located and the cathode chamber is located at the top. Layers of glass beads and glass wool divide the two rooms. The bottom of the anodes provides the substrate, which rises to the cathode and exits at the top. Between the electrodes, a gradient form, in the fuel cell's beneficial activity (Dessie *et al.,* 2020). Anode is a critical component in microbial fuel cell that permits Electro-active bacteria (EAB) to generate electroactive biofilm. As a result, the quality of anode material should have various characteristics such as great conductivity and strong biocompatibility. While choosing an anode, material factors like chemical stability, corrosion resistance, mechanical strength, and toughness should be considered. For adherence and the development of biofilms, an anode should have a wide specific surface area. Carbon materials, such as graphite rod and fiber brushes, carbon felt, reticulated vitreous carbon (RVC), and carbon cloth utilized in MFC applications, are primarily employed as anode materials (Dharmalingam *et al.*, 2019).

Types of Anodes: There are three types of anodes based on the material used such as carbon based ,metal based and natural material based on which carbon-based materials are used due to their electron biocompatibility, transport kinetics, chemical stability, high surface area and electrical conductivity and natural material-based anodes use naturally occurring waste products enhanced with organic matter since they are stable, affordable, and biocompatible. Because of their conductivity and electron movement, metals have lower internal resistance and interfacial impedance than materials based on carbon, which makes them perfect for anodes. Unfortunately, their smooth surface and caustic nature limit the growth of microorganisms and degrade performance. Stainless steel and other non-corrosive metals might not produce the best results (Banerjee *et al.,* 2022).

Nanotechnology: Nanotechnology is a highly interdisciplinary field focused on manipulating matter at the atomic and molecular scale, typically between 1 to 100 nanometers. Its impact extends across a wide array of scientific and technological domains, leading to transformative advancements in areas such as medicine, agriculture, environmental science electronics, materials science and energy generation, Nanotechnology also rapidly advances with diverse applications in catalytic reactions, absorbent materials, lubricating oils, ceramics, semiconductors, medical technology, bioengineering, contaminant detection, and physiological detectors (Natrayan *et al.,* 2023). In order to improve the barrier property of biomass materials, metal nanoparticles combined with nano polymer-like poly (lactic acid) provide effective reinforcing agents (Dey *et al.,* 2022).

Our recent study, presented in Table 1, highlights the promising applications of nanotechnology principles in several key areas: -Biomedicine: Enhancing drug delivery systems. -Agriculture- Improving the nano formulation of agroactive agents, including pesticides and herbicides. -Environmental Science-Advancing the removal of pollutants. -Food Sector-Developing active food packaging materials and nano formulations of food additives, particularly preservatives. Building on this nanotechnology research, our team is preparing a mini-review on the eco-friendly fabrication of microbial fuel cells (MFCs) using nanotechnology principles. This review aims to explore novel approaches in MFC fabrication that could significantly enhance energy generation.

Nanotechnology in energy generation: Nanotechnology has slowly yet deeply taken over different industries worldwide. This rapid pace of technological revolution can especially be seen in the developed world, where nano-scale markets have taken over rapidly in the past decade. Nanotechnology is not a new concept since it has now become a general-purpose technology. Four generations of nanomaterials have emerged on the surface and are used in interdisciplinary scientific fields; these are active and passive nano assemblies, general nano systems, and small-scale molecular nanosystems. Applications for nanotechnology include the efficient generation, use and storage of energy as well as identification and removal of environmental contaminants (Kumaş and Akyüz, 2020). Contribution of Nanotechnology to transmission, low-cost and efficient energy generation, and storage systems is evident. Nanoscale fabrication of materials can be potentially of use for producing newly developed devices with low cost, high efficiency and low energy demand in many applications such as energy saving technologies and hydrogen 11, or lamellar nanostructure, are called nanocomposites. Nanocomposites have developed as useful substitutes to address the limitations of current engineering materials. The ingredients that make up the dispersed matrix and dispersion phase of nanocomposites can be used to classify them (Sen., 2020).

Nanocomposite materials are of three types as polymer matrix nanocomposites, ceramic matrix nanocomposites & metal matrix nanocomposites (Omanović-Mikličanin *et al.,* 2019). Polymer nanocomposites are hybrid materials made up of nanoparticles acting as nanofillers and polymers acting as the matrix. Natural polymers are those that can be extracted for usage from their natural habitat. Water is a common constituent of natural polymers, including cellulose, silk, wool and proteins. Conversely, synthetic polymers are those that are created artificially, including epoxy, Teflon, nylon, polyester, and polyethylene. To create a PNC with enhanced qualities tailored to a certain application, various inorganic nanofillers, including metal-oxide nanoparticles, metal nanoparticles, carbon nanomaterials and nano clays can be added to a polymer matrix (Darwish *et al.,* 2022). The polymeric matrix and evenly distributed reinforcing elements act as a physical barrier to prevent hostile ions in the solution from attacking metallic substrates. Polymer materials are widely used in industry due to their low cost, easy production, often ductile nature and small specific weight (Muresan, 2023).

Nanocomposite coated anodes: Coating of electrodes with nanomaterials increases their surface area and conductivity. The efficiency of microbial fuel cells increases with large surface area and high electrical conductivity. In the MFC, anode electrodes made of different metallic materials, such as nickel, titanium,

Table 1: Different types of nanomaterials used in MFC fabrication

Nanocomposite	Description
polyaniline nanocomposites	PANI and its nanocomposites can be applied to the electrodes of MFCs to enhance their performance. Maximum power generation occurred when the electrode was covered with a PANI-Cu/ZnO nanocomposite (Mathew et al., 2020).
lithium (Li)-doped zinc oxide (ZnO) -impregnated polyvinyl alcohol	Based on its features and cheap synthesis cost, the Li-ZnO-impregnated PVA-based PEM is a nanomaterial for possible application in MFC, indicating its feasibility for usage in real time MFC systems (Chauhan et al., 2023).
iron carbide nanoparticles doped with nitrogen and sulfur	Compared to MFCs with S,N-GR/CC and CC anodes, those with the S,N-GR/Fe3C/CC anode had a higher COD removal rate and CE. Excellent power generation performance and strong biocompatibility were demonstrated by MFCs based on S,N-GR/Fe3C/CC anodes. (Xia et al., 2021).
Bio-FeOx/C electrode	Bio-FeOx/C electrode had highly dispersed biogenic iron oxide as an effective anode catalyst and shows great application potentials inthe fabrication of high-performance MFCs (Yang et al., 2021).
aMIL-Fe3O4	rGO–BN–Fe2O3 hybrid nanocompositecatalysts can be a less expensive cathode catalyst for MFCs (Mahalingam et al., 2020).
Biogenic Ag nanoparticles	the amount of biogenic AgNPs on graphene sheets has a direct correlation with the operational efficiency of MFCs, taking into account parameters such as the open-circuit potential (OCP), maximum power density,CE,COD removal efficacy, and decreased electrical resistance (Elkhrachy et al., 2023).

copper, stainless steel, silver and goldhave been employed. Although high and steady performance levels have been established, the metal ions emitted by their electrodes are toxic to bacteria and would negatively impact the formation of biofilms (Mohamed *et al.,* 2020). FeO has the advantages of good biocompatibility, environmental, anodic stability and low cost, which exhibited a better performance in the MFC and making as an excellent electrochemical capacitor (Mohamed *et al.,* 2020). Molybdenum has been used as an the electrode in MFCs to generate power, and it has demonstrated notable performance in the electron transfer mechanism. $FeMoO_4$ exhibits potential as a viable anode electrode for Li-ion batteries. MFC electrodes coated in a nanocomposite material based on the conducting polymer polyaniline (PANI). Being a highly conductive polymer, PANI's nanocomposites will increase the electrodes' surface area and function as an effective electro-catalyst (Mohamed *et al.,* 2020).

Graphene is also one of the emerging carbon materials that have aroused great interest as an anode in MFC, consisting of a single sheet of graphite with a two-dimensional crystalline structure. It has high electrical conductivity, good biocompatibility, excellent mechanical properties, chemical and thermal stability, greater diamagnetism, and nonlinearity than simple graphite (Abd-Elrahman *et al.,* 2022). There are two mechanisms by which iron oxide and graphene promotes EET; by accumulating on the cell surface in the form of an electrical conductor interface inside biofilms. In a study, it was reported that these inside-biofilm particles can promote the expression of c-type cytochromes responsible for electricity generation (Yang *et al.,* 2020).

Corrosion resistance: As a result of nanocomposite coatings quality, cost effectiveness and efficiency are improved. They have a wide spectrum of application in anticorrosion barrier coatings, self-scratch repair coatings and self-repair coatings. The presence of nanofillers or nano matrix in the nanocomposite releases active ingredients that slow down the corrosion process and heal the damaged surface. ZnO nanocomposite coatings, showed improved corrosion resistance, biocompatibility (Minho Lee *et al.,* 2022). Researchers have developed polymer/silica nanocomposite coatings for corrosion resistance on aluminium alloys. PMAA/AgNPs are used as a corrosion inhibitor affecting cathodic and anodic reactions. Silica nanoparticles and also Polystyrene-graphene oxide nanocomposites increased corrosion resistance, providing exceptional protection. carbon black nanocomposite and Poly (vinylidene fluoride) was tested for anti-corrosive behaviour on mild steel (Brindha *et al.,* 2022).

It has been demonstrated that modifying manganese oxide nanoparticles with conducting polymers (PPy and PANI) to create composites have anticorrosion properties, superior electro kinetics, high electron mobility, stability and biocompatibility (Yilkal Dessie *et al.,* 2020). Carbonaceous materials such as graphite brushes, carbon cloth, carbon paper, graphite rods carbon felt and reticulated vitreous carbon are widely used as anodes in MFCs because of their biocompatibility ,high electrical conductivity, chemical stability, low cost and specific surface area (Mustakeem, 2015).

Biofilm engineering: Advances in biofilm engineering techniques coupled with nanomaterial-based anodes can enable precise control over microbial community composition and activity. Engineering biofilms for enhanced electron transfer capabilities and robustness can improve MFC stability and performance. Fabricating Microbial Fuel Cell (MFC) anodes with nanomaterials tailored for biofilm adhesion is a cutting-edge approach revolutionizing renewable energy generation. The anode material inhibites bacteria adhesion to its surface for stable biofilm formation. The formation of stable biofilm is necessary for efficient electron transfer. It should also be biocompatible with the electroactive microbes and show enhanced conductivity for the

Table 2: Research findings of authors research group in the nanotechnology sector

Nanomaterial	Research Finding
Chitosan nanocomposite fabricated with fungal metabolites (Karthick Raja Namasivayam *et al.,* 2018).	An enhancement of pesticidal activity of Nomuraea rileyi derived metabolites against the life stages of Spodoptera litura (Fab.) Nanocompo site also showed noteworthy biocompatibility on the embryonic stages of zebra fish.
Various nano materials were used (Lavanya *et al.,* 2024).	Nanomaterials improve the dispersibility, stability, and availability of bioactive substances present in nanoencapsulated biopreservative agents.
Abelmoschus esculentus mucilage nano formulated with polymers polyvinyl alcohol (PVA) and polyethylene glycol (PEG) (Karthick Raja Namasivayam *et al.,* 2024).	The treatment of nanocomposite has no impact on the seedlings grown. Hemocompatibility study also revealed that the nano composite has not shown any undesirable effects on the peripheral blood cells.The nanocomposite exhibited notable antimicrobial activity pathogenic bacterial and fungal strains.
Aerosol nanoparticle (Namasivayam *et al.,* 2024).	Effect of emitted aerosol nanoparticles on various components of ecosystem. Methods for the in vitro generation of aerosol nanoparticles frombiomass was featured.
Starch-chitosan-Taro mucilage nanocomposite doped with zinc oxide nanoparticles (Priyanka *et al.,* 2024).	The nanocomposite food packaging material showed improved physical and mechanical characteristics. It also exhibited non-arget toxicity on Vigna angularis assessed through phytotoxicity experiments.
Selenium nanoparticles (Sowmya *et al.,* 2024).	nanotechnology principle of nanoscale derived selenium nanoparticles has diverse applications with high biocompatibility and are eco-friendly.
Bio based Nanofabricated food packaging material with various nanomaterials (Priyanka *et al.,* 2023).	Possible utilization of nanomaterials in the fabrication of food packaging with out affecting nutritional values.
Silver and zinc oxide nanoparticles with various microorganisms (Namasivayam *et al.,* 2023).	The formulation did not affect plant growth promotion associated with the soil conditioning effect. The formulation with agro based product promoted growth rate of the plant used.
Gold nanoparticle loaded with camptothecin (Namasivayam *et al.,* 2023).	The composite exhibited enhanced cytotoxicity against the breast cancer cell line and can be used as anticancer agent.
zero valent iron nanoparticles (Shree *et al.,* 2023).	The potential nZVI nanoparticle is used to eliminate drug effluents from wastewater.
Silver nanoparticles (Namasivayam *et al.,* 2024).	The nanocomposite derived from heat shock protein is used for the treatment of wastewater.
Silica nanoparticles (Namasivayam *et al.,* 2023).	The nanocomposite exhibited non toxic effect on stages of the Zebra fish Embryo. There was no toxic effect on soil and growth parameters of Arachis hypogaea was not affected.
Celluose nanoparticle (Namasivayam *et al.,* 2023)	Application of nano cellulosic composite in waste water treatment.
Polylysine nanoparticles (Namasivayam *et al.,* 2022)	Nano formulated polylysine as an effective, safe bio preservative.
Chitosan-silver nanocomposite (Namasivayam *et al.,* 2022)	The adsorption efficacy of CS-AgNC against methyl orange showed effective adsorption at a lower dosage of the adsorbent.

electrons. In addition, the anode material should have properties such as anti-corrosion, mechanical strength, and chemical stability. In general, the surface roughness of the anode materials is increased to ensure bacteria adherence, allowing higher power density. Additionally, the enhanced surface roughness increases durability against swelling and decomposition due to the redox condition at the electrode. On the contrary, it can increase fouling, which can affect its applicability in the long term. As a result, the durability and insensitivity to changes in operating conditions and pH should be taken into consideration while selecting appropriate materials for anodes. Moreover, the increased porosity and surface area of the anode allows stable biofilm formation. Nanomaterials like carbon nanotubes, graphene and nanostructured metals offer unique advantages in enhancing biofilm formation on MFC anodes. Their high surface area and tailored surface chemistry provide an ideal platform for microbial attachment, promoting biofilm growth and facilitating efficient electron transfer processes. By precisely engineering the surface properties of nanomaterials, researchers can control the adhesion kinetics and spatial distribution of microbial communities, optimizing MFC performance. Moreover, nanomaterial- based anodes exhibit increased durability and resistance to biofouling, prolonging operational lifespan and reducing maintenance requirements. Challenges such as scalability, cost-effectiveness, and potential environmental impacts warrant further investigation. Nonetheless, leveraging nanotechnology for MFC anode fabrication holds immense promise in advancing sustainable energy solutions and addressing pressing environmental challenges.

Challenges and Future prospects

The fabrication of Microbial Fuel Cells using nanotechnology principles present exciting opportunities but also comes with several challenges and future prospects:

One of the primary challenges in MFC fabrication using nanotechnology is scalability. While nanomaterials offer

exceptional properties at the nanoscale, scaling up production to industrial levels while maintaining performance and cost-effectiveness remains a hurdle. The production of nanomaterials are expensive, which may increase the overall cost of MFC fabrication. Finding cost-effective synthesis methods or alternative materials without compromising performance is essential for widespread adoption. Some nanomaterials may exhibit limited stability under harsh conditions present in MFCs, such as acidic or alkaline environments, high temperatures and mechanical stress. Ensuring the durability and long-term stability of nanomaterial-based components is crucial for reliable MFC operation. Integrating nanomaterials into MFC architectures without impeding microbial activity or electron transfer processes can be challenging. Achieving optimal interface interactions between nanomaterials, microbes and electrodes requires careful design and engineering. The environmental impact of nanomaterial production, usage, and disposal is a significant concern. Addressing potential environmental risks associated with nanomaterials, such as toxicity and ecological effects, is essential for sustainable MFC development.

Global and Indian Scenarios: For the development of high-performance MFCs, the choice of materials is essential. It has been proven that nanofiber technology enhances MFC performance through increased stability, durability, biofilm growth, and electron transfer rate. Long-term stability, biocompatibility, and cost-effectiveness are still challenging. Future studies should concentrate on improving the characteristics of nanofibers and investigating their possible uses in MFCs and other energy-related fields. Reducing dependency on non-renewable resources and mitigating the effects of climate change are two benefits of using MFCs as sustainable energy sources (Yalcinkaya *et al.,* 2024).

Companies also utilize MFCs for fuel, remote power supply, bioremediations, and biosensors, demonstrating its potential in clean energy development. Microbial fuel cell technology, which is being developed and optimized using Gram-negative heterotrophic bacteria and marine algae, offers dual-purpose solutions for wastewater treatment and electricity generation, and is being used in field applications. MFCs may set an optimistic baseline as an alternative energy source and for waste treatment, especially in rural areas where MFC replaces methogenesis. In urban areas, MFC technology may help industrial wastewater treatment plants lower operating costs by treating generated waste in parallel (Patel *et al.,* 2017).

The present review is centred on the application of nanotechnology principles for efficient functioning of microbial fuel cells. Numerous studies have demonstrated design of an anodes influence the overall performance of microbial fuel cell architecture and individual parts have an effect on the output performance. The operation of MFCs depends critically on the appropriate choice of anode material. Microbes in MFCs and nanocomposites have many benefits and can give the microbial fuel cells new functions that improve biocatalytic. This review focus on advances and trends in the development of composite materials, envisioning those available in relation to the possibilities in the limited materials tested so far. Further studies will be helpful in the main challenge in the scale-up of MFC involves the external energy required for starting the circuit for MFC energy extraction. The forthcoming progress should involve using innovative nanomaterials revealed innovative perspectives for the use of high-performance advanced fuel cells and use of green synthesized nanocomposites for electrodes.

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