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REVIEW

Advances in Microbial Fuel Cell Technology: Survey of Organic Substrate Utilization and Microbiological Approaches

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Abstract

Microbial fuel cell technology is seen as a viable replacement for conventional fossil fuels. It holds significant promises for energy generation, waste management and biomass enhancement. They are viewed as an emerging and economical solution for treating organic waste while generating bioelectricity. To ensure their practical application, careful optimization and precise design are essential. However, there are certain technological hurdles, including low power efficiency and operating stability. These challenges hinder the feasibility and commercialization of MFC systems. The technology behind microbial fuel cells has been shown to effectively treat chemical waste while recovering valuable chemical products like heavy metals, all while generating electrical energy. However, a major obstacle in the development of MFCs is scaling them up for real-world applications, which involves enhancing the potential for the treatment of wastewater and generating energy from several cells within a single MFC system. This review provides an extensive overview of recent breakthroughs in MFC technology, the examination of many substrates, microbial processes in MFCs, fruitful applications of this technology and insights for researchers investigating various factors in microbial fuel cell studies.

Keywords: Fuel cells, Microbes, Organic substrates, Energy, Environmental sustainability

1. Introduction

The present world increasingly depends on electricity generation to power industries, houses, gadgets, automobiles which must be constantly provided. To meet with the huge demand for energy, an ample production capacity must be installed which will deal with carbon emission standards. In an attempt to find sustainable remedy, humans have invented various processes of energy generation which includes solar, hydel, wind energy production techniques and biological based alternatives such as biomass, biogas and microbes [1−3]. Microbial fuel cells (MFCs) employ a remarkable and viable technology among other renewable sources of interest because of the utilization of organic and inorganic substrate for bioelectricity production that have frequently been developed over time [4]. MFCs are bio-electrochemical devices that use microbial metabolic activity to convert organic substrates into electrical energy. These set up functions by utilizing electrochemically active bacteria that metabolize organic matter, generating free

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electrons that flow through an external circuit to produce bioelectricity. MFCs can effectively treat wastewater while concurrently creating energy, making them a promising choice for dealing with energy shortages and environmental problems [5]. The variation of MFC technology allows for its application in diverse fields, including bioremediation, energy recovery, and as biosensors for monitoring microbial processes [6].

As research progresses, MFCs have the potential to revolutionize energy generation and wastewater treatment, paving the way for a more sustainable future. MFCs operate by utilizing metabolically active bacteria to break down organic materials in the anode compartment. This process transfers electrons to the anode, generating an electrical current that flows externally to the cathode. At the cathode, electrons are accepted, often by oxygen or other electron acceptors [7]. The dual-chamber set up of MFCs, separated by a proton exchange membrane (PEM) enhance the mobility of protons from the anode to the cathode while preventing the mixing of the anode and cathode solutions [8]. This arrangement not only facilitates efficient energy conversion but also promotes the simultaneous treatment of wastewater, as the bacteria metabolize organic pollutants while generating electricity. The versatility of MFCs is further strengthened by their ability to utilize various substrates, including waste materials, making them a viable technology for sustainable energy generation and environmental cleanup [9].

In MFCs, organic matter derived from various sources which includes wastewater or agricultural residues, serves as fuel which is oxidized by bacteria at the anodic region generates electrons and protons [10]. Electrons migrates to the cathode through external circuit producing bioelectricity, while protons migrate through a PEM [11]. The dual nature of MFCs such as wastewater treatment and bioenergy generation have handled pollution and energy challenges making them a better alternatives for sustainable development [12]. Furthermore, MFCs use a diverse nature of organic substrates to generate bioelectricity through microbial metabolism. A number of general substrates used include fruit waste, food waste, and livestock manure with huge composition of organic matter for microbial activity [13]. For instance, studies have shown the effective use of potato pulp and sugar mill effluent as substrates, stressing their potential for both wastewater treatment and bioenergy generation [14,15]. The preference of substrate remarkably affects the productivity of MFCs, as several organic materials can generate different range of bioenergy depending on their biochemical configuration and the microbial communities involved [16]. Overall, the diversity of organic substrates available for MFCs not only promotes their function in waste management but also facilitate the sustainability of energy generation in MFC systems [16,17]. For instance, studies have demonstrated the effective use of potato pulp and sugar mill effluent as substrates, highlighting their potential for both waste treatment and energy production [14,15].

A standard MFC comprises two compartments divided by a PEM, where the anodic compartment lacks oxygen and the reduction chamber contains oxygen, as illustrated in Fig. 1. The wastewater is utilized as substrate facilitating treatment in the anodic region

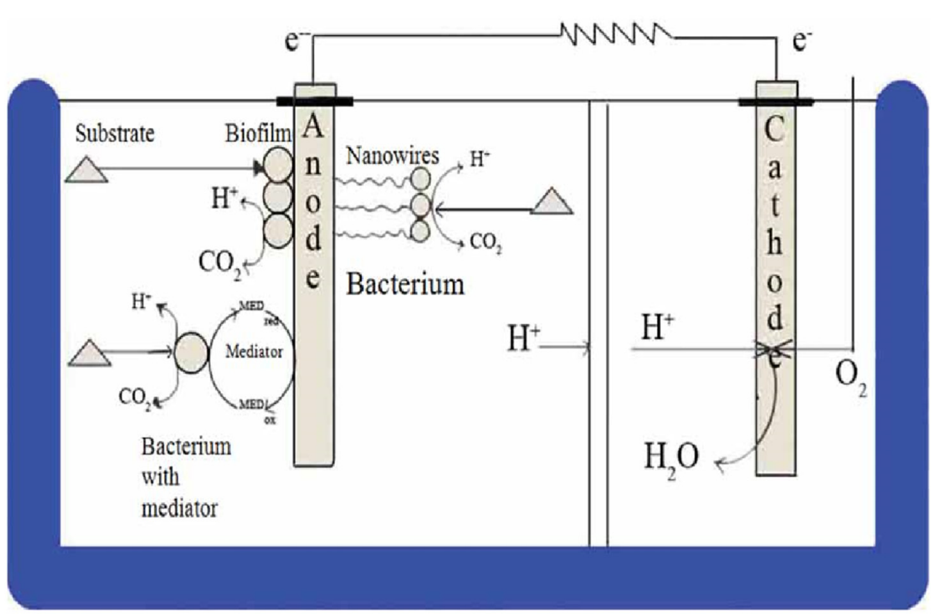

Fig. 1. Schematic view of a two chambered MFC [22].

while also generating electricity [18]. In certain instances, biocathodes have been utilized for the aerobic treatment of wastewater [19]. By eliminating oxygen through the cathodic region and adding a little voltage to the system, hydrogen will be generated as gas. This type of fuel cell is referred bio-electrochemical circuit [20]. In evaluating the performance of MFCs, electrochemical measurements such as electrochemical impendence spectroscopy (EIS) and cyclic voltammetry (CV) are usually applied [21]. Fig. 1 illustrates the schematic diagram of two chambered MFC. Consequently, this study reviews literature in this field and presents a concise discussion of the advancements in MFC technology, exploring microbiological approaches related to MFCs, the various organic substrates utilized, and practical applications of this technology in addressing environmental challenges. Additionally, it highlights current challenges and future directions for MFC technology. This article aims to serve as a valuable resource for researchers engaged in this interdisciplinary field.

2. Mechanism of MFCs in energy generation

MFCs are a type of biological reactor that houses diverse populations of bacteria, which function as biocatalysts for electrodes. These innovative devices utilize bacteria to transform organic materials into electricity. MFCs produce energy from waste placing them as an environmentally friendly waste management solution. MFCs can be useful in distant or off-grid places without normal energy infrastructure. The need for MFCs stems from their potential utility in distant places where constant energy supply is unavailable. As technological development continues, MFCs will continue to function significantly in producing clean energy, maintaining the ecosystem and developing a circular economic system through transforming waste into a useful material [23–25]. The method of producing energy using MFCs began in the twentieth century, during which diverse microorganisms such as bacteria, fungus were identified for their essential role in the decomposition of both waste particles that are either organic or in organic [26]. The electrochemical process of microbes involved in MFCs relies solely on Faraday and capacitive reactions in which immediate and assisted electron exchange mechanism takes place in both MFC chambers. Because of the degradation of organic materials included in waste matter, the created electrons are assimilated by microorganisms, resulting in a fast enzymatic process around the biofilm, with e-transmitted to the cathode. The exterior electromotive force (EMF) maintains the MFC's thermodynamic principles [27].

The rate at which electrons are transferred at the anode largely depends on the species of microbes employed, along with its metabolic processes and the capability to utilize specific molecules. The cell provides electron neutrality through the migration of H^+. In terms of bioelectricity generation, microbes metabolize various compounds for energy, including carbohydrates and other nutrients. Consequently, these components can also serve as electron donors in tricarboxylic acid cycle to generate carrier molecules such as ATP. Firstly, the process begins with glycolysis, which leads to the formation of acetyl CoA as organic compounds are cleaved, thus initiating the tricarboxylic acid pathway via oxidative reactions. This oxidation reaction involves the conversion of electron conduits such as FAD to $FADH_2$ and NAD^+ to NADH. Within the tricarboxylic pathway, electron conduits in the cell membrane facilitate the mobility of electrons outside of the cells. The plasma membrane's ATP synthase allows electrons to reach the final acceptor of electrons on a consistent basis. This process includes the transformation of ADP into ATP through the decrease in terminal acceptors during respiration. In bioelectricity generation, microorganisms operate as the terminal electron acceptor, replacing the electrode in the anodic compartment [28]. The basic processes involved in generating electricity through MFC technology via the metabolic activities of microorganisms are illustrated in Fig. 2.

3. Factors affecting the performance of MFCs

The optimal performance of MFCs is heavily influenced by operational and environmental factors. Factors influencing electrode performance include microbial populations, substrate properties, electrode materials, and ambient parameters including pH, temperature, pollutant concentrations, and a variety of other factors. Recognizing and understanding these aspects is vital for achieving a perfect MFC. Microbes in the anodic area play a crucial role in transferring electrons to the anode through metabolism and mediators. MFCs can use a variety of substrates as electron donors, which bacteria can then oxidize for metabolism. Fig. 3 presents a summary of these factors.

3.1. Temperature

Several research have shown that temperature plays a crucial role in influencing the effectiveness of MFCs across different situations. The influence of this on the breakdown of different hydrocarbon substances in petroleum wastewater on energy generation through double-chamber MFCs in semi-batch mode, has been explored. On the other hand, performance dropped at 50 °C, suggesting that 40 °C is the optimal temperature for MFCs functioning effluent polluted by petroleum hydrocarbon. The number of microbes capable of

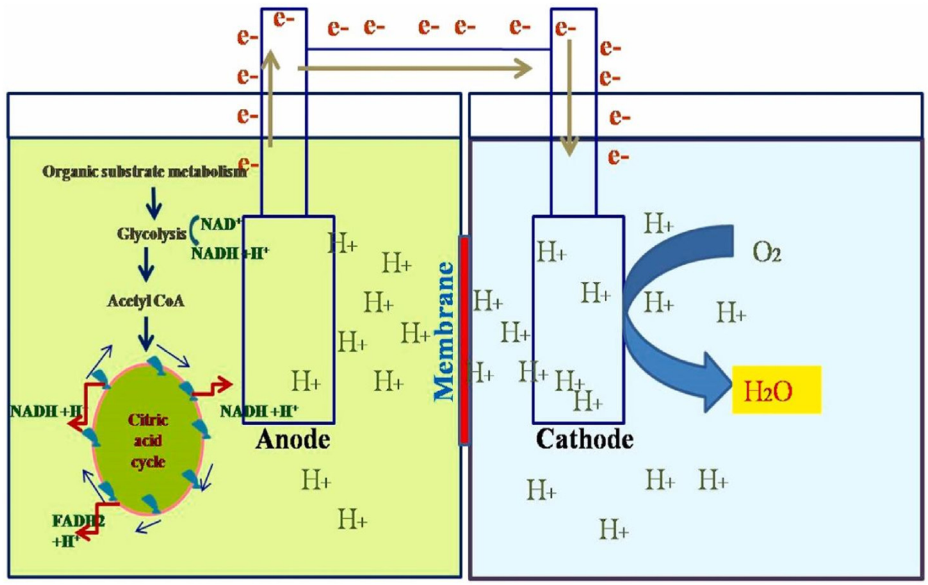

Fig. 2. Mechanisms of reactions in MFC [29].

surviving in the anodes declines at extreme temperatures, thus impacting the MFC's overall output. Most bacteria thrive in moderate temperatures, which accounts for this pattern [30].

3.2. External resistance

The external resistance has a great impact towards the capacity of different elements to be removed in

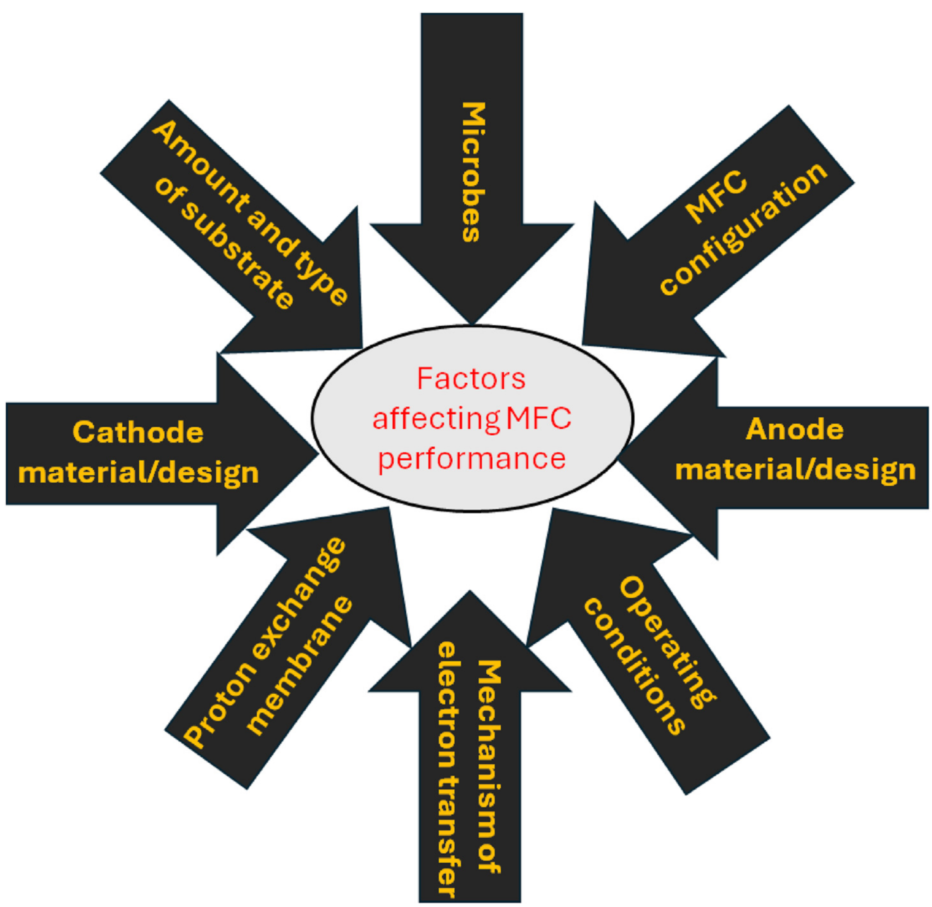

Fig. 3. Summary of factors affecting the performance of MFC.

MFCs [31,32]. External resistance can noticeably affect the potential set up in the anodic region which in turn impacts the formation of the electrochemically active biofilm and the performance of MFCs. Low external resistance is beneficial for selective electricigens as it enhances electron flow and allows the electrochemically active biofilm to maintain a higher flow of free energy [33]. Reduced external resistance results in increased power generation but decreased COD removal, as the microbial community shifts to favor more efficient electricity production over COD degradation. Conversely, an increased external resistance leads to enhanced COD removal at the expense of reduced electricity generation, as the microbial community adjusts to focus more on biodegradation of organic pollutants [31].

3.3. pH

According to studies, pH has a substantial impact on microbes' ability to create products, metabolize substrates, evolve as a community, and influence their redox potential [34]. Extracellular electron transfer performed effectively at acidophilic pH, which they thought could be due to unique intracellular electron transfers that aid in electron rearrangement. In neutral and alkaline pH environments, protons always observed declined when the substrate degradation is happening, causing the release of less electrons [35].

3.4. Substrate

The diversity of substrates utilized in MFCs is a major contributor to the creation of distinct microbial communities. A bacteria culture that has been induced in BESs create resistance to a specific substrate, and changing it will bring up an influence on the bacterial population [36]. Accordingly, it was reported that glucose, butyrate and others are also main substances of the carbon-rich substrates that may be favorable for microbial degradation. Lignocellulosic materials is a regularly used substrate for increasing the power production of MFCs. Carbohydrates are distinguished by their high carbon-rich effluent from starch manufacturing, making them ideal for MFC technology. Other elements that affect MFC include the electron transfer method, types of membrane, and design [37]. The type and quantity of organic substrates have a considerable impact on the performance of MFC. An overabundance of organic substrate might impair the microbial community near the anode, resulting in lower efficiency and power output. In contrast, selecting the optimal type and quantity of organic substrates might boost MFC performance by establishing an optimum environment for the growth and activity of anodic microbes.

4. Conventional organic substrate used in MFCs

The substrates employed are one of the many essential elements of MFC since they affect electricity generation. MFC technology may use a variety of substrates to generate energy, including pure chemicals and complicated mixtures of organic compounds found in wastewater. Substrates are otherwise referring to carbon sources in MFCs, providing the needed carbon for the bacteria metabolism process. Hence, material used in this regard is considered rich in carbon and suitable or biocompatible with electrogenic microbes. The list of organic substrates that have previously been used in MFCs has been highlighted in Table 1.

4.1. Acetate

Acetate is the most commonly used substrate for energy generation in MFC research. Unlike acetate, the recalcitrance of nature of some effluents makes it fairly difficult to employ. Acetate function as effective carbon source that is commonly employed as organic substrate to boost the growth of electroactive microorganisms [38]. In spite of its neutral reactivity for multiple microbial transformations like methane generation and can ferment at normal temperatures, acetate is frequently used effectively substrate and viable figure for innovative MFC components, under operational factors [39]. In addition, acetate is final product of multiple metabolic pathways combined with glucose metabolism. MFC applied acetate produced the highest percentage of CE with 72.3 % compared to butyrate having 43.0 % and glucose with 15 %.Contrary to waste water augmented with peptides as the substrate in MFCs, the acetate-applied MFC gained more than double the total amount of electricity and half the resistance of the exterior load [40].

4.2. Glucose

Another very common substrate that is readily available and commonly used is glucose. According to Fadzli et al. [41], carbon sources in the microorganism's starting media affect the effectiveness of MFC utilizing *Proteus vulgaris*. Cells stimulated with glucose in the MFC lasted shorter than those stimulated with galactose. It was argued that the potential of applying sediment from anaerobic conditions as a fuel in MFC for generation of energy from glucose is limited. Anaerobic sludge was used as a substrate in a baffle-chamber membrane-less MFC, producing just 0.3 mW/m^2 of power production. Glucose produced the highest production of 161 mW/m^2 [42].

Table 1. Organic substrates employed in MFCs and their performance.

Substrates	Concentration (mg/L)	Source	Nature of MFC/Current density (mA/cm^2)	Reference
Acetate	1000	Preacclimatized bacteria	Single chambered MFC using graphite-based anode/(0.8)	[46]
Arabitol	1220	Preacclimatized microbes	Single chamber MFC using carbon cloth-based electrodes/(0.68)	[47]
Azo dye with Glucose	300	Anaerobic sludge	Air cathode MFC using carbon paper-based anode/(0.09)	[48]
Carboxymethyl cellulose	1000	*Clostridium* sp. *G.sulfurreducens*	Dual chambers MFC using graphite electrodes with ferricyanide electrolyte/(0.05)	[49]
Cellulose material	4000	*Enterobacter* sp.	U-shaped MFC with carbon cloth and carbon fibre anode and cathode respectively/(0.02)	[49]
Corn stover biomass	1000	Domestic wastewater	Carbon paper anode (7.1 cm^2) and carbon cloth-based cathode/(0.15)	[50]
Cysteine	385	Ground depth sediments	2-chambered MFC and carbon paper electrodes/(0.0186)	[51]
1,2-Dichloroethane	99	Microbial consortia enriched with acetate	Double chambered MFC with graphite plate anode (20 cm^2) and graphite granules cathode/(0.008)	[52]
Furfural	6.8 mM	Preacclimatized bacteria from anode of a ferricyanide-cathode MFC	Carbon paper anode and cathode in a one-chamber air-cathode MFC (7 cm^2)/(0.17)	[53]
Galactitol	1220	Preaclimated bacteria from MFC	1-chambered MFC (12 mL) with non-wet proofed carbon cloth as anode and wet-proof CC as cathode/(0.78)	[47]

4.3. Lignocellulosic and biomass-based

Lignocellulosic materials obtained from agricultural byproducts serve as an advantageous resource for generating low-cost electricity because of their natural abundance [43]. However, microorganisms in MFC cannot directly utilize lignocellulosic biomass to generate energy. It needs to be broken down into monosaccharides units. Zhao et al. [44] indicated that each monosaccharide generated through the hydrolysis of lignocellulosic biomass serves as a viable energy source in MFC. When using cellulose as a starting material, bioenergy productionneeds microbial community that possesses both exoelectrogenic and cellulolytic functions. They focused on energy production in MFCs using biomass derived from corn stover waste by employing materials generated via neutral steam derived hydrolysis processes, which yield undissolved sugars present in hemicellulose. Numerous types of biomasses have been examined as potential fuel sources for bioenergy production within MFCs. The biomass used in MFCs can be categorized into two groups: lignocellulosic biomass which consists mainly of food nutrients. Examples of non-lignocellulosic biomass include sewage sludge, animal waste, and algae, among others. The quality of biomass is determined by particular parameters such as moisture content, energy production, bulk density, size and form [45], and this affect the biotransformation mechanisms and production of energy needed in MFCs.

4.4. Food waste derived organic substrate

Food waste generated from homes, restaurants, canteens, and cafeterias constitutes a significant environmental pollutant due to its high organic matter content, elevated salinity levels, and moisture [54]. In addition, food waste serves as an endless source that is abundant in nutrients like carbohydrates, proteins, and lipids, making it a valuable resource for generating energy [55]. Primarily, although not solely, two-chambered MFCs has been employed for power generation utilizing food-derived biowaste. Electrical performance can vary from 1 to several hundred mW/m^2, depending on the type of food substances used. Research involving residual from process of potato plant in single, double, or triple-chambered MFCs achieved a maximum PD 217 mW/m^2 in a single-chamber MFC having working volume of 28 mL, utilizing fibric graphite-based brushes anode and CC for the cathode [56]. An additional type of substrate utilized in MFCs is fruit-based, given their abundant availability. Various waste materials, including those from oranges, bananas, and mangoes, have been tested, with oranges producing a significant voltage output of 375 mV. In research carried out on a one chambered air-cathode MFC, It was found that the ratio of liquid to solid and the type of membrane are vital parameter for generating energy from food waste. They demonstrated that higher energy efficiency in MFCs was attained with a low solid-to-liquid ratio and the use of a Nafion membrane [57].

5. Organic substrate-microbe interaction

Microbes thrive and develop at the anode, generating a dense cell formation known as a biofilm, which clings to the anode of MFCs. Bacteria's metabolism converts organic substrate into CO_2 and electrons [58,59]. MFC processes are ecofriendly [60]. Instead of harmful gas in diesel engines, MFC products include CO_2, water and waste that can be utilized. MFCs would generate electricity by recovering voltage power supply from organics in wastewater with bacteria facilitating biocatalyst, eliminating the need for a complete overhaul of wastewater treatment facilities. MFCs can drive sensors in remote locations where batteries cannot be replaced by collecting energy from wastewater. To make wastewater treatment more cost-efficient, an effective resource recovery plan for existing treatment techniques must be developed [61]. In MFCs, electrons released by bacteria during substrate oxidation in the anode portion are transferred to the cathode section via conductive media. At the cathode, these electrons react with oxygen and protons that have passed through a PEM. MFCs require a constant release of electrons in the anode and a steady consumption of electrons in the cathode [62,63]. Bacterial metabolic energy gain is highly related to the differential between the anode potential and the substrate's redox potential. The electrons created at the anode provide a negative potential at that location. Protons migrate toward the cathode via the proton exchange membrane or salt bridge, creating a positive potential at the cathode. The sum of the oxidation and reduction potentials equals the voltage of the galvanic cell, also known as the electromotive force (EMF), which facilitates the passage of electrons from the anode to the cathode when connected via an external circuit [64].

5.1. Microbial activities in MFCs

In accordance with the setup of MFC system, the inoculation of the biocatalyst is an important parameter influencing the system's bioelectricity generation. Various microorganisms can transmit electrons generated during the metabolism of organic substances to the anode. Electroactive microorganisms produce electricity by oxidizing the organic components in the substrate. Table 2 illustrates these bacteria and their related substrates. These bacteria are prevalent in marine and freshwater sediments, wastewater and activated sludge [65]. Current research has explored bacteria isolation and identifications, along with the development of a chromosomal library for bacteria capable of producing electricity by breaking down organic molecules. Understanding the mechanism of anodic electron transfer in MFCs is critical for understanding their principles of operation [66]. Microbial cell membranes are typically nonconductive, comprised of polysaccharides and necessary lipids. The anode region houses both the bacteria biofilms and the anode electrode. This chamber is often fed with carbon sources in wastewater as well as a redox facilitator as shown in (Fig. 4).

The MFC reactor can be distinguished regarding the presence of exogenous mediators. The first category of

Table 2. Microorganisms utilized in MFCs and their mediators.

Microbes	Substrate	Mediator	Reference
Proteus sp.	Glucose	Metachromatic dye	[71]
Saccharomyces sp.	Galactose and glucose	Methyl blue	[72]
E. coli	Glucose	NR	[73]
Enterobacter cloacae	Glucose	Methyl Viologen	[74]
Saccharomyces cerevisiae	Sugar	Resorufin	[75]
Pseudomonas sp.	Sugar	Pyocyanin	[76]
Aeromonas sp.	Acetate and glucose	Direct transfer	[77]
Geobactersulfurreducens	Acetate	Direct transfer	[50]
Activated sludge	Pond wastewater	Direct transfer	[52]
Proteus vulgaris	Galactose and maltose	Metachromatic dye	[78]
Mixed culture	Sugar and xylose	Humic substances	[79]
Gluconobacteroxydans	Glucose	HNQ	[78]
Klebsiella pneumoniae	Glucose	Direct transfer	[80]
Shewanella oneidensis	Lactate	Direct transfer	[81]
Shewanella putrefaciens	Lactate, Pyruvate, Acetate	NR	[82]
Actinobacillus succinogenes	Glucose	NR	[82]
Mixed consortium	Glucose, Sucrose	Without mediator	[76]
Micrococcus luteus	Glucose	Thionine	[71]

Keys: NR=NeutralRed**,** Anthraquinone-2,6-disulfonate = AQDS, MB = Methylene Blue, HNQ = -2-hydroxy-1,4-naphthoquinon.

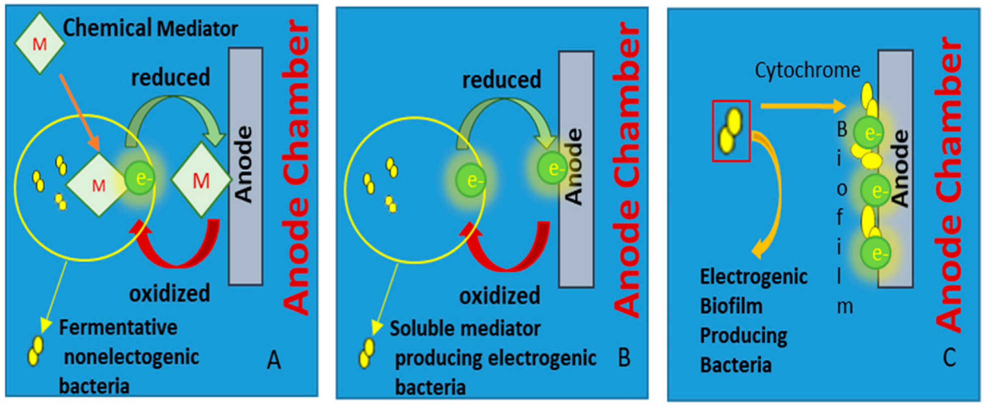

*Fig. 4. Process of electron transfer **(A)** indirect MFC; **(B)** mediator MFC; **(C)** mediator-less MFC [69].*

mediator uses a synthetic mediator (fabricated chemically) to enhance electron transport from the microbes to the anode surface. Fermentative microorganisms in both indirect and mediator MFCs require the inclusion of artificial mediators to transmit electrons between the cell membrane and the anode. Fig. 4B depicts the e-mediator's redox pair. The mediator is necessary in this category because the microorganisms used in MFCs cannot contribute electrons directly due to their nonconductive cell surfaces. A variety of mediators are utilized which include benzyl viologen, phenothiazine etc. [67]. Microbes such as *Enterococcus* and *Pseudomonas* can make their own electrode shuttles, which aid in electron transference (Fig. 4A). Microbes have been discovered to develop mediators naturally when exposed to specific stress conditions (Fig. 4B) [68]. The direct transmission of electrons in MFCs is recognized as an important method for electron transport (Fig. 4C). Electrons are often produced during this process when electroactive bacteria respire and transmit them to the anode.

The addition of biological catalysts, as well as the physical architecture of the MFC system, has a significant impact on bioelectricity generation. Various microorganisms can transmit electrons produced by the metabolism of organic substances to the anode. Hence, electroactive bacteria generate voltage by metabolizing from the organic substances in the substrate. Table 2 depicts the previous studies of such electroactive bacteria along with their corresponding substrates. These bacteria are found abundantly in riverine sediments, ponds, ground sediments, contaminated soil, effluent wastewater, and activated sludge [65]. A lot of current research efforts have laid emphasis on the specification of microbes facilitating the performance of the MFC of producing electricity through the breakdown of organic compounds [70]. Understanding the process of anodic electron transfer in MFCs is critical for understanding their working principles [66].

6. Advance MFC applications

MFCs offer a decentralized and sustainable energy alternative for rural and off-grid places without standard power infrastructure. As an additional electrical power source, MFCs can be modified to generate alternative fuels such as H_2 with little effort. An improved MFC designated as MEC leverages biochemical transformation of hydrogen at the cathodic region to manufacture hydrogen from nonfermentable carbon source; due to the fact that total reaction of the MEC is endothermic. An innovative method was created for harnessing power by investigating the interrelated structure of MEC-MFC employ the electric field overlapping hypothesis [83]. The integrated system's main anode registered an optimal peak power density of 120.9 $mW/m^{2,}$ emphasizing the necessity of an external electric field in enhancing MFC activity.

6.1. Carbon absorption by microalgae

Microalgae can utilize soluble nutrients present in wastewaters to perform photosynthesis in a mixotrophic manner. This characteristic broadens the utilization of microalgae for CO_2 extraction and environmental cleanup. Several species notably *Chlorella*, *Scenedesmus* and *Nannochloropsis,* have shown increased yield of biomass under mixotrophic conditions. The advantages of using algae in photosynthetic MFCs comprise fast growth, minimal needs for space, oxygen generation, and the production of useful byproducts like bioelectricity. MFCs with photosynthetic organisms could collect CO_2 and discharge O_2 into the atmosphere. The concentrating photosynthetic organisms found in the cathodic component, capture CO_2 from the anode region [84].

Wang et al. [85] revealed that the development of *Chlorella vulgaris* found in the cathodic region with necessary operational parameters around the anodic region leads to an optical density of 0.85 and high-power density of 5.6 Wm^{-3}. *Anabaena* sp. demonstrated a considerable value of 57.8 mWm^{-2} with the utilization of CO_2 sparger. These results indicate that MFCs offer tremendous potential for emissions-free output, with consequences for future power supply. It was also reported that a biocathode was developed using *Chlorella sorokiniana*, and the production of energy relies solely on the existence of oxygen [84]. The efficacy was further improved by attaching an additional CO_2 pump at the cathode to the anodic CO_2 pathway. The MFC's peak efficiency was evaluated via determination of an open-circuit voltage at 637 mV and the power density at 2.32 W/m^3. This technology has the potential to be applied in real-world industrial applications, particularly flue gas treatment paired with wastewater management in the future. *Nitzschia palea*was employed as inoculum source in the anode section of a plant MFC, generating 22.31 μg/mL of lipid and achieving a maximum power density of approximately 12.62 mW/m^2 [86]. It has also demonstrated great effectiveness as a sensor for identifying new toxicants at a minimal level. For example, the very first image depicts an MFC that uses heterogeneous microalgal populations as a wastewater detector [87]. The setup produced an optimal current density of 7.2 mW/m^2. In an hour, the sensor detected formaldehyde with a threshold of 69.2 ± 16.7 % cm^2. These methods are also frequently used to detect a wide range of pollutants in wastewater, making this approach more sophisticated than traditional MFCs with power density of 2.32 mW/m^2.

6.2. MFC application as biosensor

Biosensors identify certain chemicals through the combination of a physicochemical monitor and a biological element. An MFC biosensor has been utilized to detoxify wastewater of heavy metals. Researchers all over the world are concentrating on developing soil microbial fuel cell (SMFC) biosensors, which are driving progress in the biosensor field. Real-time monitoring of biochemical oxygen demand, chemical oxygen demand and toxic metals in soil is achieved with cheap SMFC biosensors. Although SMFC-based biosensors can detect a wide range of soil pollutants, their selectivity, sensitivity, repeatability, and stability need be improved [88]. In the study, experiments were conducted using a concentration of 2 mg/L of six different ionic heavy metals such as chromium, copper, cadmium, zinc, mercury and lead.

6.3. MFCs application in desalination

One of the most groundbreaking applications of MFCs is the use of microbial desalination cells, which facilitate the simultaneous generation of fresh water and energy [89]. Reverse electrolysis and osmosis are the basic processes for water desalination using external circuits that include electrodes connected by a membrane that is cation selective. Desalination is an energy-intensive technique for cleaning up wastewater that employs enormous power. The bioelectricity created by the MFC can be utilized for running other desalination systems, lowering the energy necessary for its operation. Therefore, MFC-based desalination can be shown to be less harmful to the environment as well as economically effective. In such a manner, the desalination effectiveness of two laboratory-scale MDCs located at two different sites for seawater and brackish water, using two different processes was investigated. Utilizing two similar MDC experiments and various cathodic techniques, they were able to assess 90 % desalination efficacy and discover important hurdles to technological advancement. Exoelectrogens are regarded as to be the catalyst in anode chambers when mixed consortium is utilized for MDC processes. This feasible solution has the possibility to significantly minimize the adverse effects on the environment and energy expenses linked with traditional desalination methods [90].

7. Challenges and future prospect

MFC systems present significant opportunities for sustainable wastewater management alongside energy generation. Despite published studies highlighting the potential benefits of this system, full-scale implementation remains in the nascent phase, necessitating further optimization and scale-up investigations. The current output from MFC cells is determined by the potential of the microorganisms employed to metabolize substrates and the efficiency of electron transfer between the electrodes, making the overall efficiency dependent on multiple factors. The type and composition of the waste utilized are crucial in determining the amount of energy generated. Furthermore, many experimental parameters involving cell design, electrode types, and operational circumstances might have a substantial impact on bioenergy generation and the quantity of wastewater and pollution removal. Bioenergy generation is also greatly affected by the substrate nature, its starting concentration, and operational parameters. The optimization of these variables, together with the inconsistency experienced, presents a substantial obstacle in building up permanent industrial uses. The introduction of luxurious platinum catalysts is also associated with significant costs. Furthermore, the need for regular cleaning to eliminate biofouling buildup on exchange membranes can lead to extra expenses and create high, undesirable

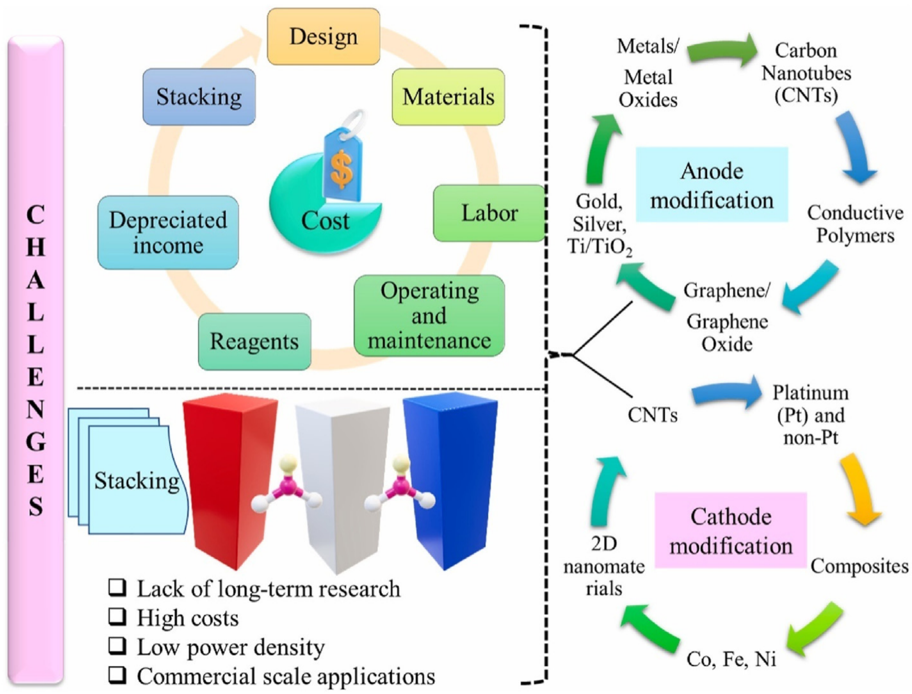

Fig. 5. Current challenges facing MFC progress as outlined by Hassan et al. [91].

resistance to electron movement, thereby impacting power generation. Research is underway to identify alternative non-platinized cathodes that can perform similarly to platinum. Potential alternatives for cathode catalysts include manganese dioxide, stainless steel, and nickel alloys, which may serve as viable replacements for platinized catalysts. Future optimization is projected to position MFCs as a promising choice for sustainable wastewater treatment, especially when compared to anaerobic digestion. Numerous studies have proved the efficiency of MFCs in eliminating different contaminants. Hence, various drawbacks of MFCs for wastewater treatment, such as high costs and energy demands, warrant additional exploration. To boost wastewater treatment efficacy, more work should concentrate on novel MFC circuits. Lastly a broad knowledge of the features and functions of electrode material and fabrication is necessary. Diverse wastewater can be significantly treated by enhancing MFCs on their own or in conjunction with other strategies. Hassan et al. [91] discussed the current challenges and limitations associated with MFC energy generation and wastewater treatment. They provided a comprehensive overview, indicating future directions for the field. Fig. 5 illustrates the problems and constraints that were identified.

8. Conclusion

MFCs provide a viable solution for electricity generation while simultaneously treating wastewater or cleaning up contaminated groundwater. They can achieve substantial COD reduction. The performance of MFCs is influenced by a variety of factors. By considering these factors, one can design an efficient MFC. Most MFCs employed for wastewater treatment have been inoculated with aerobic or anaerobic sludge that run without the requirement for a mediator. Optimal pH and temperature, as in other microbial systems, increase bacteria growth, which improves MFC efficiency. Furthermore, ionic strength and salinity are salient factors to consider. Excessive salt levels may have a negative influence on microbial growth, but higher salinity and ionic activity can improve substrate conductivity, contributing to better MFC performance. The construction and components of the anode, cathode, and membrane have a substantial impact on both expenses and effectiveness, making them major issues in MFC set up. This work supports several United Nations Sustainable Development Goals (SDGs), especially SDG 6 (Clean Water and Sanitation) and SDG 7 (Affordable and Clean Energy). By creating more efficient and cost-effective MFC systems for wastewater treatment and energy generation, we can enhance sustainable wastewater management and improve access to renewable energy sources.

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Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose.

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