Microbial Fuel Cell: Its Efficiency and Applicability

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ABSTRACT: *The economic development of a country depends on the management, applicability, and utilization of its resources. Efficient energy generation and application in the industrial and agricultural sectors are of paramount importance. Due to the high need for a healthy environment coupled with sustainable energy, it has become necessary for the government and industries to look beyond carbon-based energy sources, which most developing countries depend on heavily for their energy generation, and begin to consider other sources of energy. These carbon-based energy sources generate greenhouse gases, causing global warming and climate change. Microbial Fuel Cells (MFCs) are a promising energy source, providing sustainable and environmentally friendly energy. They can harness the chemical energy in organic compounds and channel it to the generation of electrical energy while providing environmental remediation. Its functioning is efficient, widespread, convenient, and promising. This review considers the various types of MFCs, their mode of operation, strategies for improving their performance, and future prospects.*

KEYWORDS: *Microbial fuel cell, Sustainable environment, Chemical and electrical energy, Application.*

INTRODUCTION

Over the past few years, global energy demand has continued to increase rapidly due to population growth and industrial development. Presently, nonrenewable energy sources, such as fossil fuels and nuclear power are widely used in the world for human activity and industrial applications [1, 2]. However, continous use of fossil fuel causes more damage to the environment through emissions of carbon dioxide which becomes toxic at high concentration. In addition, the massive consumption of fossil fuels had a significant impact on human life through

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air pollution, and global warming and will result in a potential energy crisis in the future [3]. Therefore, researchers have made outstanding attempts to find a viable solution to addressing the energy issue by focusing their research on alternate, renewable, and carbon-neutral energy sources [4, 5]. These attempts have been promoting the development of new energy technologies that utilize a fuel cell through the use of bacteria as catalysts in oxidizing organic and inorganic matter into the generation of electricity [6].

In recent years, the production of electrical energy using Microbial Fuel Cell (MFC) technology has become one of the most promising solutions with sustainable potential to meet the world's energy demands [7]. The MFC system operates on the conversion of chemical energy to electrical energy supported by the metabolic activity of certain bacteria. A basic microbial fuel cell design consists of an anode, a cathode, a proton exchange membrane and an electrical circuit [2, 5]. Microbial fuel cell technology have a quiet operation, generate renewable energy and produces no pollution. The major advantages of MFC system are high power density, safety to operate, and a simple structure [8]. The only disadvantages of these new energy sources are their high operational cost and high mass generation [4]. The main requirement of MFC is maintaining a high water content in the electrolyte to ensure high ionic conductivity. Also, water management has an appreciable impact on MFC performance, because at high current densities, mass transport issues associated with water formation and distribution impede cell efficiency such as operating temperature, pressure, and humidification of the gas in the cell [9]. In the last decade, researchers have tremendously enhanced the performance of MFC but certain concerns in regard to practicability and scale-up issues, for instance, the resistance of membrane during transportation of protons and problems in both MFC chambers are still critical challenges facing MFC. In addition to the earlier identified limitations, microbial fuel cells are also facing construction problems in producing energy because energy generation through the MFC system is dependent on the substrate concentration, if the concentration of the substrate present is higher than the optimum value, the production of power will be obstructed [10,11]. Therefore, this review summarises recent progress in these research fields. This paper extensively discussed the practical research findings of various authors, recent advances of microbial fuel cell systems in wastewater treatments, its efficiency, applications, and limitations of MFC technology.

THE MICROBIAL FUEL CELL

A standard MFC is composed of the cathode and the anode compartments. A membrane is used to separate them. Organic compounds generate electrons and protons when microbes that reside in the anode compartments metabolize them; this can occur through anaerobic oxidation [12]. The organic compounds then act as electron donors; the electrons are then transferred to the anode surface, from where they can migrate to the cathode via the electric circuit. On the other hand, protons move through the electrolyte, and then *via* the cationic membrane. The cathode then consumes protons and electrons. Electrical energy is harvested by placing a load between the anode and the cathode compartments [13]. The MFC device can generate electricity by utilizing bacterial action in the metabolization of inorganic and organic substrates under anaerobic conditions. Energy generated from MFC is typically evaluated in terms of power density. It is said to be clean, safe, renewable, and storable, unlike renewable electricity sources such as wind and solar, which face challenges of productivity fluctuations, power transportation, and storage; hence, it needs to be converted to storable fuels. This is the area at which MFCs bridge the gap [14].

In this section, we x-ray the single chamber MFC, which has both the anode and cathode in a single chamber, the dual or two-chambered MFC, which has the anode and cathode in separate chambers; the stacked MFC, which has MFCs connected in series or parallel; and the continuous and batch fed MFCs.

Single chambered MFC

A typical single-chambered MFC is made up of a single chamber; it has only one anode chamber, which harbors the anode; there is no defined cathode chamber, and the cathode is left exposed to air [15-17].

Dual or two-chambered MFC

A double-chambered MFC has two defined chambers, the anode chamber and the cathode chamber, which are separated by a separator, which could be a membrane or a salt bridge [19].

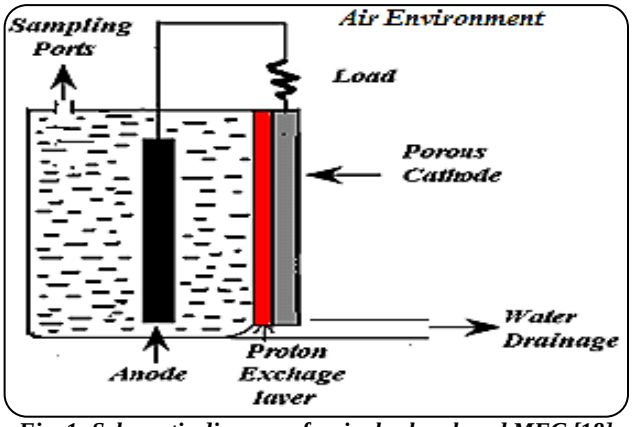

Fig. 1: Schematic diagram of a single chambered MFC [18]

Stacked MFC

Stacked MFCs are those connected either in series or in a parallel configuration. When single MFCs are connected or stacked in parallel, the voltage is the average voltage of the MFCs stacked together, while the current is the sum of the single MFC currents. Similarly, when single MFCs are stacked in a series configuration, the voltage of the stack is the sum of the voltages of the single MFCs [21]. Stacking MFCs helps to increase their power output. [15, 22] also observed that stacking MFCs led to an increase in the voltage generated.

Continuous and batch fed MFCs

Continuous-fed MFCs are those in which the feedstock is supplied continuously without stopping the operation. The MFC has influent and effluent, which go in through the inlet and come out through the outlet. The flow rate can be varied, and each concentration of influent is set for a particular time that is long enough for the MFC to reach a stable level of power output before the effluent is collected and the process continues [16]. While MFCs are supplied, allowed to stay, and analyses are performed, the MFC is cleaned up before another feedstock is supplied; these batch-fed MFCs operate single-chambered MFCs in batch mode for 30 days in series [22].

FEATURES OF A MICROBIAL FUEL CELL

Anode

This is a very important element of the MFC because it has direct contact with the electron-producing microorganism. The anode ensures electron conductivity and also influences strongly the adhesion of microorganisms, which determines the formation of biofilm needed for ensuring the electron transfer from the microorganism to the electrode [23]. In the anode chamber, microbes oxidize the substrates that generate protons and electrons, afterward; electrons are moved to the cathode through an external circuit while protons are moved through the internal membrane; the protons and electrons are then consumed at the cathode, reducing oxygen or using an alternative electron acceptor. In the treatment of wastewater for electricity generation, the anode chamber is usually operated in anaerobic conditions to avoid oxygen, unlike the cathode chamber [24,25]. The method employed in choosing an anode material is important to ensure the adequate performance of the MFC [23]. The anode material should have a large surface area, very good conductivity, chemical stability, and biocompatibility in order to ensure a good and stable relationship between the bacteria and the anode material. In recent time, carbon-based materials have been employed as anode materials [6, 24]. A practical approach to increase the output power of MFC is through the utilization of anode material made up of metal and modified carbon along with conductive polymers [26, 27]. Among various types of conductive polymers, polyaniline is the most commonly used for anode electrode modification [28]. Carbon nanotubes with polyaniline have also been utilized as a suitable material for anode electrodes in MFC [29]. *Zhang et al*. [30] reported that composite of graphite with 30% polytetrafluoroethylene (PTFE) generated electricity with power density production of 760 mW/m^2 with *Esherichia coli* as biocatalyst. Others, are metals or metal oxides, conducting polymers, or composite materials [19].

Cathode

A good cathode electrode is expected to have a high oxygen evolution potential, strong stability, and excellent electrocatalytic activity. *Chen et al*. suggested that cathode material should be fabricated such that it would have high power generation, good Columbia efficiency, and yet be cost-effective. Due to the expensive nature of some metals used in cathode fabrication, such as platinum, there is a need to develop new cathode electrodes whose surfaces have a cathode catalyst for MFCs that are inexpensive and have high performance when it comes to oxygen reduction, decreasing the activation energy barrier, and improving reaction kinetics [31]. Cathode materials with good mechanical strength, high conductivity, and good catalytic

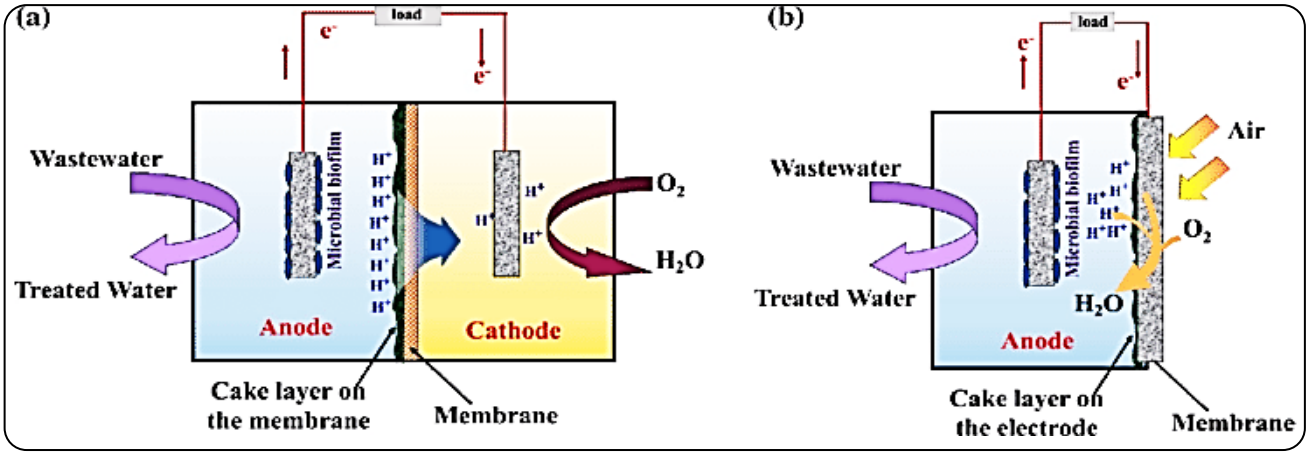

Fig. 2: Schematic diagram of the (a) dual-chambered MFC and (b) the single chamber [20]

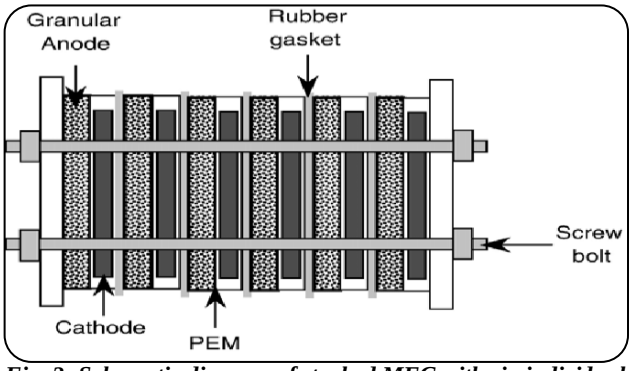

Fig. 3: Schematic diagram of stacked MFC with six individual units [12]

properties are of importance [32]. Currently, more studies are being carried out to develop nanocomposite-based cathode materials to improve the electrochemical activity of MFC systems. These co-composite cathode materials can exploit the specific advantages of each material. It is important to improve the comprehensive electrochemical performance of MFC systems including electron transfer efficiency, oxygen reduction, and operation stability [2]. Some respective anode and cathode performance of previous works are presented in Table 1-3.

Some of the materials employed as cathodes in MFCs are graphite fiber [14], graphite rods [33, 34], and graphite sheets [25]. Many of the materials mentioned as possible anode materials have also been used as cathode materials.

Membranes

These are semi-permeable materials that act as a bridge for the protons to be transferred to the cathode from the anode chamber. Membranes can also inhibit the movement of oxygen from the cathode to the anode. *Harimawan et al.* used a Nafion 202 membrane to separate the anode and cathode chambers of a series of MFCs made from acrylic material [25]. The membrane was adhered with an electrode or without an electrode, depending on the MFC variation. Some of the types of membranes that have been employed in MFCs include:

Proton Exchange Membrane (PEM)

Proton exchange membrane employed microbial fuel cell has been taken a lot of attention as a promising candidate of future power sources especially for transportation application and residential power. This type of fuel cell has many advantages such as high performance, low temperature operation, fast start-up, clean energy, noiseless, no liquid electrolyte and simple cell design. Despite the numerous advantages of PEM fuel cells, its performance and cost should be optimized before this system become economical viable to compete with the traditional combustion power sources [35,36].

Cation Exchange Membrane (CEM)

This type of membrane contains negatively charged groups such as COO^-, $C_6H_4O^-$, and others; they allow positive ions such as H^+ [37] to pass through while preventing negative ions from passing through [30]. *You et al.* used a cation exchange membrane called CM 17000 in their research work, generating a maximum power density of 77.2±4.2 mW/m^2 [16].

Anion Exchange Membrane (AEM)

These membranes contain positively charged groups such as NR_3^+, PR_3^+, SR_2^+, NH_3^+, NHR_2^+, and others that

are attached to the membrane matrix; they allow negatively charged groups to pass through while preventing positive groups from passing through [38].

Inoculum

Researchers have used mesophilic sludge as inoculum in the degradation of the liquid fraction of pressed solid waste for electricity generation [39,40]. Other researchers have also used MFC that was inoculated with 50 mL of aerobic granular sludge from a full-scale wastewater treatment plant in Lubawa, Poland [41]. *Gonzalez et al*. worked with three MFCs, and inoculation was carried out using anaerobic sludge from a wastewater treatment plant. The MFC system produced a maximum power density of 0.08 mW/m^3 [42].

APPLICATIONS OF MICROBIAL FUEL CELLS

Biomass-powered MFCs with generation of electricity

Biomass is one of the most abundant and renewable sources of energy, it constitutes a large source of bio-energy production and has shown promising prospects for the generation of electricity using MFC [43]. *Yifeng et al*. researched electricity generation from wheat straw hydrolysate and the microbial ecology of electricity-producing microbial communities. They pretreated the wheat straw in three steps by liquefaction. A two-chambered MFC was used with Toray carbon paper as an anode and cathode; they were separated by proton exchange. The Chemical Oxygen Demand (COD) concentration was 250 to 2000 mg COD/litres. The bacteria attached to the electrodes were visualized using a scanning electron microscope (SEM). After working for 15 days, they achieved a maximum power density of 13.6 mW/m^2 (0.24 volts), a stable increase in electricity was generated from the hydrolysate without a lag phase, and they were able to maintain a stable power density of 76.6 mW/m^2 (0.58 volts) for 12 days [6]. According to the study conducted by *Shrestha et al*. on the generation of electricity from defective tomatoes, they showed that tomato pomace is a viable electron donor in microbial fuel cells. They used a two-chambered MFC as a laboratory model for microbial electrochemical systems. Five test samples with a COD concentration of approximately 828 mg/L and a pH of 7±0.7 were employed. After working for 125 days of fed-batch operation, the result showed a maximum COD removal efficiency of 92 percent and a peak current and power density of 1504 mA/m^2 and 256.1 mW/m^2, respectively [44].

Superior performance was observed for the cull, which was attributed to its monosaccharide and redox-active species characterized by high electron-transfer rates. They concluded that culled tomatoes are an attractive feedstock for electricity production. The research conducted by *Parkash et al*. (2016) on bio-electricity generation from different biomasses had an aerobic condition in the anodic chamber, which contained the substrate and the biocatalyst. Microorganisms then oxidized the organic matter in the anodic chamber under anaerobic conditions, producing electrons and protons. On the other hand, the cathodic chamber contained salt water and operated under aerobic conditions. Different types of biomass were studied, including cow manure, carbo manure, wastewater, and sewage sludge. The result showed that the maximum power generation obtained was 2500 mV/L using sewage sludge, which has the highest percentage of organic matter. *Pamintuan* and *Sanchez* experimented with power generation in a microbial fuel cell assembly with graphite and stainless steel electrodes growing Vigna radiata (mung beans). They used single-chambered MFC plant, stainless steel mesh, and graphite rods were used as the electrode materials. The resistor had a load of 2000 Ω, and copper wires were then used as the external conductor that connected the electrodes with the resistor load. The polarization studies were conducted on the 30^{th} day of data collection; at this point, the plants had reached maturity and were already producing fruits. The results showed that the stainless steel systems produced a maximum power density of 0.35 mW/m2 under the resistance of 8200 Ω, which was 40% higher than the 0.25 mW/m2 produced by the default resistors of 2000 Ω. The stainless steel electrodes obtained a maximum power density that is about 200 % higher than that of the graphite electrodes. Moreover, plants growing in the fuel cell assemblies with the electrode material in their system displayed more abundance and better growth; they were also healthier and stronger than plants growing in the system without the electrode materials [10]. *Sasaki et al*. researched less biomass and intracellular glutamate in anodic biofilms, leading to efficient electricity generation by microbial fuel cells. The MFC reactor contained one cassette-electrode comprising an air cathode, a separator, and an anode. The air cathode was carbon paper coated with 4-polytetrafluoroethylene layers and a Pt-carbon catalyst [45]. Graphite felt and a glass filter were used as the anode and separator. The initial resistance of 10,000 Ω was

employed using four MFCs with the same reactor configuration, and COD removal efficiency (%) was calculated using this formula:

$$\text{COD removal efficiency (\%)} = ((COD_{in} - COD_{out})/COD_{in}) \times 100(i) \quad (1)$$

Their calculations showed that the COD removal efficiency was highest in MFC 1, giving 80.7 ± 8.30 %. Geobacter sp. was predominant in the anode biofilm and generated relatively more electricity compared to others. This means that the excessive growth of biofilm-containing microorganisms and probably extracellular polysaccharides prevented electricity generation. They concluded that electricity generation by MFCs varied despite using the same operating conditions and reactor configuration. The complex microbial community in the anodic biofilm revealed that there was a decrease in intracellular glutamate and that microbial biomass correlated with an increase in electricity generation [45].

Chaturvedi and Pradeep adopted a green approach to the utilization of waste for the generation of bioelectricity. They found out that extensive studies have corroborated new insights into MFCs, showing that a wide array of carbon sources, including waste, can be employed using various microbes [13]. *Khan* and *Obaid* conducted an experiment on the comparative bioelectricity generation from waste citrus fruits using galvanic cells, fuel cells, and microbial fuel cells. The result showed that all the cells generated electricity from the citrus fruits; furthermore, the detailed microscopic analysis of all the samples they carried out showed that all MFCs had a higher power output compared to their counterpart fuel cells. The fruits used were lemon, orange, grapefruit, and mixed fruits. Their juices were employed in the MFCs, which had zinc electrodes in the anodic chamber; and copper electrodes in the cathodic chamber, they were dual-chamber MFCs that had four cells connected in series and in parallel. The electrons left the anodic chamber via a copper wire and went to the copper electrode in the form of a current. The proton librated at the anodic chamber and then moved through the salt bridge to the cathodic chamber, where it reacted with O_2 to produce extraordinarily pure water. The result also showed that the lemon in MFC produced the highest power output of 2.92 mW as compared to the orange, which gave 2.64 mW; the grapefruit, 2.25 mW; and mixed fruits, 2.02 mW. Furthermore, comparing the lemon cell series power output of 2.92 mW with the parallel power output of 3.55 mW, the parallel setting is higher, and this is for all four unit cells. They concluded that lemon was outstanding because the physiochemical analysis showed that it has the lowest pH value, which makes it preferable to be used for bioelectricity generation in comparison to other citrus fruits [34]. *Yuta et al*. researched the generation of electricity from rice bran by a microbial fuel cell and the influence of hydrodynamic cavitation pretreatment. They constructed a single-chamber MFC with a carbon-felt anode and an air cathode contained in a carbon cloth. They examined three MFC systems that were connected to an external resistance of 510 Ω. MFC-1 had rice bran and bottom mud; MFC-2 had rice bran; and MFC-3 had bottom mud. After 49 days of working, MFC-1 gave a total electric charge of 1.58×10^3 C, which was four times higher than MFC-2 which gave 3.69×10^2 C. MFC-3 gave the lowest value of 2.04×10^1 C. Showing that both the rice bran and the bottom mud are important for electricity generation. The total electric charge was increased by 26% after pretreatment with hydrodynamic cavitation; phylogenetic analysis revealed dominant growth of fermentative bacteria such as Bacteroides and Clostridium species, as well as exoelectrogenic Geobacter species, in the anode biofilms [1].

Microorganisms-based MFCs with generation of electricity

Microorganisms play an important role as biocatalysts in the generation of electricity through the employment of their natural exoelectrogenic properties [46]. An exoelectrogenic property is the ability of a microorganism to generate and transfer electrons extracellularly. Microorganisms can generate electricity as a result of their metabolic processes; hence they are often used as anodic or cathodic biocatalysts in different reactor constructions. These electricians are capable of utilizing the anode as a terminal electron acceptor [7]. Table 1 gives examples of these microorganisms and how they were employed.

Two research scholars utilized fungi-based microbial fuel cells. They found that MFCs owe their popularity to various microorganisms such as bacteria, fungi, or algae, whose catalytic activity allows for current generation from a wide range of substrates [47]. Fungi can be used as both anode and cathode biocatalysts. They also found that fungi have been used in MFC systems in two main modes: (1) in the anode, electron transfer is realized directly *via*

redox-active fungal proteins or with the help of chemical mediators facilitating the transport of electrons; and (2) in the cathode, fungi are the source of enzymes catalyzing the reduction of a terminal electron acceptor, which is mainly oxygen. They concluded that power production in MFCs using a single strain of fungi seems comparable to power production in MFCs using a single bacteria strain. Research has shown the performance optimization of microbial fuel cells using Lactobacillus bulgaricus. They used Lactobacillus bulgaricus as an electricity producer in a dual-chamber MFC reactor, with carbon rods serving as both the cathode and the anode. They assessed the effects of the optical density (OD, 0.5, 0.6, and 0.7), the operation time (3, 30, and 100), the reactor volume (100 and 500 mL), and the type of electrolyte (potassium ferricyanide and potassium permanganate) on the performance of the MFC system. The result showed that after 100 hours of operation, the 500 mL reactor had a power density of 125 mW/m^2. When both 100 mL and 500 mL reactors were combined and connected in series, the maximum power generated increased to 201.8 mW/m^2 [27]. *Fakhrial et al*. worked on electricity generation in a Microbial Fuel Cell (MFC) by a bacterium isolated from rice paddy field soil. They used a single-chambered MFC with rice paddy field soil as both the inoculum and substrate. The anode and cathode were graphite fiber, with resistors of values 47, 100, 470, 1000, 2200, and 4700 Ω. After working for 30 days, the results obtained showed that the maximum power and current output for mixed bacterial species were 77.62 μW and 0.7 mA, while those for the pure culture were 51.32 μW and 0.28 mA respectively. *Chaijak et al.* experimented with enhancing electricity generation using a laccase-based microbial fuel cell with yeast galactomyces on the cathode. They used a two-chambered MFC; the anode electrode was plain carbon cloth, while the cathode electrode was of three types, namely, Vulcan-carbon cloth coated with 0.03 mg/cm^2 Pt (positive control), plain carbon cloth with coconut coir (negative control), and plain carbon cloth with *G. reessii* cultured for 7 days on coconut coir. External resistors of 390, 500, and 1000 Ω were connected to the electrodes. The result showed that the MFC with *G. reessii* produced a maximum OCV of 250 mV, a power density of 59 mW/m^2, a current density of 278 $mA/m^{2,}$ and a 70 % increase in cathode potential as compared with the negative control (absence of *G. reessii*). They demonstrated that the laccase–producing yeast *G. reessii* can serve as a biocatalyst in the cathode of the two-chambered MFC [28]. *Abdallar et al*. employed laccase-producing Aspergillus sydowii NYKA 510 as a cathodic biocatalyst in the self-sufficient lightning microbial fuel cell. They isolated and identified Aspergillus sydowii NYKA 510 as the most potent laccase producer among the three soil-derived fungi strains. They added copper sulphate which elevated the enzyme yield to 145 %. It was employed in an MFC with a system of sets of MFC connected in series. It produced 1.5 W and was sufficient for lighting a 0.8-watt LED light bulb for 100 h (4 days). The best performance was obtained in 2000 Ω achieving 0.76 V, 380 mA/m^2, 160 mW/m^2, and 0.4 W [46]. *Cao et al.* worked on the characterization of electricity generated by soil in microbial fuel cells and the isolation of soil-source exoelectrogenic bacteria. Seven soil samples were collected across China and packed into air-cathode MFCs to generate electricity over 270 days. Twenty-one air-cathode MFC reactors were built into beakers. Square carbon felt was used as the anode, while platinized carbon paper was used as the cathode. After working, they generated a maximum power density that ranged from 16.4 to 28.6 mW/m^2. They concluded that soil OC content had the most important effect on power generation and that the clostridiacease was the dominant exoelectrogenic bacteria group in the soil [47]. *Angelacilincy et al*. studied biofilm engineering approaches for improving the performance of microbial fuel cells and bioelectrochemical systems. They addressed the biofilm formation mechanism in electroactive microorganisms and strategies for improving the biofilm formation, leading to improved electrocatalytic rates for application in bioelectrochemical systems. They concluded that while metal-reducing bacteria, mainly Geobacter spp. and Shewanella spp., have contributed much to the MFCs, other exoelectrogens also need to be discovered, employed, and tapped for future enhancement of MFC-supported technologies [48]. *Jung* and *Regan* experimented with the influence of resistance on electrogenesis, methanogenesis, and anode prokaryotic communities in microbial fuel cells. They constructed a two-chambered MFC, the anode was a carbon paper inoculated with anaerobic sludge, and the cathode was also carbon paper but coated with 0.35 mg Pt/cm^2 and separated from the anode by a Nafion membrane. They had two sets of triplicate reactors: acetate-fed reactors and glucose-fed reactors. After working, they obtained a maximum current

Table 1: Microorganisms employed in MFC

Substrate	Separator	Chamber	Microorganisms	Maximum Power density	References
		Two chambers, Anode: Carbon paper, Cathode: Carbon paper	Consortia (Bacteria), Bacillus	123 mW/m^2	[6]
			Geobacter sp.		[45]
	Proton exchange membrane	Two chambers, Anode: Carbon rod, Cathode: Carbon rod	Lactobacillus, bulgaricus	201.8 mW/m^2	[27]
Rice paddy field soil		Single chamber, Anode: graphite fiber, Cathode: graphite fiber.	Geobacter sp., Shewanella sp., Rhodoferax sp.	77.62 µW	[14]
	Proton exchange membrane	Two chambers, Anode: Carbon cloth, cathode: Carbon cloth	Galactomyces reessii	59 mW/m^2	[28]
	Membrane-less	Single chamber	Aspergillus, Sydowii NYKA 510	160 mW/m^2	[46]
		Air cathode MFC, Anode: Carbon felt, Cathode: Carbon felt	Clostridiaceae	28.6 mW/m^2	[29]
Acetate and glucose	Nafion membrane	Two chambers, Anode: Carbon paper, Cathode: Carbon paper coated with Pt.	Geobacter, Methanosaeta spp.	43.3 ±0.4 W/m^2	[49]

of 284.5 ± 4.6 mA/m^2 and a maximum power density of 44.3 ± 0.4 mW/m^2. Their findings showed that external resistance affects not only the anode potential and current generation but also the anode biofilm community and methanogenesis [49]. Adegunloye and Olotu studied the generation of electricity using microbial fuel cells powered by benthonic mud collected from two locations in Akure, Nigeria. The electrodes used in the MFC were made of carbon rods obtained from dry cell batteries, while a salt bridge was used as the separator. Benthic mud was collected from two locations in Akure, and they isolated bacteria and fungi from the benthic mud for two days using standard microbiological techniques. The control setup was sterilized mud from the same source, and their result showed that they generated a maximum voltage of 192.5 V and a current of 0.53 A, They concluded that anaerobic microorganisms are capable of producing electricity from microbial fuel cells under appropriate conditions [50].

Dye-based MFCs with the generation of electricity

Azo dyes are characterized by the presence of one or more azo bonds, which are represented thus: (-N=N-) in association with aromatic systems and auxochromes ($^-$OH, SO_3, etc.). They are commonly used because of their chemical stability, but most dyes are carcinogenic, allergenic, non-biodegradable, and quite toxic; hence, their continuous and extensive usage poses serious human health risks and environmental hazards. Some other methods, like electrodeposition, electro-flotation, electro-coagulation, and electro-oxidation, have been employed to remove dyes from wastewater [51, 52], but they are expensive and not very efficient [53]. MFC is promising when it comes to the treatment of wastewater containing dyes. Dyes are often classified by their chromophore group as azo, anthraquinone, triphenylmethane, heterocyclic, or phthalocyanine dyes [24]. Researchers have made efforts to find an alternative to the usual conventional large-scale dye treatments; hence, bioremediation has been considered since it is less expensive and environmentally friendly. MFC technology has been considered a promising approach for the removal of pollutants while also generating electricity.

Cheng-Gan et al. used Fe(II)-EDTA-catalyzed persulfate to decolorize an azo dye, orange G, in microbial fuel cells. They used a 2-chambered MFC, which consists of an anaerobic anode chamber and an aerobic cathode chamber. Fe(II)-EDTA-catalyzed persulfate was used as the cathode solution to decolorize Orange G (OG) and harvest electricity simultaneously. After 12 hours of operation, they generated a maximum power density of 91.1mW/m^2, the OG removal rate was 97.4 % and OG degradation by Fe(II)-EDTA catalyzed persulfate was found to follow the second order kinetic model [54]. *Zakaria* and his team chose reactive orange 16 as the model dye because of its high resistance to conventional treatment methods. They used commercially available activated charcoal and charcoals from coconut trunks, mangrove wood, rubber wood, and sugar cane in an attempt to compare them and fabricate effective and low-cost electrodes for the decolorization of reactive orange 16 dye. Their result concluded that all charcoal composite electrodes had good potential for decolourizing reactive

Table 2: Dye removal employed in MFC

Separator	MFC type	Removal Efficiency (%)	Maximum Power density	Type of Dye	Reference
Proton exchange membrane	Two chamber, Anode: Graphite rod, Cathode: Graphite rod	97.4	91.1 mW/m^2	Orange G	[54]
Proton exchange membrane (Nafion 117)	Two chamber, Anode: Carbon toray sheets, Cathode: Carbon toray sheets	86 %	180.5 mW/m^2	Anthraquinone dye ramazol blue R.	[24]
Proton exchange membrane (Nafion 112)	Two chamber, Anode: Granular graphite, Cathode: graphite rod	82.59 %	28.3 W/m^2	Azo dye Amaranth	[33]
	Single chamber, Anode: graphite rod, Cathode: graphite rod	80 %	2,236 mW/m^2	Acid navy blue R.	[17]
Cation exchange membrane (CM 17000)	Two chamber, Anode: Carbon fiber, Cathode: Carbon fiber	94 %	77.2± 4.2 mW/m^2	Acid Orange 7	[30]

orange 16 textile dye [53]. Earlier studies have shown that microbial fuel cell-induced production of fungal laccase degrades the anthraquinone dye ramazol brilliant blue R. They used a two-chambered MFC, and the result showed that the MFC cathode chamber promoted both anthraquinone dye decolorization up to 80 % and a higher power density of 180.5 mW/m^2. The operation lasted for 20 days, during which 62.1 % of organic matter was removed in the anodic compartment, thus leaving the effluent with much lower toxicity [24]. Wlodarczyk and Wlodarczyk worked on the degradation of Azo dyes using in-situ Fenton reaction incorporated into H_2O_2-producing microbial fuel cells. They used two-chambered MFC with graphite as both the anode and the cathode, then proved that in addition to power yield, it was also possible to synthesize H_2O_2 in the catholyte of an MFC system. H_2O_2 produced from MFC can be mixed with an iron solution; a new external power-free electrochemical Fenton system will be established, which gives rise to what we call the MFC-Fenton system. This was then used to investigate the in-situ degradation of amaranth (Azo dye) in conjunction with power generation. When 1 mmol/L Fe^{2+} was applied, the amaranth (75 mg/L) was removed with a ratio of 82.5 % in 1 hour. In the end, they generated a maximum power density of 28.3 W/m^3 [3]. *Khan et al*. conducted research on the bioelectricity generation and bioremediation of an azo dye in a microbial fuel cell-coupled activated sludge process. They used a combined anaerobic-aerobic process; the anaerobic system was a typical single-chambered MFC that utilizes acid navy blue R (ANB) dye along with glucose as a growth substrate to generate electricity. Graphite rods were used as both the anode and the cathode, and the result showed that Columbic Efficiency (CE) and power density attained peak values of 10.36 % and 2,236 mW/m^2 for 200 ppm of ANB. A further increase in ANB concentrations resulted in a lowering of cell potential and power density values owing to microbial inhibition at high concentrations of toxic substrates [17]. *Mari et al*. worked on the role of natural laccase redox mediators in simultaneous dye decolorization and power production in microbial fuel cells. The laccase enzyme was used as a biocathode of the MFC in the presence of two natural redox mediators and a commonly used artificial mediator in order to compare them. These were then used to investigate their influence on azo dye decolorization and power production. Their result showed that after 24 hours of working, they achieved 94 % decolorization efficiency and a maximum power density of 77.2±4.2 mW/m^2. Analysis suggests that natural lacassse redox mediators may improve pigment decolorization (acid orange 7) and power density in microbial fuel cells [30].

Wastewater-powered MFCs with the generation of electricity

The pollution of the world is continuously growing, resulting in an increase in energy demand, which in turn leads to an increase in waste production. Today, wastewater can be treated to prevent pollution and used to generate electricity, making it an excellent source for meeting the world's growing energy needs. Wastewater is considered a major health hazard for the human environment and other organisms, most importantly the aquatic life where the wastewater goes directly [55]. Wastewater from various sources acts as a suitable substrate for bioremediation [64], and its application in MFC technology has proved to be an ideal solution to the long-lasting problem of wastewater management [38]. Nitrogen compounds and other nutrients discharged from wastewater and other human activities can cause

eutrophication and deterioration of the quality of water and aquatic ecosystems [56].

Harimawan et al. also studied the effect of electrode spacing on power generation from a microbial fuel cell using tapioca wastewater. A graphite sheet without a metal catalyst was used as both the cathode and anode. Four variations of electrode distances were applied. Their findings showed that the MFC with the longest electrode achieved the highest equilibrium OCV of 676 mV, while the MFC with the shortest electrode distance achieved the highest power density of 7.74 mW/m^2. Electrochemical Impedance Spectroscopy (EIS) measurement suggested that the charge transfer resistance was dominant in all MFC configurations [25]. *Adeleye* and *Okorondu* also worked on generating bioelectricity from student hostel wastewater using a microbial fuel cell. They used carbon and copper electrodes, producing a carbon-carbon and a copper-copper fuel cell, respectively. A 2 % agar proton exchange membrane was used to connect both chambers of the fuel cell. Wastewater generated from the students' hostel was used as the substrate, and after working for 14 days, the fuel cells connected in series yielded the maximum output; a combined voltage of 138 mV was obtained. They also observed that the copper-copper fuel cell yielded a better result than the carbon-carbon fuel cell [57]. *Rozsenberski et al*. experimented with a comparison of anaerobic degradation processes for bioenergy generation from the liquid fraction of pressed solid waste. They employed five MFCs, operating them in parallel with different Liquefied Pressed Waste (LPW) Supplements. They used a two-chamber MFC with carbon cloth as the anode and cathode. The result showed that cumulated energy yields, which range between 2.55 J and 18.25 J, were obtained depending on the amount of LPW added. The COD removal efficiency of most of the MFCs exceeded 80 % which showed that the MFCs are useful in wastewater treatment [39]. *Kook et al.* studied the bioelectrochemical treatment of municipal waste liquor in a microbial fuel cell for energy valorization. The electrode material was two-chambered MFC and carbon cloth fixed on a graphite rod; the membrane was Nafion N-115 proton-selective membrane. The MFCs were fitted with a 100 external resistor. After working for 15 days, the result indicated that the highest energy yield of 8-9 J/g and change in COD could be attained at the lowest input COD concentration. The maximum and average COD removal efficiencies were 94 % and 87 % [40]. *Flores et al*, experimented with agricultural products for electricity generation using microbial fuel cells. They fabricated low-cost MFCs in the absence of a proton exchange membrane. The cathode was made of copper, and the anode was made of zinc. The organic waste they used was from onions, tomatoes, and potatoes. They were crushed, and 120 mL of each substrate was homogenized with a magnetic stirrer and placed inside the cells. After 21 days of operation, the system generated a maximum power density of 129 µW/cm and a maximum current of 128 µA/cm^{2}and was operated in a pH range of 7.5 to 10. MFCs were connected in series on the last day, allowing for the successful generation of 2.35V and, as a result, the illumination of the LED light [58]. *Barua et al*. researched the generation of electricity using a microbial fuel cell. From sludge. The wastewater was collected using sterile bottles and bags for further studies. A double chamber MFC was employed and five of them were connected in series. The MFCs used zinc plates as anodes and copper plates as cathodes, which were separated by a U-shaped salt bridge. After working for 20 days, the results showed that the MFCs generated 5.05 volts and 4.72 mA [9]. Nosek and *Cydzik-Kwiatkowska* worked on microbial structure and energy generation in microbial fuel cells powered by a waste anaerobic digester. Two sets of two-chambered MFC were used. The anode in MFC 2 was larger than the anode in MFC 1, resulting in organic loading rates of 69.12 mg and 36.21 mg chemical oxygen demand in MFC 1 and MFC 2, respectively. Though the anode in MFC 2 was larger, it did not result in better power generation because the voltages were only initially higher than in MFC 1, but after reaching a plateau, they oscillated at a similar level. But the current density after reaching the plateau in MFC 1 was 836±128 µA/m^2 while that in MFC 2 was 316±101 µA/m^2. After working with the waste volatile fatty acids and aerobic granular sludge from the wastewater treatment plants for 100 hours and applying 1 kΩ resistance, a stable low voltage of 174 mV was generated, and the power density was 15.3 mW/m^2. They used carbon felt as both anode and cathode. They concluded that the use of waste from volatile fatty acids and anaerobic digesters in MFCs favours energy recovery in wastewater treatment plants [41]. *Khan et al*. conducted research on the generation of bioelectricity by microbial fuel cells. They concentrated on the performance of proton exchange membranes and cation

Table 3: Waste water employed in MFC

Substrate	MFC type	Removal Efficiency (%)	Maximum Power density	Separator	Inoculum	Reference
Tapioca waste water	Two chamber, Anode: Graphite sheet, Cathode: Graphite sheet	35-46	7.74 mW/m2	Proton exchange membrane Nafion 202	Rumen feces	[25]
Liquid fraction of pressed solid waste	Two chamber, Anode: Carbon cloth, Cathode: Carbon cloth.	71.6	-	Proton exchange membrane (Nafion 115)	Untreated mesophilic sludge	[39]
Waste volatile fatty acids	Two chamber, Anode: carbon felt, Cathode: carbon felt	85	15.3 mW/m2	Proton exchange membrane (Nafion 117)	Aerobic granular sludge	[41]
Waste water from dairy	Two chamber, Anode: graphite rod, Cathode: graphite rod	90.65	1.4 X 10-2 mW/m2	Membrane-less	-	[37]
Synthetic waste water	Single chamber, Anode: Plane Carbon fiber, Cathode: Activated Carbon	81.9-100	20.7± 1.9 mW/m2	Cation exchange membrane (CMI- 7000)	Sewage sludge	[16]

exchange resin for ion transfer. They used wastewater from the diary as the substrate, graphite rods as the cathode and anode, and the fuel cell reactor was tested as a batch system, similar to a battery. They built two sets of MFCs, one with PEM and the other without, and operated with cation exchange resin, noting that PEM is much more expensive and difficult to regenerate than cation exchange resin. Also, the microporous nature of the resin used in their study facilitates the ion exchange kinetics. The result showed that the current generation of MFC increased the cross-sectional area of the resin bed. Also, the MFC with resin showed the highest COD removal efficiency, which was 90.65 % [37].

Air-cathode MFCs with generation of electricity

Air-cathode MFC consists of a system that has cathodes exposed to air on one side and water on the other. This type of MFC is a practical way of constructing an MFC cathode because it does not require you to aerate the water. This helps to increase cathode stability while generating high power density [36]. PEM in MFCs is used because of its high proton permeability, and thermal and chemical stability, but it is expensive, which has limited its commercial application. PEM is also known for its instability in a dry state, and it depends mainly on the transport mechanism with membrane hydration [59]. Midyurova and Nenov worked on the generation of electricity in microbial fuel cells as a function of air and cathode configuration. They tested the ability of different cathodes based on the usage of polytetrafluoroethylene (PTFE) and carbon black in different ratios as elements of MFC and their influence on MFCs' performance. They found out that carbon black and PTFE are inexpensive compared to PEM. The cathode consists of stainless steel meshes, while the anode is carbon cloth connected to an external electrical circuit loaded with a 100 Ω resistor. After working for four hours, they obtained a maximum current of 291 μA. They concluded that it appears from the preliminary analysis with air cathodes that the use of carbon black (Vulcan) with PTFE binder on the cathode will be more useful for the current generation of MFCs [36]. *Gao et al*. [60] developed a novel polyethylene air-cathode material for a microbial fuel cell. They developed for the first time a new type of cathode material that contains Porous Polyethylene (PE) sheets and a blended Activated Carbon (AC) and highly conductive Carbon Black (CB) layer. They were blended at different ratios, and the cathodes were then evaluated in single-chambered MFCs. After maintaining the operation over a 2-month period, the maximum power density increased to 1.4 W/m^2 and was maintained in the range of 1.4-1.1 W/m^2. Their study suggests that this new PE cathode material has great potential for use in scale-up MFC systems due to its decent performance, simple fabrication process, and use of low-cost material. *Nam et al*. [61] did a study on how improved structures of stainless steel current collectors increase the power generation of microbial fuel cells by decreasing cathodic charge transfer impedance. They constructed a single-chambered, cubic MFC. They used three different current collectors that were made of non-corrosive stainless steel plates. The reactor had a brush electrode made with a carbon fibre brush and located horizontally to the cathode without a separator. They concluded that increasing the contacting area of a carbon cloth cathode on a metal current collector increased the power, current densities, columbic efficiency, and energy recovery of the MFC by decreasing cathode resistance. The maximum power generated was 1,136 mW/m^2, the highest optimum current was 3,752 mA/m^2 and the highest maximum current was 7, 610 mA/m^2.

Power density was calculated thus [60]:

$$\text{Power Density } P(mW/m^2) = (I \times V)/A \quad (2)$$

That i = I/A, where I is current (mA), V is a projected cathode area, i is current density (mA/m^2).

$$\text{Optimum external resistance } R_{opt} = (V_{opt}/I_{opt}) = (P_{max}/I_{opt}^2) \quad (3)$$

Where R_{opt} is the optimal external resistance for maximum power generation, V_{opt} is the optimum cell voltage for maximum power generation, A is the projected cathode area, P_{max} is the maximum power and I_{opt} is the optimal current for maximum power generation.

Other applications of MFCs

Prasad and Tripathi [22] worked on scaling up sediment microbial fuel cells for powering LED lighting. They used eight individual MFCs stacked together in series and also in a hybrid connection. The single-chambered MFCs had an anode of the copper electrode and a cathode of the zinc electrode. After 20 days of operation, a steady state maximum short-circuit current of 435.25 µA was obtained in the series configuration. The configuration provided a voltage to turn on a device; LEDs were glowing lighter in the series configuration and brighter in the hybrid configuration, which they said was due to increased current in the hybrid connection. The COD concentration was 192 mg/L with an anode compartment pH value of 7.4 average columbic efficiencies (CE) of all eight MFCs were 27.31 %. They discovered that the sediment MFC was both cost-effective and environmentally friendly; thus, they proposed that the power of the sediment MFC be scaled up by connecting in series, and a hybrid can be used in a device. *You* and *colleagues* [16] also investigated a novel analytical microbial fuel cell design for rapid in situ optimization of dilution rate and substrate supply rate *via* flow, volume control, and anode placement. They used a single-chambered MFC; the anode was plain carbon fiber, which was placed in the anode chamber; a cation exchange membrane was used; the cathode was hot-pressed activated carbon, which was open to the air; and the analytical design was a continuously fed microbial fuel cell built-in triplicate. Their results showed that COD removal rate decreased with increasing nutrient supply rate at a very low nutrient supply rate of (0.01-0.02 mmol ha1). The COD reduction rates were over 90 % which suggests that most of the carbon energy source was fully utilized for cell growth and maintenance. They also found that higher power was generated from the smaller anode working volume of 10 mL than the larger 50 mL. *Chouler et al.* investigated effective small-scale microbial fuel cells for energy generation from urine. They used a single-chambered MFC with carbon cloth as both the anode and the cathode; the cathode was open to the air, while the anode was placed inside the anode chamber. A proton exchange membrane, Nafion 115 was hot-pressed to the cathode by applying pressure. The result showed that doubling the electrode length resulted in a power density increase from 0.053 to 0.580 Wm^{-3}. When three MFCs were stacked in parallel, the power output was over 10 times higher compared to individual units. The use of biomass–derived oxygen reduction reaction catalyst at the cathode increased the power density of the MFC to 1.96 mw^{-3} [15].

LIMITATIONS OF MFCS

Microbial fuel cells have some factors that hinder their commercial application. Some of these factors are:

1. Most of the models of MFCs are efficient at a small scale, but when scaled up, their efficiency becomes unstable and possesses a question mark.
2. The continued production of power by MFC depends extensively on biofilm formation by the microbes to help facilitate the movement of electrons from the biofilm to the anode. Some microbes employed require assistance from electron mediators, which can unintentionally reduce the efficiency of the MFC.
3. The efficient generation of electricity depends on many operating conditions, such as operating temperature, internal resistance, oxygen availability, electrode potential, etc. these conditions tend to hinder the application of the MFC on a commercial scale. Researchers have also noted that the success of MFC applications depends largely on the concentration and biodegradability of the organic matter.

CONCLUSIONS

MFC has great potential for providing environmental sustainability while generating energy, however, its large-scale commercialization has not been realized because of the intricate mechanisms involved in its design and the high cost of materials required for its development. Also, the electricity recovered from MFC, in general, is still poor, typically less than 10 % of what is theoretically possible,

and the extracellular electron transfer mechanism is poorly understood. The limited and depleting non-renewable energy sources like fossil fuels will lead to an increase in the cost of conventional electricity as time goes on. Proper utilization and commercialization of MFCs will therefore lead to the development of renewable, sustainable**,** and environmentally friendly energy sources around the world**.**

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