A Comprehensive Review of the Different Methods and Materials for the Construction of MFCs and their Effect on the Performance of MFC

Geeta Mongia[1], Inderbir Kaur[1], Ruchi Gulati Marwah[2] & Aarti Malyan[3]

[1]Associate Professor, Department of Electronics, Bhaskaracharya College of Applied Sciences, University of Delhi, Delhi 110075, India
[2]Assitant Professor, Department of Microbiology, Bhaskaracharya College of Applied Sciences, University of Delhi, Delhi 110075, India
[3]Assistant Professor, Department of Electronics Bhaskaracharya College of Applied Sciences, University of Delhi, Delhi 110075, India

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Abstract - *The use of fossil fuels has increased exponentially to meet the increasing global energy demand caused by rapid industrialization and urbanization. The continuous use of fossil fuels leads to its depletion and environmental degradation, which leads to a global focus on renewable energies. Microbial Fuel Cell (MFC) is a relatively recent concept in the quest for renewable energy sources. It is steadily gaining traction as a viable "green and renewable" energy source. An MFC is an electro-biochemical system that exploits the oxidative ability of microorganisms especially bacteria to produce bioelectricity from organic waste matter. Organic-rich waste streams are being regarded as potential substrates for bio-energy production using MFC technology. MFC technology is an interesting and rapidly evolving inter-disciplinary field that needs contributions from a wide range of disciplines, including microbiology, electrochemistry, electronics, and environmental engineering. The technology is gaining attention and is becoming increasingly important in the field of renewable energy. In recent decades a lot of the work has been done primarily to minimize electrode material costs and to configure MFCs so that current densities are maximized. In this paper, we present a comprehensive review of the performance of MFC. A critical analysis of different electrode materials has been done for dual-chamber MFC and single chamber MFC. We have presented a comparative analysis for different electrode materials. Various advancements from pure electrode material to the composite material for anode and cathode and their impact on output power density have been discussed. The analysis has been focused on bio-electricity production. We tried to analyze the factors affecting the change in the output power density of MFC. We also focus to obtain optimized parameters for high electricity production. The review also highlights the use of MFC technology in wastewater treatment along with bio-electricity production.*

Keywords: **Microbial Fuel Cell, Single-Chamber MFC, Double-Chamber MFC, Bioelectricity Production, Wastewater Treatment, Biosensor**

1. INTRODUCTION

Fossil fuels are limited and have an adverse impact on the environment. Thus, a sustainable technology with high energy efficiency and lower impact on the environment is needed. A promising candidate for low-cost, high-efficiency electricity generation is the microbial fuel cell. In the past 10-15 years the scientific community has recognized the advantage of microbial fuel cell technology. This technology has a considerable potential to convert organic waste into electricity. [1] Organic matter present, particularly in industrial and agricultural waste-waters has high energy value[2]. MFC is a promising biological technology for directly converting the organic material present in wastewater to electricity[3]. By his experiments in 1991, M.C.Potter discovered that certain bacteria can release electrons (exoelectrogen) into organic matter extracellularly. It was subsequently found that microorganisms' breakdown of organic matter involves electric energy production [4]. This is achieved by the anaerobic oxidation of organic matter through the microbial component of the fuel cell. Geobacter, Shewanella, Pseudomonas, and others have been identified as potential candidates for electricity production in MFC [5]. Various factors affect the performance and power output of Microbial fuel cells. A proper selection of these physicochemical parameters can boost the overall efficiency of MFC. Electrode type, substrates material, and type of electrode assembly are affecting the performance of an MFC. The most commonly used design for the construction of MFC is either dual-chamber MFC or single-chamber MFC. The basic construction of MFC involves a cathode and an anode separated by a proton exchange membrane. The anode and cathode are connected to each other with the help of an external conductor through the load [6]. It can be explained how a microbial fuel cell functions: Microbes in this fuel cell oxidize the substrate i.e., the organic matter to carbon dioxide under anaerobic conditions. Organic matter oxidation leads to the production of free electrons and protons. The electrons get attracted by Anode due to opposite polarities. Electron being a negative charge particle passes from the anode (a positive electrode) to the cathode (a negative electrode) through the external load connection. At the same time, protons go freely through the proton exchange membrane (PEM) from the anode chamber into the cathode chamber. Finally, when oxygen molecules recombine with hydrogen and cathode electrons to produce water, the reaction is completed.. Micro-organisms can transfer electrons from the substrate to the anode based on the metabolic breakdown of organic matter. Microorganisms produce different metabolic products depending on whether they respire aerobically or anaerobically. Under aerobic conditions, when environmental oxygen is available, they consume sugar present in the substrate to produce CO_2 and H_2O. However, under anaerobic conditions, they produce CO_2, H^+ and e^-. The anodic and cathodic reaction is as follows [7].

Anodic reaction:

$CH_3COO^- + 2\ H_2O\ ===>\ 2\ CO_2 + 7\ H^+ + 8\ e^-$.

Cathodic reaction:

$O_2 + 4e^- + 4H^+\ ===>\ 2\ H_2O$

MFC technology is environmentally friendly since it can operate under environmental conditions and produce energy without any pollution. Even if CO_2 is released as one of the end products of microbial oxidation, the substrate absorbs CO_2 during its life cycle by photosynthesis is called a carbon-neutral process. MFC can generate 1.43kWh/m^3 to 1.8kWh/m^3 of power depending on the effluent strength. The effectiveness of an MFC depends largely on the materials used rather than biocatalysts alone. [8].

2. DESIGNS OF MFC

Another key parameter for MFC's efficiency is the MFC design. MFC's efficiency is mainly influenced by the type of design and type of electrode material used for different applications, such as biosensors, wastewater treatment, bioelectricity generation, and bio-hydrogen production[9]. MFCs of different forms include an MFC with double chamber, MFC with a single chamber, MFC with upflow, and stacked MFC. Lots of research work has been done with various design types depending upon their application.

2.1 Double-Chamber MFC

It is a basic design type of MFC as shown in fig1. For its construction, various materials have been used, such as plastic and stainless steel with the coating[10]. Dual Besides these two general designs, i.e. Dual chambered and single-chambered MFC, several modifications to design have been made to refine the MFC for certain applications.

Chamber or double-chamber Fuel Cells consist of two chambers i.e. the cathode and the anode separated by the membrane or the salt bridge. The separator works as a medium for the transfer of protons. H design MFC is a commonly used design[11]. Since for the breakdown process to occur, the anode has to be kept oxygen-free, therefore a separator acts as a barrier to prevent the anode to come in direct contact with oxidizers [12], [13]. The power created in H-shaped designs is affected by the surface of the membrane and also by the surface range of the cathode with respect to that of the anode [14]. Different models of dual-chamber MFCs such as rectangular, cylindrical, flat- plate, and miniature MFCs have been developed [15][16].

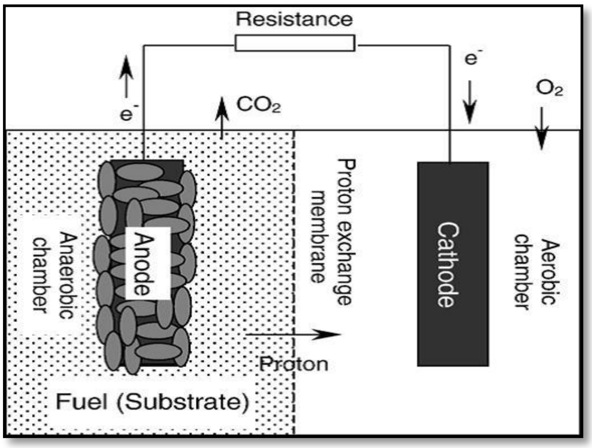


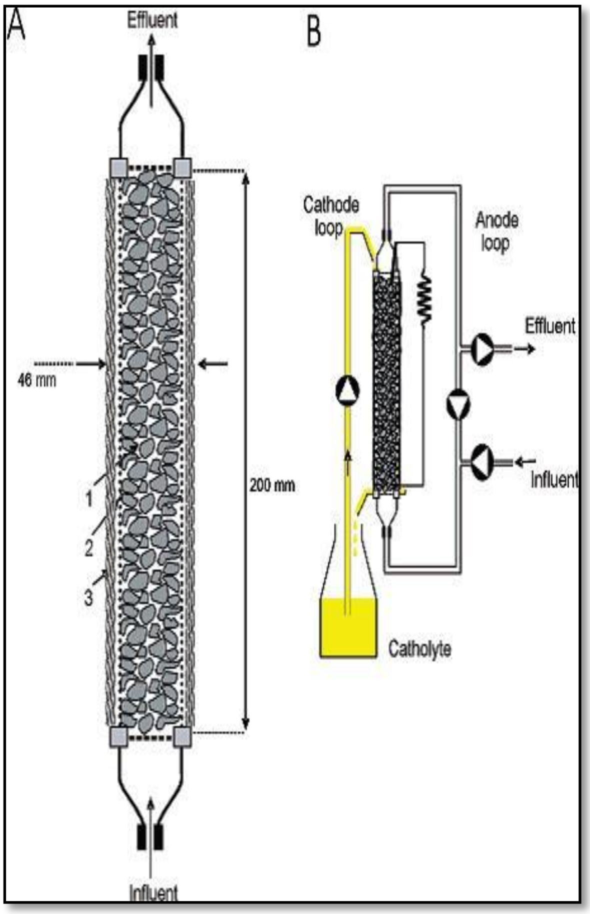
Fig-1: Image shows the Schematic of Basic Dual Chamber MFC [17]

2.2 SINGLE CHAMBER MFC

A modified design type is a single-chambered fuel cell. It is simply an anode chamber with no definitive cathode chamber and may not contain a proton exchange membrane (PEM). Single-chambered fuel cells are quite simple in comparison to the double-chambered In a single-chambered MFC without PEM, a separate rigid carbon paper is used[18]. A single-chambered MFC was designed with an anode connected with a porous air cathode [19]. The back diffusion of oxygen from the cathode and microbial substrate contamination are the main disadvantages in single-chambered MFCs without PEMs. [20].

2.3 SINGLE CHAMBERED TUBULAR MICROBIAL FUEL CELL

As a specific case, single-chambered tubular MFC using granular graphite anode in which ferricyanide was used as a catholyte for continuous flow operation. This design type finds application majorly for wastewater treatment. This arrangement generated a power density of 48W/m3 (net anodic compartment) with domestic wastewater. Coulombic efficiency of 96% that was obtained with wastewater showed that the design can be used for the treatment of wastewater containing considerable significant concentrations of volatile acids [21][22]. In consideration of the electric power, however, installation costs around $900/1W, an order 1000 higher than that of other wind turbine systems [23].



Fig–2: Image shows the Anode, cathode, membrane (A), and overall configuration (B) of the tubular MFC[23]

2.4 STACKED MICROBIAL FUEL CELLS

In stacked MFCs, fuel cells are arranged either in series or in parallel to form a battery of fuel cells, resulting in high power efficiency. In stacked MFC, the performance is affected by electron connection type, flow mode, and operating parameters. The parallel connecting method (series flow mode) has the advantage of chemical oxygen demand (COD) removal and coulombic efficiency and maximum power density due to the increased stability of the oxidation reduction potential (ORP) in the overall cells. The maximum power density of 420 mW/m^2 with an organic charge rate of 25.6 g COD/L-d has been achieved in series flow and parallel connection mode. [24]. A low-cost and high scalability tubular air cathode MFC stack was constructed and investigated in continuous flow modes for wastewater treatment and bio-electricity production. High power output was observed for the parallel stack. Further, it was observed that 83.8% of COD removal was achieved by parallel stack connection whereas the series stack connection COD removal rate was 77.1% [25].

2.5 UP-FLOW MICROBIAL FUEL CELLS

This type of configuration is commonly used for wastewater treatment. Up-flow or cylindrical MFC has an anode at the bottom and a cathode at the top. Anode and Cathode are separated by glass beads layers and glass wool. The influent is fed at the anode, it then moves upward and leaves at the cathode. In this configuration, proton transfer-related difficulties are minimal[26]. For the Up-flow microbial fuel cell, initially, it was observed a power density of 44.1 mW/m^2 and a COD removal efficiency of about 75% [27]. However, it has been reported 94% for COD removal efficiency and 2.4 W/m^3 of power density[28].

The various design has been constructed to obtain higher power densities and also for wastewater treatments. Substrates play an important role in the effectiveness of MFC, along with its design. Substrates can be classified as mediator MFC or Mediator-less MFC.

Mediator MFC- The electron mediator helps in increasing efficiency in a Microbial fuel cell. This results in more electricity generation. They are essentially just compounds in their oxidized state which can easily capture electrons generated by microorganisms and get reduced. These mediators then allow the smooth transfer of the electrons across the membrane. The mediator is oxidized again in the anodic chamber after releasing the electrons from the electrode to the anode [29]. These mediators can thus be reutilized. Methylene blue, neutral red, thionine, HNQ, etc. are toxic and expensive synthetic mediators.

Mediator-less MFC- Some microorganisms can transfer electrons from anode to cathode through the membrane by themselves without any mediator. These are called mediator-less MFCs. Such MFCs are used to remove pollutants from waste-waste streams or sludge and for the safe discharge of clean water to the environment[30]. In mediator-less MFC, due to the low oxygen reduction behavior in the graphite electrode, the fact that the oxygen limitation has been observed at high dissolved oxygen (DO) concentration. These MFCs are more suitable for Biochemical Oxygen Demand (BOD) Sensors[31].

3. ELECTRODES

Electrodes are the major component of MFC. The current conduction for electricity generation is carried out by Electrodes. The quality of the electrode is described by its morphology, its electrical conductivity, and its specific surface area. The efficiency of the microbial fuel cell is affected by these parameters. For good performance of MFC, an anode is taken aerobic and cathode is anaerobic. This results in a great potential difference in the system and these results in a maximum current density of 99.80

μA/cm². The current density is 91.6 percent higher than in a traditional constant anaerobic process. MFC's electricity production will be boosted by an integrated aerobic-anaerobic approach. [32]. Materials used for the construction of anode and cathode are discussed here. MFC performance is greatly affected by the composition and material type.

3.1 ANODE

For a cost-effective and high-performance MFC, anode material plays a major role. Various anode materials have been investigated over a decade for MFC. In the operation of an MFC, anodic resistance leads to effective cell resistance. [33]. The material selected for anode should be chemically stable, biocompatible, and conductive. The cost-effectiveness and scalability are also key factors taken into consideration when selecting the material for the electrode [34]. Since most biological reaction occurs at anode surface, anode surface becomes the major factor for developing a high-performance anode [35]. Further to upgrade the transfer of an electron from bacteria to the electrode surface, anode modification can be done. It has been observed that the power density can be increased considerably by using nanocomposite anodic materials[36]. Many studies have therefore focused on developments to the anode surface characteristics by various modification strategies.

3.2 CATHODE

The performance of the fuel cell is also affected by the cathode structure. The cathode reduction reaction is equally important as an anodic oxidation reaction. The cathode reaction yield depends on the structure and concentration of the electrode and electron acceptor species [37]. Cathode materials are classified into two categories to improve the efficiency of MFC: abiotic and biotic. In an abiotic cathode reduction of oxygen is done by using metal-based catalysts such as platinum (Pt)-carbon electrodes for the production of water. However, the use of such costly material increases the construction cost considerably. To overcome this problem less expensive materials such as Mn_2O_3 and Fe_2O_3 are used [38], [39].

Recent developments and insight on anode and cathode material modification have been discussed below for high-performance and cost-effective microbial fuel cells.

Table-1: Table illustrates the power density obtained for various electrode materials in a Dual Chamber MFC

S.No.	Electrode Material		Substrate	Power Density	Ref.
	Anode	Cathode			
1	Carbon Graphite	Carbon Graphite	Anaerobic Palm oil mill effluent (POME) Sludge	85.12 mW/m²	[40]
2	Graphite Sheets	Graphite Sheets	Food Processing Wastewater	230.3 mW/m²	[41].
3	Graphite Felt coated with platinum	Carbon Cloth (CC) coated with platinum	Brewery waste water	305 mW/m²	[42]
4	Carbon Felt	Carbon Felt	Food waste Leachate with anaerobic sludge	445.6 ± 15.2 mW/m³	[43]
5	Strip/ Mesh of platinised titanium	Strip/ Mesh of platinised titanium	Potato Starch Wastewater	502 mW/m³	[44]
6	Stainless Steel (SS) Mesh	Graphite Plate	Rice Mill Wastewater	530 mW/m²	[45]
7	Carbon Fiber Brush	Wet- proofed	Pig Farm Waste	880 mW/m²	[46]

		carbon cloth coated with Pt	water		
8	Graphite Rods	Graphite Rods	chocolate industry wastewater	1500 mW/m2	[47]
9	Graphene (Gr) modified Carbon Paper	Carbon Paper	Phosphate Buffer Solution (PBS) + Glucose	873 mW/m^2	[48]
10	Reduced Graphene Oxide (r-GO) modified Carbon Cloth	Carbon Felt	PBS + Acetate	1390 mW/m^2	[49]
11	VSG-Vacuum Stripped Graphene	Carbon Cloth	Glucose medium N	1530 mW/m^2	[50]
12	Graphene modified Stainless Steel Mesh	Carbon Paper	PBS+ Glucose	2668 mW/m^2	[51]
13	Single Walled Carbon Nano Tube (SW-CNT) on a mesoporous polysulfone matrix (MPPS)	Carbon Cloth	Lactate	1410 mW/m^2	[52]
14	Carbon Cloth	Bio-r-GO modified Carbon Cloth	Acetate	323 mW/m^2	[53]
15	Carbon Cloth	NG (Nitrogen doped graphene) modified Carbon Cloth	Acetate	776 mW/m^2	[54]

Table-2: Table illustrates the power density obtained for various electrode materials in a Single Chamber MFC

S.No.	Electrode Material		Substrate	Power Density	Ref.
	Anode	Cathode			
1	Carbon Felt	Carbon Cloth	Anaerobic Sludge with Glucose	31.3 mW/m^2	[55]
2	Anode Brush (a core of two titanium wires with graphite fibers)	Wet- Proofed Carbon Cloth	White Wine Lees Wastewater	262 mW/m^2	[56]
3	Toray Carbon Paper	Carbon Paper	Acetate	506 mW/m^2	[20]
4	Titanium wires with 4,00,000 tips of Carbon Fibers	Wet proofed Carbon Cloth coated with Pt	Dye processing wastewater	515 mW/m^2	[57]
5	Graphite Fiber Brush	Carbon Cloth	Coking Wastewater	538 mW/m^2	[58]
6	Plain graphite plates	Plain graphite plates	Dairy Waste Water	1.10 W/m^3	[59]
7	Bio-r-GO modified Carbon Cloth	Carbon Cloth coated with Pt	Acetate	1905 mW/m^2	[60]
8	Gr-modified Carbon Cloth	MnO2	Glucose medium	2850 mW/m^2	[61]
9	Carbon Cloth	N–CNT/ Carbon Cloth	Acetate	135 mW/m^2	[62]
10	Carbon Felt	MnO2/Graphene modified Carbon Plates	Acetate	2084 mW/m^2	[63]
11	Carbon Cloth	MnO2/ GO modified Carbon Cloth	Glucose	2100 mW/m^2	[64]

4. DISCUSSION

Table 1 and Table 2 above, show that advancements for dual-chamber MFC and single-chamber MFC respectively. It can be seen that for dual-chamber as well as for single chamber MFC, high power density is obtained using the graphite rods for anode and cathode material. It is observed in Chart 3, that electrode material for good performance MFC is carbon-based or graphite. Carbon materials used as an anode can significantly promote microbial colonization and accelerate the development of extracellular biofilms which eventually enhances electric power density by providing extracellular electron transfer through a conductive microenvironment. As a cathode, carbon-based materials can serve as catalysts for the reaction to oxygen reduction and nowadays also achieve the results of the Pt catalysts with satisfying activity and performance[65]. The carbon electrode material is preferred over metallic electrodes even though they are more conductive than the latter. This is due to a non-corrosive condition for anode[66]. The power density for dual-chamber MFC, maximum power density obtained is 1550 mW/m^2 and is further increased with the use of modified electrodes. It can be seen that maximum power density in single-chamber MFC, is obtained for graphite plates as an electrode material is 1W/m^2. Further, Chart 3 shows that for a typical substrate, for plane graphite plates as anode material, a power density of 1100W/m^3 can be obtained.

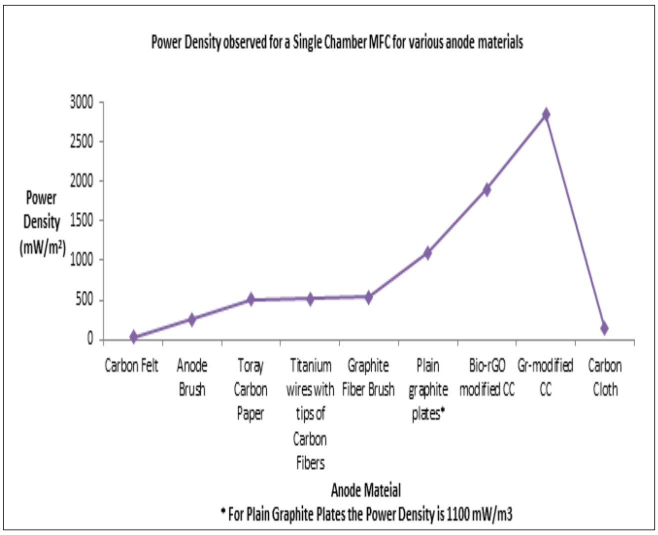


Chart-3: Graph shows the Output Power Density observed for a Single Chamber MFC for various anode materials

The power density for a given substrate for a single-chamber and two-chamber MFC is shown in Table 3 below. It can be seen that for the same substrate, the power density obtained for single chamber MFC is quite higher than dual-chamber MFC. This is due to the fact that, unlike Single Chamber MFC, periodic aeration is required in Dual Chamber MFC [67]. The lower internal resistance of the device also results in a high power generation in single-chamber MFCs [68]. Chart 4 also shows that the power density of a single chamber MFC is higher than that of a dual-chamber MFC. It can also be seen from the graph that the maximum power density is obtained for acetate as a substrate. The reason behind a higher electricity generation for MFCs having acetate as the substrate lies in the fact that the substrate possesses a shorter initiation time, higher average cell voltage, and higher coulombic efficiency[69].

Table 3: Table shows the comparison of Single Chamber and Double Chamber MFC for a given substrate

S.No.	Electrode Material		Design	Substrate	Power Density (mW/m2)	Ref.
	Anode	Cathode				
1	Graphite Fiber Brushes (titanium core)	Carbon cloth	Single Chamber	Food Wastes	556	[70]
	Carbon Rods	Carbon Rods	Dual Chamber		272	[71]
2	Toray Carbon Paper	Carbon Cloth	Single Chamber	Glucose	494±21	[72]
	Carbon Cloth	Carbon Cloth	Dual Chamber		136±87	[73]
3	Graphite Felt	Metallic Graphite	Single Chamber	Sewage Sludge	788	[19]
	Carbon Toray Paper	Carbon Toray Paper	Dual Chamber		36.8-40.1	[74]
4	Carbon Toray Paper	Carbon Paper coated with Pt	Single Chamber	Acetate	661	[20]
	Graphite Felt	Graphite Felt	Dual Chamber		593.4	[75]
5	Carbon Cloth	Carbon Cloth	Single Chamber	Brewery	483	

		coated with Pt		Wastewater		[76]
	Graphite Felt	Graphite Cloth coated with Pt	Dual Chamber		305	[42]
6	Carbon Paper	Carbon Paper coated with Pt	Single Chamber	Swine Wastewater	261	[77]
	Carbon Paper	Carbon Paper coated with Pt	Dual Chamber		45	[77]

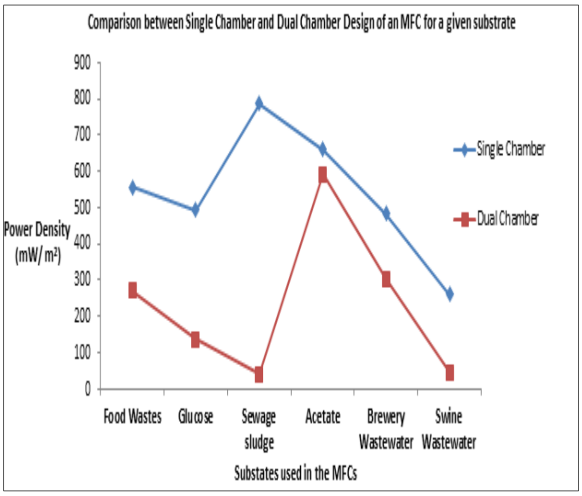


Chart-4: Graph shows the comparison between Single Chamber MFC and Dual Chamber MFC for a given substrate on the basis of Output Power Density

The continuous advancements in the design, substrate material, and electrode material used to result in high-performance MFC. Microbial Fuel Cells generate (bio)energy from waste streams that decrease environmental pollution and also reduce processing costs. For a pollution-free environment, MFCs are a bracing technology that finds their applications in bioelectricity generation and wastewater treatment. They are such bioelectrochemical devices that are expected to tackle the crisis of renewable energy recovery and water shortage by cultivating the idea of recycling wastewater[78]. Much advancement has been done in the technology so that efficient and complete bioremediation of wastes and toxic chemicals can be done leading to wastewater treatment along with electricity generation. The type of design and the electrode material selection majorly depends upon the application of MFC. Two major applications are discussed here.

4.1 BIOELECTRICITY PRODUCTION

Bioelectricity generation is one of the main applications of MFC. The various factors that affect the bioelectricity production in an MFC are: configuration or design of the cell, electrode materials and the spacing between them, substrates, proton exchange membrane, internal/external resistance of the cell, inoculum sources, and ions strength of solution [12][79][80]–[83].

The design of an MFC directly affects the voltage and output power [66]. In a single-chamber MFC, the close placement of the two electrodes results in an increase in the power density due to a decrease in the internal resistance [17]. An annular single chamber has been designed to produce an open-circuit voltage of 810 mV with the maximum power density of 22 w/m^3, by the cell using a Plexiglass cylindrical chamber with a spiral anode. This power density was obtained from wastewater having mixed organic compounds and the power density obtained was much higher than previously published data [84]. In further advancement, a rectangular dual-chamber MFC was designed using Nafion 117 proton exchange membrane and lemon peel waste. A voltage of 0.58 V ± 0.02 V and a maximum power density of 371 ± 30 mW/ m^2 were obtained[85]. The performance of an MFC can also be improved upon by the variations in the electrode materials [66]. It has been reported various anode materials and their mechanisms and advanced anode modification strategies to boost bioelectricity generation. MFC consisting of carbon brush anodes give good bioelectricity production as compared to a stainless steel mesh anode[86]. The bioelectricity production can be further enhanced considerably by modifying the electrode material of the bioelectrochemical system compared to carbon-based electrodes[32]. The maximum current density derived using the anode made of pomelo peel was 40.2 A/m^2, whereas it was equal to 32.5 A/m^2 for the one using anode made of kenaf [25]. The diversity of the culture of microbes being used in an MFC affects the production of electricity[66]. Among the various microbial species used in the MFCs as a source for electricity generation, bacteria are the most promising species whereas the MFCs using yeast have limited applications in the area. An MFC using yeasts essentially requires a mediator for electron transport such as methyl orange, or methylene blue[66]. Recently, it has been observed that Polypyrrol/molybdenum oxides composite (Ppy/MoO2) in a single chamber microbial fuel cell as cathode catalyst (SCMFC) has enhanced the performance of SCMFC drastically. By using Ppy/MoO2 (2:1) Cathode Catalyst(OCP-0.688V), the SCMFC open-circuit potential had been 1.8 times higher than carbon cloth (OCP-0.380 V). This catalyst has a high potential for charge transfer and oxygen reductions [87].

4.2 WASTEWATER TREATMENT

Besides generating electricity, MFCs have another major application for wastewater treatment which further adds value to this novel technology. MFC is a technology involving microbes that accomplishes the breakdown of organic matter. It has been observed by using membrane-less microbial fuel cells helps in the removal of BOD and COD up to 87% and 88% respectively. [88]. Since sulfur compounds are- present in wastewater, the use of hexacyanoferrate cathodic electrolyte in MFC helps in the removal of sulfides thereby making it suitable for wastewater treatment [89]. In comparison to conventional anaerobic processes, biogas produced is used for the production of renewable energy. However, in MFC technology bioconversion process results in electricity production along with wastewater treatment. MFCs offer various advantages such as lower cost of operation and biomass generation, low temperatures operation (<20°C), and concentrations of the substrates [90]. Different types of waste materials such as Municipal waste, wheat straw hydrolysate, dairy wastewater, potato wastewater, paper wastewater, and food waste act as fuel for MFCs. The percentage of COD removal is obtained for the MFC system which in turn determines the efficiency of wastewater treatment[66]. Wastewater treatment results in COD removal efficiencies greater than 80%. This can be attributed to the lower organic loading rates Also COD removal efficiency increases with the addition of granular material to the electrode chamber. It is due to the fact that the granular material creates an increased surface area which increases biofilm attachment and adsorption of pollutants leading to an increase in COD removal [15]. In H-type MFC (dual chamber) using sugarcane molasses as the substrate, the percentage of COD removal was increased from 11.7% after 5 days to 81.7% by the end of the operation (30 days) [91]. A comparative analysis in various wastewaters like chemical wastewater, wastewater from the rice mill, domestic wastewater inoculated by activated sludge has been done. Depending on the use of catalyst at the electrode, power density variation of the range from 593mW/m^2 to 4W/m^2 can be obtained[92]. Electricity is generated using either biocatalysts or enzymes to transform organic matter. MFC is a highly efficient technology with low internal strength. It has large applications for the production of electricity and wastewater treatment.

5. CONCLUSION AND FUTURE PERSPECTIVES

Based on the above data and analysis it can be concluded that the use of biofuels as substitutes for fossil fuels provides a promising alternative source of energy production. Different factors influence the efficiency of MFC and thus affect the output power density. In this paper, we tried to present a comprehensive review based on the chamber design and electrode used respectively for the bioelectricity production in MFC. MFC has a great potential to become a major renewable energy resource in the future. For many applications such as biosensors, portable diagnostic devices, etc. small-scale Microbial Fuel Cells have also been developed. For future perspective, there is a special type of Microbial Fuel Cell: Sediment MFC. Sediment MFCs harvest energy from natural sediments and are also capable of generating greater electric power. More research work is in progress for Sediment MFC. SMFC can effectively treat wastewater while generating electricity. The efficiency of the cell can be increased many folds by optimizing various parameters such as types of electrodes, types of substrates, and construction of the assembly[93]. Further, this technology is a potential candidate for different wastewater treatment. MFCs' performance for efficient energy generation and simultaneously treating wastewater at low cost and with small space claims its candidature for future applications.

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REFERENCES

[1] C. Santoro, C. Arbizzani, B. Erable, and I. Ieropoulos, “Microbial fuel cells: From fundamentals to applications. A review,” J. Power Sources, vol. 356, pp. 225–244, Jul. 2017, doi: 10.1016/j.jpowsour.2017.03.109.

[2] R. Mike, “Microbial fuel cells: A new approach to waste-water treatment - EE Publishers,” Energize, 2018. https://www.ee.co.za/article/microbial-fuel-cells-a-new-approach-to-waste-water-treatment.html.

[3] V. Chaturvedi and P. Verma, “Microbial fuel cell: a green approach for the utilization of waste for the generation of bioelectricity,” Bioprocess, vol. 3, p. 38, 2016, doi: 10.1186/s40643-016-0116-6.

[4] D. Pant et al., “Bioelectrochemical systems (BES) for sustainable energy production and product recovery from organic wastes and industrial wastewaters,” RSC Advances, vol. 2, no. 4. The Royal Society of Chemistry, pp. 1248–1263, Feb. 21, 2012, doi: 10.1039/c1ra00839k.

[5] E. Y. Konovalova et al., “The microorganisms used for working in microbial fuel cells,” in AIP Conference Proceedings, Apr. 2018, vol. 1952, no. 1, p. 020017, doi: 10.1063/1.5031979.

[6] J. Li, “An Experimental Study of Microbial Fuel Cells for Electricity Generating: Performance Characterization and Capacity Improvement,” J. Sustain. Bioenergy Syst., vol. 03, no. 03, pp. 171–178, 2013, doi: 10.4236/jsbs.2013.33024.

[7] Z. Du, H. Li, and T. Gu, “A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy,” Biotechnology Advances, vol. 25, no. 5. Biotechnol Adv, pp. 464–482, Sep. 2007, doi: 10.1016/j.biotechadv.2007.05.004.

[8] C. Munoz-Cupa, Y. Hu, C. Xu, and A. Bassi, “An overview of microbial fuel cell usage in wastewater treatment, resource recovery and energy production,” Science of the Total Environment, vol. 754. Elsevier B.V., p. 142429, Feb. 01, 2021, doi: 10.1016/j.scitotenv.2020.142429.

[9] R. Kumar, L. Singh, and A. W. Zularisam, “Microbial fuel cells: Types and applications,” in Waste Biomass Management - A Holistic Approach, Springer International Publishing, 2017, pp. 367–384.

[10] D. Borah, S. More, and R. N. S. Yadav, “Construction of Double Chambered Microbial Fuel Cell (MFC) Using Household Materials and Bacillus megaterium Isolate from Tea Garden Soil,” Adv. Biol. Res. (Rennes)., vol. 7, no. 5, pp. 136–140, 2013, doi: 10.5829/idosi.abr-.2013.7.5.1109.

[11] S. P, “Simultaneous Chromium Removal and Power Generation Using Algal Biomass in a Dual Chambered Salt Bridge Microbial Fuel Cell,” J. Bioremediation Biodegrad., vol. 04, no. 05, pp. 1–4, Jun. 2013, doi: 10.4172/2155-6199.1000190.

[12] B. E. Logan, “Exoelectrogenic bacteria that power microbial fuel cells,” Nat. Rev. Microbiol., vol. 7, no. 5, pp. 375–381, 2009, doi: 10.1038/nrmicro2113.

[13] S. Karmakar, K. Kundu, and S. Kundu, “Design and Development of Microbial Fuel cells,” undefined, 2010.

[14] F. Li, Y. Sharma, Y. Lei, B. Li, and Q. Zhou, “Microbial fuel cells: The effects of configurations, electrolyte solutions, and electrode materials on power generation,” Appl. Biochem. Biotechnol., vol. 160, no. 1, pp. 168–181, Jan. 2010, doi: 10.1007/s12010-008-8516-5.

[15] A. Janicek, Y. Fan, and H. Liu, “Design of microbial fuel cells for practical application: A review and analysis of scale-up studies,” Biofuels, vol. 5, no. 1. pp. 79–92, Jan. 2014, doi: 10.4155/bfs.13.69.

[16] A. J. Slate, K. A. Whitehead, D. A. C. Brownson, and C. E. Banks, “Microbial fuel cells: An overview of current technology,” Renewable and Sustainable Energy Reviews, vol. 101. Elsevier Ltd, pp. 60–81, Mar. 01, 2019, doi: 10.1016/j.rser.2018.09.044.

[17] Z. Du, H. Li, and T. Gu, “A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy,” Biotechnology Advances, vol. 25, no. 5. pp. 464–482, Sep. 2007, doi: 10.1016/j.biotechadv.2007.05.004.

[18] S. Cheng, H. Liu, and B. E. Logan, “Power densities using different cathode catalysts (Pt and CoTMPP) and polymer binders (Nafion and PTFE) in single chamber microbial fuel cells,” Environ. Sci. Technol., vol. 40, no. 1, pp. 364–369, Jan. 2006, doi: 10.1021/es0512071.

[19] D. H. Park and J. G. Zeikus, “Improved fuel cell and electrode designs for producing electricity from microbial degradation,” Biotechnol. Bioeng., vol. 81, no. 3, pp. 348–355, Feb. 2003, doi: 10.1002/bit.10501.

[20] H. Liu, S. Cheng, and B. E. Logan, “Production of electricity from acetate or butyrate using a single-chamber microbial fuel cell,” Environ. Sci. Technol., vol. 39, no. 2, pp. 658–662, Jan. 2005, doi: 10.1021/es048927c.

[21] K. Rabaey, P. Clauwaert, P. Aelterman, and W. Verstraete, “Tubular microbial fuel cells for efficient electricity generation,” Environ. Sci. Technol., vol. 39, no. 20, pp. 8077–8082, Oct. 2005, doi: 10.1021/es050986i.

[22] G. Bhargavi, V. Venu, and S. Renganathan, “Microbial fuel cells: Recent developments in design and materials,” in IOP Conference Series: Materials Science and Engineering, Apr. 2018, vol. 330, no. 1, p. 012034, doi: 10.1088/1757-899X/330/1/012034.

[23] Q. Yang, Y. Feng, and B. E. Logan, “Using cathode spacers to minimize reactor size in air cathode microbial fuel cells,” Bioresour. Technol., vol. 110, pp. 273–277, Apr. 2012, doi: 10.1016/j.biortech.2012.01.121.

[24] J. Choi and Y. Ahn, “Continuous electricity generation in stacked air cathode microbial fuel cell treating domestic wastewater,” J. Environ. Manage., vol. 130, pp. 146–152, Nov. 2013, doi: 10.1016/j.jenvman.2013.08.065.

[25] L. Zhuang, Y. Zheng, S. Zhou, Y. Yuan, H. Yuan, and Y. Chen, “Scalable microbial fuel cell (MFC) stack for continuous real wastewater treatment,” Bioresour. Technol., vol. 106, pp. 82–88, Feb. 2012, doi: 10.1016/j.biortech.2011.11.019.

[26] S. Venkata Mohan, G. Velvizhi, J. Annie Modestra, and S. Srikanth, “Microbial fuel cell: Critical factors regulating bio-catalyzed electrochemical process and recent advancements,” Renewable and Sustainable Energy Reviews, vol. 40. Elsevier Ltd, pp. 779–797, 2014, doi: 10.1016/j.rser.2014.07.109.

[27] W. E. Thung et al., “Simultaneous wastewater treatment and power generation with innovative design of an upflow membrane-less microbial fuel cell,” Water. Air. Soil Pollut., vol. 226, no. 5, pp. 1–7, May 2015, doi: 10.1007/s11270-015-2410-x.

[28] R. J. Marassi, L. G. Queiroz, D. C. V. R. Silva, F. T. da Silva, G. C. Silva, and T. C. B. d. Paiva, “Performance and toxicity assessment of an up-flow tubular microbial fuel cell during long-term operation with high-strength dairy wastewater,” J. Clean. Prod., vol. 259, Jun. 2020, doi: 10.1016/j.jclepro.2020.120882.

[29] D. H. Park and J. G. Zeikus, “Electricity generation in microbial fuel cells using neutral red as an electronophore,” Appl. Environ. Microbiol., vol. 66, no. 4, pp. 1292–1297, Apr. 2000, doi: 10.1128/AEM.66.4.1292-1297.2000.

[30] A. Parkash, “Generation of Electricity by Mediator less Microbial Fuel Cell Using Sewage Wastewater as a Substrate,” vol. 6, no. March, pp.

2–5, 2016, doi: 10.4172/2090-4568.1000146.

[31] G. C. Gil et al., "Operational parameters affecting the performance of a mediator-less microbial fuel cell," Biosens. Bioelectron., vol. 18, no. 4, pp. 327–334, Apr. 2003, doi: 10.1016/S0956-5663(02)00110-0.

[32] B. Wang, Z. Wang, Y. Jiang, G. Tan, N. Xu, and Y. Xu, "Enhanced power generation and wastewater treatment in sustainable biochar electrodes based bioelectrochemical system," Bioresour. Technol., vol. 241, pp. 841–848, 2017, doi: 10.1016/j.biortech.2017.05.155.

[33] L. Liu, O. Tsyganova, D. J. Lee, J. S. Chang, A. Wang, and N. Ren, "Double-chamber microbial fuel cells started up under room and low temperatures," in International Journal of Hydrogen Energy, Nov. 2013, vol. 38, no. 35, pp. 15574–15579, doi: 10.1016/j.ijhydene.2013.02.090.

[34] J. Wei, P. Liang, and X. Huang, "Recent progress in electrodes for microbial fuel cells," Bioresource Technology, vol. 102, no. 20. pp. 9335–9344, Oct. 2011, doi: 10.1016/j.biortech.2011.07.019.

[35] A. Dumitru and K. Scott, "Anode Materials for Microbial Fuel Cells," in Microbial Electrochemical and Fuel Cells: Fundamentals and Applications, Elsevier Inc., 2016, pp. 117–152.

[36] C. Zhao et al., "Polyaniline networks grown on graphene nanoribbons-coated carbon paper with a synergistic effect for high-performance microbial fuel cells," J. Mater. Chem. A, vol. 1, no. 40, pp. 12587–12594, Oct. 2013, doi: 10.1039/c3ta12947k.

[37] M. Rahimnejad, A. Adhami, S. Darvari, A. Zirepour, and S. E. Oh, "Microbial fuel cell as new technol ogy for bioelectricity generation: A review," Alexandria Engineering Journal, vol. 54, no. 3. Elsevier B.V., pp. 745–756, Sep. 01, 2015, doi: 10.1016/j.aej.2015.03.031.

[38] M. Zhou, M. Chi, J. Luo, H. He, and T. Jin, "An overview of electrode materials in microbial fuel cells," Journal of Power Sources, vol. 196, no. 10. pp. 4427–4435, May 15, 2011, doi: 10.1016/j.jpowsour.2011.01.012.

[39] E. Martin, B. Tartakovsky, and O. Savadogo, "Cathode materials evaluation in microbial fuel cells: A comparison of carbon, Mn2O3, Fe2O3 and platinum materials," Electrochim. Acta, vol. 58, no. 1, pp. 58–66, Dec. 2011, doi: 10.1016/j.electacta.2011.08.078.

[40] M. H. Nor et al., "Bioresource Technology Bioelectricity generation in microbial fuel cell using natural microflora and isolated pure culture bacteria from anaerobic palm oil mill effluent sludge," Bioresour. Technol., 2015, doi: 10.1016/j.biortech.2015.02.103.

[41] H. Jafari, A. Hossein, A. Jonidi, M. Mehdi, A. Rajabizadeh, and N. Khanjani, "Enzyme and Microbial Technology Bioelectricity generation using two chamber microbial fuel cell treating wastewater from food processing," Enzyme Microb. Technol., vol. 52, no. 6–7, pp. 352–357, 2013, doi: 10.1016/j.enzmictec.2013.03.004.

[42] W. Miran, M. Nawaz, A. Kadam, S. Shin, and J. Heo, "Microbial community structure in a dual chamber microbial fuel cell fed with brewery waste for azo dye degradation and electricity generation," 2015, doi: 10.1007/s11356-015-4582-8.

[43] X. M. Li, K. Y. Cheng, A. Selvam, and J. W. C. Wong, "Bioelectricity production from acidic food waste leachate using microbial fuel cells: Effect of microbial inocula," Process Biochem., vol. 48, no. 2, pp. 283–288, Feb. 2013, doi: 10.1016/j.procbio.2012.10.001.

[44] E. Herrero-hernandez, T. J. Smith, and R. Akid, "Biosensors and Bioelectronics Electricity generation from wastewaters with starch as carbon source using a mediatorless microbial fuel cell," Biosens. Bioelectron., vol. 39, no. 1, pp. 194–198, 2013, doi: 10.1016/j.bios.2012.07.037.

[45] M. Behera, P. S. Jana, T. T. More, and M. M. Ghangrekar, "Bioelectrochemistry Rice mill wastewater treatment in microbial fuel cells fabricated using proton exchange membrane and earthen pot at different pH," Bioelectrochemistry, vol. 79, no. 2, pp. 228–233, 2010, doi: 10.1016/j.bioelechem.2010.06.002.

[46] J. Ma, H. Ni, D. Su, and X. Meng, "Bioelectricity generation from pig farm wastewater in microbial fuel cell using carbon brush as electrode," Int. J. Hydrogen Energy, vol. 41, no. 36, pp. 16191–16195, 2016, doi: 10.1016/j.ijhydene.2016.05.255.

[47] S. A. Patil et al., "Bioresource Technology Electricity generation using chocolate industry wastewater and its treatment in activated sludge based microbial fuel cell and analysis of developed microbial community in the anode chamber," Bioresour. Technol., vol. 100, no. 21, pp. 5132–5139, 2009, doi: 10.1016/j.biortech.2009.05.041.

[48] Y. Wang, C. Zhao, D. Sun, J.-R. Zhang, and J.-J. Zhu, "A Graphene/Poly(3,4-ethylenedioxythiophene) Hybrid as an Anode for High-Performance Microbial Fuel Cells," Chempluschem, vol. 78, no. 8, pp. 823–829, Aug. 2013, doi: 10.1002/cplu.201300102.

[49] J. Hou, Z. Liu, and P. Zhang, "A new method for fabrication of graphene/polyaniline nanocomplex modified microbial fuel cell anodes," J. Power Sources, vol. 224, pp. 139–144, Feb. 2013, doi: 10.1016/j.jpowsour.2012.09.091.

[50] Z. He, J. Liu, Y. Qiao, C. M. Li, T. Thatt, and Y. Tan, "Nano Lett._2012_12_4738_4.pdf," pp. 10–13, 2012.

[51] Y. Zhang et al., "A graphene modified anode to improve the performance of microbial fuel cells," J. Power Sources, vol. 196, no. 13, pp. 5402–5407, 2011, doi: 10.1016/j.jpowsour.2011.02.067.

[52] T. H. Nguyen, Y. Y. Yu, X. Wang, J. Y. Wang, and H. Song, "A 3D mesoporous polysulfone-carbon

nanotube anode for enhanced bioelectricity output in microbial fuel cells," Chem. Commun., vol. 49, no. 91, pp. 10754–10756, Oct. 2013, doi: 10.1039/c3cc45775c.

[53] L. Zhuang, Y. Yuan, G. Yang, and S. Zhou, "In situ formation of graphene/biofilm composites for enhanced oxygen reduction in biocathode microbial fuel cells," Electrochem. commun., vol. 21, no. 1, pp. 69–72, Jul. 2012, doi: 10.1016/j.elecom.2012.05.010.

[54] Y. Liu, H. Liu, C. Wang, S. X. Hou, and N. Yang, "Sustainable energy recovery in wastewater treatment by microbial fuel cells: Stable power generation with nitrogen-doped graphene cathode," Environ. Sci. Technol., vol. 47, no. 23, pp. 13889–13895, Dec. 2013, doi: 10.1021/es4032216.

[55] T. S. X. Wu and C. C. Zhou, "Effect of different acclimation methods on the performance of microbial fuel cells using phenol as substrate," 2013, doi: 10.1007/s00449-013-0975-6.

[56] T. Pepe et al., "Electricity generation using white and red wine lees in air cathode microbial fuel cells," J. Power Sources, vol. 274, pp. 393–399, 2015, doi: 10.1016/j.jpowsour.2014.10.050.

[57] T. Karuppiah, A. Pugazhendi, S. Subramanian, and M. T. Jamal, "Deriving electricity from dye processing wastewater using single chamber microbial fuel cell with carbon brush anode and platinum nano coated air cathode," 3 Biotech, vol. 0, no. 0, p. 0, 2018, doi: 10.1007/s13205-018-1462-1.

[58] L. Huang, X. Yang, X. Quan, J. Chen, and F. Yang, "A microbial fuel cell – electro-oxidation system for coking wastewater treatment and bioelectricity generation," no. 2, pp. 621–627, 2010, doi: 10.1002/jctb.2320.

[59] S. V. Mohan, G. Mohanakrishna, G. Velvizhi, V. L. Babu, and P. N. Sarma, "Bio-catalyzed electrochemical treatment of real field dairy wastewater with simultaneous power generation," vol. 51, pp. 32–39, 2010, doi: 10.1016/j.bej.2010.04.012.

[60] Y. Yuan, S. Zhou, B. Zhao, L. Zhuang, and Y. Wang, "Microbially-reduced graphene scaffolds to facilitate extracellular electron transfer in microbial fuel cells," Bioresour. Technol., vol. 116, pp. 453–458, Jul. 2012, doi: 10.1016/j.biortech.2012.03.118.

[61] A. T. Najafabadi, N. Ng, and E. Gyenge, "Electrochemically exfoliated graphene anodes with enhanced biocurrent production in single-chamber air-breathing microbial fuel cells," Biosens. Bioelectron., vol. 81, pp. 103–110, Jul. 2016, doi: 10.1016/j.bios.2016.02.054.

[62] Y. R. He, F. Du, Y. X. Huang, L. M. Dai, W. W. Li, and H. Q. Yu, "Preparation of microvillus-like nitrogen-doped carbon nanotubes as the cathode of a microbial fuel cell," J. Mater. Chem. A, vol. 4, no. 5, pp. 1632–1636, Feb. 2016, doi: 10.1039/c5ta06673e.

[63] Q. Wen et al., "MnO 2-graphene hybrid as an alternative cathodic catalyst to platinum in microbial fuel cells," J. Power Sources, vol. 216, pp. 187–191, Oct. 2012, doi: 10.1016/j.jpowsour.2012.05.023.

[64] G. Gnana kumar, Z. Awan, K. Suk Nahm, and J. Stanley Xavier, "Nanotubular MnO2/graphene oxide composites for the application of open air-breathing cathode microbial fuel cells," Biosens. Bioelectron., vol. 53, pp. 528–534, Mar. 2014, doi: 10.1016/j.bios.2013.10.012.

[65] S. Li, C. Cheng, and A. Thomas, "Carbon-Based Microbial-Fuel-Cell Electrodes: From Conductive Supports to Active Catalysts," Adv. Mater., vol. 29, no. 8, p. 1602547, Feb. 2017, doi: 10.1002/adma.201602547.

[66] P. Choudhury et al., "Performance improvement of microbial fuel cells for waste water treatment along with value addition: A review on past achievements and recent perspectives," Renewable and Sustainable Energy Reviews, vol. 79. Elsevier Ltd, pp. 372–389, 2017, doi: 10.1016/j.rser.2017.05.098.

[67] S. Das and N. Mangwani, "Recent developments in microbial fuel cells: a review," 2010.

[68] S. J. You, Q. L. Zhao, J. Q. Jiang, J. N. Zhang, and S. Q. Zhao, "Sustainable approach for leachate treatment: Electricity generation in microbial fuel cell," J. Environ. Sci. Heal. - Part A Toxic/Hazardous Subst. Environ. Eng., vol. 41, no. 12, pp. 2721–2734, Dec. 2006, doi: 10.1080/10934520600966284.

[69] G. Sun, A. Thygesen, and A. S. Meyer, "Acetate is a superior substrate for microbial fuel cell initiation preceding bioethanol effluent utilization," Appl. Microbiol. Biotechnol., vol. 99, no. 11, pp. 4905–4915, Jun. 2015, doi: 10.1007/s00253-015-6513-5.

[70] J. Jia, Y. Tang, B. Liu, D. Wu, N. Ren, and D. Xing, "Electricity generation from food wastes and microbial community structure in microbial fuel cells," Bioresour. Technol., vol. 144, pp. 94–99, 2013, doi: 10.1016/j.biortech.2013.06.072.

[71] S. S. Rikame, A. A. Mungray, and A. K. Mungray, "Electricity generation from acidogenic food waste leachate using dual chamber mediator less microbial fuel cell," Int. Biodeterior. Biodegrad., vol. 75, pp. 131–137, 2012, doi: 10.1016/j.ibiod.2012.09.006.

[72] H. Liu and B. E. Logan, "Electricity generation using an air-cathode single chamber microbial fuel cell in the presence and absence of a proton exchange membrane," Environ. Sci. Technol., vol. 38, no. 14, pp. 4040–4046, Jul. 2004, doi: 10.1021/es0499344.

[73] N. Ali, M. Anam, S. Yousaf, S. Maleeha, and Z. Bangash, "Characterization of the electric current generation potential of the pseudomonas aeruginosa using glucose, fructose, and sucrose in double chamber microbial fuel cell," Iran. J. Biotechnol., vol. 15, no. 4, pp. 216–223, Sep. 2017,

doi: 10.15171/ijb.1608.

[74] B. Xiao, F. Yang, and J. Liu, “Enhancing simultaneous electricity production and reduction of sewage sludge in two-chamber MFC by aerobic sludge digestion and sludge pretreatments,” J. Hazard. Mater., vol. 189, no. 1–2, pp. 444–449, 2011, doi: 10.1016/j.jhazmat.2011.02.058.

[75] K. L. Dinh et al., “Lactate and acetate applied in dual-chamber microbial fuel cells with domestic wastewater,” Int. J. Energy Res., 2021, doi: 10.1002/er.6550.

[76] X. Wang, Y. J. Feng, and H. Lee, “Electricity production from beer brewery wastewater using single chamber microbial fuel cell,” Water Sci. Technol., vol. 57, no. 7, pp. 1117–1121, 2008, doi: 10.2166/wst.2008.064.

[77] B. Min, J. R. Kim, S. E. Oh, J. M. Regan, and B. E. Logan, “Electricity generation from swine wastewater using microbial fuel cells,” Water Res., vol. 39, no. 20, pp. 4961–4968, 2005, doi: 10.1016/j.watres.2005.09.039.

[78] B. E. Logan and M. Elimelech, “Membrane-based processes for sustainable power generation using water,” Nature, vol. 488, no. 7411. Nature Publishing Group, pp. 313–319, Aug. 16, 2012, doi: 10.1038/nature11477.

[79] B. E. Logan and J. M. Regan, “Electricity-producing bacterial communities in microbial fuel cells,” Trends in Microbiology, vol. 14, no. 12. Elsevier Limited, pp. 512–518, Dec. 2006, doi: 10.1016/j.tim.2006.10.003.

[80] C. S. Butler and R. Nerenberg, “Performance and microbial ecology of air-cathode microbial fuel cells with layered electrode assemblies,” Appl. Microbiol. Biotechnol., vol. 86, no. 5, pp. 1399–1408, May 2010, doi: 10.1007/s00253-009-2421-x.

[81] J. Y. Nam, H. W. Kim, and H. S. Shin, “Ammonia inhibition of electricity generation in single-chambered microbial fuel cells,” J. Power Sources, vol. 195, no. 19, pp. 6428–6433, Oct. 2010, doi: 10.1016/j.jpowsour.2010.03.091.

[82] Y. Qiao, S. J. Bao, and C. M. Li, “Electrocatalysis in microbial fuel cells - From electrode material to direct electrochemistry,” Energy and Environmental Science, vol. 3, no. 5. The Royal Society of Chemistry, pp. 544–553, May 05, 2010, doi: 10.1039/b923503e.

[83] N. Yang, Y. Ren, X. Li, and X. Wang, “Effect of graphene-graphene oxide modified anode on the performance of microbial fuel cell,” Nanomaterials, vol. 6, no. 9, Sep. 2016, doi: 10.3390/nano6090174.

[84] M. Mahdi Mardanpour, M. Nasr Esfahany, T. Behzad, and R. Sedaqatvand, “Single chamber microbial fuel cell with spiral anode for dairy wastewater treatment,” Biosens. Bioelectron., vol. 38, no. 1, pp. 264–269, Oct. 2012, doi: 10.1016/j.bios.2012.05.046.

[85] W. Miran, M. Nawaz, J. Jang, and D. S. Lee, “Sustainable electricity generation by biodegradation of low-cost lemon peel biomass in a dual chamber microbial fuel cell,” Int. Biodeterior. Biodegrad., vol. 106, pp. 75–79, Jan. 2016, doi: 10.1016/j.ibiod.2015.10.009.

[86] A. A. Yaqoob, M. N. M. Ibrahim, and S. Rodríguez-Couto, “Development and modification of materials to build cost-effective anodes for microbial fuel cells (MFCs): An overview,” Biochemical Engineering Journal, vol. 164. Elsevier B.V., p. 107779, Dec. 15, 2020, doi: 10.1016/j.bej.2020.107779.

[87] S. Karthick and K. Haribabu, “Bioelectricity generation in a microbial fuel cell using polypyrrole-molybdenum oxide composite as an effective cathode catalyst,” Fuel, vol. 275, p. 117994, Sep. 2020, doi: 10.1016/j.fuel.2020.117994.

[88] M. M. Ghangrekar and V. B. Shinde, “Performance of membrane-less microbial fuel cell treating wastewater and effect of electrode distance and area on electricity production,” Bioresour. Technol., vol. 98, no. 15, pp. 2879–2885, Nov. 2007, doi: 10.1016/j.biortech.2006.09.050.

[89] K. Rabaey et al., “Microbial fuel cells for sulfide removal,” Environ. Sci. Technol., vol. 40, no. 17, pp. 5218–5224, Sep. 2006, doi: 10.1021/es060382u.

[90] T. H. Pham et al., “Microbial Fuel Cells in Relation to Conventional Anaerobic Digestion Technology,” Eng. Life Sci., vol. 6, no. 3, pp. 285–292, Jun. 2006, doi: 10.1002/elsc.200620121.

[91] S. H. A. Hassan, A. el Nasser A. Zohri, and R. M. F. Kassim, “Electricity generation from sugarcane molasses using microbial fuel cell technologies,” Energy, vol. 178, pp. 538–543, Jul. 2019, doi: 10.1016/j.energy.2019.04.087.

[92] K. Kasipandian, S. Saigeetha, A. V. Samrot, S. Abirami, R. Emilin Renitta, and S. Dhiva, “Bioelectricity production using microbial fuel cell–a review,” Biointerface Research in Applied Chemistry, vol. 11, no. 2. AMG Transcend Association, pp. 9420–9431, Apr. 15, 2021, doi: 10.33263/BRIAC112.94209431.

[93] T. S. Song, Z. S. Yan, Z. W. Zhao, and H. L. Jiang, “Construction and operation of freshwater sediment microbial fuel cell for electricity generation,” Bioprocess Biosyst. Eng., vol. 34, no. 5, pp. 621–627, Jun. 2011, doi: 10.1007/s00449-010-0511-x.