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# A glimpse into the microbial fuel cells for wastewater treatment with energy generation

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**ABSTRACT**

Energy and water storage are a global challenge due to various factors such as ecological changes, increasing population, increasing demand for energy at both commercial/domestic level, and high material cost. To overcome these problems, microbial fuel cells (MFCs) is considered as an emerging novel technology where one side it can generate electricity and on the other hand it also exhibits better removal efficiency of different pollutants from wastewater. In this technology, MFCs can use natural waste materials to produce energy and is also efficient in wastewater treatment. This review covers the basics of the technology around MFCs, focusing on the mechanism of energy production along with wastewater treatment. Some current challenges regarding the MFCs approach (especially electrode play a vital role in the field of MFCs) and some future perspectives are also addressed in this article. Moreover, electrodes constitute a significant component of this technique in deciding the working efficiency of MFCs during wastewater treatment. Hence, the selection of the electrode is a great challenge to make MFCs more prolific and commercial. Therefore, this review addressed these issues along with the concept of electro microbiology.

*Keywords:* Microbial fuel cells; Pollutants; Electricity; Wastewater; Electrodes

## 1. Introduction

Recently, the modern world is facing many problems, but some factors are crucial to address as human beings and other living organisms life depends on these factors. Currently, due to the rising of the global population, the energy demand is becoming immensely high. The report of the International Energy Agency (IEA) shows that the expected energy requirement will be 18 billion tonne oil in 2035, as compared to the current situation which is near to 12 billion tonne oil [1]. Currently, the world obtains its energy by utilizing fossil fuel resources, but their working efficiency, security, and other environmental issues (global warming) make them unsuitable for long-term use. Furthermore, depletion of fossil fuels has also occurred at a rapid pace [2]. So, there is an urgent need to solve this major issue of the modern world related to energy demand. Natural fossil fuels are not classified as renewable energy sources, and this has led to a global energy crisis. To fulfill energy demand in the current scenario of the world, there

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is utmost needs to explore reliable, clean, and sustainable energy resources because non-renewable sources cannot fulfill current demand whilst also producing clean energy and reducing environmental pollutions. Not long ago, the scientific community felt that nuclear energy might be an excellent alternative source of energy, but the safe and proper implementation of this idea still requires more attention [3]. Therefore, there is an urgent requirement to develop a method which can generate renewable and safe energy without the emission of net $CO_2$ [4]. To provide clean and freshwater to the modern world, which is responsible to cover the basic needs of life is also a big task of 21st century. Water is a major part of substance for all living organisms on earth [5,6]. Water is also called the universal solvent because it has ability to dissolve many substances. Therefore, polluted water has unwanted minerals and chemicals that have adverse effects on human health and cannot be used for any direct purpose [7]. Nowadays, natural water sources have become contaminated due to different factors like high residential ratio, commercial factors, industrial demand, improper irrigation system, agricultural wastes, global warming, and medicinal waste, etc. The effect of these factors on natural sources of water has resulted in a shortage of freshwater to maintain a healthy environment for living organisms [8,9]. The acute level of pollution emerging from industries zones like electronic, chemicals, and electroplating are primary sources of wastewater production which has ultimately severe effect on human being and the aquatic environment [10]. Water pollution also has a severe effect on human health and their environment. Recently, the World Health Organization (WHO) reported that there were more than 1.7 million deaths and near four billion suffering from different diseases due to water pollution. This also has a significant impact on the social and economic cost [11,12]. Therefore, it is indispensable to treat wastewater to overcome the environmental pollution problem and save the ecosystem. There were many traditional methods reported for bioremediation of different toxic organic compounds and metals that have adverse effects on living organisms [13,14]. These conventional methods include ozonation, degradation, electrolytic reduction, coagulation, *in situ* and *ex-situ* treatment, thermal treatment, chemical precipitation, *in-situ* confinement [15]. The above-mentioned methods are quite efficient, but they have several drawbacks like no proper electron acceptor or donor's mechanism and are quite expensive, such that they are not easy to maintain at a commercial level. Moreover, all these conventional methods have prolonged process of degrading of organic pollutants by catalyst (microbes). To address these problems, an idea reported by a researcher in 1911 used an innovative method Microbial fuel cells (MFCs) to produce clean and safe energy along with the treatment of wastewater [16]. It also plays a vital role to eliminate water pollution from the environment. MFC is an innovative, eco-friendly, and low-cost method to generate electricity along with water treatment. MFCs is most promising and developing research field for the scientific community to transform chemical/organic energy into electrical energy through using microbes. This technology has significant potential to make renewable energy by utilizing organic waste. So, MFC is a method with great potential and very preferable than other conventional methods [17].

## 2. Functioning of MFCs

MFCs is further categorized into sediment MFCs and benthic MFCs. Both are commonly used for the generation of electricity and bioremediation of pollutant water [18,19]. Generally, MFCs has two chambers consisting of a cathode and anode, respectively. The anode chamber is enclosed into wastewater solutions (heavy metal or organic solutions) and other (cathode) in surface water [20]. There are many types of microbes which can degrade different type of organic compounds and heavy metals from wastewater solutions and produce electrons and protons. The electrons travel from anode chamber to cathodic part by using an external circuit while protons move directly to the cathode and react with oxygen to make a water molecule. MFC depends upon electroactive microbes, usually called exoelectrogens, to remove toxic organic waste along with the generation of renewable clean energy in the form of electricity [21]. In simple words, MFCs is a tool used to degrade organic waste to convert organic energy into electric form by oxidation of substrates, using microbes that serve as a biocatalyst in the whole process, that is, it is modified type of an electrochemical fuel cell. However, there are many factors that play a significant role in the performance of MFC such as internal resistance, catalyst, ion concentration, chemical substrate, and electrodes spacing, MFC modeling, and electrode material properties [22–25]. Electrode material is considered as a significant to make MFC more reliable and commercially attractive because MFC performance depends upon the conductivity and compatibility of electrodes. In MFC electrotrophs microbes accept electrons from electrodes and convert toxic compounds into less toxic components [26]. To generate power in MFCs, different type of exoelectrogens can transfer electrons from electrodes through four mechanisms such as short-range electron transfer through redox-active proteins, soluble electron shuttling molecules, and long-range electron transport by conductive pili, direct interspecies electron transfer. The powerful and efficient mechanism is long-range electron transfer through conductive pili. The pili have similar characteristics like metal, that is, conductivity [27]. Previously, MFC technique was used for remediation of one compound (metal/organic). However, according to development in MFC, now it is very significant and useful to remediate multiple toxic compounds (cobalt, chromium, mercury, zinc, lead, etc.) along with a good generation of electricity by using multi-electrodes in an anode chamber [28–30]. However, MFC is a technique to provide safe, clean, low emission of carbon dioxide, highly efficient energy generation along with wastewater treatment to the modern world (Fig. 1). There were different sources of water pollutants with their adverse effect on the fresh and natural water, as shown in Table 1.

### 2.1. Mechanism of energy production by MFCs

MFCs is an innovative and emerging technique to generate energy along with wastewater treatment. MFC has two major parts, including the anode chamber and cathode chamber, as presented in Fig. 1. Anode electrode is exposed to wastewater and cathode electrodes exposed to surface water [20]. In MFC chambers, many microbes have the ability to

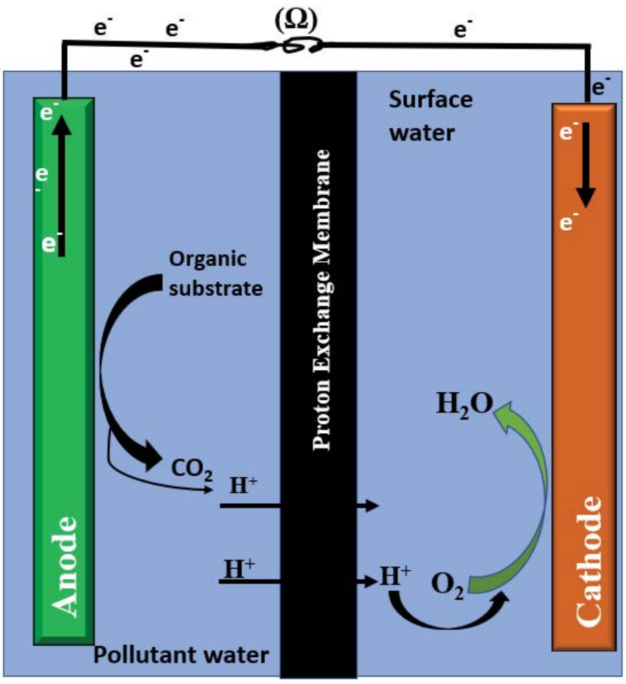


Fig. 1. Schematic diagram of MFCs.

transfer electrons and protons through electrodes [42]. There were five dominant microbes' groups such as *Firmicutes*, *Proteobacteria*, *Acidobacteria*, fungi, and algae that show the electricity generation for their respiration in MFC chamber [43]. Moreover, there were also some microbes reported as electron exchanger with electrodes, these are *Clostridium butyricum* [44], *Rhodoferax ferrireducens* [45], *Shewanella* sp. [46], *Geobacter* sp., and *Aeromonas hydrophila* [47]. They also show some electric properties in nature. During the MFC working, microbes can break down different organic and heavy metals complexes to produce electrons and protons to empower their respiration system. They have the ability to produce a flow of electrons by using electrodes. However, microbes can transfer electrons into the insoluble state of electron acceptors. For example, *Geobacter* has pili which are conductive like metal. Microorganisms grow on the surface of electrodes and make biofilm to transfer electrons more efficiently than using insoluble electron acceptors [48]. Microbes transfer the electrons extracellularly is called exoelectrogens and there were some reported species has ability to transfer electrons, include *Geobacter lovleyi* [49], *Geothrix fermentans*, *Thermincola carboxydophila*, *Geobacter sulfurreducens* [50], *Shewanella oneidensis* [51], *Rhodopseudomonas palustris*, *Thermincola potens* [52], *Escherichia coli* [53], and *Shewanella putrefaciens* [54,55]. For the generation of electricity, exoelectrogens can transfer electrons from electrodes through stated mechanisms such as short-range electron transfer through redox-active proteins, soluble electron shuttling molecules, and long-range electron transport by conductive pili, and direct electron transfer. The direct electron transfer means a direct contact of microbes and electrode surface. There is no mediator or source to transfer the electrons to the anode surface [56]. The better way is long-range electron transfer via conductive pili. The microbes generally follow the routes to transfer electrons as shown in Fig. 2. Different types of wastewater sources are used as a substrate to enhance current density were summarized in Table 2.

Furthermore, there were some reported exoelectrogens are summarized in Table 3 with electron transfer intermediates and their power density.

## 3. Bioremediation of pollutants from wastewater using MFCs

MFC has potential to remove different types of pollutant from wastewater and make it suitable for human use. Several toxic heavy metals, organic, and inorganic compounds are found in wastewater. In this review, bioremediation of toxic heavy metals has been discussed and summarized the general mechanisms of wastewater treatment through MFC. The microbe's properties to accept electrons from (anode and cathode) electrodes are known as electrotrophs. This gives a new direction for the treatment

Table 1
Sources of water pollutants and their adverse effects

| Sources of water pollution | Pollutants | Effect of water pollutants | Reference |
|---|---|---|---|
| Metals complexes, trace major and minor elements, mineral and salts, and heavy toxic metals | Inorganic based pollutants | Public health issues | [31] |
| Agricultural chemicals | Agricultural waste | Adverse effect on natural water sources | [32] |
| Detergents, insecticides, pesticides, and herbicides | Organic pollutant | Aquatic life issues and carcinogenic problems | [33] |
| Different bacteria and viruses | Pathogens | Waterborne diseases | [34] |
| Municipal contaminated water | Industrial waste | Responsible for water and air pollution | [35] |
| Plant debris and different fertilizers | Nutrients pollutants | Adverse effect on eutrophication process | [36] |
| Isotopes | Radioactive waste | Bones, teeth, and skin diseases | [37] |
| Marine debris | Macroscopic wastes | Plastic pollution | [38] |
| Sewage and domestic wastes | Water pollutant | Waterborne diseases | [39] |
| Pharmaceutical drugs | Drug pollutants | Environmental pollution | [40,41] |

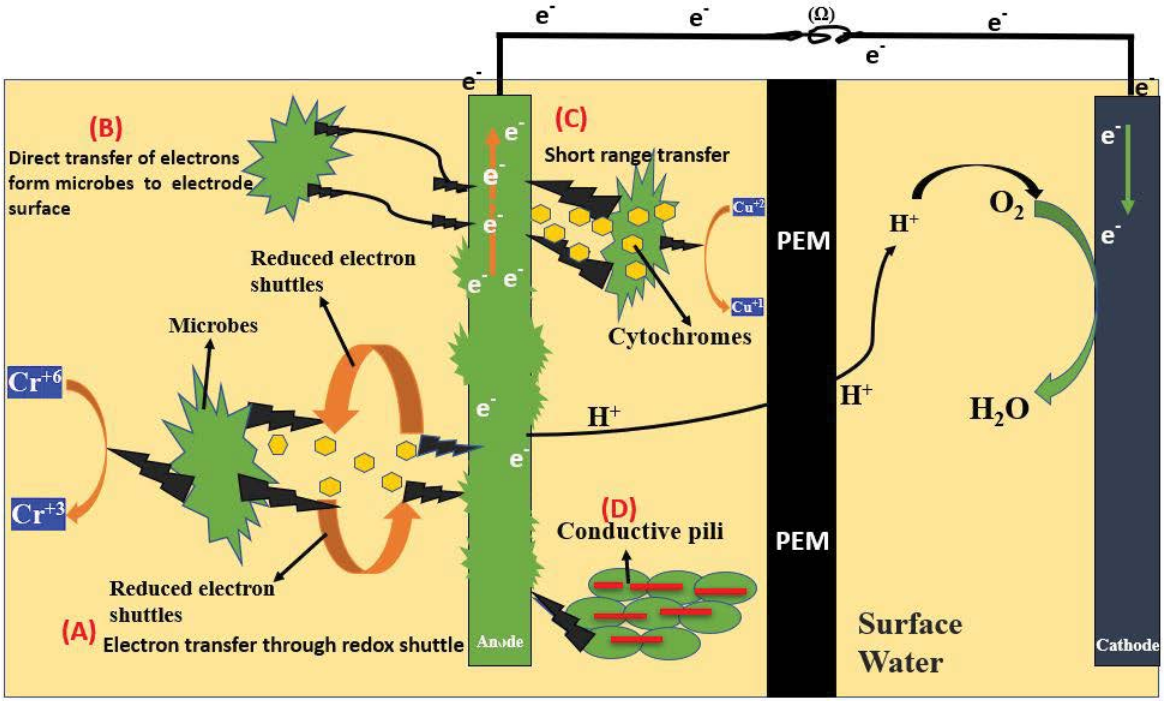


Fig. 2. Mechanism of electron transfer from the electrode to microbes. (A) Electron transfer through electron shuttles, (B) direct electron transfer from microbes to the electrode surface, (C) short range transfer of electrons, and (D) long-range electron transfer via conductive pili.

of heavy metals via reduction, as even some metals are removed by the oxidation process. There were many types of bacteria with the ability to gain electrons directly from electrodes [92,93]. In the previous reported study, electrons are used to transfer by using different types of artificial electron shuttles, but there were many disadvantages reported of artificial shuttle electrons. Moreover, there are many types of microbes which can serve as electron shuttles to get electrons from electrodes of MFC. It can empower bacteria to enhance reduction of fermentation and different inorganic substrates. These bacteria are *Staphylococcus carnosus*, *Clostridium ljungdahlii*, *Shigella flexneri*, *Streptococcus mutans*, and *Acinetobacter calcoaceticus*, etc. and they also carrying active redox molecules [94].

A research group already extensively studied the mechanism of microbes feeding and movement of electrons from electrode to microbes [6,55,56,]. The protons released by microbes are being reduced to hydrogen gas that lowers the potential of electrodes. Hydrogen is not soluble because the gas needs a high amount of energy or a catalyst at the electrode surface to overcome the reduction of protons that can reduce its applications. It is therefore essential to induce a high transfer rate of electrons by empowering the microbes with high current density. The hydrogen gas and redox molecules did not excite the cell which was attached to electrodes. The attached cell remains linked and separated from end products. Thrash and Coate's discussed first time the power concept of microbes by studying *Geobacter* species as electrodes. The reported studies show that *Geobacter* species can transfer electron directly to electrodes [95]. There were many toxic heavy metals such as chromium ion, nickel, zinc, lead, mercury, copper, and vanadium, etc. that can be removed by different microbes through same mechanism [95–97]. For example, *G. sulfurreducens* accept electrons directly from electrodes and reduce the U(VI) into U(IV) form (soluble to insoluble). The U(VI) is insoluble form and it was adsorbed on electrodes. *G. sulfurreducens* also has the capacity to reduce Cr(VI) to Cr(III), it means able to convert highly toxic nature to less toxic nature. The reduce Cr(VI) depends on the oxidation of the substrate (acetate) at anode electrode to transfer the microbes and reduction of chromium occur at the cathode. Butler et al. [98] stated the *Enterobacter*, *Macellibacteroides*, and *Lactococcus* microbes can remove vanadium with 93.6% removal efficiency and high current density of 543.4 mW/m$^2$. Removal of different metals through MFCs are summarized in Table 4. In the whole studies, there is gap that no proper molecular mechanism is known to accept electrons from electrodes. This could be a very useful direction for researcher in future [99].

### 4. Current challenges

Recently, MFC has become a most attractive and emerging research direction for the scientific community. However, still there are some associated issues which limits its application to wastewater treatment along with the generation of energy. Therefore, there is still a need to make a useful model to generate clean, safe, $CO_2$ emission free and renewable energy along with wastewater treatment to remove pollutants. To make this technique more favorable and practical at the commercial level, should overcome

Table 2
Generation of current and different wastewater sources used as substrates in MFCs

| Reactor configuration | Wastewater Source | Current density | Reference |
|---|---|---|---|
| DMFC | Glucose | 283 mA/m$^2$ | [57] |
| DMFC | Synthetic wastewater | 0.086 mA/cm$^2$ | [58] |
| DMFC | Alcohol distillery | 1,000 mA/m$^2$ | [59] |
| DMFC | Bad wine wastewater | 3.8 W/m$^2$ | [60] |
| SMFC | Synthetic wastewater | 0.017 mA/cm$^2$ | [61] |
| DMFC | Cheese whey | 42 mA/m$^2$ | [62] |
| SMFC | Acetate | 0.08 mA/cm$^2$ | [63] |
| DMFC | Domestic pollutant water | 0.06 mA/cm$^2$ | [64] |
| SMFC | Domestic wastewater | 1.7 W/m$^3$ | [65] |
| SMFC | Bakery and brewery | 10 mA/m$^2$ | [66] |
| SMFC | Brewery wastewater | 0.2 mA/cm$^2$ | [67] |
| DMFC | Farm manure | 63.8 mW/m$^2$ | [68] |
| DMFC | Chocolate industry wastewater | 0.302 mA/cm$^2$ | [69] |
| DMFC | Protein-rich wastewater | 0.008 mA/cm$^2$ | [70] |
| DMFC | Human feces | 70.8 W/m$^2$ | [71] |
| SMFC | Paper wastewater | 125 mA/m$^2$ | [66] |
| DMFC | Palm oil effluent with acetate | 622 mW/m$^2$ | [72] |
| DMFC | Landfill leachates | 0.0004 mA/cm$^2$ | [73] |
| SMFC | Rhizodeposits | 105 mA/m$^2$ | [74] |
| DMFC | Forest detritus | 1.27 mA | [75] |
| Tubular MFC | Sewage sludge | 73 mA/m$^2$ | [76] |
| SMFC | Dairy/food wastewater | 15 mA/m$^2$ | [77] |
| SMF | Pharmaceutical | 117.36 mW/m$^3$ | [78] |
| SMFC | Distillery wastewater | 245.3 mA/m$^2$ | [79] |
| DMFC | Food waste-compost leachate | 209 mA/m$^2$ | [80] |
| SMFC | Landfill leachates | 20.9 W/m$^3$ | [81] |

DMFC: double chamber of MFC; SMFC: single chamber of MFC.

Table 3
Different exoelectrogens with electron transfer intermediates and their power density

| Microbes | Electron transfer intermediates | Current density | Reference |
|---|---|---|---|
| *G. sulfurreducens* | c-Cytochrome z | 3,147 mA/m$^2$ | [82] |
| *S. oneidensis* | Riboflavin, flavins | 5,000 mA/m$^2$ | [83] |
| *Chlorella vulgaris* | Methyl viologen, methylene blue | 30 mA/m$^2$ | [84] |
| *R. palustris* | c-Type cytochromes | 2,720 mA/m$^2$ | [85] |
| *Geobacter lovleyi* | Methyl viologen | 480 mA/m$^2$ | [86] |
| *Pseudomonas aeruginosa* | Phenazine-1-carboxamide, pyocyanin | 4,300 mA/m$^2$ | [87] |
| *Klebsiella pneumonia* | 2,6-Di-tert-butyl-p-benzoquinone | 199 mA/m$^2$ | [88] |
| *T. ferriacetica* | Anthraquinone-2,6-disulfonate | 12,000 mA/m$^2$ | [55] |
| *Desulfovibrio desulfuricans* | c-Type cytochromes | 1,580 mA/m$^2$ | [89] |
| *Desulfuromonas acetoxidans* | c-Type cytochromes | 2,000 mA/m$^2$ | [90] |
| *Geobacter metallireducens* | c-Type cytochromes, OmcE and OmcB | 450 mA/m$^2$ | [91] |

the current challenges and explore their future opportunities. This review may be useful for researchers to overcome current challenges and may encourage them to explore the role of MFCs in further applications. Some significant and important challenges are discussed in the subsections with some fruitful suggestions.

### 4.1. Design and model of MFCs

The design of the MFCs device is a crucial factor in enhancing its working efficiency. The removal efficiency of the waste pollutants from wastewater is dependent upon many factors like anode size, anode chamber

Table 4
Removal efficiency of heavy metals by MFCs and their power density

| Toxic heavy metals | Reactor configuration | Removal efficiency | Current density | Reference |
|---|---|---|---|---|
| Cr(VI) | DMFC | 99.5% | 1,600 mW/m$^2$ | [100] |
| Cr(VI) | DMFC | 100% | 150 mW/m$^2$ | [101] |
| Cr(VI) | DMFC | 97% | 0.80 V | [102] |
| Cr(VI) | DMFC | 100% | 52.1 mW/cm$^2$ | [103] |
| Cr(VI) | DMFC | 93% | 0.5–0.6 mA | [104] |
| $Au^{3+}$ | SMFC | 79% | 42 mA/m$^2$ | [105] |
| Metal Cu and $Cu_2O$ | DMFC | 99% | 339 mW/m$^2$ | [106] |
| $Ag^{+}$ wastewaters | DMFC | 99.91% | 4.25 W/m$^2$ | [107] |
| Selenium | WMFC | 98% | 12.8 W/m$^2$ | [108] |
| Co(II) as hydroxide | SMFC | 90% | 1.5 W/m$^3$ | [109] |
| | DMFC | 70% | | |
| $Cu^{2+}$ wastewater | DMFC | 97.8% | 536 mW/m$^3$ | [110] |
| Cd and Zn | SMFC | 90% Cd | 3.6 W/m$^2$ | [111] |
| | | 97% Zn | | |
| Fe(III) | SMFC | >89% | 658 ± 6 mWm$^2$ | [112] |
| Oil sands tailings | DMFC | 97.8% Se, 96.8% Ba, 94.7% Sr, 81.3% Zn, 77.1% Mo, 66.9% Cu, 44.9% Cr, 32.5% Pb | 392 ± 15 mW/m$^2$ | [113] |
| Tetrachloroaurate | DMFC | 99% | 6.58 W/m$^2$ | [114] |
| Cr(VI) | SMFC | Paper wastewater | 419 ± 4 mW/m$^2$ | [112] |

DMFC: double chamber of MFC; SMFC: single chamber of MFC; WMFC: wetland MFC; Cr: chromium; Fe: iron; Au: gold; Ag: silver; Cu: copper; Co: cobalt; Zn: zinc; Cd: cadmium.

distance, cathode size, cathode chamber distance, the spacing between two electrodes, and length of the MFC model. All these factors indirectly affect the working efficiency of MFCs. For example, when the distance between anode and cathode is increased, the ohmic losses ratio also increases because these factors are directly proportional to each other [115]. Other factors can also increase ohms losses, such as adding more water or increasing anode electrode depth into wastewater. Researchers should consider all these factors when designing a MFCs for high efficiency.

### 4.2. Electrode materials

The electrodes material is also another important component for MFCs because exoelectrogens growth is dependent upon the efficiency of electrodes, and it also serves as an electron acceptor. Recently, electrode configuration and its material have become attractive points for scientific research to enhance MFCs efficiency because the electrode is responsible for the transfer of the electrons from anode to cathode. The electrodes are generally classified into two categories, viz. bio and chemical electrodes, depending on whether the catalyst is present or not. Electrode material should be highly conductive, chemically stable, have high mechanical and thermal stability, high surface area, high porosity, biodegradation, non-fouling nature, low in cost, and electron discharging ability. These kinds of properties make any electrode feasible for ideal MFCs. Besides, there are few more particular requirements for bio and chemical electrodes. Bio electrodes have the dual ability which serve as a carrier of microbes and can also conduct electricity. Bio electrodes exhibit high surface area for bacterial growth, improved biocompatibility, surface roughness, and provide biocatalytic properties. Despite these benefits, there is poor bacterial adhesion and transfer of electrons as well. The research community needs to consider electrode modification with other materials like metals, high conducting polymer, and a high conductive compound to overcome this issue. Moreover, chemical electrodes can act as a current collector and as a highly conductive material. However, it requires a catalyst to immobilize the substrate surface and a hydrophobic coating is necessary to prevent water loss. Deng et al. [116] suggested that researchers should use a catalyst-free material to overcome this limitation, such as activated carbon material [116]. Currently, a significant challenge in MFCs performance regarding electrodes is its configuration. A unique configuration is to provide a large surface area for bacterial growth that can produce large amount current and enhance the pollutant removal efficiency from wastewater. Furthermore, electrodes are also classified into two categories based on configuration; plan and 3D electrodes. The plan configuration of the electrode is generally used for chemical based electrodes. The practical and powerful configuration is required when the catalyst is used for chemical based electrodes to proceed oxygen reduction process into three-phase reaction. Generally, metal materials have more conduction capability than carbon materials, like stainless steel or titanium that is used as electrode due to high mechanical power and conductivity. However, there are some drawbacks like low surface area, corrosion ability, that make it unfit at commercial use [117]. Metal-based material has a smooth surface which fails to facilitate adhesion of microbes. Conducting polymers like polypyrrole, polycarbazole, polyaniline can also be used for electrodes. However, they showed more efficient performance when modified with metals or carbon materials, for example, Ag@polpyrrole and Ag@polycarbazole which exhibit high performance for energy production [30,118]. Carbon materials like carbon paper, cloth, fiber, sheet, carbon coke, carbon plain, carbon brushes, carbon plates, rod, graphite foils, graphite plates, graphite rods, graphite felts, and graphite sheets are commonly used due to high surface area and biocompatibility [119]. The surface areas of some materials are summarized in Table 5. Platinum and copper coating on carbon material may increase the power density as compared with graphite. Furthermore, using graphene material as an electrode is also beneficial because it has high surface area as compared to conventional carbon material, high mechanical and thermal stability and good biocompatibility to the microbial community [120]. Another most important research direction is to chemically modify the electrode materials. Researchers should use different materials to carry out modification and make electrodes more efficient by decreasing cost issues, increasing mechanical, thermal stability, and biocompatibility to the microbial environment.

### 4.3. Electrode cost

There are many electrode materials such as carbonaceous material, metal and metal oxide, conducting polymer, composite material but they are costly and make this technique unfit to use at a commercial level to purify wastewater. Despite all development in MFCs, there is still a desire to reduce the working cost of MFCs and make it more favorable at the commercial level. So, it is very critical to reduce the cost of the electrodes for practical implementation. The development of low-cost material can enhance the use of this application. Zhang et al. [129] reported that a cathode electrode could be fabricated through metal mesh resources such as stainless steel with a coating low-cost catalyst. There is a high number of demands for cheap catalysts with metals. Another method was also reported earlier to reduce the cost by developing the bio-cathodes. Currently, carbon (paper, rode, brushes, fiber, and sheets), graphite (sheets, fiber, cloth, and rod), metal (Ag, Pt, Cu, and titanium), and some conducting polymer are very commonly used at laboratory scale. We concluded some commercial prices of used material in electrode preparation in Table 6.

Now day's graphene is an excellent material used as an electrode to reduce the cost of MFCs with better working efficiency. Graphene has high conductivity and surface area than traditional material. The commercial graphene is very expensive (~150 US dollar per gram). Marcano et al. [134] explained an improved synthesis method by upgrading Hummer's method to use carbonized material as the raw material. He used different waste material to carbonize and then convert into graphene oxide with high conductivity and surface area. Therefore, graphene could be used with other materials to reduce cost and make more conductive and efficient. The scientific community can reduce the cost by using this method to make electrode instead of buying commercial material.

Table 5
Electrode materials with their surface area

| Materials | Surface area, $m^2/g$ | Reference |
|---|---|---|
| Graphite foil | 90 | [121] |
| Carbon black | 15–64 | [122] |
| Carbon nanotubes | 1,315 | [123] |
| Carbon cloth | 2.39–15 | [124] |
| Carbon aerogel paper | 600 | [125] |
| Carbon nanotube paper | 400 | [125] |
| Carbon fiber paper | 80 | [125] |
| Coke carbon | 300 | [126] |
| Graphene oxide | 2,600 | [127] |
| Activated carbon | 1,000 | [127] |
| Graphite oxide | 1,200 | [128] |

### 4.4. Electromicrobiology concept

Electromicrobiology is a broad field and there are much opportunities to do some innovative research to explore further practical applications. In MFCs, electromicrobiology has received significant attention but still, it is not a fully known concept, that is, during the generation of energy and wastewater treatment, how monoculture electron transferable to electrodes and then electrodes to microbes. This concept is under consideration because the proper mechanism is still unknown [135]. There are many reported bacterial groups like *Acidobacteria*, fungi, *Firmicutes*, algae, and *Proteobacteria* phyla shows electricity generation from their bodies to maintain their aquatic environment within chamber. Some common bacteria species are *R. ferrireducens*, *C. butyricum*, *Geobacter* spp., *Shewanella* species, and *Aeromonas hydrophila*, etc. show electric properties in nature. In former studies, further advances have been achieved due to the growth of common bacteria named; *G. sulfurreducens* and *S. oneidensis*. The *G. sulfurreducens* and *S. oneidensis* which have different electron transfer mechanism than other species because every species has its own properties to transfer the electrons. There is an urgent need to address conductive pili and conductive filament of microorganisms [136]. The conductive pili typically act as metal, because pili often carry the same characteristics. The direct electron transfer mechanism is also very useful in order to save time because electron moves to electrode then from electrode to bacteria rapidly to enhance reduction of

Table 6
Commercial cost of electrode's material

| Material | Cost (US$) | Reference |
|---|---|---|
| Graphene powder | 150/g | [130] |
| Carbon powder | 0.11/g | [131] |
| Carbon nanotubes | 8.4/g | [132] |
| Graphite oxide powder | 175/g | [130] |
| Carbon black | 86/kg | [133] |

compounds. Therefore, to properly understand the mechanism of electron movement, there is a need to address biofilm morphology and functioning to enhance bio electrogenic activity in bio-catalyzed systems. The biofilm can hamper the electron movement to electrodes. Therefore, the isolating electroactive biofilms are vital to explore further in applications such as bioremediation, biosensors, biocorrosion, and different metal reduction processes.

## 5. Conclusion and future perspectives

MFCs has offered a novel research direction and are controllable, eco-friendly, and environmentally stable for the generation of electricity along with offering bioremediation of wastewater. Currently, MFCs have been receiving significant attention and it is applicable in many applications like bioremediation of wastewater (removal of heavy metals, organic, and inorganic compound) biological oxygen demand sensors and gastrobots (food digester device). The types of MFCs, that is, benthic and sediment MFC both offer many opportunities to empower sea-bred devices, monitoring and tracking systems, etc. Therefore, fabrication of high conductive electrodes and their modification with different metals or conducting polymers make MFCs more prolific and significant with regard to electronic applications at a larger level. MFC is a novel device to produce clean, safe, and renewable energy for humankind and to maintain a clean environment on the earth [137]. Moreover, MFCs is an emerging field within the scientific community, so in order to make it feasible at the commercial level, electrodes must be derived from natural wastes such as vegetable, fruit fibers, agricultural wastes, industrial wastes, medicinal wastes, etc. It is also possible to convert these materials into useful materials by processing this waste material through different methods such as hammer's method as described earlier [138]. This waste has the ability to show electricity generation as carbon support. For instance, researchers could modify this material to enhance the porosity of the material that gives high surface area as anode electrode [139]. The anode material should be further explored by analyzing its compositional influence, texture, size, and surface activities. In addition, the electron mechanism from bacteria to the electrode and from electrode to microbes also needs to be explored in order to build more understanding in the generation of electric current. The scientific community needs to find simple and less expensive materials to promote charge transformation at the anode electrode. In the case of metal and composites, mono, di, tri, or quarter catalyst should be favorable to enhance catalytic sites and surface area for better results. Previously, researchers used this technique to recover non-complex material but in the future there is a need to develop it further to recover complex material. All these stated challenges could be addressable by joint research of multi-disciplines like the electrical field, material science, computer science, biological science, and chemistry.

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