



A review of microbial fuel cell and its diversification in the development of green energy technology



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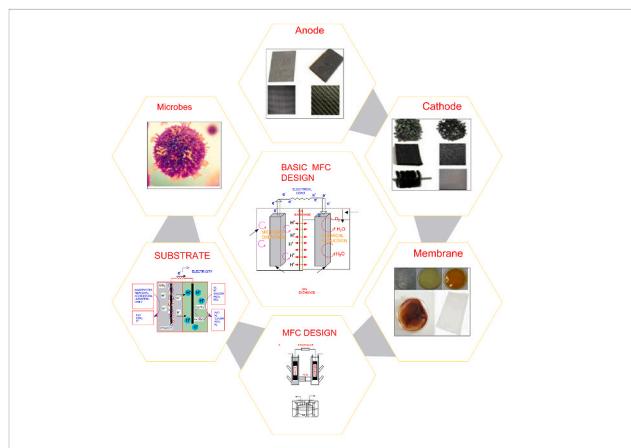
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HIGHLIGHTS

- A comprehensive analysis of the electron transfer process in microbial fuel cells (MFC) is provided.
- Microbial fuel cells (MFC) provide advantages in both waste management and green energy production.
- Microbial fuel cell designs influence substrate utilization.
- MFC hybrid systems simultaneously remove organic pollutants and generate electricity.

GRAPHICAL ABSTRACT



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ABSTRACT

The advancement of microbial fuel cell technology is rapidly growing, with extensive research and well-established methodologies for enhancing structural performance. This terminology attracts researchers to compare the MFC devices on a technological basis. The architectural and scientific successes of MFCs are only possible with the knowledge of engineering and technical fields. This involves the structure of MFCs, using substrates and architectural backbones regarding electrode advancement, separators and system parameter

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MFC configurations
Polymeric membranes
Energy to wealth

measures. Knowing about the MFCs facilitates the systematic knowledge of engineering and scientific principles. The current situation of rapid urbanization and industrial growth is demanding the augmented engineering goods and production which results in unsolicited burden on traditional wastewater treatment plants. Consequently, posing health hazards and disturbing aquatic veracity due to partial and untreated wastewater. Therefore, it's sensible to evaluate the performance of MFCs as an unconventional treatment method over conventional one to treat the wastewater. However, MFCs some benefits like power generation, stumpy carbon emission and wastewater treatment are the main reasons behind the implementation. Nonetheless, few challenges like low power generation, scaling up are still the major areas needs to be focused so as to make MFCs sustainable one. We have focused on few archetypes which majorities have been laboratory scale in operations. To ensure the efficiency MFCs are needed to integrate and compatible with conventional wastewater treatment schemes. This review intended to explore the diversification in architecture of MFCs, exploration of MFCs ingredients and to provide the foreseen platform for the researchers in one source, so as to establish the channel for scaling up the technology. Further, the present review show that the MFC with different polymer membranes and cathode and anode modification presents significant role for potential commercial applications after change the system form prototype to pilot scale.

1. Introduction

Microbial fuel cells are innovative devices that harness the power of microorganisms to convert organic matter into electricity, holding immense potential in the realm of sustainable energy. The primary objective of this review is to elucidate the evolution of MFC technology, highlight its progress over time, discuss its advantages, delve into the challenges encountered by scientists, and ultimately underscore the scientific rationale behind the need for this comprehensive review. MFC is unique in the resourceful electrochemical techniques persistently explored to treat wastewater. Sustainable development, pollutant transformation and environmentally safe practices are the main objectives of these technologies. These technologies provide clean energy and water for mankind, achieving an energy-neutral approach to the well-being of ecosystems (Logan et al., 2006a,b). Conventionally, MFC is a revitalized bio-electrochemical technique capable of oxidative conversions in an anodic compartment with the help of microorganisms and microbial or chemical reduction in the cathodic compartment (Pandey et al., 2016). This promising technology is anticipated to address the anaerobic oxidation of organic substrates and consists of an anode and cathode chamber separated by a proton exchange membrane (PEM). The anode and cathode are interconnected through an external circuit with an external load (Rabaey and Verstraete, 2005). The Exo-electrogenetic oxidation of different substrates was taken at an anode chamber in the presence of microorganism-producing electrons and protons (Logan et al., 2006a,b). Electrons are transferred through an external circuit and proton through PEM (Rikame et al., 2012). The basic structure of MFC is shown in Fig. 1. Different anaerobic microorganisms are used to enhance the transformation of the substrate into electricity (Kim et al., 2002; Bond and Lovley, 2003).

The dire challenges of potable water scarcity and heavy demand of

electricity with rapid industrialization and urbanization ensued the smart alternatives for wastewater management and energy production (Logan, 2008)). The MFC review analysis in particular focuses on the diversified MFC structure with convenient prototype modifications in terms of anodes and cathodes (Ma et al., 2023). However, the evolutionary substrate and technology driven membranes also plays the crucial role in the MFC scenario (Palanisamy et al., 2019). The review also aimed to study the operational efficiency with different conceptual design with available prototypes evaluated by the different researcher teams. In existing studies and with some practical experiments, new environment efficient and sustainable electrochemical cells were used like MFCs (Singh et al., 2019). MFCs are more convenient in terms of less or no chemical use, handling huge quantities of wastewater and no greenhouse emission. However, the close monitoring and continuous evaluation is required to reduce the capital cost and detention time for efficient use. In this way the MFC technology have initiate a lot of novel considerations on a worldwide scale with hindered challenges like low energy generation and high initial cost (Yaqoob et al., 2020). An integral component of the review is the elucidation of the myriad advantages associated with microbial fuel cells. These include their potential for renewable energy generation, environmentally friendly operation, and versatility in utilizing various organic substrates. Also, the potential applications of MFCs in wastewater treatment and remote power generation, further accentuating their significance in the broader context of sustainable energy solutions. The MFCs are mediator MFCs and mediator-less MFCs. Most of the microbes used in MFCs are inactive, so the electron transmission from microbes to the anode surface is boosted by some mediators like humic acid, methyl blue, thionine, methyl viologen and neutral red (Park and Zeikus, 2000; Delaney et al., 2008). The anode is the crucial material in MFC. It must have high mechanical strength, biocompatibility, eco-friendly, low cost, corrosion resistance, and a specific surface area for bio-film development (Santoro et al., 2018). Carbonaceous material proved best suited to the characteristics mentioned above: carbon cloth, carbon brush, carbon rod, activated carbon, coarse graphite, graphite plate, graphite felt, reticulated vitreous carbon, etc. (Baudler et al., 2014). The other electrodes are copper, gold, silver, steel mesh, scrubber, and nickel sheet (Baudler et al., 2015). The other important part of MFC is the cathode, where ORR was carried out in the presence of platinum as a catalyst (Logan et al., 2006a,b). The cathode chamber is open to the atmosphere, or sometimes the air is purged externally. The present review serves as a critical examination and consolidation of the advancements in microbial fuel cell (MFC) technology and hurdles such as low power density, limited scalability. By dissecting these challenges, the review provides insights into the complexities that researchers have grappled with and underscores the importance of ongoing investigations in overcoming these obstacles. The present review on MFC offering a holistic perspective on the current state of microbial fuel cell technology and its further development as a green energy solution.

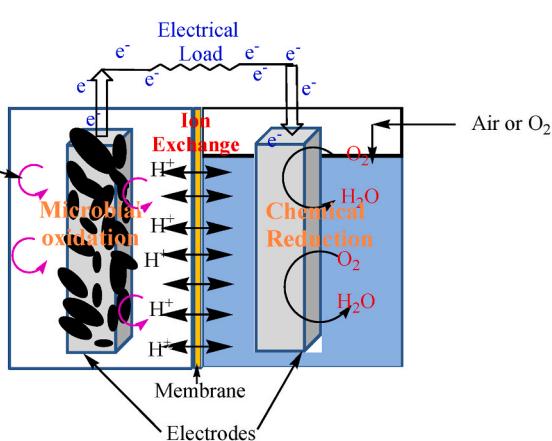


Fig. 1. Microbial Fuel cell and its mechanism.

2. Mechanism of MFC and energy generation

MFCs are an attractive and continuously growing technology that uses bio-catalytic redox activity combined with abiotic electrochemical reactions (Logan et al., 2006a,b; Logan and Rabaey, 2012; Logan and Elimelech, 2012). The addition of microorganisms was responsible for enhancing catalytic electrochemical reactions, which gives redox activity responsible for electricity generation. The MFCs are working with the biotic electro-active bacteria at the anode (Erable et al., 2010; Borole et al., 2011), the ambient temperature range between 15 °C and 45 °C (Tee et al., 2017), almost at neutral pH conditions (Fan et al., 2007; Ye et al., 2016), use of different and complex biomass as a substrate and anodic fuel (Pant et al., 2010; Pandey et al., 2016) with a promising environmental impact assessment confirm through life cycle assessment (Foley et al., 2010; Pant et al., 2011). The MFC working mechanism is shown in Fig. 1.

The basic idea of MFC was to use microbes to generate electricity (Potter, 1911). Now significant development regarding electron transfer mechanism, development of low-cost electrode material, and efficient bio-electrocatalytic transfer has been going on, but a lot of work is still required to commercialize and industrialize MFCs (Rahimnejad et al., 2015; Trapero et al., 2017). MFC is an anaerobic device with promising potential to treat mixed organic waste into bioelectricity with the aid of bacteria as a catalyst (Allen and Bennetto, 1993; Logan et al., 2006a,b; Feng et al., 2008). Some microbial communities are capable of transferring an electron to electrodes. Rabaey et al. (2003) and Du et al. (2007) have widely studied this and referred to them as communities that adopted anodophilic consortia. A comprehensive study has been taking place on using microbes in MFC and maximizing power output, as the mediators are toxic and expensive (Logan et al., 2005).

Remarkable progress has been made with different wastewaters and substrates. Few wastewaters have already been used in MFC as a microbial fuel (Pant et al., 2010; Pandey et al., 2016). A MFC converts chemical energy from a bio-convertible substrate directly into

electricity. Table 1 shows the electricity generation using different wastewaters. The benefits of MFC are used for wastewater treatment and count for safe, clean and direct electricity production. This study reveals the overview of MFC in wastewater treatment and diversification in the research that has been taking place with different elements of MFC, like PEM. Two-compartment MFCs are typically run in a batch mode, often with a chemically defined medium such as glucose or acetate solution to generate energy. They are currently used only in laboratories. A typical two-compartment MFC has an anodic chamber and a cathodic chamber connected by a PEM, or sometimes a salt bridge, to allow protons to move across to the cathode while blocking the diffusion of oxygen into the anode. The compartments can take various practical shapes. The schematic diagrams of five two-compartment MFCs are shown in Fig. 2 (a, b and c). The interaction between electrodes and electro-active bacteria remains poor. The electron transfer mechanism between porous electrodes and bacteria has not yet been unstated (Richter et al., 2009; Kiely et al., 2011).

In the final stages of attraction of microbes towards electrodes (Read et al., 2010), biofilm development on the anode surface (Reguera et al., 2006; Read et al., 2010) and the effect of environmental parameters on microbial consortia remains unknown (Rahimnejad et al., 2015). The interaction of microbes with electrode surfaces was studied with some morphological changes and surface chemistry (Beyenal and Babauta, 2015). Some of the metals have been tested in MFC cathode as an electron acceptor, which includes U (Gregory and Lovley, 2005; Wang and Ren, 2014), Cu (Heijne et al., 2010; Ntagia et al., 2016), Cr (Nanchariah et al., 2015; Q. Li et al., 2015) and many more. Primarily oxygen is an electron acceptor due to its availability and high redox potential (Zhao et al., 2006). Different kind of organic wastewater can offer large number of nutrients for the metabolism and growth of microbes. A lot of studies revealed the use of municipal solid wastewater in MFC like micro flora based natural substrate for MFC system gives maximum current density of $147 \pm 10 \text{ mW/m}^2$ using complete septic tank wastewater (Thulasinathan et al., 2021a). The same type of wastewater also treated in dual chamber MFC using *Cronobacter sakazakii* and *Pseudomonas otitidis*. It was found that maximum power density of 280 mW/m^2 obtained using the single strain of *Pseudomonas otitidis* (Thulasinathan et al., 2021b).

There are so many challenges left for MFC technology, including low energy production compared to other fuel cells. So, there may be different sources of wastewater was used for evaluating the performance of MFC. Ramu et al. (2020) have used the food-based industry wastewater for the evaluation of performance of MFC. It was observed that *Klebsiella pneumonia* based strain gives maximum power density of 428.71 mW/m^2 with maximum coulombic efficiency of 74.6%. The dual chamber MFC with rice mill wastewater gives maximum power density of 656.10 mW/m^2 and maximum coulombic efficiency of 17.21% with alternating air exposure (Raychaudhuri and Behera, 2020). In this way substrate oxidation is the crucial and only way to generate the electrons in MFC system. Electro-genic microbes like *Shewanella* and *Geobacter*, yeast strains like *Saccharomyces cerevisiae*, *Kluyveromyces marxianus* and *Candida melibiosica*, proteobacteria, cyanobacteria and archaebacteria are some common examples which are participating in the MFC operation for energy generation. The anodic inoculation in MFCs might contain pure as well as mixed consortia culture. However pure culture is more advantageous than mixed over the efficient degradation of substrates into power generation due to simple and organized metabolic passageways. Therefore, specific substrates might limit the performance of MFC on basic requirement of purity and concentration (Cao et al., 2019).

3. Membrane synthesis and its application

Membrane technologies are ubiquitous because of their relationship with wastewater and environmental issues. As it separates protons and electrons, the proton exchange membrane (PEM) plays an essential role

Table 1
Electricity generation using different wastewaters.

Types of Waste	Power Generation	References
Palm oil mill wastewater	$504.1 \pm 8.7 \text{ mW/m}^3$	Ng et al. (2023)
Septik Tank Wastewater	$147 \pm 10 \text{ mW/m}^2$	Thulasinathan et al. (2021a)
Septik tank wastewater (Pseudomonas otitidis)	280 mW/m^2	Thulasinathan et al. (2021b)
Food based industrial waste	428.71 mW/m^2	Ramu et al. (2020)
Rice mill wastewater	656.10 mW/m^2	Raychaudhuri and Behera (2020)
Agro-food wastewater	27.00 W/m^3	Cecconet et al. (2017)
Electroplating waste	150.50 mW/m^2	Kim et al. (2017)
Swine wastewater	37.50 W/m^3	Ding et al. (2017)
Seafood processing wastewater	105.00 mW/m^2	Jayashree et al. (2016)
Ethanolamine wastewater	1990.00 mW/m^2	An et al. (2016)
Distillery wastewater	72.90 mW/m^2	Lin et al. (2015)
Mustard tuber wastewater	246.00 mW/m^2	Guo et al. (2013)
Food waste leachate	1500.00 mW/m^2	Rikame et al. (2012)
Cassava mill wastewater	1771.00 mW/m^2	Kaewkannetra et al. (2011)
Grass silage	54.00 mW/m^2	Catal et al. (2010)
Canteen food waste	107.89 mW/m^2	Goud et al. (2011)
Biodiesel production waste	2110.00 mW/m^2	Feng et al. (2010)
Rice mill wastewater	172.20 mW/m^2	Behera et al. (2010)
Food industry waste	78.00 mW/m^2	Cercado et al. (2009)
Azo dye	552.20 mW/m^2	Li et al. (2010)
Composite veg waste	57.38 mW/m^2	Mohan et al. (2009)
Distillery wastewater	124.34 mW/m^2	Mohankrishna et al. (2009)
Starch processing wastewater	239.40 mW/m^2	Lu et al. (2009)
Chemical Wastewater	198.00 mW/m^2	Mohan et al. (2008)
Cereal Wastewater	381.00 mW/m^2	Oh and Logan (2005)

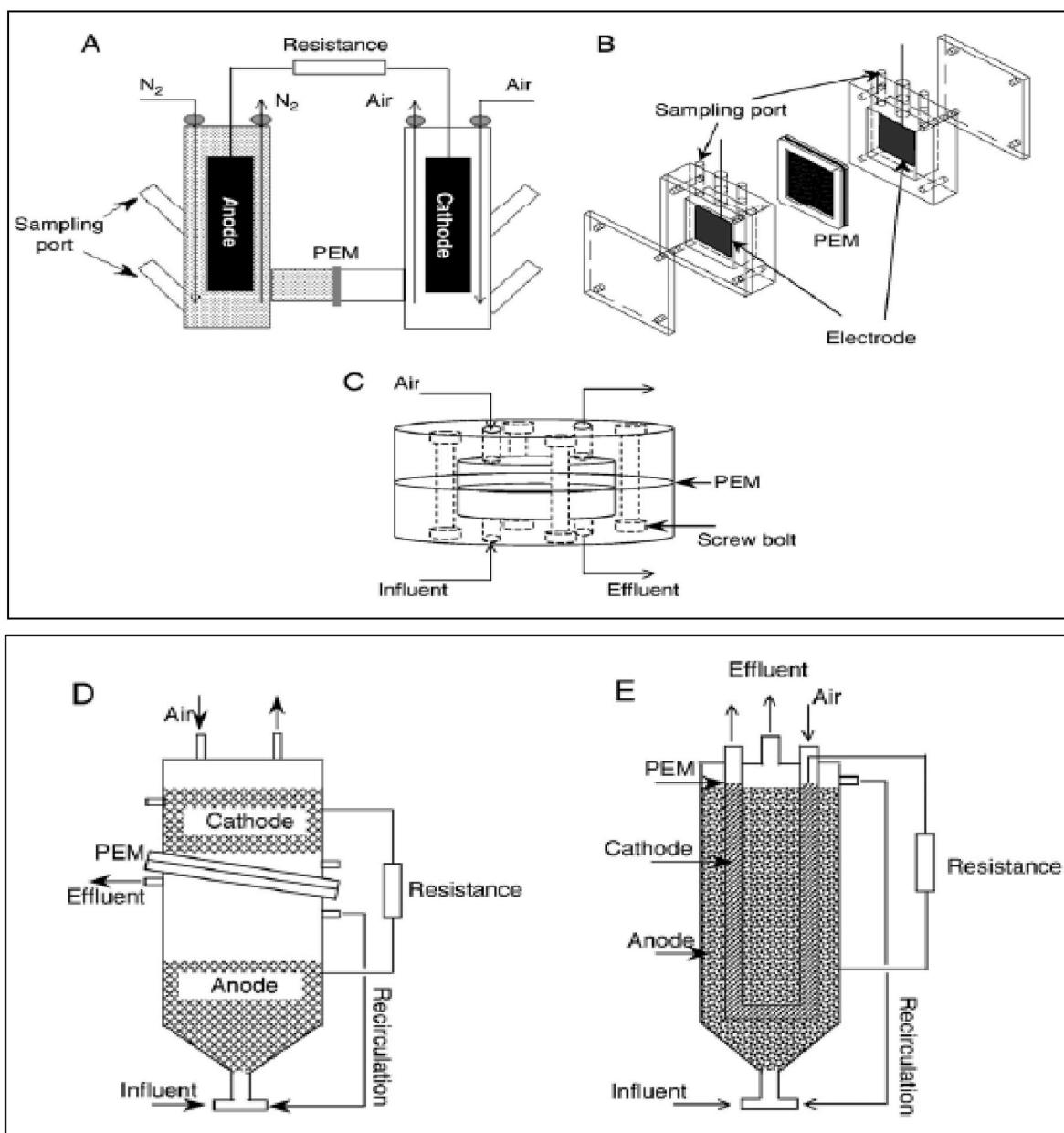


Fig. 2. Two-compartment MFC in cylindrical (A), rectangular (B), miniature (C), up flow configuration (D), cylindrical with a U-shaped cathodic compartment (E) shape (Reproduced from Du et al., 2007 with permission from Elsevier).

in the fuel cell, whether it be a hydrogen fuel cell or MFC. The mechanism and working principle of MFC is illustrated in Fig. 3. The acetate fermentation yields 8 protons and 8 electrons. PEM is used to transmit protons to the cathode electrode, while electrons are transmitted via the external circuit. This mechanism leads to the cathodic reaction, which yields water. DuPont's perfluorinated Nafion-117 is a super membrane widely used in MFC applications (Gresham and Connolly, US3282875A. 1966). Nafion-117 exhibits near-unity proton conductivity, excellent ion conductivity, and low electron conductivity (Beuscher et al., 2005). However, Nafion-117's key drawbacks include its high cost, limited water absorption, and poor oxidation resistance (Saga et al., 2008). Many chemical and inorganic compounds have been investigated to improve conductivity. Zirconium polyphosphate (Song et al., 2004), Heteropoly acid (HPA) (Shao et al., 2004), composite of multi-walled carbon nanotubes (MWCNTs) and thiophene polymer aided by a cationic surfactant (Reddy et al., 2010a), SiO₂/poly (3-aminophenyl boronic acid) composite (Zhang et al., 2007), composite of silanized

magnetic nanoparticles and sulfonated polyaniline (PANI) (Reddy et al., 2007a,b), Au and Ag like PANI functionalized MWCNT with noble metal (Reddy et al., 2009) and micelle system like Fe₃O₄/PANI composite (Yao et al., 2012). Poly (ortho-toluidine)/gold and palladium nanoparticle composites were developed to improve electrical conductivity (Reddy et al., 2007a,b). Graphene/steric acid/low-density polyethylene (LDPE) composites (Han et al., 2014), TiO₂/PANI composites for photocatalytic degradation (Reddy et al., 2010b), and cationic PANI/anionic graphene oxide (GO) nanocomposite for supercapacitor electrode (Hassan et al., 2014). However, for proton transport, these inorganic fillers require considerable relative humidity and temperatures. To chelate the acid groups, sufficient water must be absorbed into the membrane matrix. Most PEM's proton conductivity improves with optimum water activity, lowering proton transfer resistance. Water content decreases and influences membrane performance in high-temperature MFC applications (Zawodzinski et al., 1993; Xiang et al., 2009). Fullerene-based proton conductors have been widely examined and proven to be appropriate for

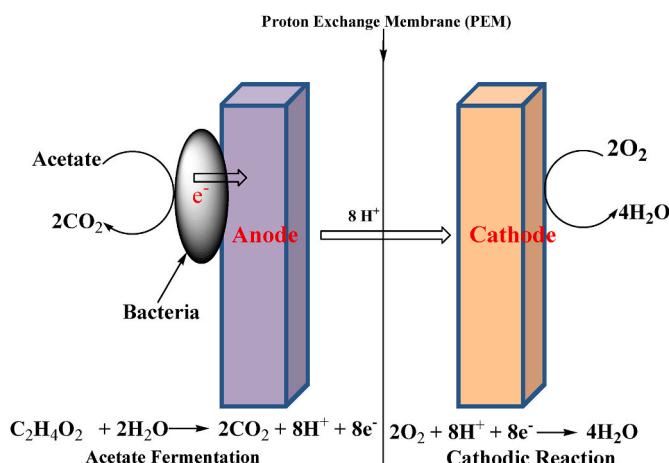


Fig. 3. The working mechanism of PEM in MFC.

proton conduction without humidification, such as the phosphoric acid derivative of fullerene and polyhydroxy fullerene (Tasaki et al., 2006; Wang et al., 2007). Because fullerene possesses strong electrophilic characteristics, the proton may readily dissociate from the fullerene cage's oxygen sites. Because of its strong acidic nature, self-dissociation, and charge separation in acids, the phosphoric acid group (-PO₃H₂) has received considerably greater attention, resulting in the high proton concentration necessary for membrane performance in low humidity and high-temperature conditions (Zhao et al., 2013). Kimoto (2009)/0297914A1, 2009) suggests that phosphorylated fullerene may improve ion exchange capacity and proton conductivity.

PVA is a superb polymer matrix with high mechanical and chemical stability (Kim et al., 1999). The purpose of sulfonation is to introduce the sulfonic acid group into the PVA matrix, hence decreasing its hydrophobicity. PVA sulfonation improves PEM's water absorption, thermal stability, and proton conductivity (Kundu et al., 2007; Bi et al., 2010). The membrane must have a greater proton concentration and must be capable of interacting with acidic or hydroxyl groups (Park et al., 2011; Robert et al., 2011). Fullerene phosphorylation (Wegener et al., 2014) and PVA sulfonation (Fujita et al., 2013) inject more acidic groups into the membrane matrix, enhancing its hydrophilicity, mechanical and chemical durability. **Table 2** lists the synthesized membrane with their ion conductivity and power density.

The suggested composites in **Table 3** will prospect the development of a new alternative to replace high-cost ion exchange membranes such as Ultrex, Nafion®, Flemion® and Aciplex®. These commercial membranes possess good properties like high chemical and mechanical stability with good proton conductivity. But due to some limitations like high cost and lower performance in low humidity and high temperature, demand for cost-effective alternatives. The uses of hydrocarbon polymers are prominent in developing proton-conducting polymer electrolyte membranes. It is necessary to obtain high thermal and chemically stable material to synthesize PEM. Few scientists have reported the synthesis of PEM for different applications. Sun et al. (2012) have studied the graphene oxide membrane for selective ion penetration. **Fig. 4** shows the selective ion that can be penetrated through the graphene oxide (GO) membrane.

Cao et al. (2011) have demonstrated the polyethylene/graphene oxide membrane for the low-temperature polymer fuel cell. The power density developed was 53 mW/cm². The membrane developed was ion conductive. It was observed that with the rise in temperature from 25 to 60 °C, the ion conductivity increases from 0.086 to 0.134 S/cm in 100 % relative humidity. **Fig. 5** (1) shows the PEO/GO membrane synthesized for a fuel cell by Cao et al. (2011).

Kim et al. (2013) have studied the ultra-filtration MFC (UF-MFC) instead of expensive CEM. It was observed that the UF-MFC membrane

Table 2
List of the synthesized membrane with their ion conductivity and power density.

Synthesized Membrane	Ion Conductivity	Power Density	Reference
Sulfonated chitosan (SCS)/sulfonated polyvinyl alcohol (SPVA) blend	0.0038 S/cm and 0.93–1.03 mA	630–750 mV and 0.93–1.03 mA	Atkar et al. (2024)
Polypropylene	–	0.7 mW/m ²	Eslami et al. (2023)
Agar-KCl membrane	2.43 mS/cm	2374 mW/m ³	Flores et al. (2019)
Phosphorylated fullerene and sulfonated PVA (PFSP)	0.11 mS/cm	499.1 mW/m ²	Rikame et al. (2017)
Chitosan membrane	0.99 mS/cm	–	Srinophakun et al. (2017)
Polybenzimidazole (PBI)	0.50 mS/cm	1521 mW/m ³	Angioni et al. (2017)
Nafion/TiO ₂ membrane	12.6 mS/cm	330 mV (OCV)	Bajestani and Mousavi (2016)
Sulfonated polybenzimidazole	0.08 mS/cm	110 mW/m ²	Singha et al. (2016)
Ionic liquids membranes	–	103.9 mW/m ³	Fernández et al. (2015)
Sulfonated SiO ₂ in sulfonated polyether ether ketone	1.01 S/cm	1008 mW/m ²	Sivasankaran and Sangeetha (2015)
Polyvinylidene fluoride (PVDF)/Nafion composite membranes	–	4.9 mW/m ²	Shahgaldi et al. (2014)
Sulfonated porous poly (vinylidene fluoride) membranes	9.07 mS/cm	15.8 mW/m ²	Kim et al. (2014)
Ultrafiltration	–	53.5 mW/m ²	Kim et al. (2013)
Quarternized poly ether Ketone	12.00 mS/cm	60 W/m ³	Mahendiravarman and Sangeetha (2013)
CEM, Biobag and Ceramic	–	4 W/m ³ , 2 W/m ³ , 4.6 W/m ³	Winfield et al. (2013)
Sulphonated biphenyl perfluorocyclobutyl	212.00 mS/cm	–	Kalaw et al. (2013)
Sulphonated biphenyl/biphenyl perfluorocyclobutyl	58.00 mS/cm		
Sulphonated biphenyl/SO ₂ perfluorocyclobutyl	83.00 mS/cm		
Graphene Oxide membrane	5–29 mS/cm	–	Sun et al. (2012)
Fe ₃ O ₄ /PES	–	20 mW/m ²	Rahimnejad et al. (2015)
Poly (2,5-benzimidazole)-silica nanocomposite	38.01 mS/cm	–	Linlin et al. (2012)
Nafion-117	80.00 mS/cm	290 mW/m ²	Xu et al. (2012)
Graphene oxide/Polyethylene composite	0.134 S/cm	53 mW/cm ²	Cao et al. (2011)
Sulphonated Polyether ether ketone (SPEEK)	0.148×10^{-3} S/cm	57 W/m ³	Ayyaru and Dharmalingam (2011)
Alkaline anion exchange membrane	0.028 S/cm		Wu et al. (2011)
Silicone tubing	–	11.7 mW/m ²	Hussain et al. (2011)
Silicone membrane		18 mW/m ²	
Carbon Cloth, Anion exchange membrane and cation exchange membrane	–	96 mW/m ² , 64 mW/m ² , 59 mW/m ²	Zhuang et al. (2010)
Salt Bridge	–	37.8 mW/m ²	Mohan and Das (2009)

Table 3

The different anodes and their modification for maximum power generation.

Sr. No.	Anodes	Modification with polymer	Maximum Power Generation	References
1	Carbon felt	biohybrid constituted of a carbon paste, an $\text{Ni}_2\text{Zn}_{0.5}\text{Fe}$ layered double hydroxide, and bacteria	472.17 mW/m ³	Ouzi et al. (2023)
2	Carbon felt	5 % Graphene oxide	132 mW/m ²	Yang et al. (2022)
3	Carbon cloth	Cobalt oxide	170 mW/m ²	Veeramani et al. (2020)
4	Carbon felt	graphene/ Fe_2O_3	334 ± 4 mW/m ²	Fu et al. (2020)
5	Carbon felt	Dosing zero-valent iron	27.3 mW/m ²	Li et al. (2020)
6	Carbon nanorods	Co-modified MoO_2 nanoparticles	2.06 ± 0.05 W/m ²	Li et al. (2019a)
7	Graphite felt	bentonite-Fe Fe_3O_4	29.98 mW/m ²	Yu et al. (2019)
			18.28 mW/m ²	
8	Porous carbon	Nitrogen doping	2777.70 mW/m ²	Bi et al. (2018)
9	Carbon Felt	Porous tetrahedral zeolite clay composited with graphene oxide	280.56 mW/m ²	Paul et al. (In press)
10	Activated Carbon	Polydopamine (PDA)	803 ± 6 mW/m ²	Du et al. (2017)
11	Carbon Foam	Polydopamine (PDA)	1735.00 mW/cm ²	Jiang et al. (2017)
12	Stainless Steel mesh	Acid etching, binder-free carbon black (CB) coating	1.91 mA/cm ²	Peng et al. (2016)
13	Carbon cloth	Peptide nanotubes (PNTs)	767.00 mW/m ²	Xu and Quan (2016)
14	Carbon cloth	Polyaniline/graphene	884 ± 96 mW/m ²	Huang et al. (2016)
15	Carbon cloth	Biogenic Pd nanoparticles	605.00 mW/m ²	Quan et al. (2015)
16	graphite felt	Carbon nanotubes and polyaniline	257.00 mW/m ²	Cui et al. (2015)
17	Carbon Felt	Polypyrrole (PPy)/9,10-anthraquinone-2-sulfonic acid sodium salt (AQS) composite films and RuO_2 Nanoparticles	48.00 W/m ²	Lv et al. (2014)
18	Pt Anode	Mixed metal oxide titanium ($\text{Ti}-\text{TiO}_2$)	1313.00 mW/m ²	Akman et al. (2013)
19	Graphite	An iron/sulfur solid chemical catalyst	12.00 W/m ³	Bouabdalaoui et al. (2013)
20	Carbon Paper	Novel Graphite sheet	2249.00 mW/m ²	Gao et al. (2013)
21	Carbon cloth	Graphene/polyaniline nano complex	1390.00 mW/m ²	Hou et al. (2013)
22	Activated Carbon	Nanosemiconductor goethite	693 ± 20 mW/m ²	Peng et al. (2013)
23	Carbon Nanotubes (CNT)	Bamboo-like nanostructure (Bamboo-NCNTs) by catalytic pyrolysis of ethylene diamine	1.04 W/m ²	Ci et al. (2012)
24	Carbon Cloth	Graphene	56.00 mW/m ²	Liu et al. (2012)
25	Carbon Paper	Gold nanoparticles	346.00 mW/m ²	Guo et al. (2012)
26	Carbon Felt	Ruthenium oxide (RuO_2)-coated carbon felt	3.08 W/m ²	Lv et al. (2012)
27	Activated Carbon	Activated carbon (AC) with Stainless steel mesh Fe_3O_4 added with activated Carbon	664 ± 17 mW/m ² 809 ± 5 mW/m ²	Peng et al. (2012)

Table 3 (continued)

Sr. No.	Anodes	Modification with polymer	Maximum Power Generation	References
28	Carbon Mesh	Nitric Acid	792.00 mW/m ²	Zhou et al. (2012)
29	Carbon Cloth	Polyaniline	5.16 W/m ³	Lai et al. (2011)
30	Stainless Steel Mesh	Carbon nanotube SS	187.00 mW/m ²	Lamp et al. (2011)
31	Graphite	Graphite electrodes were modified with the reduction of aryl diazonium salts	118.00 mW/m ²	Picot et al. (2011)
32	Carbon felt	Nitric acid and ethylene diamine	1304.00 mW/m ²	Zhu et al. (2011)

physically separates the anode and cathode chambers. The effluent also need not require further effluent treatment due to the ultra-filtration membrane. The function of CEM is to maintain the pH by transferring the proton across it. But the MFC performance might get fully deteriorated due to unbalance pH gradient due to inactive proton transfer. Although the UF-MFC generates less power than the Nafion membrane, it gives continuous organic pollutant removal in an anode chamber with simultaneous physical separation and electricity generation. Fig. 5 (2) shows the setup used by Kim et al. (2013). Eslami et al. (2023) prepared the inexpensive polypropylene membrane for the dual chamber MFC. The main objective of this study was to replace the expensive Nafion 117. The performance was evaluated in terms of voltage, maximum power density and current density. It was observed that maximum 500 mV power output was obtained with 0.7 mW/m². The main purpose to use the polypropylene membrane was to find an alternative to costly Nafion 117 and ease to recycle the separators for reuse. As the strong polymer backbone of Nafion 117 poses serious environmental problem. Winfield et al. (2013) have compared starch-based compostable bags (Biobags) and ceramics with CEM in the microbial fuel cell. It was observed that for long-term operation, CEM shows maximum development of internal resistance compared to bio bags and ceramic membrane exhibit good mechanical stability and could be a better alternative for CEM as a cost matter. Fig. 5 (3) shows the photograph of (a) acrylic MFC design used for Bio-Bag and CEM membranes and (b) ceramic MFC.

Kalaw et al. (2013) have synthesized perfluorocyclobutyl-based polymer blends for proton exchange membrane fuel cells. In this study, sulphonated biphenyl perfluorocyclobutyl membrane was prepared. Its performance was checked in a proton exchange membrane fuel cell with Nafion as a commercial membrane. It was found that the performance of composites of membrane prepared from sulfonated biphenyl perfluorocyclobutyl was comparable with Nafion in terms of ion exchange capacity, water uptake and proton conductivity. The membrane provided a more structurally stable system and proton conductivities equivalent to Nafion's. Atkar et al. (2024) synthesized the sulfonated chitosan and sulfonated PVA membrane for the MFC performance. The performance of membrane was exceedingly depending on the certain factors like film formation as membranes were brittle with inadequate mechanical strength due to improper polymer ration. However, the membrane with 90:10 ration possesses good proton conductivity of 0.0038 @ 25 °C. The selected synthesized membrane was used in MFC to check the performance in terms of power and current output. It was observed that 630–750 mV and 0.93–1.03 mA stable voltage and current produced during the 48h MFC performance.

Mahendiravarman and Sangeetha (2013) have compared the performance of AMI-7000 with high-performance hydroxide exchange membrane by chloromethylation and quaternization of polyether ether ketone (PEEK) in microbial fuel cell application. The study revealed the better performance of PEEK in terms of ion exchange capacity, water uptake, diffusion and power density compared to AMI 7000.

Various polymers are utilized in the manufacture of PEM in the

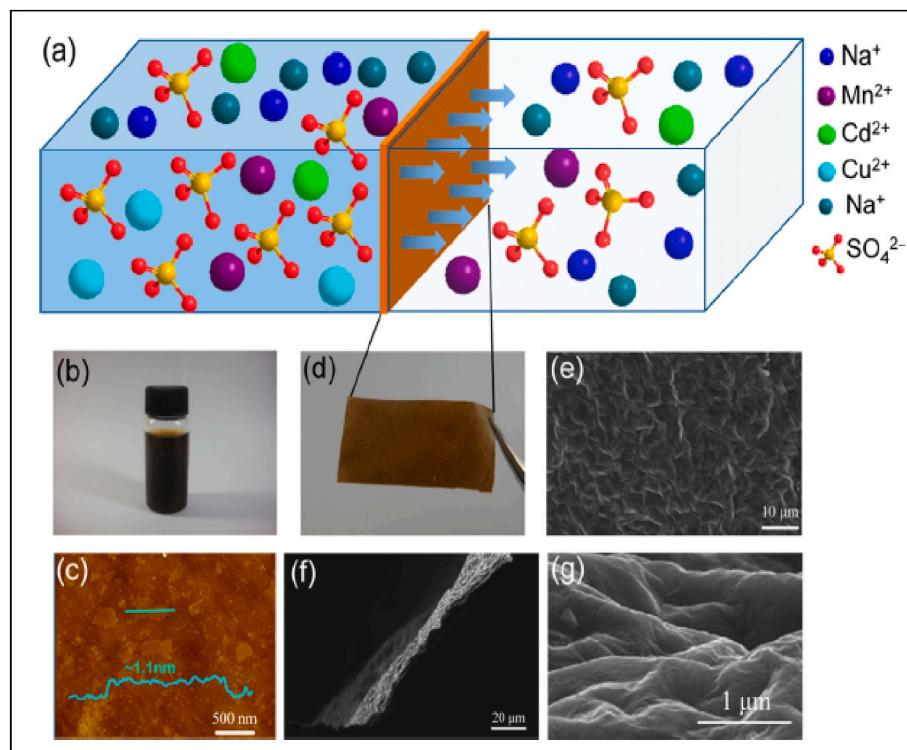


Fig. 4. (a) The Schematic of penetration of different ions through GO membrane, (b) Colloidal solution of GO, (c) AFM image, (d) Picture of GO membrane, (e) SEM images of prepared GO membrane, (f) cross section and (g) Enlarged view of GO panel (Reproduced from Sun et al., 2012 with permission from Elsevier).

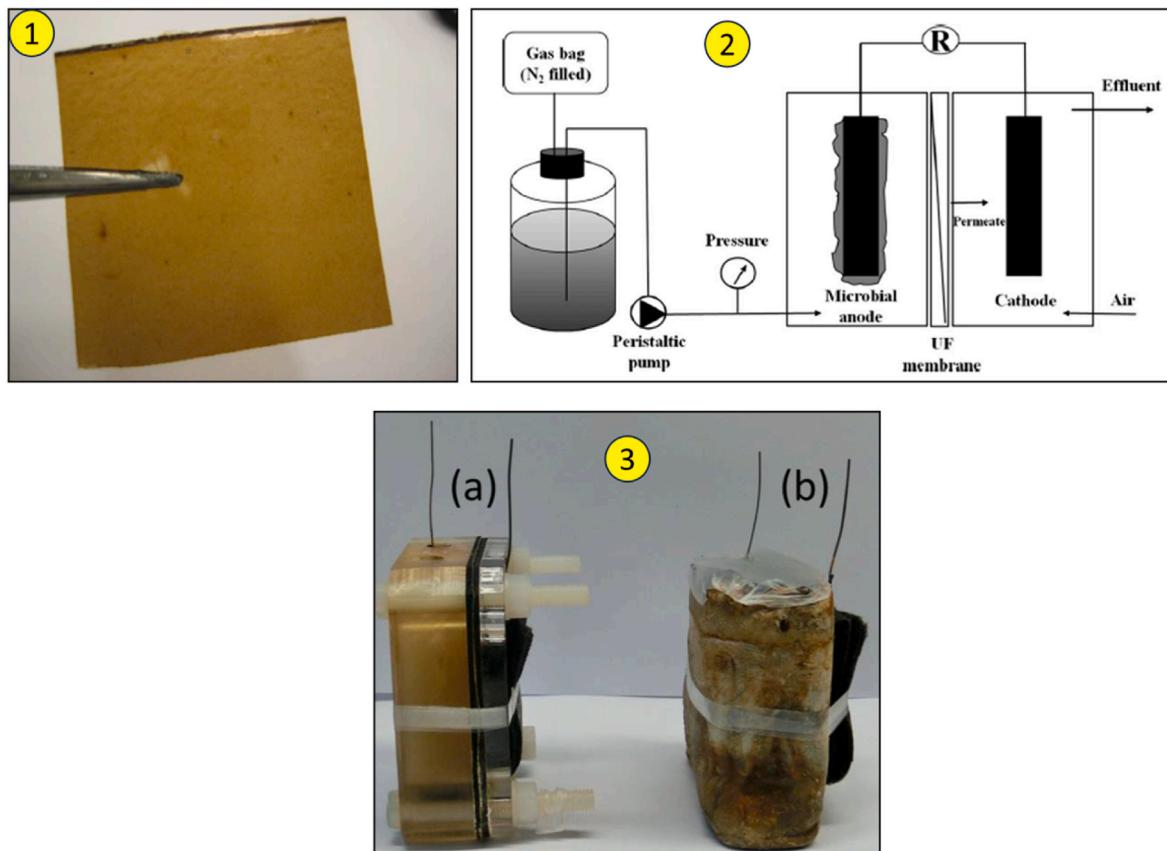


Fig. 5. (1) Synthesized PEO/GO membrane for fuel cell (Reproduced from Cao et al., 2011 with permission from Elsevier); (2) Experimental setup of UF-MFC (Reproduced from Kim et al., 2013 with permission from Elsevier) and (3) Photograph of (a) Acrylic MFC design used for BioBag and CEM membranes and (b) Ceramic MFC (Reproduced from Winfield et al., 2013 with permission from Elsevier).

literature. However, they have certain disadvantages, such as reduced proton conductivity in low-temperature fuel cells when polybenzimidazole (PBI) is doped with heteropoly acids (HPAs) (Staiti et al., 2000). As a proton-conducting membrane, a PBI/phosphotungstic acid composite was employed. However, owing to the synthesis and dispersion of acid molecules in water, the chemical stability of this barrier was limited (Xing and Savadogo, 1999; Y. Li et al., 2015). The sulfonated PBI membrane's principal shortcoming was its low mechanical strength (Anis and Al-Zahrani, 2012). Proton conductivity is high in the sulfonated poly ether ketone (SPEEK) membrane. However, if extensively sulfonated, it dissolves quickly in weak solvents such as water, rendering them unsuitable for fuel cell applications (Fathima et al., 2007). A poly(vinylidene fluoride) co-hexafluoropropylene mix has also been shown to be an effective PEM. However, its severe hydrophobicity lowers its water content and ion exchange capability (Das et al., 2014).

Rahimnejad et al. (2015) studied the MFC's $\text{Fe}_3\text{O}_4/\text{PES}$ nanocomposite membranes. It was observed that the prepared membrane is capable of conducting the protons cheaply and offers superior resistance against fouling. The prepared membrane shows improved performance in terms of power and current density. Fig. 6 (1a,b) shows the MFC setup with all the auxiliaries required for power generation. Linlin et al. (2012) studied the polybenzimidazole (PBI) silica nanocomposite membrane for high-temperature PEM fuel cells. This study suggested that Nafion, a sulfonated tetrafluoroethylene-based membrane, could

only be used up to 100 °C. The membrane prepared by PBI and nanocomposite possesses good thermal, chemical and mechanical properties. It also suggested that PBI doped with phosphoric acid gives good electrochemical properties at a higher temperature than Nafion. Several types of PBI membranes were also investigated to study the improvement in proton conductivity and mechanical properties. It was observed that PBI with silica a nanofiller gives better results in all aspects of fuel cell applications. Fig. 6 (2) shows the systematic depiction of the synthesis of PBI.

Wu et al. (2011) have studied alkaline anion exchange membranes (AEM) for fuel cell application. The prepared membrane shows higher hydroxyl conductivities and alkaline stability than other fluorinated membranes. This research provides an environment-friendly way to prepare AEM for the fuel cell.

Ayyaru and Dharmalingam (2011) have developed a sulfonated polyether ether ketone (SPEEK) membrane and compared its performance with the Nafion-117 commercial membrane in MFC. It was suggested that the proton conductivity of SPEEK can be significantly enhanced by controlling the degree of sulfonation by varying the sulfonation parameter. It was observed that oxygen transfer and substrate loss had been minimized using SPEEK. It also observed that power density; columbic efficiency could be significantly enhanced for dairy wastewater (57 W/m^3). Fig. 7 (a) shows the schematic diagram of a single chamber MFC used by Ayyaru and Dharmalingam (2011).

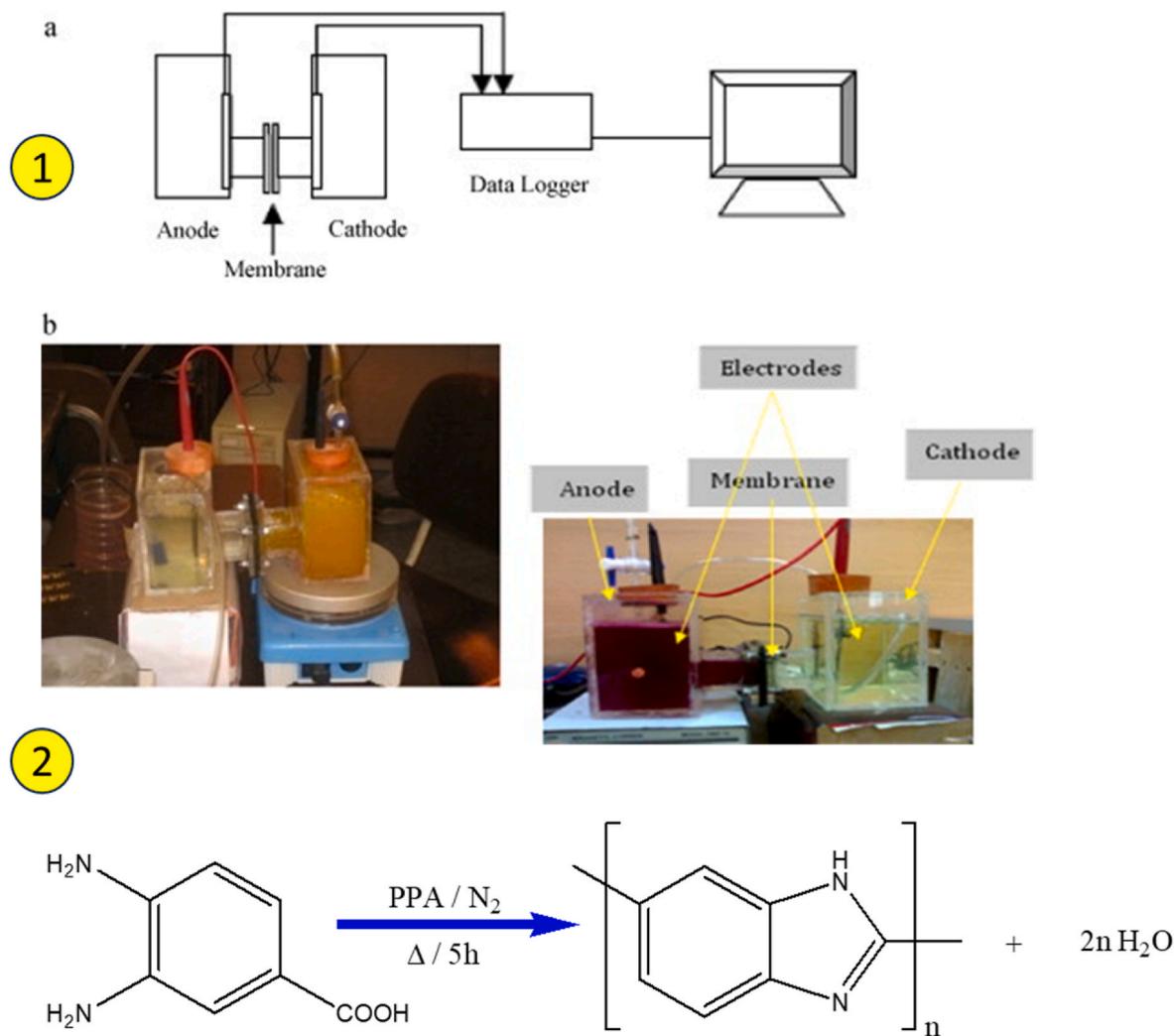


Fig. 6. (1a) Schematic drawing of MFC and (1b) MFC picture of fabricated MFC with the auxiliary equipment (Reproduced from Rahimnejada et al., 2012 with permission from Elsevier); (2) Systematic depictions for the synthesis of PBI (Reproduced from Linlin et al., 2012 with permission from Elsevier).

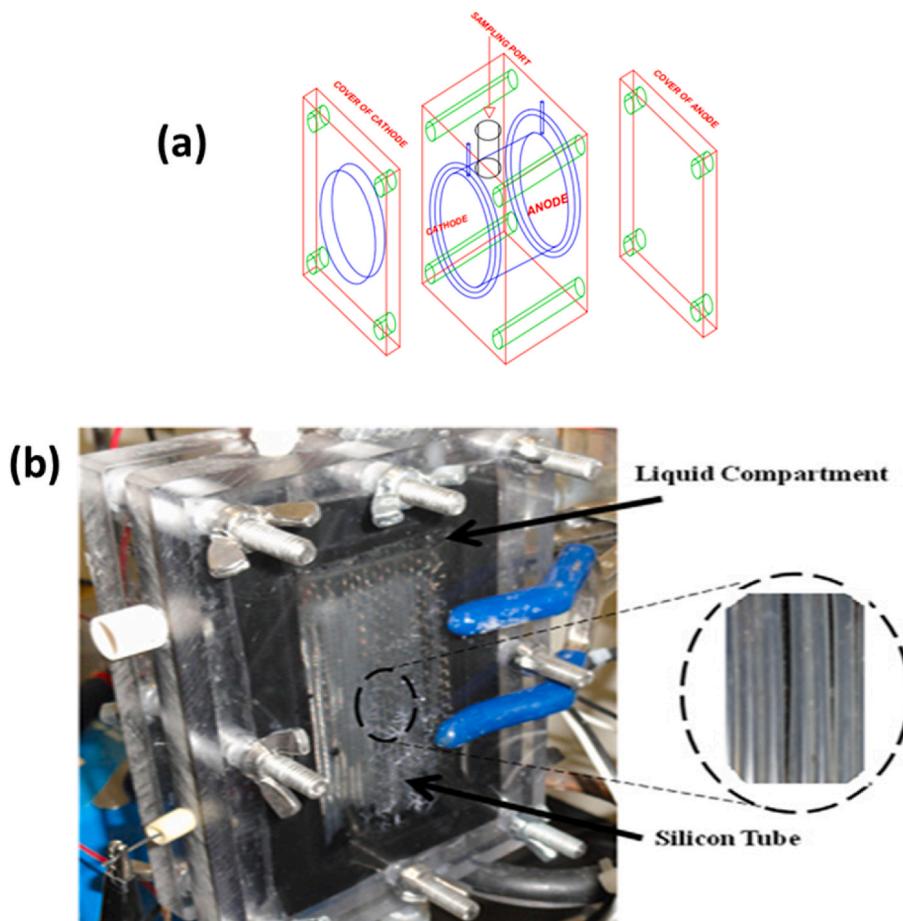


Fig. 7. (a) Schematic diagram of single chamber MFC (Reproduced from Ayyaru and Dharmalingam, 2011 with permission from Elsevier) and (b) Real picture of setup and incorporation of silicone membrane in MFC (Reproduced from Hussain et al., 2011 with permission from Elsevier).

Hussain et al. (2011) studied the use of silicone membranes and silicone tubes in MFC to enhance CO gas transfer across it. Fig. 7 (b) shows the silicone membrane incorporated in MFC. Due to the application of silicone membrane and silicone tubing, mass transfer was improved with a reduction in reactor volume for carbon monoxide operation.

Zhuang et al. (2010) have shown that a membrane can be used to prepare the cathode instead of using it as a separator. It also develops the membrane cathode assembly (MCA) but also reduces the overall cost of MFC by improving overall performance. The study revealed that anion exchange membrane, cation exchange membrane and cloth cathode prepared and suitable for cathode preparation. In this study, the membrane was hot pressed on the cathode surface. The study shows that cloth cathode performs better in terms of power production and reduces the cost of the membrane. It is easy to prepare and implement.

While exploring the newly synthesized MFC membranes, Agar-KCl also one of the best suited membranes exhibited excellent properties for MFC performance. It was observed that the membrane performance solely depends on the Agar and KCl concentration. As the Agar concentration is increased up to certain limit like 4 % it gives maximum power output of 2374 mW/m³. The cost of prepared agar-KCl membrane was obviously much lower than the commercial Nafion 117. Mohan and Das (2009) have studied the performance of MFC for salt bridges and PEM. It was found that PEM gives the manifold performance in terms of current density and power density over the salt bridge. It may be due to the higher internal resistance offered by salt bridges compared to PEM.

Grzebyk and Pozniak (2005) have studied the interpolymer cation exchange membrane with MFC. For this preparation, polyethylene/polystyrene co-divinyl benzene was sulphonated with

chlorosulphonic acid in 1, 2-dichloroethane. It was found that the percentage of divinyl benzene (DVB) affects the membrane properties and performance. The ion exchange capacity and water uptake were also changed due to the percentage of DVB. It also affects the fuel cell performance in terms of voltage and current.

4. Bioremediation of metal copper using single chamber MFC

The development of alternative sources like bio-mass for environmental benefits is required to reduce the dependency on polluting and depleted fossils (Zhuwei et al., 2007). MFCs provide a new platform for sustainable energy production from bio-mass with the development of new devices for energy generation (Logan et al., 2006a,b). The self-sustaining catalysis of organic bacteria in MFC produces bio-energy by the self-sustaining oxidation of bio-mass (Logan, 2007). The various substrate used in MFCs are carbohydrates, volatile fatty acids, alcohols, proteins and amino acids, sulfides, and acid mine drainages (Min and Logan, 2004; Logan, 2007). The type of substrate decides the structure and composition of microbial consortia. Analysis of other factors like substrate concentration, external resistance, rate of electron transfer and anode potentials are also critical. These are the crucial parameters when deciding on MFC's power production capability using bacteria (Lovley, 2008).

The metal-containing wastewater has caused severe environmental pollution problems. These are iron, cadmium, copper, chromium etc. In MFC, microorganisms completely oxidize the organic substrate into compounds, with an anode serving as an electron acceptor. Acetate and other fermentative acids can be totally oxidized to CO₂ and act as a

primary source of electrons and current generation (Lovley, 2008). Besides power generation, the most important use of MFCs for wastewater treatment is savings in wastewater aeration, pumping and sludge treatment. The MFC is essentially an anaerobic technology consuming wastewater heavily polluted with organic matter and staid metals (Lovley, 2008). The architecture of MFCs (single or double) was used to remove heavy metals such as chromium, copper, mercury, and vanadium. These metals were removed either by precipitation or metal reduction (G. Wang et al., 2008; Heijne et al., 2010, Tang et al., 2011). The removal efficiency was exceeded 95% for many metals. The bio-sorption and sulfide precipitation was the main reason for the removal of metals in single chamber MFC. Many have targeted the removal of organic pollutants in MFC as an anolyte (Min and Logan, 2004; Santoro et al., 2012).

The metal removal was targeted in dual chamber MFC as metal was responsible for the prudent inhibition of anodic bacteria in single chamber MFC. Also, the membrane cost, the complicated structure of dual chamber MFC and the high internal resistance demand a suitable alternative. The traditional methods for metal treatment also demanded the alternative as the use of costly reagents, expensive auxiliaries and generation of un-disposable were prominent (Chen et al., 2009; Baig et al., 2009). The microbial consortia were consumed in MFC due to its less adaptation to environmental changes over the pure culture (Carpio et al., 2014). Many bio-sorbents like algae, yeasts and bacteria were used to remediate the targeted metals from wastewater (Romera et al., 2008; Lezcano et al., 2010; Monteiro et al., 2011; Moon and peacock, 2011, Carpio et al., 2014). The bioremediation of metals was mainly done due to the active and passive uptake mechanisms of microorganisms, which involve the bio-accumulation through surface reactions. It includes the extra and intra-cellular complexion and precipitation reactions (Wilde and Benemann, 1993; Aksu, 1998; Donmez and Aksu, 1999). This was the new approach for metal copper remediation by combining the effect of electrochemical and bioremediation in a single chamber MFC.

5. Anode modification in MFC and its application for metal recovery

The crucial part of MFC is anode which needs modification mainly emphases on enhancing surface properties and specific surface area. Several methods including acid and heat treatments increases the definite surface area of an anode (Yaqoob et al., 2020). The advanced electrochemical oxidation can facilitate the improvement in specific surface area of an anode with impregnation of new functional groups to anode exterior. (Yaqoob et al., 2020; Nosek et al., 2020). Beside these methods wide range of studies have used for facilitating the electrical interaction of microbe cells to electron conducting biofilms. However more studies have also focussed on the electron shuttle to electrode surface via proper electron adhesion to electrode surface. Different kind of metals and their oxides are widely utilized for electrode modification with consequent surface properties modifications. Yu et al. (2019) improves the performance of graphite felt by modified it with bentonite-Fe and Fe₃O₄ for studying the performance of soil microbial fuel cell. The performance was evaluated in terms of maximum power density, stable voltage, and internal resistance. It was observed that the stable voltage was increased by 40.87 % for bentonite -Fe modified graphite felt up to 324 mV. The maximum power density obtained was 29.98 mW/m² with minimum internal resistance of 219 Ω. This result shows that anode modification contributed to enrichment in electrogene for better performance of soil microbial fuel cell. The zero valent iron dosing with carbon felt also improved the MFC performance by enriching anode with functional microbe communities and controlled biofilm. (Li et al., 2020). High dosing may also lead to complete inhibition of MFC performance. Many studies also revealed the performance of MFC using carbon-based materials like graphene oxide and carbon nanotubes. The use of GO and Fe₂O₃ improved the MFC performance as compared to carbon felt anode. The performance was quite improved to maximum power density of 334

± 4 mW/m² as 2.59 time more than unmodified carbon felt anode.

Energy use is directly correlated with a civilization's comfort, eminence and growth. Many researchers have studied electrode modification anode for enhanced power generation. Table 4 shows different anode materials for power generation using MFC. The brief discussions of their findings are amended below. Akman et al. (2013) have studied the bioelectricity generation using duel chamber MFC (see Fig. 8a) for Pt and Ti-TiO₂ electrodes. It was observed that the Pt electrode gives a maximum power density of 642 mW/m², four times higher than mixed metal oxide titanium (Ti-TiO₂). It may be due to the more excellent electrolytic activity of the Pt electrode compared to Ti-TiO₂. It was also observed that Pt electrode bio-film adhesion is good compared to the Ti-TiO₂ electrode.

Bouabdalaoui et al. (2013) have presented a new design of MFC with an iron/sulfur chemical catalyst for anode with graphite named FePS. The new design is not only cost-effective but also improves power generation. Fig. 8b shows the MFC modified with the anode used in this study. The new electrode was synthesized using Fe²⁺ and HS⁻ ion deposited on suspended graphite particles. It was observed that power and current density increased when compared with pure graphite or activated carbon used as an anode. This was an excellent example of implementing a solid chemical catalyst for anode modification in MFC.

Ci et al. (2012) decorated the anode with bamboo nitrogen-doped nanoparticles and studied the performance in MFC. In this study, bamboo-NCNTs were prepared by catalytic pyrolysis of ethylene diamine and checked its performance as a modified anode for MFC. It was observed that it gives better current and power output than plain carbon nanotubes and unmodified anodes. It also shows that the biocompatibility of the anode increases due to nitrogen doping. It provides a high surface area and better surface for electrochemical reactions, consequently improving the power and current output.

Guo et al. (2012) have studied the layer-by-layer assembled gold particle-modified anode performance in MFC. The study reveals that gold nanoparticles provide a high surface area for electrochemical reactions and reduce the interfacial resistance for electron transfer. Study shows that gold nanoparticle enhances the electron transfer and biocompatibility for reaction, more excellent adhesion of enzymes and enzymatic activity for MFC. Fig. 8c shows the TEM image of gold colliding and an accurate experiment picture. The study shows that 50 % more power generation and less start-up time are required.

Hou et al. (2013) modified the carbon with electrochemically reducing graphene oxide and polyaniline nano-fiber coating. The electrochemical performance of the cell improved significantly due to better electrochemical compatibility of the modified anode compared with the plain carbon electrode. The new modification improves the charge transfer efficiency and bacterial bio-film loading. The new material offers high modulus, high electrochemical properties, and high surface area for biocompatibility in MFC operation. The improved power density was achieved (1390 mW/m²) compared to the plain carbon atom, which is three times higher. Graphene is an effective material for anode modification with uniform, controllable and reproducible electrochemical performance.

Gao et al. (2013) show that a novel graphite sheet can be used as a novel material for anode development and modification. The study again revealed that new material enhances the electrochemical activity of the anode and gives an improved power output (2249 mW/m²). Fig. 9 shows the SEM of graphite sheet morphology and *E. Coli* adhesion to the sheet's surface. In this way, one more material was added to the anode modification, which significantly improved the power output. Peng et al. (2013) have checked the MFC performance with a newly modified anode with nano-semiconductor goethite. In this study, different percentage of goethite is added to carbon powder and rolled on stainless steel mesh to develop a new anode. The MFC performance was 36% higher (693 mW/m² compared to 508 mW/m²) than the plain activated carbon anode. The study revealed that the new material enhances the

Table 4

The different cathode and their modification.

Sr. No.	Cathode	Modification	References
1	Carbon	Cobalt Iron -layered double hydroxide (CoFe-LDH)	Zhang et al. (2024)
2	Activated carbon	Areca nut husk	Subran et al. (2023)
3	Carbon	Pd and MnO ₂	Das et al. (2020)
4	Carbon felt	bacterial cellulose doped with copper (Cu) and phosphorous (P)	Li et al. (2019b)
5	Carbon	Iron (II) phthalocyanine supported on graphene oxide	Mecheri et al. (2018)
6	Carbon black	Nickel nanoparticles	Gebresemati et al. (2017)
7	Carbon	Nickel phthalocyanine	Tiwari et al. (2017)
8	Carbon cloth	Nanoflower-shaped graphene oxide hybridized MgO (GO/MgO)	Li et al. (2017)
9	Carbon nanotube	Copper selenide nanoparticles	Tan et al. (2016)
10	Carbon cloth	rGO/Ni nanoparticle	Valipour et al. (2016)
11	Carbon paper	Carbon nanotube polypyrrole	Ghasemi et al. (2016)
12	Carbon black	Cobalt oxide/nanocarbon hybrid materials	Song et al. (2015)
13	Carbon paper	Manganese oxide/functionalized carbon nanotubes (MnO ₂ /f-CNT) nanocomposite	Liew et al. (2015)
14	Carbon cloth	Mesoporous nitrogen-rich carbon (MNC)	Ahn et al. (2014)
15	Carbon paper	Nano-bio composite polypyrrole (PPy)/kappa-carrageenan (KC)	Esmaeili et al. (2014)
16	Carbon cloth	MnO ₂ nanostructures/MnO ₂ /GO with 1 wt% polytetrafluoroethylene	Kumar et al. (2013)
17	Carbon black/platinum	Manganese-polypyrrole-carbon nanotube	Lu et al. (2013)
18	Graphite felt	Fe deposition by thermal deposition	Wang et al. (2013)
19	Carbon	Fe-nitrogen functionalized graphene	Li et al. (2012)
20	Carbon paper	Ti/nano-TiO ₂ /Pd nano structure	Hosseini and ahazadeh, (2012)
21	Carbon-supported iron phthalocyanine (FePC)	Carbon-supported cobalt oxide - iron phthalocyanine (FePC)	Ahemad et al. (2012)
22	Carbon cloth	Crumpled graphene	Xiao et al. (2012)
23	Carbon mesh	Carbon meshes are modified with nitric acid or hydrazine hydrate.	Jin et al. (2012)
24	Spectrographic Pure graphite	Prussian blue/polyaniline (Pb/PANI)	Fu et al. (2011)
25	Carbon cloth	Carbon nanotube (CNT) cathodes	Wang et al. (2011)
26	Carbon	Catalysts based on Pt, Mn ₂ O ₃ and Fe ₂ O ₃ were supported using carbon powder	Martin et al. (2011)
27	Carbon	Platinum	Zhu et al. (2011)
28	Carbon (vulcan xc-72r)	5% Nitric acid, 0.2 N Phosphoric acid, 0.2 N Potassium hydroxide and 10% Hydrogen peroxide.	Duteanu et al. (2010)
29	Carbon	Polypyrrole (PPy)/anthraquinone-2,6-disulfonate (AQDS) conductive film of bare carbon	Feng et al. (2010)
30	Carbon cloth	15% Wet-proofed carbon cloth on which a Nafion layer and a catalyst layer at the electrolyte interface and a PTFE layer at the air interface	Lefebvre et al. (2009)

Table 4 (continued)

Sr. No.	Cathode	Modification	References
31	Carbon	Mn(iv), Fe(iii)	Roche and Scott (2009); Yu et al. (2008)
32	Carbon	Iron phthalocyanine supported on ketjen black	Yu et al. (2008)
33	Graphite	Mn (iv)	Park and Zeikus (2003), (2002)

extracellular transfer between the electrode and bacteria, enhancing the cell's electrolytic activity. This may increase the capacitance and diffusion on the electrode surface.

Kipf et al. (2013) have tested various carbon base materials as an anode and their performance in MFC with *S. oneidensis* MR-1 as an inoculating media. The study shows that the electrode material significantly affects the performance of the corresponding fuel cell anode, which underlines the need to develop hierarchically structured materials with optimized transport characteristics. A recent study based on anode modification (Kumar et al., 2013) shows that anode modification can be done by surface treatments like ammonia treatment, heat treatment, acid treatment and electrochemical oxidation. Kumar et al. (2013) also suggested that anode modification can be done using nanostructure material, conductive polymer and its composites and polymer nanocomposites. The investigation also examines at surface area and porosity, fouling and poisoning reduction, electrical conductivity, biocompatibility, stability and durability, and electrode cost and availability. Fig. 10 depicts the energy portfolio of energy devices as well as the benefits of MFC.

Anode materials must be highly conductive, non-corrosive, have a high specific surface area (area per volume), be porous, non-fouling (i.e., bacteria do not fill it up), be affordable, and be easily produced and scaled to higher quantities. The most fundamental difference between these bio-film reactors is that the material must be electrically conductive. A basic voltmeter test is adequate to conduct the initial assessment of the material by measuring its resistance across a distance. Placing the voltmeter electrodes on a surface, say 1 cm apart, and detecting the resistance results in an instant categorization of the material's conductivity. Electrons created by bacteria must pass from the site of creation on the material's surface to the collecting point (contact with the wire), and simply a few ohms of increased internal resistance may dramatically diminish power. As a result, we need to develop highly electrically conductive materials that are also non-corrosive, which rules out many metals. Furthermore, bacteria must be able to cling to the substance and form excellent electrical connections. As a result, we shall see certain materials, such as stainless steel, fail to generate adequate power generation while satisfying several anode material criteria. As a result, even excellent conducting materials may not be adequate. We must also examine how the material, or coatings applied to the material, impact the capacity of bacteria to transport electrons to that surface (through nanowires, mediators, or direct contact).

Numerous efforts were taken to improve the MFC performance (Watanabe, 2008; Reddy et al., 2010b). The power density, electron transfer efficiency, and MFC cost are still the major issues while working with MFCs (Logan and Regan, 2006; Huang and He, 2010). The essential properties of anodes are high electronic conductivity, large surface area, good biocompatibility and stability (Logan et al., 2006; Zhou et al., 2011). The anode should be capable of collecting current from all regions and be a biocompatible and good conductor to facilitate electron transfer (Ding et al., 2012; Okamoto et al., 2014). The ammonia treatment (Cheng and Logan, 2007), electrochemical oxidation (Tang et al., 2011), polyaniline modification (Lai et al., 2011) and Fe₃O₄ (Peng et al., 2012a,b) are the few anode modification techniques were used for the MFC operation. Copper is precious metal recovered using MFC technology with power generation (Heijne et al., 2010; Tang et al., 2011).

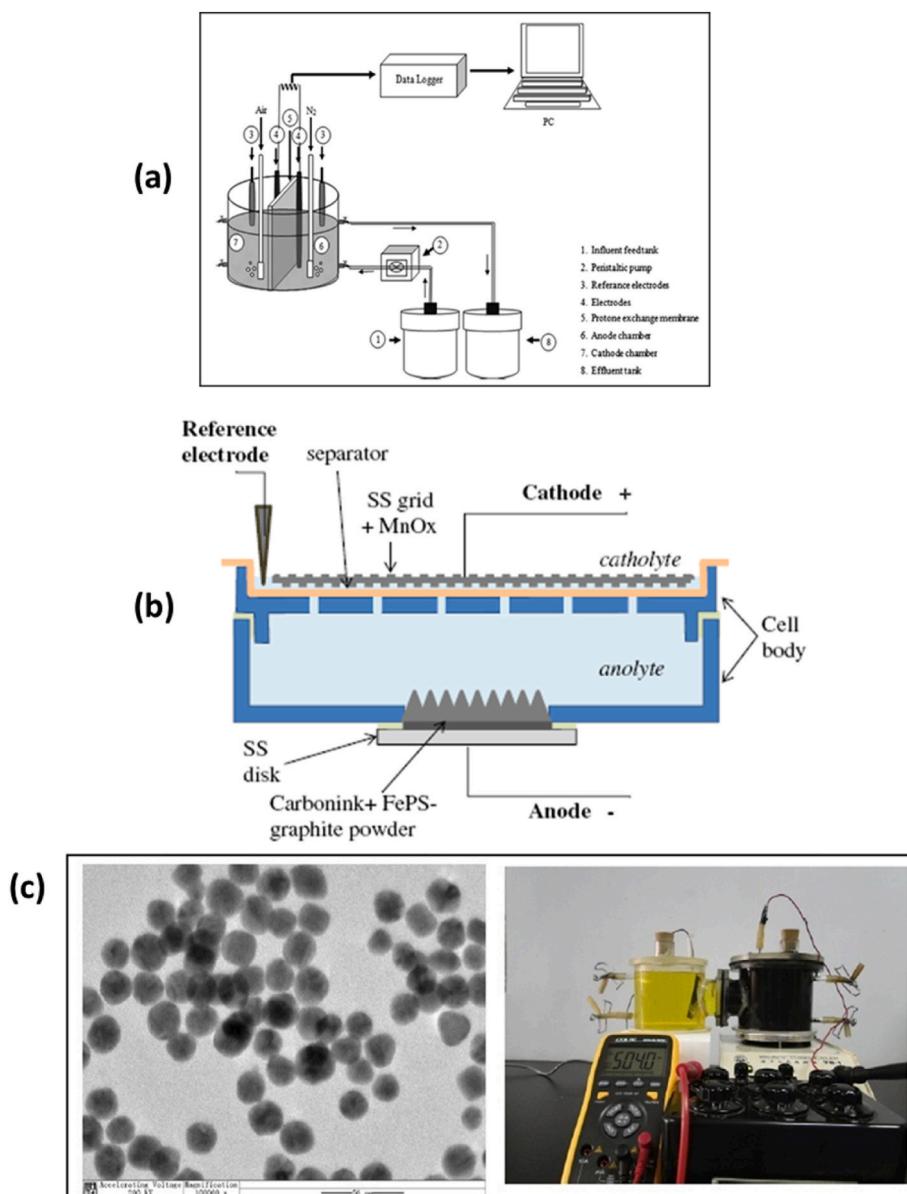


Fig. 8. Schematic of MFC (Reproduced from Akman et al., 2013 with permission from Elsevier); (b) Schematic of MFC modified with Carbon Ink FePS graphite powder (Reproduced from Bouabdalaoui et al., 2013 with permission from Elsevier) and (c) TEM image of gold colloid and real picture of the experiment (Reproduced from Guo et al., 2012 with permission from Elsevier). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

However, due to low electron transfer between bacteria and the anode surface, less electrons are available for copper reduction at the cathode (Zhao et al., 2015a,b).

Graphene and its compounds show the best thermal, electrical and mechanical properties to be used as electrode material in energy-related devices (X. Wang et al., 2008; Yu et al., 2010). Graphene shows good electron transfer capability, bio-compatibility, and mechanical strength (Sun et al., 2011; Yu et al., 2011; Choi et al., 2012). But the GO shows poor performance when used for an extended period with low electronic conductivity (Zhu et al., 2012; Liu et al., 2013a,b). Fullerene on the other hand, also has applications in batteries, supercapacitors, sensors and bio-sensors (Zhao et al., 2015a,b). The high electrical conductivity and electron-accepting capacity in photovoltaic cells (Wudl, 2012) facilitated its use in electrochemical activities. The biocompatibility and excellent electronic conductivity of reduced fullerene offered it a suitable working electrode (Csiszar et al., 2001).

The PPy, PANI and thiophene are extensively used for improving

bacteria adhesion and electron transfer (Benetton et al., 2010; Zhou et al., 2011). Carbon's low extracellular efficiency and poor electrical conductivity restrict its application in MFC (Zhao et al., 2015a,b). As a result of the adaptability of GO and C60, we created reduced GO poly-pyrrole (rGO/PPy) and reduced C60 poly-pyrrole (rC60/PPy) composite anodes in this work using electro-polymerization and simple electrochemical techniques, respectively. The efficacy of modified rGO/PPy and rC60/PPy composites as an effective electrochemical platform for removing copper metal via MFC was evaluated and compared to bare graphite and PPy-modified anodes. This new approach makes electrochemical cleanup of valuable copper metal possible. This research comprises the characterization of composites using SEM, FT-IR, XRD, CV, and EIS methodologies, as well as the performance of MFCs in terms of power and copper removal.

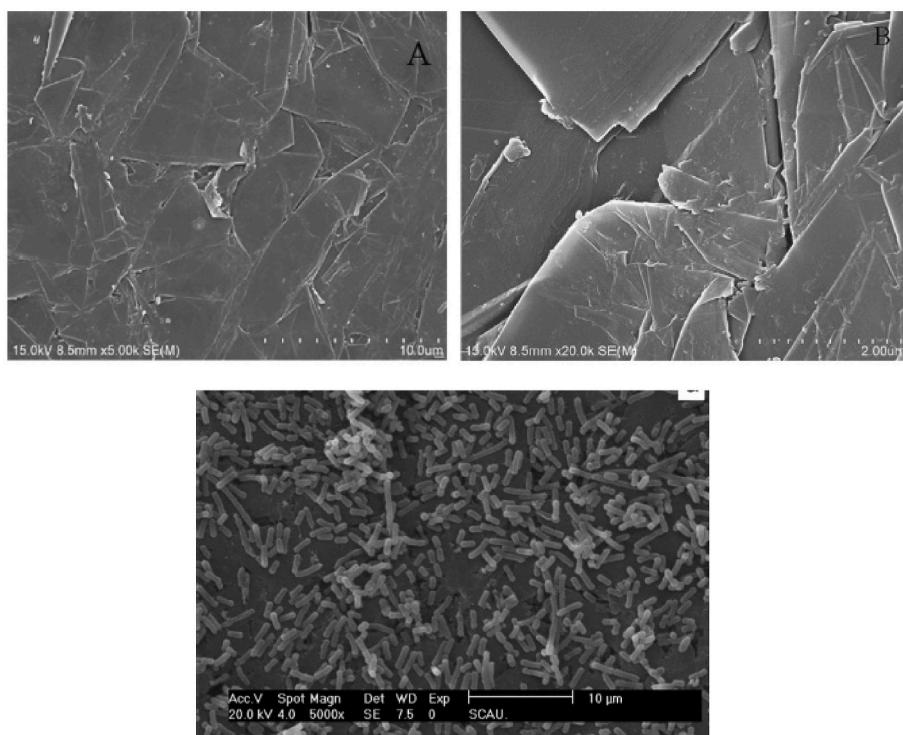


Fig. 9. The SEM of graphite sheet morphology and *E. Coli* adhesion to the surface of the sheet (Reproduced from Gao et al., 2013 with permission from Elsevier).

6. Cathode modification and its application in MFC for metal removal

The fundamental part of MFC is the cathode. In a Microbial Fuel Cell (MFC), the cathode serves as the electrode where reduction reactions occur. Specifically, it facilitates the acceptance of electrons generated by microbial oxidation reactions at the anode. Oxygen is typically the electron acceptor at the cathode, undergoing reduction to form water. This electrochemical process completes the circuit, allowing for the generation of electrical energy in the MFC. The critical cathode function is highly dependent on the precious metal catalyst, which might be costly. Many researchers approached replacing metallic catalysts with transition metal and non-precious metal compounds. The MFC uses the abiotic cathode for power generation and wastewater treatment (Logan et al., 2005). Many researchers show the improved power of the MFC in the range of 200–250 W/m³ (Pandit et al., 2009). Compared with the chemical fuel cell, it's many folds less. The power generation of MFC is greatly attributed to the cathode electrode material's surface area, the material's chemical composition, types of catalyst, stability, etc. (Rodriguez-Reinoso, 1998). Yang et al. (2012) have shown that spacers introduced in the cathode chamber may reduce the reactor size. The anode related to microbial metabolism and the cathode to cathodic reduction might be the limiting factor for MFC power generation (Feng et al., 2010). The oxygen reduction reaction (ORR) is costly. It needs to catalyze with some material like platinum (pt) to overcome the high potential barrier using plain carbon or graphite electrodes (Martin et al., 2011). It reveals an urgency to replace costly Pt with a comparable alternative. Many researchers have studied the modification of cathode for better MFC performance.

Feng et al. (2010) have modified the cathode with a polypyrrole (PPy)/anthraquinone-2, 6-disulfonate (AQDS) conductive film and found that electro-catalytic activity towards oxygen reduction is greatly enhanced due to increased conductive surface area. It is attributed to increased power generation too. Martin et al. (2011) have prepared a cathode with catalysts based on Pt, Mn₂O₃ and Fe₂O₃ nano powders on carbon powder. Based on volumetric power output and ORR, it has been

observed that Mn₂O₃ is the better option to replace the costly Pt catalyst for better electro-catalytic ORR.

Increased use of single-chamber MFC attracted and challenged researchers to modify the carbon cathode electrode with simple pre-treatment or metal coatings. Duteanu et al. (2010) studied the effect of chemical modification of air broth cathode by modifying the carbon (Vulcan XC-72R) cathode with 5% nitric acid, 0.2 N phosphoric acid, 0.2 N potassium hydroxide and 10% hydrogen peroxide. It was observed that HNO₃-modified Vulcan confirmed significant ORR activity. It also shows improved results in terms of current density as compared to the Pt catalyst. Lefebvre et al. (2009) studied the cathode modification by applying 15% wet-proofed carbon cloth on which a Nafion layer, a catalyst layer at the electrolyte interface, and a PTFE layer at the air interface. It was observed that ambient oxygen's sputtered cobalt deposition contacts greatly enhanced power generation.

Kumar et al. (2013) also modified the carbon cloth cathode with a catalyst slurry of MnO₂ nanostructures/MnO₂/GO with 1 wt % poly tetra fluoro ethylene and observed that the power density was significantly enhanced compared to plain carbon cloth. It was also comparable with Pt/C as a suitable and cheap alternative for Pt. P. Wang et al. (2013) suggested that cathode with Fe deposition proved cheaper than cathode with Pt catalyst as it cost 0.25 % only if compared with Pt. It also improved the cathodic electron activity and improved power density with reduced internal resistance. Li et al. (2012) observed that power density and ORR activity also increase remarkably if the cathode is used with iron-nitrogen functionalized graphene. It was suggested by Li et al. (2012) that Fe-N-G would be the best option to replace costly Pt with a non-precious Fe-N-G compound. Hosseini and Ahadzadeh (2012) also suggested that the Ti/nano-TiO₂/Pd nanostructure modified anode and cathode shows comparable results with Pt and carbon paper cathode. Hence, Ti/nano-TiO₂/Pd nanostructure would be the best option to replace the high-cost Pt catalyst.

Fu et al. (2011) modified spectrographic pure graphite cathode with Prussian Blue/polyaniline (PB/PANI) by electrochemical and chemical methods. Fu et al. (2011) also found that a modified catalyst shows good stability and enhanced power density compared with a platinum

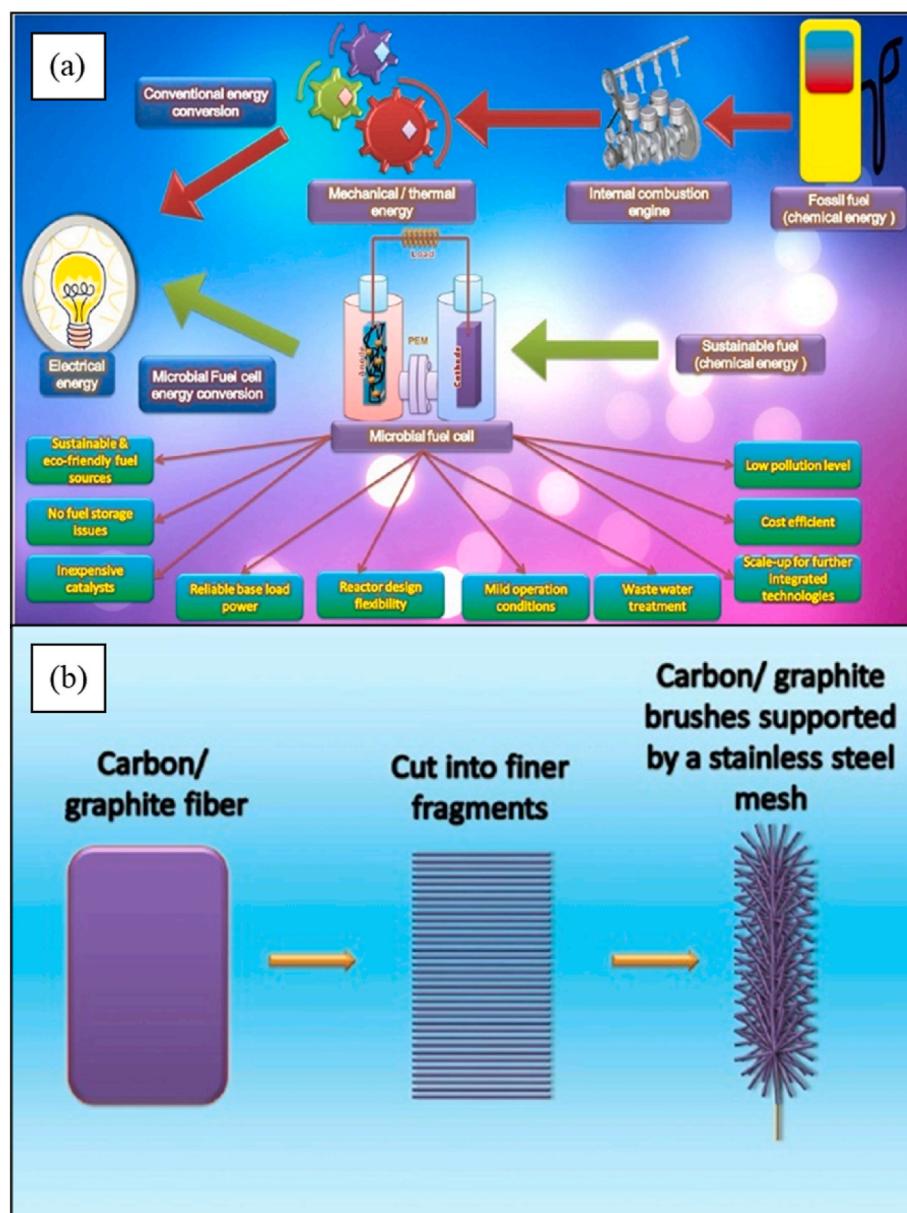


Fig. 10. (a) Energy portfolio of energy devices and advantages, and (b) Modification of anode for surface area improvement (Reproduced from Kumar et al., 2013 with permission from Elsevier).

catalyst. However, Fu et al. (2011) tried the spectrographic pure graphite cathode in a ferricyanide liquid state. Carbon nanotubes show excellent properties in fuel cell applications due to their high surface-to-volume ratio and good electrical and mechanical properties. Wang et al. (2011) show that cathode modifications with CNTs mesh proved cheap and enhanced power density compared to plain carbon cloth. Even CNTs modified cathode with Platinum catalyst gives the highest power density. Wang et al. (2011) also suggest that due to CNTs, electrolytic oxygen reduction improved and enhanced the electrolytic activity at the cathode. Ahmad et al. (2012) also modified the cathode with cobalt oxide-iron phthalocyanine (FePc). They showed excellent, improved results compared to the platinum catalyst as a costly catalyst hindered the use of MFC on a commercial scale. The iron phthalocyanine (FePc) incorporation improved the cathode's ORR activity and improved and stabilized power density. Xiao et al. (2012) suggested the option of platinum-carbon cloth with crumpled graphene as a modified cathode for better oxygen reduction. The power density obtained with crumpled graphene cathode is low, but the surface area and electrical

conductivity improved and are comparable with platinum-carbon cloth cathode. Therefore, crumpled graphene is the better option for platinum-carbon cloth for better oxygen reduction. Table 4 lists the different cathode and their modifications.

Many researchers have attempted anode modification for MFC power production (Wei et al., 2011; Zhou et al., 2011). The power density obtained was correlated with the anode surface area. As the anode surface area is higher, the power density is also higher (Chaudhuri and Lovley, 2003). Different anode material was tested, like plain graphite, carbon paper, carbon cloth and carbon felt (Logan et al., 2005).

The release of heavy metals by metal processing industry may endanger aquatic and living organisms. Cu, Ni, As, Pb, Cd, Cr, Zn, and other metals are used. These most hazardous metals cause severe health disorders in living (Babel and Kurniawan, 2004). Chemical precipitation, ion exchange, and electrochemical techniques are all energy consuming and have several problems such as partial treatment and the formation of hazardous sludge (Eccles, 1999). Adsorbents such as

minerals, zeolites, biomass, agro-waste, and polymeric materials are being used more recently (Kurniawan et al., 2005). Other methods for eliminating metal contaminants in water include ultrafiltration, nanofiltration, and reverse osmosis (Kurniawan et al., 2006), electrodialysis (Pedersen, 2003), and photocatalysis (Skubal et al., 2002). Numerous techniques for metal cleanup based on less expensive and more effective technologies have been investigated. To fulfil the maximum contamination criteria, ideal, reasonable, and relevant remedies must still be undesirable. Graphene has high electron transport capabilities but poor electron uptake (Yu et al., 2011). Graphene oxide (GO), on the other hand, has poor long-term stability and electrical conductivity (Zhu et al., 2012; Liu et al., 2013a,b). Although graphene has high conductivity, non-ballistic conduction was detected in bulk samples. This might be caused to impurities or morphological flaws. This may impede the reduction process and raise the internal resistance of the cathode (Miao et al., 2007; Ilyin et al., 2009; Adam et al., 2009). As a result, it is simple to enable graphene's enhanced conductivity for MFC applications. Conducting polymers, on the other hand, such as polyacetylene, polypyrrole, polyaniline, and polythiophene, have attracted significant research attention due to their wide range of applications in batteries (Scrosati, 1998), membranes (Misoska et al., 2001), biomedical devices (Benabderrahmane et al., 2005), biosensors (Yamato et al., 1997), and metal removal (Eisazadeh, 2007, 2008). Because of its ease of synthesis, high conductivity, and environmental durability, polypyrrole synthesized via electropolymerization has piqued the curiosity of a wide range of researchers. However, the use of PPy in MFC introduced difficulties such as poor relative conductivity, limiting MFC performance. When rGO is combined with PPy, it can increase catalytic sites and conductivity when compared to PPy alone (Ci et al., 2015).

As cathode is the crucial part of MFC, the power generation is solely depending on the cathode catalyst. As cathode centered oxygen reduction principally affect the power output in MFC. The suitable cathode catalyst largely enhances the electron transfer and subsequently increases the oxygen reduction. The materials like precious platinum (Pt) are the best suited cathode catalyst for the MFC (Das et al., 2020). But the major drawback of precious Pt was huge cost and availability at large scale (Priyadarshini et al., 2021). The electrochemical exfoliation of iron-based catalyst impregnated over graphene oxide can be used to enhance the ORR activity over the cathode. It was observed that the performance of air cathode MFC increased as compared to bare carbon (Mecheri et al., 2018). The bacterial cellulose doped with copper (Cu) and phosphorous (P) was utilized as a cathode catalyst in MFC. The maximum power density obtained was 1177.31 mW/m² with current density of 6.73 A/m². The doping enhances the more active site for the effective ORR activity over the electrode surface enhances the power generation in MFC (Li et al., 2019a,b). Nickel metal organic framework and CoFe-layered double hydroxide nanosheet were synthesized by hydrothermal method. This synthesized cathode catalyst was utilized for MFC performance. The composites provide the active electrochemical sites for the ORR, which improve the power density up to 211 mW/m² with stable power output of 225 mV for 150 h (Zhang et al., 2024). To overcome the energy barrier activated carbon was impregnated with areca nut husk. The pyrolyzed amorphous graphite structured activated carbon with areca nut husk possess the excellent electrochemical characterization for oxygen reduction in air cathode MFC. The performance enhanced with 590 mW/m² power density and 1.03517 A/m² current density was obtained (Subran et al., 2023). More studies were endeavored for developing conductive materials with specific advantages like operation stability, excellent electron transfer efficiency and improved ORR activity. This will lead to improved MFC concert in terms of electrochemical performance.

This study investigates a potential replacement for the conventional carbonaceous material. Carbonaceous materials have shown to be appropriate for MFC, however their weak electrical conductivity and low extracellular efficiency as compared to noble metals restrict their utilization in MFC applications (Zhao et al., 2015a,b). Platinum metal

was utilized as a cathode catalyst in MFC; however, its utilization is not commercially practical (Yuan and He, 2015). Graphene oxide and PPy structural flaws may give improved adsorption sites for solution species (Selvaraj et al., 2014). The effectiveness of rGO/PPy composites as a cathode catalyst for effective metal copper remediation was compared to pure graphite.

7. Constructed wetland (CW) integrated microbial fuel cell

Constructed wetland integrated microbial fuel cell (CW-MFC) is an innovative approach that combines two sustainable technologies: constructed wetlands (CW) and microbial fuel cells (MFC). Constructed wetlands are artificial systems designed to mimic the natural processes of water purification that occur in wetland ecosystems. They use plants, soil, and microorganisms to treat wastewater by promoting biological, chemical, and physical interactions that remove pollutants. Microbial fuel cells, on the other hand, are bio-electrochemical devices that harness the power of microorganisms to generate electricity through the degradation of organic matter. In an MFC, bacteria break down organic compounds, releasing electrons that can be captured as electrical current. Mittal et al. (2023) demonstrates a substantial effect on the performance of CW-MFC due to Evapotranspiration (ET) water loss in the actual field. Thus, ET is a critical aspect and worth considering for large-scale implementation of CW-MFCs, especially in tropical regions or with dense plantations.

The integration of constructed wetlands with microbial fuel cells in CW-MFC systems takes advantage of the synergies between the two technologies. As wastewater flows through the wetland, it undergoes natural treatment processes, and the organic matter present in the wastewater serves as a substrate for microbial growth. The microbial activity in the wetland enhances the degradation of organic pollutants and promotes the release of electrons, which can be captured by the MFC for electricity generation. The electricity generation performance of CW-MFC systems depends on various factors, including the type of wetland plants, the composition of wastewater, and the design of the microbial fuel cell. Studies have shown that CW-MFC systems can effectively treat wastewater while simultaneously producing electricity. This dual-functionality makes them an attractive option for sustainable water treatment and energy generation. Overall, CW-MFC systems offer a promising approach to address both wastewater treatment and electricity generation challenges, providing an environmentally friendly and integrated solution for resource recovery.

8. CO₂ conversion in microbial electrosynthesis cells

Microbial electrosynthesis cells (MECs) are bioelectrochemical systems that use microorganisms to convert carbon dioxide (CO₂) into valuable chemicals or fuels while generating electrical energy. The concept of using cathode materials to boost CO₂ conversion in MECs involves optimizing the electrode materials at the cathode to enhance microbial activity and electron transfer efficiency, ultimately leading to improved CO₂ reduction. The key aspects of this concept as like Cathode Material Selection, Enhanced Electron Transfer, Catalytic Properties, Surface Modification, Electrochemical Performance Monitoring, and Microbial Community Interaction.

By tailoring the cathode material properties and optimizing its design, researchers aim to create MECs that efficiently convert CO₂ into valuable products while harnessing electrical energy. This concept aligns with the broader goal of developing sustainable technologies for carbon capture and utilization, contributing to the mitigation of greenhouse gas emissions. Optimizing the surface properties, porosity, and conductivity of the cathode material is essential for creating an environment conducive to microbial activity and efficient CO₂ conversion in MECs.

9. Prototype to pilot scale MFC application for electricity generation

Moving from a prototype to a pilot-scale for Microbial Fuel Cell (MFC) applications for electricity generation involves a critical transition that considers various technical, economic, and practical aspects. There are various stages in prototype and pilot scale MFC for the application of electricity generation. In prototype MFC various critical stages like to designed and demonstrate the feasibility of MFC technology for electricity generation. Further, emphasis is on understanding basic principles, microbial interactions, and initial electricity generation capabilities. Prototypes typically operate at a small scale in laboratory conditions. The focus is on controlled experiments to optimize parameters, electrode materials, and microbial consortia. Prototypes often exhibit lower power outputs compared to what is needed for practical applications. Challenges in the prototype MFC includes low current densities, limited scalability, and issues related to stability and reliability. Reddy et al. (2019) reported the fundamental knowledge, critical constraints, current status and some insights for making A-MFC technology a reality at commercial scale operation.

In the case of pilot scale primary goal is to address scalability issues observed in prototypes. Scaling up involves dealing with challenges related to maintaining optimal conditions across larger volumes. Pilot-scale MFCs require durable and cost-effective materials that can withstand prolonged operation and larger volumes of wastewater. Also, consideration of electrode materials, membrane properties, and overall system durability becomes critical. In pilot scale MFC, understanding the impact of increased size on mass transfer, microbial distribution, and electron transfer is essential. Pilot-scale systems should demonstrate consistent performance, withstanding variations in microbial activity, temperature, and other environmental factors. Economic factors, including the cost of materials, construction, and maintenance, become more pronounced at the pilot scale. Assessing the feasibility of large-scale deployment requires a thorough economic analysis. Pilot-scale MFCs should align with real-world applications and be adaptable to existing wastewater treatment infrastructure.

Transitioning from prototype to pilot scale for MFC applications for electricity generation is a crucial step towards practical implementation. Success depends on addressing scalability issues, optimizing processes, ensuring durability, and demonstrating economic viability. Collaboration between researchers, engineers, and industry stakeholders is essential for overcoming challenges and realizing the full potential of MFC technology in real-world applications.

Green biomaterials play a crucial role in the quest for sustainable and environmentally friendly energy production. These materials, derived from renewable resources, offer a promising avenue for addressing the challenges associated with traditional energy sources. Green biomaterials are derived from renewable resources such as plants, algae, and other organic sources. Utilizing these resources ensures a continuous and sustainable supply, reducing dependence on finite fossil fuels. Biomass can be converted into energy through various technologies, including combustion, gasification, and fermentation. Each method has its advantages and challenges, and researchers are exploring ways to optimize these processes for higher efficiency and reduced environmental impact. Green biomaterials should be compatible with existing energy infrastructure to facilitate a smooth transition toward renewable energy. Compatibility with existing technologies, such as power plants and distribution systems, is crucial for widespread adoption. Therefore, the use of green biomaterials for energy production aligns with the principles of sustainability and offers a viable pathway toward reducing the environmental impact of energy generation (Rabiee et al., 2023).

10. Future perspectives of MFC technology

The development of MFC technology is depends on the tackling of some addressed issues which may limit the commercialization of

technology (Jadhav et al., 2017). The lab scale methodology is not enough to propose the technological advances at field-scale solicitations. The major losses accounted in MFC technology emanates from ohmic losses, activation, and concentration losses (Logan and Regan, 2006). The reduction in activation energy for oxidation reduction reaction (ORR) at cathode is enhanced by using platinum-carbon (Pt-C), which overcome the activation losses and catalyzes the reaction. As the cost of Pt-C is huge, this prevails the use of costly Pt-C at commercial scale (Chen et al., 2018). To address this issue, a lot of cathode catalyst were used like MnO₂ nanostructures/MnO₂/GO with 1 wt % poly tetra fluoro ethylene (Kumar et al., 2013), cathode with Fe deposition (L. Wang et al., 2013), cathode with iron-nitrogen functionalized graphene (Li et al., 2012) and many more. However, the various routes of synthesis methods and non-recognized methods leads to incapacity of these catalysts to perceive the light of hope (Jiang et al., 2020; Liang et al., 2020). There are so many issues that need to solve while attempting the MFC scale up. Distinctly, other serious issues before making MFC qualify for field scale presentation are membrane high cost (Rikame et al., 2018), Bio fouling and stability of membrane (Choi et al., 2011), electrodes issues (Yuan et al., 2016), metabolism and substrate issues, oxygen crossover (Koók et al., 2019), etc.

In addition to these in tangled issues, diffusion barriers, low power performances, structural reliability of materials, electron transfer issues, reactor manufacturing, dead pocketing, and short circuiting due to wastewater are the major issues needs to be addressed and solved before proper on field MFC applications (Gajda et al., 2018). Hence advance amplification of these critical issues are needed while addressing the MFC field scale implementations. The commercialization of MFC necessitates the development and manufacturing of efficient and cheap material sources; bio film formation scenario and its easy analysis, its working environment and adaptability; operating conditions and their optimization; capable substrates for microbial development and most important MFC products and their analysis. However, recent research development and breakthroughs in MFC technology establish the opportunities among the industry and scientist to make it commercialize. Many scientists addressed the barriers to overcome the commercialization of MFC begins essentially. But still many issues need to be addressed for attending the proper breakthrough in MFC technology. Logan (2008) addressed the latent losses related to scale of MFC like stability and economic benefit of MFC, irreversible activation losses, mass transfer and ohmic losses. To overcome the activation losses in MFC, some of the issues needs to be addressed like substrate concentration, enriched bio-film and its temperature and active catalyst to enhance the MFC performance (Singh et al., 2010).

Sometimes unavoidable circumstance creates the potential losses like ohmic losses due to internal resistance. Membrane surface and different electrolytes may also offer some internal resistance. This type of losses can be overcome by reducing the distance between the electrode and many more ways. In this way electrogenic reaction and efficient electron transfer can be achieved. This type of losses can be recovered by using low resistive membrane materials and high conductive electrolyte for MFC operation. The major losses in MFC performance arises due to the improper mass transfer between the electrode surface and electrolyte interaction. The rate of mass transfer between the electrode surface and chemical species bounds the current production. This type of losses can be minimized by providing the high electrode porous surface and maximum possible uniform electrolyte concentration across the MFC chambers. Specific design of MFC, best operating conditions and efficient material selection also improve the MFC performance (Hamid et al., 2008). Clearly MFC technology addressing the energy and environmental solutions in a diversified way. However, the much more practical orientation is needed to alleviate the commercialization of MFC technology. The performance consistency, stability in terms of operation, repeatability of product output and forthcoming innovation feasibility are the key components considered to be the critical barriers for the diversification and scale up of MFC

technology.

11. Conclusions

The present article is extensively reviewing the recent literature of the MFC and its application for significant amount of energy generation using different types of sources. Using the MFC technique, one can easily obtain the clean energy and water for mankind. In addition, using the MFC system one can achieve an energy neutral approach to the well-being of ecosystem. The MFC mechanism for the energy generation and clean water production have been extensively studied in the present review article using the different configurations. Basically, there are different types of wastewater sources available such as agro food wastewater, seafood processing wastewater mustard wastewater, cassava mill wastewater, canteen food waste, rice mill wastewater and distillery wastewater. The MFC performance for the energy generation and production of clean water can be enhanced by using different types of membranes. The prepared and used membranes ion conductivity and power density play an important role in the energy production. Overall, the MFC mechanism of energy generation, clean water production, membrane synthesis, wastewater treatment has been covered in the present review article. Using the different literature studies, it is found that the MFC is a highly significant and more commercial potential based technology for the future energy source and clean water.

CRediT authorship contribution statement

Amol V. Sonawane: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Satish Rikame:** Investigation, Formal analysis, Data curation. **Shirish H. Sonawane:** Validation, Investigation, Formal analysis. **Mahendra Gaikwad:** Validation, Resources, Formal analysis. **Bharat Bhanvase:** Resources, Methodology, Formal analysis, Data curation. **Shriram S. Sonawane:** Resources, Formal analysis, Conceptualization. **Arvind Kumar Mungray:** Resources, Formal analysis, Data curation. **Ravindra Gaikwad:** Visualization, Validation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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