Microbial Fuel Cell (MFC)-A review of Design components, Selection of Substrate and Microbes, Parameters affecting the Design and Applications

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Abstract

Recently, Microbial Fuel Cells (MFCs) have achieved colossal attention among the researchers due to the thoughtful operating conditions, using a mixture of organic substrates and industrial effluents as fuel. MFC promises Eco-friendly production and wastewater regimen and proves to be better than the present technologies for the generation of electricity from non-conventional sources. This fuel cell can convert substrate into electricity at all surrounded warmth. In MFC, bio-energy generation depends on the type of microorganism, electrolyte, characteristics of the effluent, suitable electrode materials, proton exchange membrane, design and parameter optimization. However, a few drawbacks and practical barriers are present like high internal resistance, current instability, low electricity production and usage of expensive materials.. In this article, various designs and types of MFC, various components of MFC and its effect in current generation were reviewed. Also, this review has suggested few possible alterations in MFC design which can help in detailed study of MFC. Various advantages and applications of MFC are also laid down in this review.

Contents

1. INTRODUCTION

Microbial Fuel Cell is an electrochemical cell in which micro-organisms are employed to utilize the carbon sources for power generation (Tardast A et al., 2012). The main principle behind this process is the production of electrons alongside carbon-di-oxide and protons, when a carbon source is utilized by a micro-organism anaerobically. The conversion of acetic acid by a microorganism Shewanella putrefaciens under anaerobic condition is given as follows:

$$C_2H_4O_2 + 2H_2O \xrightarrow{\text{Anaerobic condition}} 2CO_2 + 8e^- + 8H^+$$

The organic matter which acts as the feed is fed along with the micro-organisms in the anodic compartment which consists of an anode. This anodic compartment is maintained in anaerobic condition. The microorganisms employed in Microbial Fuel Cell mostly belong to the Exoelectrogens class. The exoelectrogenic microorganisms releases the electron produced during its metabolic processes, in the outer membrane of the microbial cell. These electrons get shuttled from the outer cell of the microorganisms to the anode. The MFC also consists of a Proton Exchange Membrane (PEM) which separates the anodic compartment from the cathodic compartment (Ghasemi M et al., 2012). The cathode and anode are connected externally to generate electricity. Oxygen is supplied at the cathodic chamber where the electron from anodic chamber, proton which diffuses from PEM reacts with it to form water.

$$2O_2 + 8H^+ + 8e^- \longrightarrow 4H_2O$$

There are several advantages in using the microbial fuel cell other than power generation. One of the major advantages is the utilization of MFC in wastewater treatment. Other uses include bio-sensor, bio-hydrogen production etc.

2. VARIOUS DESIGNS OF MFC

Based on design, MFC is classified as Single Chambered MFC and Dual Chambered MFC. The fundamental MFC system is ‘H’ type design, which is a two-chamber system having two chambers divided by a hose containing the membrane (PEM) as of Nafion (Kim HJ et al., 2002; Logan BE 2004; Min B et al., 2005) or by a salt bridge. Fig. 1 shows the basic dual chambered MFC design with its methodology. Since the dual-chamber design of microbial fuel cell is complex, it cannot be used for the bigger systems involving continuous power generation. The active parts of MFC might be included in simple designs and cost-effective materials will offer more perspective for increasing the current density from the organic source (Jun Xing Leong et al., 2013). A single chamber MFC design consists of an anodic part at the lower position and a cathodic part in floating condition placed at the top in a chamber shown in Fig. 3. Performance and efficiency of the microbial fuel cell will vary for its types (Pham CA et al., 2003; Prasad D et al., 2007; Quezada BC et al., 2010). The cathode is directly exposed to air to eliminate the constraints in the electrode by supplying the oxygen, due to mass transport issues. This modification improvises internal resistance and enhances power generation (Oh SE et al., 2009). Besides, this kind of design is more appropriate for commercial-scale production of bio-energy (Logan BE et al., 2006). Normally, for large scale applications, a series of MFC will be used together for effective power generation. This model is called as stacked type MFC (Aelterman et al., 2006). Table 1 shows various designs of MFCs along with its power density. Also, some unique changes like coupling a Photo Bio Reactor with MFC has also proved to generate power along with wastewater treatment (Jiang et al., 2013). Such MFCs are called as Photosynthetic Microbial Fuel Cell (PMFC). Also, using PMFC, bio-diesel can also be produced as a valuable by-product along with power generation (Powell and Hill., 2009).

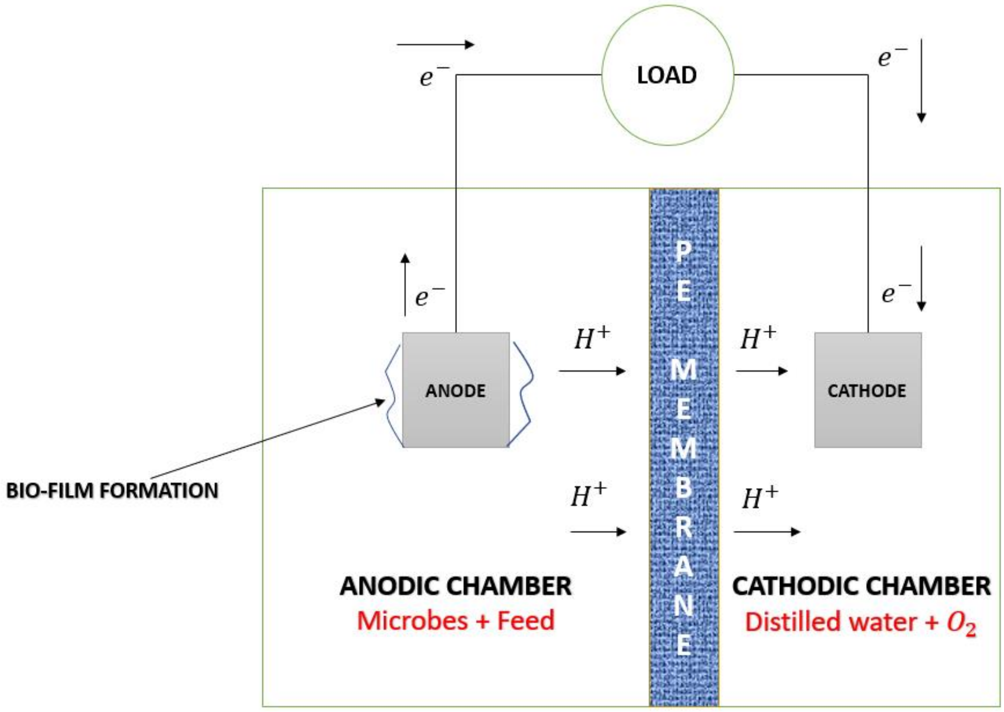

Figure 1. Working mechanism of microbial fuel cell

Table 1. Various designs of MFCs and its Power densities

Type of MFC	**Fuel**	**Power Density (mW/m^2)**	**Reference**
Single chamber	Glucose	766	(Cheng S et al. 2006a)
Single chamber	Domestic wastewater	464	(Cheng S et al. 2006a)
Two chamber	Glucose	860	(Liu H et al. 2005)
Two chamber	Acetate	480	(Cheng S et al. 2006b)
Up flow	Sucrose	560	(Bond and Lovely 2003)
Single chamber	Complex substrate	600	(Zhang T et al .2007)
Single chamber	Glucose	355.5	(Bond DR et al. 2002)
Two chamber H type	Acetate	13	(Chaudhuri and Lovely 2003)
Two chamber H type	Glucose	33.4	(Bond and Lovely 2003)
Two chamber	Glucose	40.3	(Bettin C 2006)
Single chamber	Sewage sludge	6000	(Franks AE and Nevin K 2010)
2-chamber aircathode MFC	Glucose	283	(Rahimnejad M et al. 2011)
Two chamber	Marine sediment (acetate)	14	(Zhou M et al. 2013)
Two chamber	Lactate	52	(Jung S and Regan JM 2007)
Two chamber	Ethanol	36	(Kim JR et al. 2007)
Two chamber H type	Lactose	17.2	(Antonopoulou G et al. 2010)

3. TYPES OF MFC

The two common types of MFC based on the type of the microorganism employed are Mediated Electron Transfer (MET) MFC and Direct Electron Transfer (DET) MFC shown in Fig. 2. Mediated Electron Transfer MFC uses a mediator to bring the electron from the cell cytoplasm and to shuttle it towards the anode (Li Huang et al., 2018). In MET, electrons are transferred through the base of electrochemical, which could produce metabolite by microbes or an endogenous redox mediator (Reguera G et al., 2005; Evelyn et al., 2014). The commonly used mediators are Thionin (Thurston et al., 1985), Sulphate (Park et al., 1997), and Natural red (Park et al., 1999). These mediators are in the oxidized state until they are reduced by the electrons from the cytoplasm of the microbial cell. These reduced mediators then deposit the electron they obtained from the cytoplasm to the anode (Schroder 2007). On electron deposition, the mediator gets oxidized again and the same process continues again. These mediators are needed to be fed into the MFC at frequent intervals due to the high instability of these mediator compounds. Frequent addition of mediator adds up the cost of operation and also the toxicity of the chemical mixture in the anodic compartment. But some mediators can be produced by the microorganism itself which shuttles the electron to the anode. Some of them include pyocyanin, 2-amino-3-carboxy-1,4naphthoquinone, and ACNQ (Rabaey et al., 2004; Hernandez and Newman 2001). In Direct Electron Transfer MFC, a unique class of microorganisms called as Exoelectrogens are employed. Here, electrons are directly transferred to the cell and electrode through the membrane of multiheme cytochromes (Gorby Y A et al., 2006; Schroder U 2007). They are gram negative microorganisms which release the electrons extracellularly into the anodic chamber. Hence, mediators are not required here to extract the electrons within the microbial cell. Some of the Exoelectrogens are Desulfuromonas acetoxidans, Geobacter sulfurreducens, Shewanella putrefaciens etc. The absence of mediator proves to be very advantageous as they require only less cost and non-toxic.

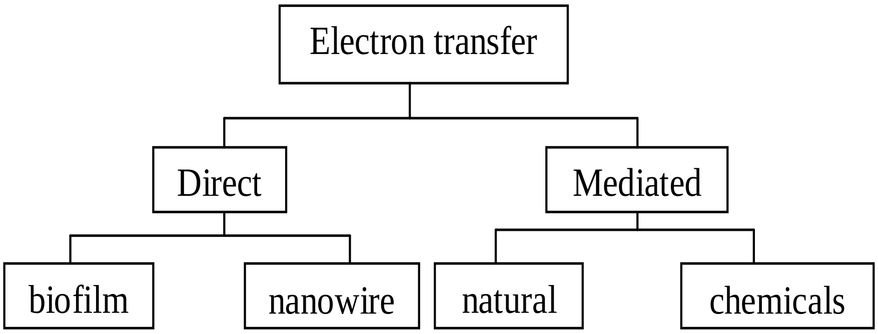

Figure 2. Mechanism of Electron transfer in microbial fuel cell

4. COMPONENTS OF MFC

The MFC primarily consists of a cathodic chamber, an anodic chamber and a Proton Exchange Membrane along with the electrodes. Table 2 reviews the basic components of microbial fuel cell.

Table 2. Basic components of microbial fuel cell

Item	**Materials**
Anode	Carbon paper, Carbon cloth, Reticulated vitreous carbon, Graphite rod, Graphite felt, Graphite granules bed, Graphite fiber brush, Conductive polymers
Cathode	Carbon paper, Carbon cloth, Reticulated vitreous carbon, Graphite rod, Graphite felt, Graphite granules bed, Graphite fiber brush, Conductive polymers
Anode compartment	Glass (Borosil/acrylic), polycarbonate, plexiglass
Cathode compartment	Glass (Borosil/acrylic), polycarbonate, plexiglass
Membrane	Nafion, Ultrex, polyethylene.poly (styrene–co–divinylbenzene), salt bridge, porcelain septum
Microorganisms	Aerobic or anaerobic or Facultative groups
Electron catalyst	Pt, Pt black, MnO2, Fe3+, polyaniline, electron mediator immobilized on anode

4.1 Anodic chamber

The Anodic chamber consists of anode, the organic source and the microorganism. In aerobic conditions, the electrons released by the microbe will be attracted towards highly electro-negative component like oxygen. So, the anodic chamber has to be maintained in an anaerobic condition. Criteria for choosing anode materials include qualities like excellent electrical conductivity, low resistance, chemical stability & corrosion resistance, high exterior area, robust biocompatibility, suitable mechanical strength and hardiness. Several MFC studies have been carried out with the carbon electrode material. Anodes synthesized from Carbon can be reused in numerous structures such as carbon-cloth, carbon-paper, fibre brush, graphite rod and carbon fibre (Ishii SI et al., 2008; Jayapriya J et al., 2012). The most commonly used carbon material is graphite rod due to its good conductivity and cheap price. Carbon papers &carbon clothes were used in H_2 fuel cells during initial periods (Park DH and Zeikus JG 1999; Patil SA et al., 2009). Then, synthesized anode materials were later applied in MFC to reduce the inner resistance and get better performances (Dumas C et al., 2007; Fabian Fisher 2018; Jung S and Regan JM 2007). Some non-corrosive metals like stainless steel and titanium were tested and compared with carbon materials. The efficiency of anodic electrodes made by stainless steel is less in comparison with the graphite anode (Dumas C et al., 2008; Kim JR et al., 2007). Table 3. Reviews the different materials used for electrodes along with their merits and demerits. The organic matter is fed inside the anodic chamber along with the microorganisms. The organic matter is utilized by the microbes to produce electrons and protons. The main function of the anode is to conduct the electrons produced in the anodic chamber to the cathodic chamber through the external circuit.

Table 3. Different materials used for electrodes with their merits and demerits

Materials	**Merits**	**Demerits**	**References**
Stainless steel	High conductivity, Low cost	Poor bacteria attachment, low power production	(Kim JR et al. 2007)
Carbon paper	High conductivity	Brittle, low specific surface area, expensive	(Ishii SI et al. 2008)
Carbon cloth	High conductivity, flexible, high specific surface area	Expensive	(He z et al. 2005)
Reticulated vitreous carbon	High conductivity, high porosity, large specific surface area	Brittle	(Liu H et al. 2005)
Graphite rod	High conductivity, defined surface area	Low specific surface area, expensive	(Kim HJ et al. 2002)
Graphite felt	High conductivity, high porosity, large specific surface area, flexible	Low strength	(MirellaDi Lorenzo et al. 2009)
Graphite granules bed	Low cost, high porosity, high surface area	High contact resistance	(Ahn Y et al. 2014)
Graphite fiber brush	High conductivity, high porosity, large specific surface area, flexible	Expensive	(Chao Li et al. 2012)
Conductive polymers	Large surface area, flexible	Low conductivity	(Yu E H et al. 2007)

4.2 Cathodic Chamber

In a typical MFC, the cathodic chamber consists of cathode, distilled water, and an aerator. Generally, in MFC, the anode electrode materials are also used for the cathode. However, the possible cathode materials must have the properties of good electrical conductivity, excellent strength, and outstanding catalytic environment (Om Prakash et al., 2018). Generally, MFC will be worked in the pH of 7-8 at ambient temperature conditions. In this condition, oxygen's reduction rate is very less. So, it limits the efficiency of an MFC (Ahn Y et al., 2014). In the cathode chamber of MFC, the carbonaceous materials must be revised with additional catalysts for vigorous reactions (Yu EH et al., 2007). For the majority of MFC operations, Platinum is placed, because it has the major role to survive the cathode catalyst and also has an excellent O_2 reduction rate performance. Usages of costly metals as cathodes are limiting commercialization of MFC concept. In spite of being costly, the Platinum cathode gets fouled easily when low quality water is used in the cathodic chamber. Numerous researches attempted the minimization of expenditure of cathode materials using effective but inexpensive materials. An attempt has been examined for cathode materials prepared of metal porphyrins & phthalocyanines carried on Ketjenblack carbon to increase the rate of oxygen in MFC along with the catalytic activity. Iron phthalocyanine as a cathode has resulted in more oxidation rates at neutral pH than Pt catalyst. An optimum power density of 634 mW/m^2 has resulted with Iron phthalocyanine - Ketjenblack carbon at pH of 7-8, which is more expensive compared to Pt catalyst (593 mW/m^2) at identical conditions. The transition metal of macro-cyclic catalysts is cheap and has been deduced from the investigation that it can be fruitfully applied to practical applications of MFC (Xu Y et al., 2012).The aerator is used in the cathodic chamber to facilitate the flow of oxygen in the compartment.

4.3 Proton Exchange Membrane

The PEM is a vital component in the MFC. The main objectives of PEM are (i) maintaining the anaerobic environment in the anodic compartment, (ii) transferring protons from anodic chamber to the cathodic chamber (iii) reduction of back diffusion of oxygen in the anodic compartment, (iv) maintaining long-time operating conditions. The majority of microbial fuel cell operations use the Nafion membrane as its PEM, because of its high proton conductivity. Fig. 3 show the mechanism of proton transfer by Nafion membrane. Nafion membrane is made of chemically stabilized perfluoro sulfonic acid polymer. The drawbacks in using Nafion as a membrane are, they can spread the cause of contamination thereby reducing power generation and depreciating MFC efficiency (Park DH and Zeikus JG 2003). The Nafion membrane is also costly. Several investigations are being conducted for finding an alternative PEM. A few examples are Salt Bridge (Park DH and Zeikus JG 2003), porcelain septum, interpolymer cations exchange membrane (Grzebyk M and Poźniak G 2005), microporous filter (Biffinger et al., 2007), physical barriers (Jang JK et al., 2004) and

Sulfonated Polyether Ether Ketone (SPEEK) (Ayyaru S and Dharmalingam S 2011). All of the above-mentioned membranes are permeable to protons that are present in the system. In the present situation, the membrane market is persistently increasing. However, intense research is needed for increasing the performance of the membrane and its long-time stability (Cheng S et al., 2011, Rozendal RA et al., 2006).

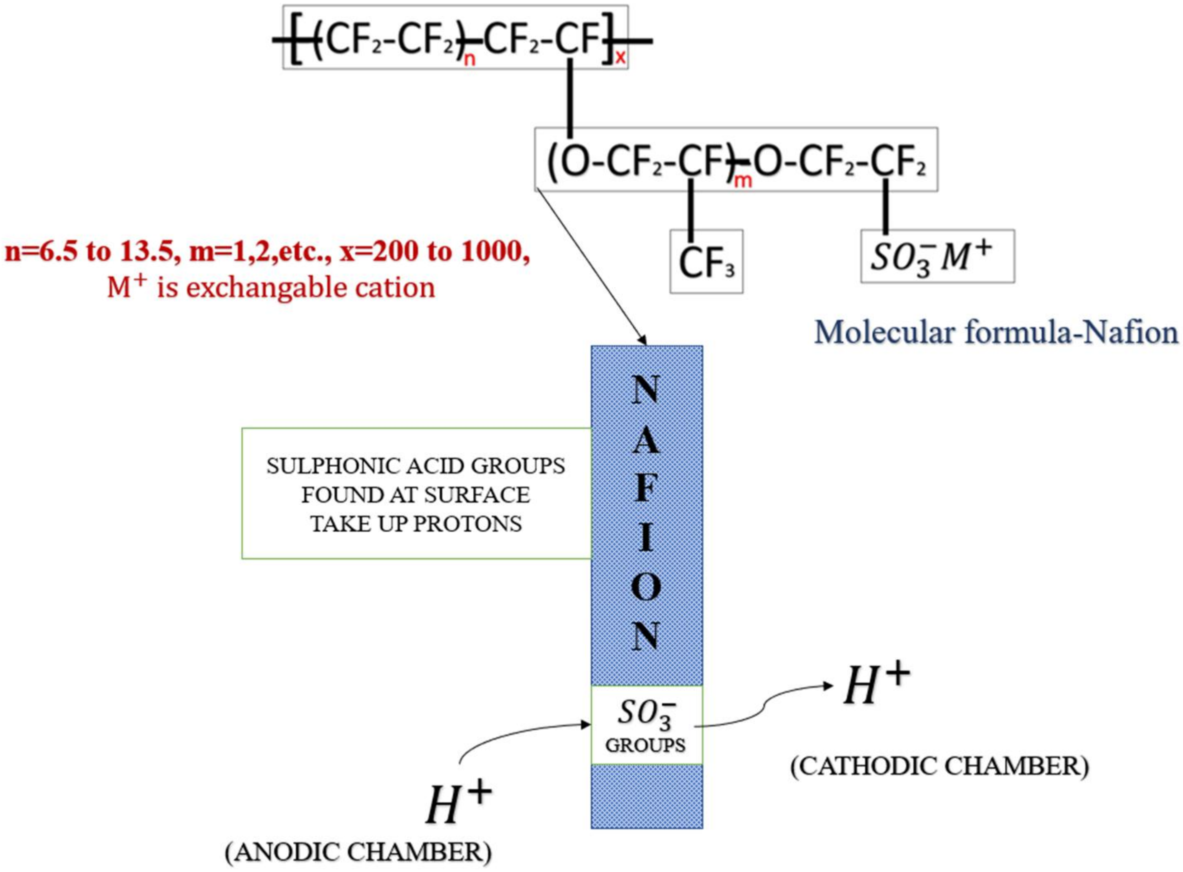

Figure 3. Mechanism of Proton transfer by Nafion membrane

5. SELECTION OF SUBSTRATE

The biological process primarily depends on substrate factors as it provides carbon (nutrient) and energy source. In MFC, acetate and glucose are the substrates investigated by most of the investigators in various compositions (Antonopoulou G et al., 2010; Jadhav GS and Ghangrekar MM 2009; Liu H et al., 2005). Several types of substrates like non-fermentable substrate (for example acetate, butyrate), the fermentable substrate (glucose, sucrose) and compound substrate (effluent from domestic, food process) may be added into the anodic chamber of the MFC (Sun M et al., 2008; Sun M et al., 2009; Tender LM et al., 2002). But it is difficult to compare and analyse MFC performances based on data available in literature as it depends upon different operating conditions like temperature, type of microbial fuel cell, surface area, electrode material and different respiration species (microorganisms) for increased electricity production (Rahimnejad M et al., 2011).The substrate is also playing a vital role in affecting the production of bio-energy in MFC (Bahareh Aesfi et al., 2019; Li He et al., 2016; Venkata Mohan S et al., 2014). Table 4 reviews various substrates used in Microbial fuel cells.

Table 4. Substrates used in microbial fuel cells

Substrates	Concentration	Microorganisms	Current density (mA/cm^2)	Reference
Artificial/Synthetic wastewater	510 mg/L	Anaerobic culture from a pre-existing MFC	0.008	(Jadhav and ghangrekar 2009)
Food firm wastes	8169 CO mg/L	Aerobic sludge	0.025	(Quezada BC et al. 2010)
Swine wastewater	60 CO gm/L	paddy field soil	0.700	(Ichihashi and hirooka 2012)
Slaughterhouse	900 COD mg/L	Granular anaerobic sludge	0.130	(Katuri KP et al. 2012)
Food waste	16 g/L	Anaerobic culture	0.045	(Choi J et al. 2011)
Rice straw hydrolysate	400 mg/mL	Desulfobulbus and Clostridium	137.6	(Wang Z 2014)
Sucrose	2674 mg/L	Anaerobic sludge from septic tank	0.19	(Behera and Ghangrekar 2009)
Brewery wastewater	600 mg/L	Anaerobic mixed consortia	0.18	(Wen Q et al. 2009)
Chocolate industry	1459 mg/L	Activated sludge	0.302	(Patil SA et al. 2009)
Cellulose	4 g/L	Pure culture of Enterobacter cloacae	0.02	(Rezaei F et al. 2009)

6. SELECTION OF MICROORGANISMS

The microorganism is employed in the anodic chamber along with the substrate. Only, certain class of microorganism which has an external cellular layer is used in MFC (Logan 2008). These microbes are gram-negative microbes and come under the class electricigens. Initially, the microbial activity will be aerobic when it is introduced into the anodic chamber. Later, with the depletion of oxygen initially present in the chamber, the microbe starts to act anaerobically and releases electrons and protons. The exo-electrogenic capability may also be induced by providing a shock load in the anodic chamber (Cuijie Feng et al., 2014). The interaction of microbes with the anode is also important for effective power generation. The microbial interaction with the anode can be easily observed with the formation of biofilm over the anode (Scott, K et al., 2007). The biofilm enhances the electron transport. The microbes can be of a same species or can be of a mixed culture. Other microbial selection depends on the nature of substrate and various other properties of the substrate like pH, temperature etc. Table 5 describes various microbes used in MFCs.

Table 5. Microbes used in MFCs

Mediator electricity-producing bacteria		
Microorganisms	**Note**	**Reference**
Klebsiella pneumoniae	HNQ as mediator	(Logan BE 2009)
Proteus mirabilis	Thionin as mediator	(Rhoads A et al.2005)
Gluconobacter oxydans	Mediator (HNQ, resazurin or thionine) needed	(Choi Y et al. 2003)
Desulfovibrio desulfuricans	Sulphate/sulphide as mediator	(Lee SA et al, 2002)
Streptococcus lactis	Ferric chelate complex as mediators	(Park DH et al. 1997)
Proteus mirabilis	Thionin as mediator	(Vega CA 1987)
Escherichia coli	Mediators such as methylene blue needed	(Thurston CF et al. 1985)
Actinobacillus succinogenes	Neutral red or thionin as electron mediator	(Schroder U et al. 2003)
Mediator-less electricity-producing bacteria		
Desulfuromonas acetoxidans	Deltaproteobacteria identified from a sediment MFC	(Park DH and Zeikus JG 1999)
Geobacter sulfurreducens	generated current without poised electrode	(Bond DR et al. 2002)
Aeromonas hydrophila	Deltaproteobacteria	(Bond DR and Lovley DR 2003)
Pichia anomala	Current generation by yeast (kingdom Fungi).	(Pham CA 2003)
Acidiphilium sp. 3.2 Sup5 Power	production at low pH	(Prasad D et al. 2007)
Thermincola sp. strain JR	Phylum Firmicutes	(Borole AP et al. 2008)
Desulfobulbus propionicus	Deltaproteobacteria	(Wrighton KC et al. 2008)

7. PARAMETERS AFFECTING CURRENT GENERATION

Several parameters interact among themselves to determine operation of MFC which is a complex variable. Table 6 explains various parameters affecting current generation in microbial fuel cells. Some of the parameters are grouped as follows:

Table 6.Parameters affecting current generation in microbial fuel cells

Component	Parameters	Effects	References
Anodic chamber	Nature of Substrate	Determines number of electrons to be released	[Sharma Y and Li B 2010]
	Microbe used	Selection is based on feed	[Dávila D et al. 2008]
	Volume of chamber	At constant microbial concentration, it is inversely proportional to current generation	[Dávila D et al. 2008]
	Microbial concentration	Directly proportional to power generation	[Dávila D et al. 2008]
	Anode used	Determines effective electron transport	[MirellaDi Lorenzo et al. 2009]
	Surface area of anode	Directly proportional to power generation	[Hyung Soo Park et al. 2001]

	pH & temperature	Optimum condition varies with microbe; Affects bacterial growth	[Venkata Mohan et al. 2014]
Cathodic chamber	pH of distilled water	Higher generation of current at pH 6-7	[Venkata Mohan et al. 2014]
	Cathode used	Determines effective electron transport	[MirellaDi Lorenzo et al. 2009]
	Surface area of cathode	Directly proportional to power generation	[Hyung Soo Park et al. 2001]
	Flow rate of Oxygen	Determines DO content in cathodic chamber	[Rago L et al. 2017]
PEM	Proton permeability	Directly proportional to current generation	[Dharmalingam S et al. 2019]

7.1 Parameters from Anodic chamber

The main parameter in the anodic chamber is the type of substrate (Sharma Y and Li B 2010). The substrate plays an important role as the electron donor. The feed also affects the bacterial growth. Also, the bacterial concentration plays an important role in converting the organic matter to electrons, protons and carbon di oxide. At high bacterial concentration, the reaction rate will be faster (Dávila D et al., 2008). The type of culture will also affect the current density. Higher power density is found in mixed cultures. The area of the electrodes is directly proportional to the power generation. The nature of electrode also has a minimal role. The type of microorganism also plays a major role in power generation. Other parameters of feed like BOD, COD, pH and temperature also have a considerable effect on power generation (Venkata Mohan et al., 2014).The volume of the compartment is inversely proportional to the current generation.

7.2 Parameters from Cathodic chamber

The electrode material should be successfully employed to dissolve the electrons in cathodic chamber from anodic chamber. The maximum power density is achieved with neutral pH (6-7). The Dissolved Oxygen content also plays an important role in MFC function (Rago L et al., 2017). The dissolved oxygen is introduced by the aeration. Also, with an increase in electrode area, power generation is increased. The selection of materials is important as the electrons should not be transported to the wall of MFC.

7.3 Parameters from PEM

The Proton Exchange Membrane prevents the short-circuiting of the electrons with protons in anodic chamber while maintaining anaerobic environment at the cathode side. The protons produced in the anodic chamber should be transported vigorously to the cathodic side (Wen-Juan Hu et al., 2011). The rate of transportation of protons depends on the resistance offered by the PEM. Rate of transportation of protons will be high if the resistance offered by the PEM is low. So, the proton conductivity property of the PEM plays a vital role in energy production.

8. APPLICATIONS OF MFC

Recently, MFC plays a massive role in environmental applications. The usage of MFCs is extremely advantageous to the environment and it aids in pollution prevention and minimizes the manufacturing cost enormously. The following are the applications of the microbial fuel cell in different areas in our society, helping to create a sustainable environment:

8.1 Electricity generation

Through the complementary action of microbes, MFC can make an energy transfer from chemical to electrical energy. The research on MFC fields tilted as bioelectricity production was taken away by the bountiful wastes since 1988. A novel photosynthetic bio-electrochemical cell was constructed (Rezaei F et al., 2009; Tsujimura S et al., 2001) and the obtained maximum power output was around 0.3–0.4 W/m^2. The light energy conversion efficiency was approximately 2–2.5%. When activated sludge supplied with glucose in a single-chambered cell along with manganese ion (Mn^{4+})-graphite anode & Ferric ion (Fe^{3+})-graphite cathode have been used as electrodes, power density was reported as 0.7 W/m^2 (Patil SA et al., 2009; Rhoads A et al., 2005). Assessment results among dual-chambered and single-chambered MFC revealed that for the same value of voltage the bio-energy produced was maximum in latter one. Four cells have been joined as one block and the experiments were performed with graphite electrodes (Korneel Rabaey et al., 2003). The setup was evaluated with various loading rates ranging from 1.5 to 3.5 g/L of glucose. Microbial fuel cells were able to produce bio-energy from effortlessly metabolized bio waste to complex effluent by microbes. Platinum group metal-free catalysts are combined into an air-breathing cathode of the MFC because it activates the sludge on addition with acetate for the source of Carbon energy (Bhargavi G et al., 2018; Rosenbaum M and Schroder U 2006). Using Iron

Amino antipyrine (Fe-AAPyr) catalyst, the highest power density of a maximum of 1.3 W/m^2 is achieved in this category of MFC continuously operated on wastewater and shows constancy and enhancement in longtime operation (Iwona Gaiga et al., 2018). In MFC experiments were performed using leachate substrate collected from recent and old landfill to eliminate toxins and during the experimental study, it was found that bountiful energy with the power output of 96.8 mW/m^2 has been generated (Muhammad Hassan et al., 2018). For implantable medical devices (IMD), the MFC may be able to embed in an individual to provide long-term and defensive power (Schroder U et al., 2003; Patil S and Mulla AKS 2013; Han Y et al., 2010; Wolfson S et al., 1973). Glucose fuel cells are part cells in the implantable device function (John Ho 2014).

8.2 Bio-hydrogen production

From the literature, it is observed that hydrogen was found to be a good quality alternative energy source compared to fossil fuel from 1970 (Balat H and Kirsty E 2010). Hydrogen is produced from fossil fuel and also from water by electrolysis or steam reforming (Li J et al., 2009; Zhou M et al., 2013; Oh S and Logan BE 2005). Steam reforming is a separation of hydrogen atoms and carbon atoms from methane. The process of electrolysis is splitting water into hydrogen and oxygen by supplying current. Fermentation method can also be used to produce hydrogen from biomass which is rich in carbohydrates (Madhulika Shukla and Sachin Kumar 2018). Implanting MFC in wastewater treatment plant might help to generate hydrogen along with effluent treatment. This practice facilitates counterbalancing the expenditures of effluent management and providing input in H_2 production or generating the required bio-electricity for effluent treatment (Senthilkumar K et al., 2018).

8.3 Wastewater treatment

Every year an enormous quantity of effluent from various industrial & man-made activities and agriculture activities are generated (Katuri KP et al., 2012; Ichihashi O and Hirooka K 2012; Agency UEP 2013). Most of the industrial effluent treatment plants are require a huge quantity of energy to treat effluent. A few numbers of effluent treatment plants are producing entire energy which is required for them to operation plants. Since the power needed for effluent treatment is 0.6 quadrillion British thermal units, the bio-energy generated for industrial effluent treatment is enough to supply these stations (Yang F et al., 2013). MFC is highly efficient in the treatment of effluent which is wealthy in organic substances like domestic wastes, corn stover and food industry effluent (Zuo Y et al., 2006; Rensing C and Maier RM 2003).

8.4 Biosensor

The biosensor is a kind of equipment which is combined by microbes along with transducer to generate an assessable signal. In the biosensors like Bioluminescence (Karube I et al., 1992) and Fluorescence (Roundy S et al., 2003) discharge changes concerning the concentration. To measure BOD and water toxicity MFCs have mostly employed as biosensors. Biological Oxygen Demand is a measurement of degradable organic matter in wastewater. BOD sensors with MFC-kind are advantageous compared to the other types (Kui Hyun Kang et al., 2003). The advantages are outstanding working stability, excellent reproducibility and accuracy. Microbial fuel cell-kind BOD sensor fabricated with enriched microorganisms could be used in operations for more than five years without further maintenance and better life period compared to further categories (Yong Jiang et al., 2018; Monzon et al., 2017). MFC can also find its application as a power source for sensors due to its low-cost operation (Barceló et al., 2018). Detection of heavy metals is also possible with MFC (Cui et al., 2019).

8.5 Desalination plants

The primary study of MFC working with hypersaline produced water exemplifies the possibility to combine MFC and capacitive deionization to facilitate desalination and recycle of hypersaline effluent (Kokabian et al., 2018). The effect of total dissolved solids (TDS) concentration was also studied in desalination section on the overall performance of static photosynthetic microbial desalination cells. TDS and Chemical Oxygen Demand (COD) removal rates increased by enhancement in TDS concentrations in desalination section. The experimental results represented as TDS removal rates were found to be 21.4%, 29%, and 32.2% with subsequent COD removal of 58%, 63%, and 64% at the concentrations of 5 g/L, 20 g/L and 35 g/L respectively (Surajbhan Sevda et al., 2017). Petroleum refinery wastewater was treated within microbial desalination cell for the first time and the studies were conducted to analyse the influence of salt concentration and catholyte. The experiments were performed using real seawater in microbial desalination cell and phosphate buffer solution obtained the maximum efficiency of 19.9% desalination (Roundy S et al., 2004).

9. RECENT DEVELOPMENTS

Recently, plenty of researchers are analysing multiple aspects of the microbial fuel cell to attain maximum energy and to enrich the future needs like batch mode operation for enrichment of acetate using electro-autotroph by control system of acetate fed (Kuo TiChen et al., 2019). The microbes' diversity mode could change from complex to simple, after the five-batch operation, and Geobacter species is the most copious microbes in the experimental process. In MFC, experiments were conducted for denitrification under autotrophic and heterotrophic conditions and their power output and higher removal rate were achieved (Ankisha Vijay et al., 2019). The air cathode MFC experimental run was performed to analyse the possibilities for treating dye effluent (Karuppiah T et al., 2018). The results have shown that the maximum power density and Coulombic efficiency. The total COD, soluble COD and TSS removal were also achieved (Cucui Lv et al., 2018). Carbon derived from chitosan, followed by phosphoric acid activation during thermal treatment to obtain N and P dual-doped catalyst, was studied as the catalytic substance for air–cathode in MFC. The MPD of $1603.6 \pm 80\,\mathrm{mW/m^2}$ was attained, which was five times greater compared to $322.4 \pm 16\,\mathrm{mW/m^2}$ when N, P doped carbon was calcinated at 850 °C (Bolong Liang et al., 2019). Groundnut oil mill effluent utilized as the substrate in MFC (Lawan SM 2018). Power densities in all batches were obtained by differentiating the rate of constant run in MFC. Experimental results exposed that maximum bio-energy of effluent was produced in every unit contrast to other mixture cultures reported in the literature. Besides, the results demonstrated that MFC might generate maximum power density by continuous mode (160 $\mathrm{mW/m^2}$) contrast to batch mode (54 $\mathrm{mW/m^2}$) (Ying Zhang et al., 2019). However, the most fascinating technology for industrial effluent treatment and bio-energy generation is achieved in MFC technology because of its unique performance and high efficiency when compared to the conventional treatment methods (Anthony J Slate et al., 2019; Rajeev K Gautham and Anil Verma 2019).

10. FUTURE IMPROVEMENTS

The MFC is thus one of the fascinating and capable technologies in wastewater treatment and electricity generation. Hence, future research will be centred upon the following issues in MFC. Firstly, the slow cathode reactions are important limiting factors that considerably influence MFC performance. Secondly, low cathode reactions are the most important obstacles in commercial applications of MFC. Metals like Platinum illustrate their outstanding performance; however, the factors such as high cost and durability and limitations of environmental toxicity are playing the most significant role in their useful applications. O_2 are the most appropriate and good electron acceptors in MFC. But, Oxygen Reduction Reaction (ORR) has an extremely slow kinetic. Different materials like carbon, metal oxide, carbon–metal hybrids & nano-composites have been examined for enhancing oxygen reduction reaction ORR (Ekant Tamboli J and Satya Eswari 2019; Farooqui UR et al., 2018). MFC design and arrangement are the most important parameters influencing its efficiency, scalability, membrane–electrode assembly, etc. (Hindatu Y et al., 2017). Also, the gas that would be released in the anodic chamber by microbes for different feed compositions should be analysed. If CO_2 is released, sequestration can be done to form value added products.

11. CONCLUSION

This review paper concludes that MFC will prove to be an effective non-conventional energy. Further focus should be made on all the operational parameters associated with power generation along with its optimization. Several scientific studies are being made in making the MFC as a scalable product. Also, the environment is mostly polluted by wastewater when compared with other foulness. Some of the drawbacks are not restricted by recent effluent treatment technologies. Achieving a sustainable environment and fulfilling their future needs is quite difficult in conventional treatment technologies. MFCs have been investigated and are now being accepted as a novel technology which has more merits, particularly in wastewater treatment and bio-electricity generation. MFC produces more energy and produces less sludge. For the past few years, research on MFC has increased and the technology has improved at least in lab-scale studies. However, commercialization of MFC is a difficult one because of its complications in various parts of the reactor. Besides the high cost of materials, current fluctuation and more interior resistance are the barriers for electricity generation and hold down the application fields. Therefore, upcoming research should give more importance to new effective costing of MFC materials to treat the wastewater efficiently. It is more essential to realize the character in nature and role of MFC electrode. The multiplicity of wastewaters can be radically degraded by them or along with additional processes. Wastewater treatment technology mainly focuses on cost and energy demands. Practically, MFC is a promising technology for removing pollutants from industrial effluent in an effective manner.

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