Microbial Fuel Cells: Types of MFC and Different Source of Substrate

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***Abstract*—Microbial fuel cell is the device which converts energy present in the chemical bond of a substrate into electrical energy with the help of catalytic activity of microorganism. The electricity can be generated by breaking down the organic matters present in the Wastewater. The organic matter acts as a substrate for microorganism which intern convert it into electricity. There are many sources for Wastewater which can be utilized for this purpose. Microbial fuel cell technology can be used to reduce the energy crisis and treat the waste simultaneously. There are many microorganisms which can break down the organic matter under the aerobic or anaerobic condition and generate electrons. These electrons can be entrapped and utilized as an energy source. Coulombic efficiency and power output of MFC are depends on microbe used in the anodic chamber, operating condition of MFC, design, and configuration of MFC and many other factors. Commercial application of MFC is limited because of its low power density and bulk design. Extensive effects are made to reduce the cost, improvise design, increase compactness, durability and the efficiency of MFCs. This review emphasis on the types of MSC configuration and different Wastewater source used in MFCs for electricity generation and provide the basic information about the operation of MFCs. Basic information about MFC technology such as MFC design, microorganisms involved, substrate source and mediators is clearly depicted in this review.**

***Keywords*— Microbial fuel cells; Waste water; Microorganism; Electricity generation; Proton exchange membrane.**

I. INTRODUCTION

Biological Wastewater treatment plant consumes a huge amount of energy. One such process is activated sludge process which utilizes energy that accounts for about 50% of operating cost, with 1000 W of energy requirement for oxidation of 1 kilogram of organic substance during treatment [1]. A large amount of solid residue is produced during aerobic treatment process which intern increase the cost of treatment and disposal [1]–[3]. In future, one cannot rely on fossil fuel as a source of energy and hence energy crisis increases drastically. In such a situation the main energy source would be renewable energy such as solar energy, bioenergy, and biogas etc. Depending on energy sources which emit harmful substance may cause environmental pollution. In such case, we have to depend on technologies where harmful emission should be nil or negligible [4]. A microbial fuel cell is one such device which converts waste into electric current. Annually Wastewater is generated in larger volumes from industries, houses, and agriculture etc. The animal waste which is generated from the industries such as poultry, dairy etc. should be treated properly before releasing into the environment to avoid odour problems and contamination of water bodies by organic substances [5]–[7]. When this Wastewater is released to surface water eutrophication of water can take place due to high nitrate and phosphate content [5], [6], [8]. There are many methods to remove the organic and inorganic pollutants from wastewater but require a high amount of energy and money [5], [9]. By using MFC we can actually reduce the cost of operation, also generate renewable bioenergy such as electricity, methane, and hydrogen and meanwhile accomplish treatment process [1], [5], [10].

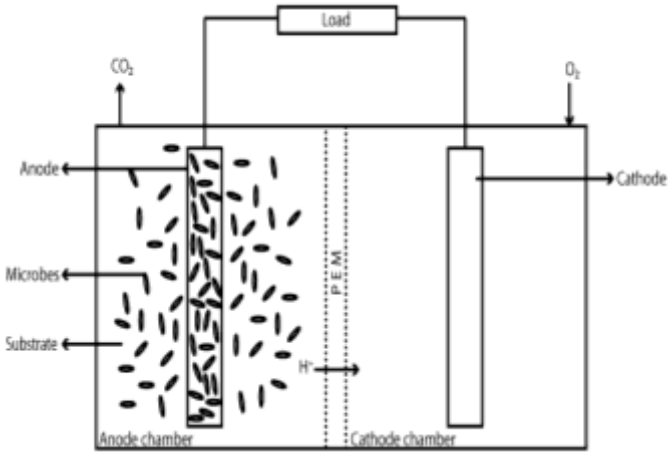

Fig. 1 Typical two chambered microbial fuel cell

Typically Microbial fuel cell consists of two chambers an anode and a cathode chamber as shown in figure 1. Microbes grow on the anode in anode chamber utilizing substrate from media whereas cathode chamber contains fresh water. The two chambers are separated by proton exchange membrane which allows the only the proton to pass through the membrane. The microbes in anode utilize carbon source (glucose, lactose, acetate etc) present in wastewater and produce electron, proton and carbon dioxide. The proton passes through PEM and electron pass through the external

circuit. The electron, proton, and oxygen combine together to form water in the cathode. Usually, the anode will be anaerobic and cathode will be aerobic (supply oxygen).

Electricity generation from microbial fuel cell was first demonstrated by potter in the year 1911. However, its importance was recognized recently and tremendous research work is carried out to commercialize this technology [11]. Over the period of time researchers are working on many factors which affect the performance, cost, and efficiency of MFC.

The power generated by MFC mainly depends on following factors MFC design, the distance between electrodes, proton exchange membrane, electrode, mediators, substrate, microorganism and some external factors. Many configurations are used to design MFC such as single chambered [12]–[14] and double chambered design [15], [16]. Proton exchange membranes (PEM) which are commonly used in MFC are Nafion, cellophane, agar composition etc[17], [18]. The power output of MFC also depends on the PEM. If the area of PEM is smaller than the electrode surface area the power output decreases. Logan and Sang found that power density increases if the area is in the ratio 2Aanode=APEM=2Acathode [17]. Mediators are added to increase the power density. Mediators are the compound which carry electron from microorganism to electrode surface. There intercellular mediators such as NADPH, NADH and Cytochromes within microorganisms [4], [19]. Synthetic mediators can also be used which include metallorganics and dyes. Some of the examples of synthetic mediators are meldola's blue, thionine, neutral red, methylene blue, Fe(III)EDTA and 2-hydroxy-1,4-naphthoquinone [4], [19], [20]. Synthetic mediators are toxic and hence their applications are limited. Recently new discoveries are lead to the direct transfer of electrons from the cell surface to anode surface with high stability, Coulombic efficiency and yield[4], [21]. The microbes are capable of transferring the electrons to anode directly are Rhodoferaxferrireducens[21], Shewanellaputrefaciens[22], Geobactermetallireducens[5], Geobactersulfurreducens[23] and Aeromonashydrophila[24]. Microbes require nutrient which can be obtained from any sources such as swine waste [5], dairy waste [25], [26], domestic waste [27] and municipal waste[28].

B.Types of Microbial Fuel cells

Microbial fuel cell basically contains an anode chamber, cathode chamber, PEM or salt bridge and electrode assembly. Microbial fuel cells were classified based on design and mode of operation of MFC.

1) Two compartment Microbial fuel cells:

As the name suggests it consist of anode and cathode compartment separated by a Proton exchange membrane or salt bridge. Anode chamber contains microbes, media (Glucose, acetate etc.) and electrode whereas cathode chamber contains electrode, fresh water, and oxygen supply. Copper, stainless steel mesh, graphite, carbon paper, graphite fiber brush and carbon cloth is commonly used as electrode [29], [30]. If the anaerobic condition is to be maintained in anode compartment then nitrogen should be supplied continuously. The basic design in this category is H type MFC. Logan et al on 2004 designed the basic H type MFC [31]. It was constructed using two borosilicate glass bottles of capacity 300 mL. The glass bridge of two chambers was connected together by clamp system. The two chambers were separated by PEM (Nafion). The carbon paper of dimension 2.5 X 4.5 cm was used as an electrode for both anode and cathode. But the cathode was impregnated with platinum catalyst (0.35 mg/cm^2). The sediment obtained from the lake was used as an inoculum. The microorganism were grown in mineral salts medium (MSM) and stored in 4 ºC for further use. The maximum power density was 19mW/m^2 and was increase 39 mW/m^2 by increasing the concentration of cysteine (0.770 g/L) [31].

2) Single compartment Microbial fuel cells

In single chambered MFC only anode compartment is present whereas cathode is exposed to the atmosphere. Aeration or supply of O_2 in cathode chamber is not necessary since it is directly exposed to air. The design is simple and can be operated in batch or continuous mode. Since the design is simple the scale-up process is very simple and the cost of the design decreases [32]. Min and Logan on 2004 designed a simple flat plate MFC [27]. The nonconductive polycarbonate plate was used to construct the MFC with the dimensions 15cm x 15 cm x 3 cm (L x B x H). The serpentine path was created for wastewater retention with the total surface area of about 55 cm^2 and volume of about 22 cm^3. The plates were sealed using screw and bolt system. Porous carbon paper of dimension 10 cm x 10 cm was used as an anode, whereas carbon cloth of the same dimension impregnated with the platinum catalyst was used as cathode. Nafion membrane was used as proton exchange membrane and copper wire was used to connect electrodes with external circuit [27].

3) Up-flow Microbial fuel cells

In Up-flow MFC design the wastewater is pumped into the system from the bottom and the effluent flow out of the system from the top and it operates in continuous mode [4]. A typical up-flow MFC was designed by Jang et al on 2004 without proton exchange membrane [33]. The MFC was tubular in shape with the total height of 100 cm and diameter 10 cm and was made with polyacrylic plastic. Graphite felt (196 g) was used as an anode and the same material (53.3 g) was used as the cathode. In between anode and cathode series of layers of glass beads and glass wool was used and the sample ports were situated throughout the length of the reactor. The total area of the anode was 465 cm^2 and cathode was 89 cm^2. The fuel (artificial wastewater containing

glucose and glutamate) at the rate of 0.28 mL/min was supplied from the bottom of the reactor and the effluent was taken out from the top. The aerators were used to aerate the cathode layer, and platinum wire resistance 10 Ω was used to connect the electrodes to an external circuit. The main advantage of this design is the absences of proton exchange membrane and can also be operated in continuous mode which intern reduces the cost. The main disadvantage of this method is energy utilized to pump the wastewater is high when compared to energy generated from it. Hence, it can be used to treat wastewater where electricity generation is not a first priority [33].

4) Stacked Microbial fuel cells

Many MFC is stacked together either in series or parallel connection. Since many MFC are connected together high output or current generation can be obtained. Stacked MFC which was designed by Aelterman et al on 2006 consisted of six individual continuous microbial fuel cells stacked together [34]. Graphite granules were used as anode and cathode Graphite granules provide a maximum surface area for microbes to transfer electrons and graphite rod was used to connect the external circuit (check again). The volume of one MFC unit is 60 mL and the overall volume of stacked MFC is 360 mL. The proton exchange membrane which separated anode and cathode was Ultrex CMI7000. It was observed that parallel connection of cells has a better performance than series connection due to high efficiency and higher Chemical Oxygen Demand (COD) removal [34].

5) Paper microbial fuel cells

Paper was used for fabricating the MFC which was low cost, chemical free and disposable. The design was simple which consists of anode and cathode. The graphite particles were deposition on the paper using four different strokes of pencil act as an electrode. Parchment paper was used as PEM which allow the H+ to pass through them. The crayon was added to the corners to make it hydrophobic. The microbes were added to the anode chamber along with few microliters of growth media. The air cathode was used, where electrons were accepted by O_2. The microorganism which was used in paper MFC was Shewanellaoneidensis. The maximum voltage and current generated was found to be 300 mV and 11 µA , respectively [35].

C. Common microorganism used in MFC

Microorganisms can be used for many purposes as they act as mini-reactors to produce many products. Similarly, electricity can be generated by many organisms, but harvesting this is a challenging job. Earlier mediators were added to transfer electrons from microbe cell surface to anode electrode. But recently it is been discovered that few microorganisms are capable of transferring electrons to the anode and these are known as Exoelectrogenic bacteria. In MFC many mixtures of microorganism forms a biofilm which contains both exoelectrogenic bacteria and non-exoelectrogenic bacteria. The exoelectrogenic bacteria can transfer electrons to the anode with the help of nanowires, mediators or by direct contact with the electrode. There are some non-exoelectrogenic bacteria which can use the mediator or nano wires produced by exoelectrogenic bacteria and transfer electrons to the electrode. Few examples for exoelectrogenic bacteria are Shewanellaputrefaciens, Clostridium butyricum, Desulfuromonasacetoxidans, Geobactermetallireducens, Geobactersulfurreducens, Rhodoferaxferrireducens, Pseudomonas aeruginosa, Desulfobulbuspropionicus, Geopsychrobacterelectrodiphilus, Geothrixfermentans, Shewanellaoneidensis, Escherichia coli, Rhodopseudomonaspalustris, Ochrobactrumanthropi, Desulfovibriodesulfuricans, Klebsiella pneumonia and Pichiaanomala[36], [22], [5], [23], [21], [37], [38], [39].

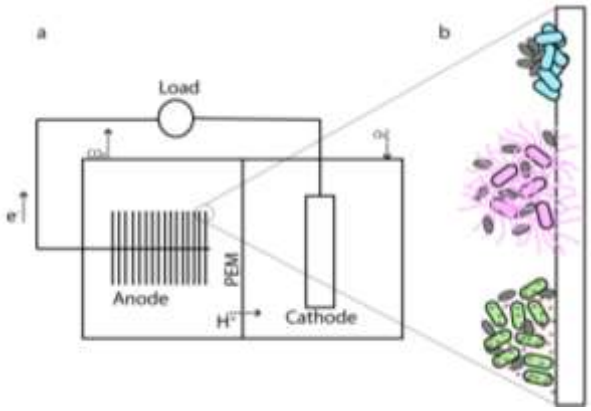

Fig. 3 a| Microbial fuel cell set up. b| Types of exoelectrogenic bacteria formed in anode biofilm includes bacteria which can transfer electrons on direct contact with anode represented in blue color. The bacteria which can transfer electrons using nanowires are represented in pink color. The bacteria which can transfer electrons by mediators (red) are represented in green. Non-exoelectrogenic bacteria which can transfer electrons with the help of mediators and nanowires produced by exoelectrogenic bacteria are represented by the color grey (The modified figure is drawn after Bruce E Logan [36]).

D. Source of Substrate

The source of the substrate also matters in electricity generation using MFC. A wide variety of organic material can be used such as acetate, glucose, lactate etc as a substrate for microbes. The Wastewater source contains a mixture of organic compounds which can be utilized by microbes as a source of energy. Various industries which produce wastewater can be used as source of substrate because of high content of organic matter. Some of the commonly used substrates are mentioned below.

1) Acetate as a carbon source

Acetate is a simple compound with the molecular formula of CH_3COOH and molecular weight is 59.004 g/mol. It can act as a source of carbon for the bacterial growth and electricity generation, respectively [40]. Acetate is stable and

cannot be metabolized by another organism (methanogens) at room temperature. It is the end product of many metabolic pathways (glycolysis pathway). Liu et al on 2005 found that the electricity generated using acetate as a substrate when compared to butyrate was 66% higher [41]. Other than acetate many other compounds such as butyrate, propionate, and glucose were also used as a source of carbon. The conversion efficiency of acetate, butyrate, propionate, and glucose are 72.3%, 43%, 36% and 15%, respectively. Acetate has maximum conversion efficiency when compared to other sources. However, in a real situation, the acetate can support the growth of few organisms and cannot solve the present problem such as wastewater treatment. The mixture of compounds in Wastewater is utilized by many organisms which interact with each other and intern effect the power output [42].

2) Monosaccharides as a carbon source

Glucose is a monosaccharide and a commonly used substrate with the molecular formula $C_6H_{12}O_6$ and the molecular weight is 180.156 g/mol[43]. Catal et al on 2010 generated electricity by utilizing 12 monosaccharide molecules [11]. The monosaccharide molecules include hexose (glucose, fructose, galactose, mannose, rhamnose, and fucose), pentose (xylose, arabinose and ribose) and sugar derivatives (galacturonic acid, glucuronic acid and gluconic acid). Glucuronic acid showed maximum power density of 2770 +/- 30mW/m^2 whereas xylose and glucose also showed power density of about 2330 +/- 60mW/m^2 and 2160 +/- 10mW/m^2, respectively [44]. Energy conversion efficiency is less for glucose when compared to acetate this is because the glucose can be competitively used by other organism and undergo methanogenesis and fermentation. Methanogenesis and fermentation process cannot produce electricity [11].

3) Polysaccharide as a carbon source

Lignocellulosic material can be used as a source of carbon for the microorganisms. Lignocellulose includes cellulose, hemicellulose, and lignin. This is polymers of simple monosaccharide and hence known as polysaccharides. All plant matter consists of Lignocellulose in it, so agro waste can be used as source of Lignocellulose. Due to its abundance and relatively cheap, it is considered as the cost-effective substrate for MFC. However, it cannot be directly used in MFC as the microorganism cannot utilize or break down this complex substrate. The complex biomass should be broken down into simple monosaccharide. This is done either by heat treatment or enzymatic treatment [11]. Logan et al on 2009 discovered microorganism Enterobacter cloacae which are capable of degrading cellulose to glucose and utilize it for electricity generation. In paper recycling plant the initial inoculum was obtained, the cellulolytic and exoelectrogenicbacteria were enriched by dilution to extinction method. The U type MFC design was used for power generation. The maximum power density obtained by using E. cloacae FR strain was 4.9 +/- 0.01 mW/m^2 [45]. Similarly, Corn Stover biomass was used as a carbon source which was broken down into simple sugars by neutral steam exploded hydrolysis [46].

4) Starch Processed Wastewater

Starch is a polysaccharide consisting of many glucose units which are linked together by glycosides linkage. Starch is abundantly found in potato, rice, wheat and many other plant materials. The wastewater obtained from starch processing industries contains a high amount of carbohydrate 2.3 – 3.5 g/l. It contains sugar, protein, and starch in the proportion around 1.18%, 0.15% and 1.5 – 2.6 g/l, respectively. This can be used as a potential source of substrate for microorganisms [47]. The wastewater rich in starch should be treated before releasing into the main water stream. As the energy consumed by activated sludge process is high the starch wastewater can be treated using MFC technology and electricity can be generated simultaneously. Kin et al in 2003 designed MFC for wastewater treatment and it was observed that within a duration of 6 weeks the COD was reduced from 1.7 g/L to 0.05 g/L [48].

5) Wastewater from Brewery industries

Wastewater obtained from brewery industries contains organic matter such as glucose, ethanol, and acetate etc. Hence, it is ideal to use as a source of carbon for microbes. It is favourable because it does not contain compounds which are inhibitory for microorganism such as ammonia in animal wastewater [49]. In comparison with domestic wastewater the brewery wastewater is 10 times more concentrated (3 – 5 g of COD/L) [50]. Feng et al on 2008 used air cathode MFC and beer industry wastewater and able to generate the power density of about 0.528 W/m^2 [49]. It was found that, when the similar concentration of the solution was used the power produced by domestic wastewater was more when compared to brewery wastewater this is because both have different conductivity. Hence, to decrease the conductivity (3.23 mS/cm to 0.12 mS/cm) of brewery wastewater dilution with deionized water is necessary [49].

6) Swine wastewater

Swine wastewater can also be used as a fuel in microbial fuel cells. Ogugbue et al on 2015 conducted a 60 days experiment by using swine wastewater obtained from Pig Farm Garden [51]. About 800 mL of swine wastewater was sterilized and fed into the anode and 800 mL of distilled water was filled in the cathode and studied. In another setup, they used 400 mL of unsterilized wastewater in the anode and 400 mL of KMnO4 solution as a mediator in the cathode compartment. The copper and carbon were used as an electrode and the maximum generation of power was 250.54 µW (copper) and 52.33 µW (carbon) [51]. Similarly, Min et al on 2005 used swine wastewater of concentration 8320 +/- 190 mg/l soluble COD [5]. Swine wastewater was obtained

from Pennsylvania State University Swine Farm. Power density obtained for swine wastewater (261 mW/m^2, 200 Ω) was high when compared to domestic wastewater (146 mW/m^2, 200 Ω). It was found that 83% of ammonia (198 to 34 mg/l) was removed from wastewater [5].

7) Chocolate industry wastewater

Chocolate industries produce wastewater which contains sugars, protein and other components which can act as a fuel for MFC. Patel et al on 2009 conducted an experiment in which they used chocolate wastewater in MFC to generate electric current [52]. They used activated sludge as an inoculum obtained from municipal wastewater treatment plant. Chocolate wastewater was collected from chocolate industries and about 200 mL of wastewater was added to the anode chamber along with 20 mL of activated sludge. Phylogenetic analysis of anode biofilm was done and found that in the mixture of organism β-Proteobacteria was dominating in number about 50.6%. COD of wastewater was reduced from 1459 to 368 mg/l and BOD was reduced from 640 to 230 mg/l. The maximum generated current was 3.02 A/m^2 and 2.3 A/m^2 for PEM and salt bridge, respectively[52].

8) Meat processing wastewater

Meat processing wastewater contains fats, blood and large amount of protein which can be used as a source of carbon for microbes in microbial fuel cells. Heilmann and Logan on 2006 demonstrated the use of meat processed wastewater in single chamber MFC [53]. They compared the performance of MFC for domestic wastewater and meat processed wastewater. The power density (80 +/- 1m W/m^2) was increased by 33% by diluting the wastewater from 6010 to 1420 mg/l COD. More than 86% of total organic carbon and Biochemical oxygen demand was removed by this method and it was effective for wastewater treatment [53].

9) Municipal wastewater

In wastewater treatment plant the activated sludge process is cost-intensive process which has to be replaced. The effort was made by Fornero et al on 2010 to replace activated sludge process by MFC as a secondary treatment process [28]. Municipal wastewater may cause many limitations for electricity generation since it contains many chemical both organic and inorganic which can inhibit the growth of microbes. Also, it contains a large diverse number of microbes (bacteria, virus etc.), which can interact with each other and can affect the electricity generation. Hence, many parameters need to be considered during scale-up process. It would be attractive if BOD and COD are reduced along with electricity generation [28]. Feng et al on 2014 designed MFC which can handle high volumes of wastewater [54]. Stacked horizontal microbial fuel cells (SHMFC) were used for electricity generation and wastewater treatment. One SHMFC module can handle volume up to 250 L which is considered to be the largest MFC ever. Anaerobic granule sludge was used as an inoculum. About 10 L of inoculum was mixed with 240 L of wastewater and allow it to settle in the tank for 1h before it is pumped into the SHMFC setup. The initial setup period was 240 h during which the resistance of the system reduced from 1000 Ω to 2 Ω. Carbon mesh impregnated with platinum was used as cathode and carbon fiber brushes which were connected parallel with the help of titanium wire core was used as an anode. Both anode and cathode were separated by porous polypropylene plastic plate. The maximum current obtained was around 0.435 +/-0.01 A and the maximum power density was 116 mW. The removal rate of COD and total nitrogen was 79 +/- 7% and 71 +/- 8%, respectively [54].

10) Synthetic/ artificial wastewater

Synthetic wastewater is artificially created wastewater whose composition can be well defined and load strength can be easily controlled. There are many media composition which can be used as wastewater. Venkata Mohan et al on 2009 used the synthetic wastewater as a fuel for MFC at different load rate and observed the changes in the performance of similar configuration MFCs [55]. Many bacterial growth media contains redox mediator like cysteine, if the concentration of this mediator is high it can donate electron in an anaerobic condition and can increase power density for short duration. This can mislead the true performance representation of the system. To solve this problem the minimal medium can be used which contains glucose/ acetate as an electron donor [56]. Rodrigo et al on 2009 studied the performance of two similar MFC which was fed with two different artificial wastewaters [57]. The same organic materials/ pollutants (peptone and glucose) and same organic load (3.15 g/l) were used but at a different ratio. It was observed that efficiency of MFC was high for slowly degradable waste due to fact that intermediates formed will favour electricity generation [57].

11) Paper recycling wastewater

Paper industries use wood pulp to produce paper. The wood pulp contains cellulose which is a good source of carbon for microorganisms. Huang and Logan on 2008 used paper recycling wastewater for MFC to generate electricity and simultaneously treat the wastewater [58]. The phosphate buffer (50 mM) was added to the wastewater. The maximum power density and columbic efficiency obtained was 501 +/- 20 mW/m^2 and 16 +/-2% mW/m^2, respectively. The organic load was effectively removed 73 +/-1% from wastewater out of which the cellulose was almost completely removed 96 +/- 1%. Conductivity of the wastewater was increased by adding 100 mM of phosphate buffer which intern increases the power density from 144 +/-7 mW/m^2 to 672 +/-27 mW/m^2 [58].

12) Dye wastewater as a source

Dyes are a harmful chemical substance which is commonly found in the effluent of textile industries. Dyes, when exposed

to the environment can cause a serious problem such as reduction in re-aeration and obstruction of light transfer into water bodies which may lead to loss of habitat of an aquatic living organism. Apart from this many dyes are highly toxic, hence effort has been many to remove these dyes by a microorganism and simultaneously produce electric current. Pant et al on 2008 studied decolourization activity by a fungus (Phanerochaetechrysosporium) [59]. In the experiment, they used 3 dyes and they are Congo red, Malachite green and Crystal violet. It was found that there was significant COD reduction of dye (79 to 84% reduction) [59]. Sun et al on 2009 studied about the decolourization of ABRX3 (active brilliant red X-3B) using the mixture of the microorganism of both aerobic and anaerobic sludge in the ratio 1:1. Electricity was generated using single-chamber MFC [60]. It was found that concentration of dye would affect the generation of electricity. At lower concentration of dye (300 mg/l) the power generation was unaffected but if the concentration increases beyond 300 mg/l a significant reduction in power generation can be observed. This is because the larger concentration of dye would inhibit the microorganism growth [60].

E. Other Application

1) Hydrogen production

Apart from electricity generation using microbial fuel cell, it can also be used for hydrogen production (reframe). In conventional method, the two chambers (anode and cathode) are separated by PEM and proton passes through this membrane whereas electrons pass through the external circuit. The proton combines with oxygen and electron in cathode chamber and forms water. If the cathode chamber is maintained in an anaerobic condition and a small amount of external potential (to break thermodynamic barrier) is provided a thermodynamically favourable reaction takes place in the cathode chamber. The protons (H+) combine with electrons (e-) to form Hydrogen molecules (H2). Theoretically, only 110 mV is required to break the thermodynamic barrier whereas about 1210 mV is required to split the water molecules (electrolysis). Approximately about 8 to 9 mol H_2 is generated for 1 mol of glucose which is 2 times greater than conventional fermentation methods were about 4 mol of H_2 generated for each mol of glucose [61].

2) Methane production

Apart from hydrogen and electricity generation, one can also generate methane by MFC technology. The methanogen bacteria are used in this process for methane production. The design contains two compartments anode and a cathode separated by PEM which is quite similar to those design used for hydrogen and electricity generation but the mode of operation varies. A small power source is supplied for splitting of water in anode compartment under anaerobic condition and it does not contain microbes. The cathode compartment is supplied with CO_2 and proton which is produced near anode passes through PEM, reacts with carbon dioxide to form CH_4 and H_2O. The methane which is produced in this process is pure and can be utilized directly [62], [63].

3) Wastewater Treatment

Treating wastewater is a major problem today which has to solve in a much cost-effective manner. In 1991 the MFC was used to treat the wastewater [64]. Wastewater could be from any source such as municipal wastewater, domestic wastewater, and wastewater from industries etc. Out of this entire source, it is found that the municipal wastewater is very difficult to treat because of its most diversified composition. Apart from treating wastewater they can also be used for generating electricity which can be utilized as an energy source. It is also found that less solid waste (50 – 90% less) is generated for disposal and it can also convert molecules such as acetate, butyrate and propionate etc. into CO_2 and H_2O before releasing into the environment [4].

4) Biosensors

MFCs can also be used as biosensors to detect the pollutants level in the environment. There is a correlation between wastewater strength and Coulombic yield. Hence, it can be used as BOD (biological oxygen demand) sensors. There is a linear relationship between BOD and Coulombic yield. The current increases linearly with increase in BOD. MFCs BOD sensors are more reliable when compared to other BOD sensors because of stability and accuracy. MFC BOD biosensors have more lifespan (over 5 years) without maintenance when compared to other sensors [4].

II Conclusion And Future Aspects

This review provides basic information about the MFC technology, utilization of substrate from different sources as fuel, MFC designs, mediators and different microorganism participated in MFC. The power density which is produced by these MFCs is less when compared to conventional power sources so it is a challenging job to improvise the efficiency of the MFC. Moreover, it is difficult to scale up the device and use it for wastewater treatment process. However, some of the design can handle high volumes of wastewater and can be used for practical purpose. Extensive research work is done to reduce the cost of MFCs. Since the cost of proton exchange membranes is high an alternative method is developed in which there is no requirement of PEM. Continuous MFCs are designed for maintaining the consistency in electricity generation and wastewater treatment process which intern reduces the cost and duration of the process. A wide variety of substrate can be utilized in MFCs which will make it more reliable and robust in future. MFCs can be integrated to treatment plants instead of activated sludge process which will reduce the cost of treatment. In

future, it is expected to increase the efficiency, power density, and reliability of MFCs. Hence, one can utilize them as a power source and generated renewable energy sources such as hydrogen, methane and electricity generation. Biosensors to detect the impurities present in the water source can be designed by utilizing this technology. In near future the MFCs can also be utilized to extract energy from sunlight using phototropic MFCs.

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