REVIEW ON MICROBIAL FUEL CELL

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SUMMERY

The demands of energy in the world continue to accelerate and this triggers the global energy crisis and environmental Pollution. The reliance on fossil fuels (oil and gas) is unsustainable because of its finite, depleting supplies and impact on environment. As a result researchers are focusing on alternative, renewable and carbon neutral energy sources which are necessary for environmental and economic sustainability. MFC, is a bioreactor that converts chemical energy present in the organic or inorganic compound substrates (chemical bonds form) to electrical energy through catalytic reactions of microorganisms, electricigens, under anaerobic conditions. Many substrates involve in generating electricity including carbohydrates, proteins, volatile acids, cellulose and wastewaters used as feed in MFC studies. MFC has a wide range of applications, including serving as household electrical generators and powering items such as small portable electronic devices boats, automobiles, electronics in space and self-feeding robots. The construction and analysis of MFCs requires knowledge at both scientific and engineering fields, ranging from microbiology and electrochemistry to materials and environmental engineering. We conclude that for further development of MFC technology a greater focus on the understanding of its components, microbial processes, factors of limitations and designs of the construction the in MFC systems is mandatory, in order to be simplified and large scale system developed; so that it will be cost-effective and to increase electricity production. This paper aimed to review on the current microbiology knowledge in electricity production, the materials and methods used to build the technology and the applications to MFC technology also highlighted.

Key words: *Microbial fuel cell, microorganisms, electricity, substrate, organic matter.*

1. INTRODUCTION

In recent years, energy needs in the world continue to increase/accelerate and this triggers the global energy crisis. So the reliance on fossil fuels, especially oil and gas, is unsustainable due to finite supplies (Kim *et al.*, 1999; Bond *et al.*, 2002; Kim *et al.*, 2002; Lovley, 2006; Davis and Higson, 2007) and pollution or environmental effect (Venkata *et al.*, 2008). In recent years, researchers are moving towards microbiology and biotechnology to find the solution by focusing their researches on alternate, renewable and carbon neutral energy sources. Renewable bioenergy is viewed as one of the ways to decrease the current global warming crisis (Lovely, 2006). This mean, new electricity production from renewable resources without a net carbon dioxide emission is much desired (Lovley, 2006; Davis and Higson, 2007). Production of electrical energy using microorganisms through microbial fuel cells (MFC) is a renewable and sustainable technology that is considered to be one of the most efficient (HaoYu *et al.*, 2007; Salgado, 2009) and carbon neutral energy sources (Lovley, 2006).

Microbial fuel cells are devices that use bacteria as the catalysts to oxidize organic and inorganic matter to generate current. The potency of the MFC in energy generation has been widely studied. Energy is been harvested from various wastewater sources including industrial brewery wastewater (Mathuriya and Sharma, 2009; Franks and Nevin, 2010), Paper wastewater (Mathuriya and Sharma, 2009), Sugar processing (Mathuriya and Sharma, 2009), Agro allied wastewater (Franks and Nevin, 2010; Momoh and Neayor, 2010) and Domestic wastewater and Synthetic water (Ghangrekar and Shinde, 2006). Thus, MFC is an ideal solution for wastewater treatment and domestic energy production (Schwartz, 2007).

Microbial fuel Cells technology has generated considerable interests among academic researchers in the last decades (Venkata *et al.*, 2008). So, recently the increased interest in MFC technology was highlighted by the naming of *Geobacter sulfurreducens* KN400, a bacterial strain capable of high current production, as one of the top 50 most important inventions for 2009 by Time Magazine (Time, 2010).

Many microorganisms can contribute to electricity production in microbial fuel cell. Recently researchers have discovered a new metabolic type of electricity-producing microorganisms that has indicated that a wide diversity of organic compounds can be effectively converted to electricity in self-sustaining microbial fuel cells. These organisms, known as electricigens, can completely oxidize organic compounds to carbon dioxide, with an electrode serving as the sole electron acceptor, and conserve energy to support growth from this electron transfer (Wilkinson, 2000).

The basic microbial fuel cell design consists of an anode, a cathode, a proton exchange membrane (PEM) and an electrical circuit. Over the past 40 years researchers have been suggested that microbial fuel cells might be developed for a wide range of applications, including serving as household electrical generators and powering items such as small portable electronic devices boats, automobiles, electronics in space and self-feeding robots (Wilkinson, 2000).

Another interesting area of MFC is developing large-scale MFC for the conversion of sewage and other organic waste to electricity and the bioremediation of contaminated environments. However, none of these applications is yet practical. At present, MFCs can produce enough current to power small electronic devices for short periods or to tricklecharge capacitors for applications with higher power demands. While the MFC is studied vigorous in the past six to seven years, resulting in the development of several MFC configuration and higher electricity harvesting MFC setup, there are many limitations in the system leading to few field applications. Scale-up, high production cost and low electricity generation has been reported as areas that needed to be improved upon in the MFC technology (Oji, 2012). The objective of this paper was to review on the current microbiology knowledge in electricity production, the materials and methods used to build the technology and the applications and limitations to MFC technology also highlighted.

2. LITERATURE REVIEW

2.1.History of Microbial Fuel Cells

Earlier, it was thought only few microorganisms can be used to produce electricity. Recently most microorganisms can potentially be used as a biocatalyst in MFC. The earliest MFC concept was demonstrated by Potter in 1910 (Ieropoulos *et al.*, 2005a) when from living cultures of *Escherichia coli* and *Saccharomyces* sp. were used to generate electricity using platinum electrodes (Potter, 1912). However, not drawing much attention till early 1980s when the concept was boosted with advent of use of electron mediators to enhance the generation of electricity many folds.

Mediators in an oxidized state can easily be reduced by capturing the electrons from within the membrane. The mediators then move across the membrane and release the electrons to the anode and become oxidized again in the bulk solution in the anodic chamber. This cyclic process accelerates the electron transfer rate and thus increases the power output. According to Ieropoulos *et al.* (2005a) good mediators possess the following features: able to cross the cell membrane easily, able to grab electrons from the electron carries of the electron transport chains, possessing a high electrode reaction rate, having a good solubility in the anolyte, non-biodegradable and non-toxic to microbes and low cost.

2.2.Microbial Fuel Cells

Microbial fuel cells are devices that use microorganisms, as catalyst, to directly produce electrical current from biodegradable organic and inorganic compounds (Rabaey and Verstraete, 2005; Logan *et al*. 2006). Generally bacteria are used in MFCs to generate electricity while accomplishing the biodegradation of organic matters or wastes (Park and Zeikus, 2000; Wilkinson, 2000). Many types of wastewaters have been successfully treated using MFCs, including domestic, animal, brewery, and food processing wastewaters (Oh and Logan 2005), by removing organic contaminants in wastewaters and then produce valuable energy (electrical power or hydrogen gas) (Jacobson *et al.*, 2011).

The basic microbial fuel cell design consists of an anode, a cathode, a proton exchange membrane and an electrical circuit. The anodic and cathodic chambers partitioned by a proton exchange membrane (Kim *et al.*, 2003; Rabaey and Verstraete, 2005). The anode compartment is typically maintained under anaerobic conditions, whereas the cathode can be suspended in aerobic solutions or exposed to air. Electrons flow from the anode to the cathode through an external electrical connection that typically includes a resistor, a battery to be charged or some other electrical device (Kim *et al.*, 2003).

Microbes in the anodic chamber of an MFC oxidize added substrates and generate electrons and protons in the process. Carbon dioxide is produced as an oxidation product. However, there is no net carbon emission because the carbon dioxide in the renewable biomass originally comes from the atmosphere in the photosynthesis process. Unlike in a direct combustion process, the electrons are absorbed by the anode and are transported to the cathode through an external circuit. After crossing a PEM or a salt bridge, the protons enter the cathodic chamber where they combine with oxygen to form water. Microbes in the anodic chamber extract electrons and protons in the dissimilative process of oxidizing organic substrates (Rabaey and Verstraete, 2005).

Typical electrode reactions are shown below using acetate as an example substrate.

Anodic reaction: $CH_3COO^- + 2H_2O \longrightarrow 2CO_2 + 7H^+ + 8e^-$

Cathodic reaction: $O_2 + 4e^- + 4H^+ \longrightarrow 2H_2O$

The overall reaction is the breakdown of the substrate to carbon dioxide and water with a concomitant production of electricity as a by-product. The efficiency of the process depends on various factors. Optimization of these factors can solve out energy crisis in an efficient way to utilize the industrial and domestic waste to produce electricity. Power generation from MFCs using anaerobic microbes is a novel technology with great potential for alternative energy generation and environmental remediation (Du *et al.*, 2007).

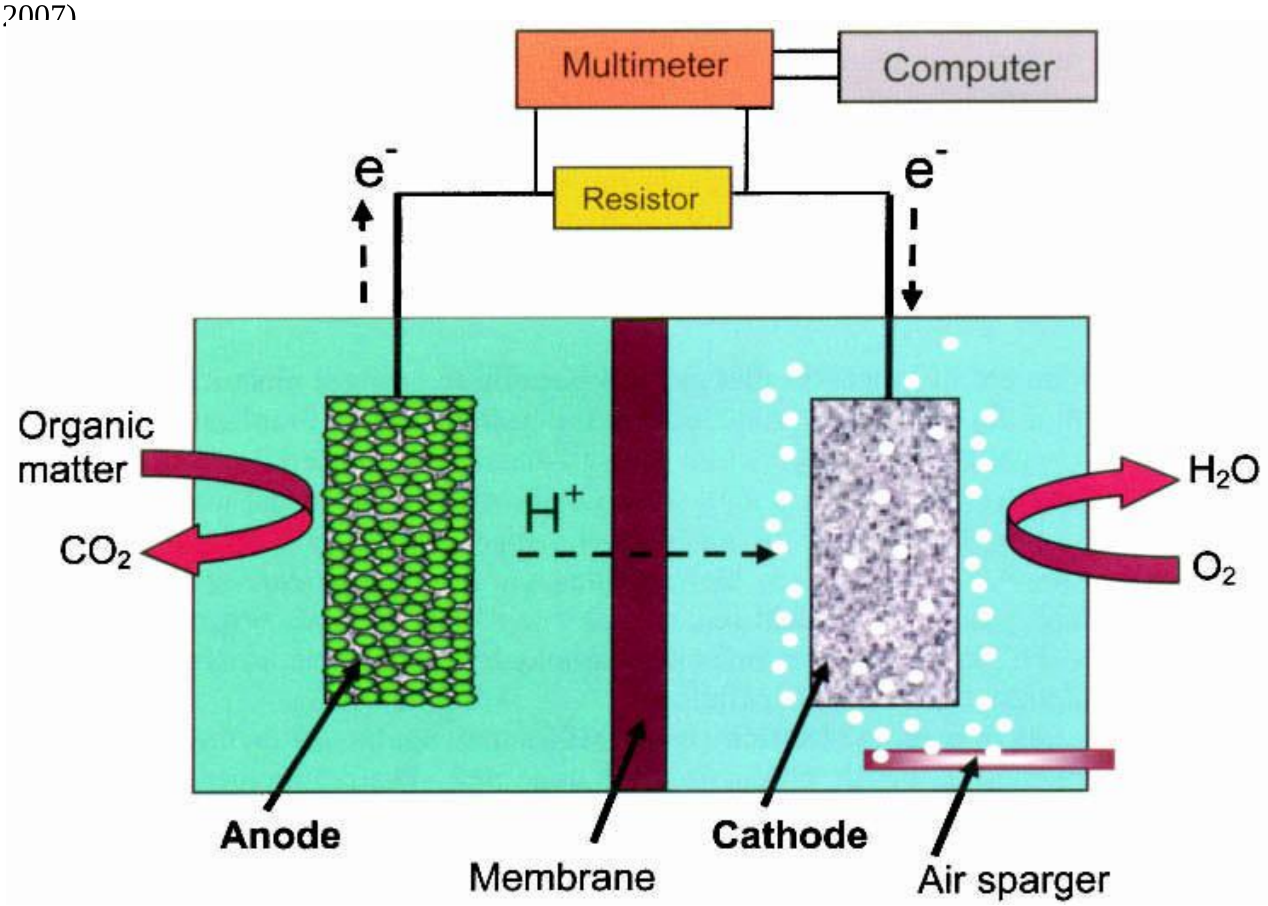


Figure 1: Graphical representation of a simple setup of microbial fuel cell (Logan, 2008).

2.3. Designs of Microbial Fuel Cells

2.3.1. Microbial fuel cells components

The electrodes used in the construction of MFCs should have a good electrical conductivity, more surface area, less resistance, and should be non-corrosive, biocompatible, chemically and mechanically stable to obtain a reproducible result (Jang, 2004)

The distance between the electrode is also plays an important role the performance of the MFC so the distance should be as close as possible to overcome the electrical leakage and to have a more internal resistance (Jang, 2004). One of the critical challenges in MFC is selecting proper electrodes (cathode and anode) which affect the power output (Logan *et al.,* 2006). Another limiting factors to use MFC is the high cost of materials which are used in the construction of MFC such as electrodes and proton exchange membrane which is nafion membrane so attempts are made to replace these costly membranes with the low cost earthen pots, cheaper stainless steel mesh as a cathode material and graphite plate as anode (Behera, 2009). The basic components of MFC include anode, cathode, proton/ ion exchange membrane, substrate and electrode catalyst (Das and mangwani, 2010):

Anode: anodic materials must be conductive, biocompatible and chemically stable in the reactor solution. Metal anodes consisting of non-corrosive stainless steel mesh can be utilized but copper is not useful due to the toxicity of even trace copper ions to bacteria. The most versatile electrode material is carbon, available as compact graphite plates, rods or granules, as fibrous material (felt, cloth, paper, fibers, and foam) and as glassy carbon**.** The simplest materials for anode electrodes are graphite plate or rods as they are relatively inexpensive, easy to handle and have unambiguous surface area. Much larger surface areas are achieved with graphite felt electrodes which can have high surface areas. Carbon fiber, paper**,** foam and cloth (Toray) have been extensively used as electrodes. Reticulated vitrified carbon has been used in several studies. It is quite porous (97%) with different effective pore sizes specified by a manufacturer. The main disadvantage of the material is that it is quite brittle. It has been shown that current increases with overall internal surface area in the order carbon felt > carbon foam > graphite (Chaudhuri and Lovley, 2003).

Cathode: due to its good performance, ferricyanide (K_3 [Fe (CN) $_6$]) is very popular as an experimental electron acceptor in microbial fuel cells (Park and Zeikus, 2003). The greatest advantage of ferricyanide is the low over-potential using a plain carbon cathode, resulting in a cathode working potential close to its open circuit potential. The greatest disadvantage, however, is the insufficient reoxidation by oxygen, which requires the catholyte to be regularly replaced. The choice of the cathode material greatly affects performance and is varied based on application (Rhoads *et al.*, 2005).

Membrane: the majority of MFC designs require the separation of the anode and the cathode compartments by a PEM. The most commonly used PEM is Nafion. Alternatives to nafion, such as Ultrex CMI-7000 also are well suited for MFC applications and are considerably more cost-effective than nafion. When a PEM is used in an MFC, it is important to recognize that it may be permeable to chemicals such as oxygen, ferricyanide, other ions, or organic matter used as the substrate (You *et al.*, 2009).

Substrate: is the substance contained in the anode chamber that is to be oxidized. In a microbial fuel cell the substrate used can be any form of organic matter. Microbial fuel Cells have been successfully operated on chocolate, wine, wastewater, acetate, glucose and more. Most frequently glucose, wastewater and acetate are used in experiments with the highest results being obtained with acetate (Logan, 2006).

Catalysts/catholytes: The cathode chamber is where protons and electrons recombine and reduce an electron acceptor. Oxygen is the most suitable electron acceptor for an MFC due to its high oxidation potential, availability, low cost (it is free), sustainability and the lack of a chemical waste product (water is formed as the only end product). When oxygen is used however the reaction is very slow therefore the need for a catalyst arises. Most MFCs use platinum as the catalyst however this is extremely expensive. Due to the expense, which affects the viability of fuel cells, much research is aimed at finding an equally efficient but less expensive catalyst. One option is to use a catholyte to replace oxygen as the terminal electron acceptor. Chemicals such as ferricyanide and potassium permanganate have been used successfully with results comparable to those achieved with platinum. These chemicals are far less expensive than platinum however the disadvantage is that they are consumed in the reaction and must be replaced (He and Angenent, 2006).

Table 1: Shows the material use for the microbial fuel cell. **Source**: (Du et al., 2007)

Items	**Materials**	**Remark**
Anode	Graphite, graphite felt, carbon paper, carbon-cloth, Pt, Pt black, RVC	Necessary
Cathode	Graphite, graphite felt, carbon paper, carbon-cloth, Pt, Pt black, RVC	Necessary
Anodic Chamber	Glass, polycarbonate, Plexiglas	Necessary
Cathodic Chamber	Glass, polycarbonate, Plexiglas	Optional
Proton Exchange system	Proton exchange membrane: Nafion, Ultrex, polyethylene. poly,(styrene-co-divinylbenzene); salt bridge, porcelain septum, or solely electrolyte	Necessary
Electrode catalyst	Pt, Pt black, Mno_2, polyailine electron mediator immobilize on anode	Optional.

2.3.2. Design of microbial fuel cells

Different configurations and modes of MFC have been developed in a bid to optimize the efficiency of the MFC and reduce the limitations in the fuel cell units. Electrodes, wirings, glass cell and salt bridge have an important role in MFCs construction. The MFC types based on configuration includes (Kim *et al.*, 2003):

Single chambered fuel cell: the anode and cathode compartment house in the same compartment with the cathode exposed directly to air while their electrolyte is the same (Park and Zeikus, 2003) (Figure 2). Porous cathodes form one side of the wall of the cathode chamber utilizing oxygen from atmosphere and letting protons diffuse through them. They are quite simple to scale up than the double chambered fuel cells and thus have found extensive utilization and research interests lately. The anodes are normal carbon electrodes but the cathodes are either porous carbon electrodes or proton exchange membrane bonded with flexible carbon cloth electrodes. Cathodes are often covered with graphite in which electrolytes are poured in steady fashion which behaves as catholytes and prevent the membrane and cathode from drying. Thus, water management or better fluid management is an important issue in such single chambered fuel cells (Park and Zeikus, 2003).

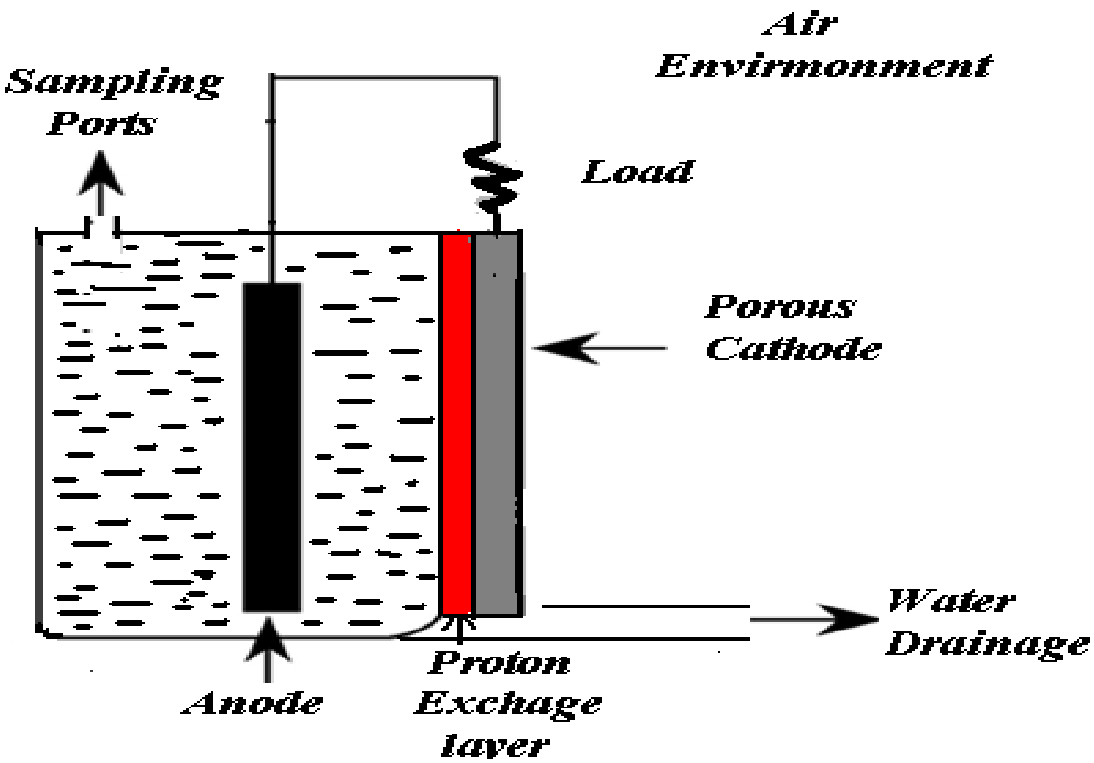
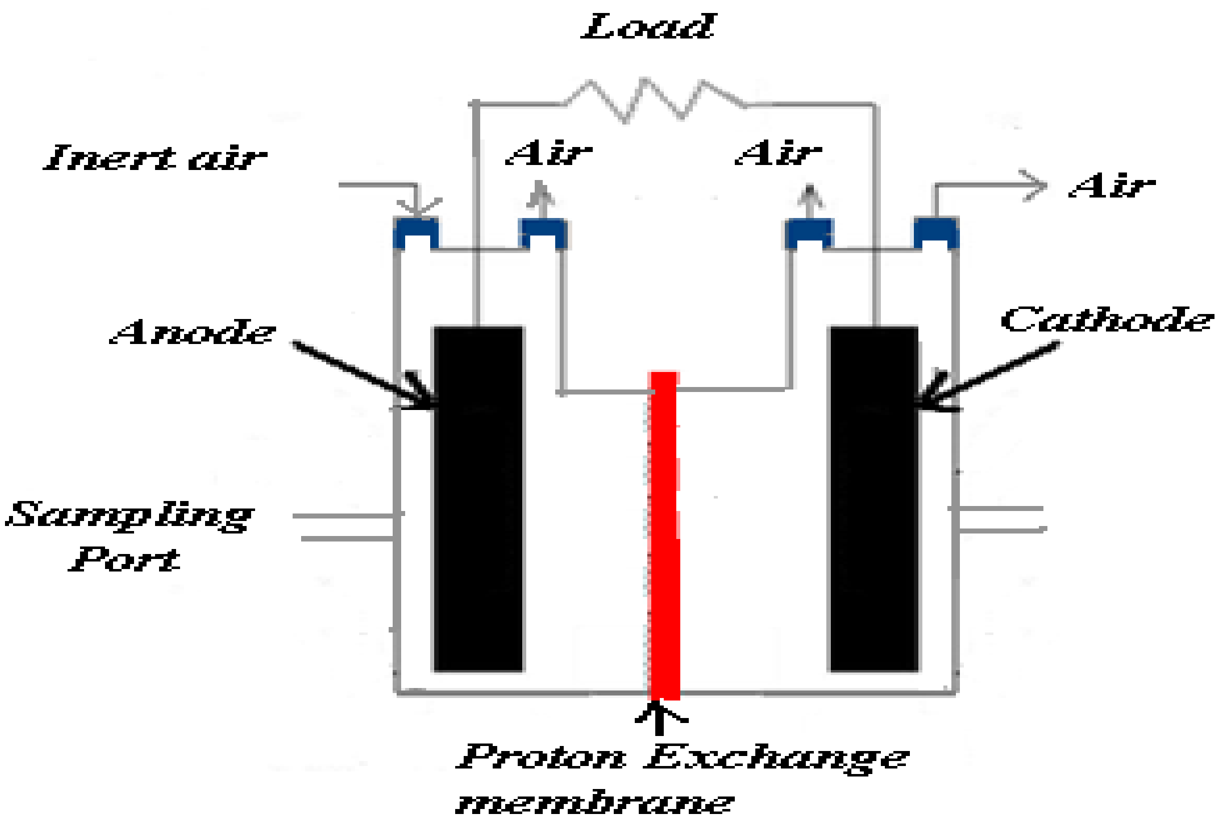


Figure 2: Graphical representation design of Single chambered Microbial Fuel Cell (Park and Zeikus, 2003).

Double chambered fuel cells*:* is made of two separate compartments connected together by a Proton exchange membrane or sometimes salt bridge mainly functions as medium for transfer of proton to make the circuit complete (Ringeisen *et al.*, 2006) (Figure 3). This Proton exchange membrane or Salt Bridge is not only completes the reaction process but also prevents anode to come in direct contact with oxygen or any other oxidizers. They are run in batches and can be used for producing higher power output and can be utilized to give power in much inaccessible conditions. It can be suitable designed to scale up to treat large volume of wastewater and other source of carbon (Jang *et al.*, 2004).



to form battery of fuel cell. This type of construction doesn't affect each cell's individual Columbic efficiency but in together it increases the output of overall battery to be comparable to normal power sources. These can be either stacked in series or stacked in parallel. Both have their own importance and are high in power efficiency and can be practically utilized as power source (Aelterman *et al.*, 2006).

The Mediator-less Microbial Fuel Cells is a type of MFC does not use mediator to transfer electrons to the electrode. Mediator which were in use in the earlier development of the Microbial Fuel Cells have been found to be toxic to the endogenous anodophile microorganism there by reducing the efficiency of the Microbial Fuel Cell. The additional advantage of the Mediator-less Microbial Fuel Cells is cost of the mediator which increase the overhead cost of the MFC. Cost is reduced by the adoption of the mediator-less MFC (Du *et al.,* 2007; Das and Mangwani, 2010).

Up-flow microbial fuel cell: the cylinder shaped microbial fuel cell consists of the anode (bottom) and the cathode (top) partitioned by glass wool and glass beads layers. The feed is supplied from the bottom of the anode passes upward of the cathode and exits at the top. The diffusion barrier among the electrodes provides a gradient for proper operation of the MFCs (Du *et al.,* 2007; Schwartz, 2007). This design has no physical separation and so there are no proton transfer associated problems and is attractive for wastewater treatment (Kim, 2003).

2.4. Microbes Used in Microbial Fuel Cells

Earlier it was thought only few microorganisms can be used to produce electricity. Recently, it was observed that most of the microorganisms can be utilized in MFCs. MFC concept was demonstrated as early in 1910 where *Escherichia coli* and *Saccharomyces* sp. were used to generate electricity using platinum electrodes (Potter, 1912). Even not giving much attention till early 1980s when the concept was improved to begin the use of electron mediators to enhance the generation of electricity many folds (Davis and Higson, 2007).

Nowadays, many microorganisms possess the ability to transfer the electrons derived from the metabolism of organic and or inorganic matters to the anode. Marine sediment, soil, wastewater, fresh water sediment and activated sludge are all rich sources for these microorganisms (Niessen *et al.,* 2006). A number of recent publications discussed about the screening and identification of microbes and construction of microbial fuel cells for microorganisms that are able to generate electricity from degrading organic matters (Logan *et al.,* 2005).

Microorganisms in the MFC use to metabolize the organic substrates and extracellular transfer electrons to an electrode surface. The oxidation of the organic material liberates both electrons and protons from the oxidized substrate. As such, an electrical current is generated in a fashion similar to a chemical fuel cell, but with microbes acting as a catalyst on the anode surface. Catalysts generally increase the rate of a reaction without being changed or receiving energy from the reaction they catalyze. Whereas, the microbes in a microbial fuel cells are not true catalysts since they obtain energy from the oxidation of the substrate to support their own growth and create an energy loss. Microbes in a MFC may gain all the energy and carbon required for cellular growth from the oxidation of the complex organic material and as such MFC technology has been considered self-sustaining (Ashley and Kelly, 2010).

Pure cultures capable of producing current in a MFC include representatives of the Firmicutes and Acidobacteria (Zhang et al., 2008), four of the five classes of Proteobacter ia (Holmes *et al.,* 2004) as well as the yeast strains *Saccharomyces cerevisiae* and *Hansenula anomala* (Prasad *et al.,* 2007). These organisms interact with an anode through a variety of direct and indirect processes producing current to varying degrees (Kim *et al.*, 2004).

One of the most extensively studied microorganisms capable of high current densities in a MFC is *Geobacter sulfurreducens.* This organism has become a model for bacterial processes in a MFC. It belongs to class of microbes referred to as electricigens, a term used to describe microbes that conserve energy to support growth by completely oxidizing organic compounds to carbon dioxide with direct electron transfer to the anode of the MFC(Chang *et al.*, 2006). The terms used for the microorganisms that can transfer electrons to an electrode include: anodophiles, exoelectrogens, electrogenic microorganis ms, anode-respiring bacteria and electrochemically active bacteria (EAB) (Chang *et al.*, 2006).

When microorganisms in the MFC system are capable of completely oxidizing the organic substrate to CO_2 higher columbic efficiencies have been reported. Bacteria reported to be capable of the complete oxidation of an organic substrate in a MFC system include *Geothrix fermentans* (Bond and Lovley 2005), *Geobacter* species (approaching 100 % efficiency oxidizing acetate or 84% oxidizing benzoate) (Nevin *et al.*, 2008), and

Rhodoferax ferrireducens (83% efficiency oxidizing glucose) (Chaudhury and Lovley, 2003).

Table 2: Indicates the microbes used in microbial fuel cells.

Microbes	Substrate	Applications
Actinobacillus succinogenes	Glucose	Neutral red or thionin as electron mediator (Park and Zeikus, 2003).
Aeromonas hydrophila	Acetate	Mediator-less MFC (Pham *et al.*, 2003).
Clostridium butyricum	Starch, glucose, lactate, molasses	Sulphate/sulphide as mediator (Niessen *et al.*, 2004b).
Escherichia coli	Glucose, sucrose	Mediators such as methylene blue needed (Schroder *et al.*, 2003).
Geobacter metallireducens	Acetate	Mediator-less MFC (Min *et al.*, 2005a).
Geobacter sulfurreducens	Acetate	Mediator-less MFC (Bond and Lovley, 2005).
Klebsiella pneumoniae	Glucose	HNQ as mediator biomineralized manga nese as electron acceptor (Menicucci *et al.*, 2006)
Lactobacillus plantarum	Glucose	Ferric chelate complex as mediators (Vega and Fernandez, 1987)
Proteus mirabilis	Glucose	Thionin as mediator (Choi *et al.*, 2003)
Pseudomonas aeruginosa	Glucose	Pyocyanin and phenazine-1- carboxamide as Mediator (Rabaey *et al.*, 2004)
Rhodoferax ferrireducens	Glucose, xylose, sucrose, altose	Mediator-less MFC (Liu *et al.*, 2005)
Shewanella oneidensis	Lactate	Anthraquinone-2,6-disulfonate (AQDS) as Mediator (Ringeisen *et al.*, 2006)
Shewanella putrefaciens	Lactate, pyruvate, acetate, glucose	Mediator-less MFC but incorporating an electron mediator like Mn(IV) or NR into the anode enhanced the electricity production (Park and Zeikus, 2003)
Streptococcus lactis	Glucose	Ferric chelate complex as mediators (Vega and Fernandez, 1987)

2.5. Electron Transfer Mechanism

In Microbial fuel cell, the electrons liberated from the organic matter are transferred to electrodes and generates the electricity. Except anodophiles, the microbes are incapable of transferring electrons directly to the anode. The outer layers of the majority of microbial species are composed of non-conductive lipid membrane, peptididoglycans and lip polysaccharides which stop the facilitation of electron transfer to the anodes (Davis and Higson, 2007). The problem can be solved with mediators. The bacterial transfer of electrons from the organic matters to electrode is mainly through (Yan-ping, 2008):

2.5.1. Direct electron transfer

There are several microorganisms reported that can transfer electrons across the membrane by themselves to anodes (Kim *et al.,* 1999). These microorganisms are stable and have current high efficiency. *Shewanella putrefaciens* (Kim *et al.,* 2002), *Geobacteraceae sulferreducens* (Bond and Lovley, 2003), *Geobacter metallireducens* (Min *et al.*, 2005a) and *Rhodoferax ferrireducens* (Chaudhury and Lovley, 2003) are all effective and transfer electrons directly to electrode across the membrane. These microorganisms brought a revolution in study as it reduced the use of mediators. The anode here acts as the final electron acceptor for the cell and thus effectively enhances the electricity generation. There are also reported studies on cathodophillic microorganisms such as *Thiobacillus ferrooxidans* which forms a biofilm on cathode and the cathode acts as the electron donor. These organisms cause a potential difference in cathode driving a suitable reaction at anode by anodophillic microorganisms to produce the electricity (Bond and Lovley, 2003).

2.5.2. Indirect electron transfer by products

In the earliest days of microbial fuel cell research investigators used fermentation microorganisms like yeast for power generation and they don’t have the well-defined mechanisms that understand the power generation. It was implied/ indirect that reduced products of microbial fermentation were oxidized at the anode surface to provide electrons. These products might include hydrogen, alcohols or ammonia. However, there were no studies that actually documented this mechanism or directly quantified which reduced products were oxidized at the anode (Aston and Turner, 1984).

2.5.3. Artificial mediator

In this mechanism electrons are transported by artificial mediators, sometimes referred to as electron shuttles. This chemical materials offer the possibility for microorganisms to generate reduced products that are more electrochemically active than most fermentation products. These electron shuttles are typically capable of crossing cell membranes, accepting electrons from one or more electron carriers within the cell, exiting the cell in the reduced form and then transferring electrons onto the electrode surface (Lovely, 2006). Mediators are important in microbial fuel cells which use microorganisms such as *Escherichia coli*, *Pseudomonas*, *Proteus*, and *Bacillus* species that are unable to effectively transfer electrons derived from central metabolism to the outside of the cell (Davis and Higson, 2007).

Commonly used electron shuttles involve such as thionine, benzylviologen, 2, 6-dichlor phenolindophenol, 2 - hydroxyl - 1, 4 - naphthoquinone and different phenazines, phenothiazines, phenoxoazines, iron chelates and neutral red. The good mediators should possess the following characters for efficient electron transportation: able to cross the cell membrane easily; able to grab electrons from the electron carries of the electron transport chains; possessing a high electrode reaction rate; having a good solubility in the anolyte; non-biodegradable and non-toxic to microbes; low cost (McKinley and Zeikus, 2004). These characteristics describe the efficiency of mediators. Methylene blues, neutral red, thionine, Meldola’s blue, Fe (III) EDTA are sysnthetic mediators but the problem is their toxicity which limits their use in MFCs (Davis and Higson, 2007).

2.5.4. Use own mediator

Some of the microorganisms can produce their own mediators to promote extracellular electron transferring. This was first proposed as a mechanism to facilitate electron transfer to Fe_3^+ in *Shewanella oneidensis* (Park and Zeikus, 2003). Other organisms, such as *Geothrix ferementans* (Newman and Kolter, 2000) and *Pseudomonas* species also produce electron shuttles (Nevin and Lovley, 2002).

Biosynthesizing an electron shuttle is energetically expensive and therefore an electron shuttle must be recycled many times in order to recoup/earn this energy investment. For this reason, microorganisms that produce electron shuttles are expected to be at a competitive disadvantage in open environments in which the shuttle will rapidly be lost from the site of release. This might explain why species from the *Geobacteraceae* predominate over other species under Fe_3^+- reducing conditions in many sedimentary environments. *Pseudomonas aeruginosa* produce phenazine electron shuttles that could aid in electron transfer to electrodes. Significant limiting factor in electricity production by several microorganisms that produce an electron shuttle is that they only incompletely oxidize their organic fuels (Rosso *et al.*, 2003).

2.6. Factors Affecting of Microbial Fuel Cells

So far, performances of laboratory MFCs are still much lower than the ideal performance. There may be several possible reasons like Microbe type, fuel biomass type and concentration, ionic strength, pH, temperature, electrode materials, Proton exchange membranes or salt bridge and operation conditions of anode and cathode have important effect on MFCs (Oh and Logan, 2005).

2.6.1. Electrode materials

Type of material used in electrode preparation will show vital effect on MFCs efficiency. Better performing electrode materials usage will always improve the performance of MFC because different anode materials result in different activation polarization losses. The electrode material determines the diffusivity of oxygen in single chambered MFCs. If the electrodes are more porous it allows diffusion of oxygen to anode which reduces the efficiency of fuel cells. The electrode material also determines the power loss of fuel cell in terms of internal resistance (Oh and Logan, 2005). Pt and Pt black electrodes are superior to graphite, graphite felt and carbon-cloth electrodes for both anode and cathode constructions, but their costs are much higher. MFCs with Pt or Pt-coated cathodes yielded higher power densities than those with graphite or graphite felt cathodes (Oh *et al.*, 2004).

2.6.2. PH buffer and electrolyte

If no buffer solution is used in a working MFC, there will be an obvious pH difference between the anodic and cathodic chambers, though theoretically there will be no pH shift when the reaction rate of protons, electrons and oxygen at the cathode equals the production rate of protons at the anode. The PEM causes transport barrier to the cross membrane diffusion of the protons, and proton transport through the membrane is slower than its production rate in the anode and its consumption rate in the cathode chambers at initial stage of MFC operation thus brings a pH difference. However, the pH difference increases the driving force of the proton diffusion from the anode to the cathode chamber and finally a dynamic equilibrium forms. Some protons generated with the biodegradation of the organic substrate transferred to the cathodic chamber are able to react with the dissolved oxygen while some protons are accumulated in the anodic chamber when they do not transfer across the PEM or salt bridge quickly enough to the cathodic chamber (Gil *et al.*, 2003).

It was possible that the buffer compensated the slow proton transport rate and improved the proton availability for the cathodic reaction. Increasing ionic strength by adding NaCl to MFCs also improved the power output possibly due to the fact that NaCl enhanced the conductivity of both by anolyte and the catholyte (Jang *et al.*, 2004).

2.6.3. Proton exchange system

proton Exchange membranes, can affect an MFC system's internal resistance and concentration polarization loss and then influence the power output of the MFC, play an important role but they are very costly and needed proper installation procedures for limiting the dangers of clogging/blockage and drying (Rozendal *et al*., 2006).The ratio of membrane surface area to system volume is important for the power output to the system performance. Alternative membranes such as porous polymers and glass wools have been tested but are not utilized by researchers most of the time. Some researchers prepared their own polymer using Polyethylene by sulphonation with chlorosulphonic acid in 1, 2 dichloroethane (Grzebyk and Pozniak, 2005).

Nafion is most popular because of its highly selective permeability of protons. However, side effect of other cations/positively charged/ transport is unavoidable during the MFC operation with nafion. But its usage is better in the sense of charge balance between the anodic and cathodic chambers. Hence nafion as well as other PEMs used in the MFCs are not a necessarily proton specific membranes. The MFC internal resistance decreases with the increase of PEM surface area over a relatively large range (Oh and Logan, 2005).

2.6.4. Operating conditions in the anode chamber

Substrate type, concentration and feed rate are important factors that impact the performance of an MFC. Power density varies greatly with different substrates using same a given microbe or microbial consortium. Electricity generation is dependent on substrate concentration in MFCs. Usually a higher substrate concentration yields a higher power output in a wide concentration range. Moon *et al*. (2006) investigated the effects of substrate concentration on the performance of an MFC and showed that the power density was increased with the increase in substrate concentration (Rabaey *et al.*, 2004).

2.6.5. Operating conditions in cathodic chamber

Oxygen is the most commonly used electron acceptor in MFCs for the cathodic reaction. Power output of an MFC strongly depends on the concentration level of electron acceptors. Several studies indicated that dissolved oxygen (DO) was a major limiting factor when it remained below the air-saturated level. Using hydrogen peroxide solution as the final electron acceptor in the cathodic chamber increased power output and current density (Tartakovsky and Guiot, 2006).

Surely changing operating conditions can improve the power output level of the MFCs. The bottlenecks responsible for the low power output are Low rate of metabolism of the microbes in the MFCs, and the biotransformation rate of substrates to electrons inherently slow. To improve the MFCs efficiency one should be focused on how to break the inherent metabolic limitation of the microbes for the MFC application. As we know high temperature can accelerate nearly all kinds of reactions including chemical and biological ones. Use of thermophilic species might benefit for improving rates of electron production, however, to the best of our knowledge, no such investigation is reported in the literature. Therefore this is probably another scope of improvement for the MFC technology from the laboratory research to a real applicable energy source (Tartakovsky and Guiot, 2006).

2.6.6. Dissolved oxygen

Operating condition of DO content is important parameter. Anode uses low DO but Cathode uses high DO. But higher DO facilitates diffusion of more oxygen into anode compartment through the porous membrane. Oxygen saturated catholytes are found to be the optimum. Increasing the DO more than that doesn't give any considerable change in efficiency of the system. Fuel or substrate concentration also plays an important role. Though higher fuels are preferable but most of the time it is inhibitory to microorganism. So a proper feed rate should be maintained in continuous systems and proper feed concentrations in batch mode of working (Oh and Logan, 2004).

2.7. Applications of Microbial Fuel Cells

2.7.1. Electricity generation

Microbial fuel cells are capable of converting the chemical energy stored in the chemical compounds in a biomass to electrical energy with the aid of microorganisms, because chemical energy from the oxidization of fuel molecules is converted directly into electricity instead of heat. However, MFC power generation is still very low, that is the rate of electron abstraction/idea is very low. One feasible way to solve this problem is to store the electricity in rechargeable devices and then distribute the electricity to end-users (Ieropoulos *et al.*, 2003a).

Microbial fuel cells are especially suitable for powering small telemetry/associated technology/ systems and wireless sensors that have only low power requirements to transmit signals such as temperature to receivers in remote locations. MFCs themselves can serve as distributed power systems for local uses, especially in underdeveloped regions of the world. Locally supplied biomass can be used to provide renewable power for local consumption. Applications of MFCs in a spaceship are also possible since they can supply electricity while degrading wastes generated onboard (Melhuish *et al.*, 2006).

2.7.2. Biohydrogen

Microbial fuel cell can be readily modified to produce hydrogen instead of electricity. Under normal operating conditions, protons released by the anodic reaction migrate to the cathode to combine with oxygen to form water. Hydrogen generation from the protons and the electrons produced by the metabolism of microbes in an MFC is thermodynamically unfavorable. Applied an external potential to increase the cathode potential in a MFC circuit and thus overcame the thermodynamic barrier. In this mode, protons and electrons produced by the anodic reaction are combined at the cathode to form hydrogen. MFCs can potentially produce about 8–9 mol H_2/mol glucose compared to the typical 4 mol H_2/mol glucose achieved in conventional fermentation (Liu *et al.*, 2005c).

In biohydrogen production using MFCs, oxygen is no longer needed in the cathodic chamber. Thus, MFC efficiencies improve because oxygen leak to the anodic chamber is no longer an issue. Another advantage is that hydrogen can be accumulated and stored for later usage to overcome the inherent low power feature of the MFCs. Therefore, MFCs provide a renewable hydrogen source that can contribute to the overall hydrogen demand in a hydrogen economy (Liu *et al.*, 2005c).

2.7.3. Wastewater treatment

The MFCs were considered to be used for treating waste water early in 1991 (Habermann and Pommer, 1991). Municipal or community wastewater contains a huge amount of organic compounds that can fuel MFCs. The amount of power generated by MFCs in the wastewater treatment process can potentially halve the electricity needed in a conventional treatment process that consumes a lot of electric power aerating activated sludge. MFCs yield 50–90% less solids to be disposed of. Furthermore, organic molecules such as acetate, propionate, and butyrate can be thoroughly broken down to CO2 and H_2O. A hybrid incorporating both electrophiles and anodophiles are especially suitable for wastewater treatment because more organics can be biodegraded by a variety of organics. MFCs using certain microbes have a special ability to remove sulfides as required in wastewater treatment (Rabaey *et al.,* 2006).

Microbial fuel cell can enhance the growth of bioelectrochemically active microbes during wastewater treatment thus they have good operational stabilities. Continuous flow and single-compartment MFCs and membrane-less MFCs are favored for wastewater treatment due to concerns in scale-up. Sanitary wastes, food processing wastewater, swine wastewater and corn Stover are all great biomass sources for MFCs because they are rich in organic matters(Kim *et al.,* 2005).

2.7.4. Implanted medical devices

A strange application for MFC technology is to power implanted medical devices using glucose and oxygen from blood. An implanted MFC could provide power indefinitely and negate the need for surgery to replace batteries (Kerzenmacher *et al.,* 2008). Interest has also been expressed in using human white blood cells as a source of electrons for an anode. Experiments using white blood cells in phosphate-buffered saline solution with a ferric-cyanide cathode produced a low current level of 1–3 μAcm^2 but it could not determine if electron transport to the anode was through a direct or indirect process (Justin *et al.,* 2005).

Some scientists predict that in the future a miniature MFC can be implanted in a human body to power an implantable medical device with the nutrients supplied by the human body. The MFC technology is particularly favored for sustainable long-term power applications. However, only after potential health and safety issues brought by the microorganisms in the MFC are thoroughly solved, could it be applied for this purpose (Chia, 2002).

CONCLUSION AND RECOMMENDATION

Nowadays, MFCs field, a novel discovery technology, is an interesting, economical and renewable an alternative energy source an infant promising researchable area; and this is an exciting time in MFC research. The MFC technology involves biochemical conversion of organic and inorganic substrate into electrical energy (carbon neutral energy sources) through catalytic reactions of microorganisms, electricigens, under anaerobic conditions using and also has a wide range of application. The efficiency of the process depends on various factors; optimization of these factors can solve out energy crisis in an efficient way to utilize the domestic and industrials wastes (brewery wastewater, paper wastewater, sugar processing), as a source of organic and inorganic substrate which are effectively converted to electricity. Different configurations and modes of MFC have been developed to optimize the efficiency of the MFC and reduce the limitations in the MFC.

Therefore, based on the above conclusion I recommended the following points:

- The well coordination efforts of different scientific fields like microbiologists, electrochemists, materials scientists and engineers is well require in the development of the several potential practical applications of MFCs.
- Intensive studies needs to elucidate the behavior of bacteria in the process and the designs of MFC to reduce the complexity limiting steps then has enhanced higher current outputs.
- Materials of construction can be studied to lower the internal resistance and corrosion. The PEM is also a costly hindrance and can be suitably replaced to lower the cost and simply the mode of operation.
- Consequently, a good knowledge of the MFC is required for sustainable improvement of the MFC applications and also greater impact in the development of clean energy, carbon neutral energy.

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