ENERGY PRODUCTION FROM WASTE-WATER USING MICROBIAL FUEL CELLS

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ABSTRACT

Natural energy sources like fossil fuels are depleting due to increased human activities. Different types of alternatives are being explored to solve this problem with the consideration that they are sustainable. There are many environmental concerns connected with fossil fuel burning, which after oxidation processes release greater amounts of carbon emissions in atmosphere. Now the trends are shifting towards exploiting renewable energy options, such as bioethanol, biodiesel, biohydrogen, biogas, and bioelectricity. Bioelectricity is harvested from organic substrates using Microbial Fuel Cells (MFC) that operate on oxidation reduction (redox) reactions. MFCs produce electricity in the presence of microorganisms from biodegradable substances. Waste-water contains enormous amount of organic matter that can be oxidized in MFC for electricity harvesting. In this review, the main focus is made on the applicability of microbial fuels cells for simultaneous waste-water treatment and electricity production.

Keywords: *Microbial Fuel Cell, bacteria, power, electricity, waste-water*

1. INTRODUCTION

Renewable energy is the need of the hour. Efforts in the developed world are being made to explore the alternative options of renewable energy resources that do not further exacerbate the carbon foot-prints. The exploitation of microorganisms for the production of electrical energy through Microbial Fuel Cells (MFC) is considered to be one of the most effective options [1]. MFCs are the types of fuel cells that convert chemical energy present in the molecules of organic substrates into electrical energy by oxidizing the biodegradable substrates using biocatalysts, such as bacteria. MFC has become the best solution for wastewater treatment and energy production at domestic level because of the fact that bacteria can oxidize the substrates into electricity [2]. MFC technology is now taking a significant position as a source of bioenergy production. Therefore, its applicability at domestic level has been studied extensively. Bruce Logan reported that MFCs can generate electrical power as much as 1kW/m^3 of biological reactor volume [3]. This paper focuses on the technology, technical challenges and future perspectives in using MFC.

An MFC is basically made up of two electrolytic chambers, i.e., anodic and cathodic chambers that are kept separated using proton exchange membrane (PEM), along with an external circuit (Figure-1). In the anode compartment of MFC, bacterial community is present that through bio-electrochemical system consume organic substrates (organic matter in wastewater) as a fuels source to produce electrons and protons [4]. The electrons generated in this process are accepted in the electron-transport chain by nicotinamide adenine dinucleotide (NADH), and subsequently transferred to terminal electron acceptors, such as nitrate, sulphate and oxygen [5]. These electrons are then transferred to anode through bacteria from where they reach the cathode via an external electrical circuit, thus electric current is produced. In external circuit, the presences of suitable resistance is required. The potential difference and electrical current production are estimated by means of a voltmeter or ammeter, respectively, connected to the device [6].

Protons are generated during oxidation process in cathode chamber, which are then transported or diffused by means of proton exchange membrane (PEM). Protons subsequently combine with the electrons and oxygen to form water at the cathode in the cathodic chamber. Anaerobic conditions are maintained in the anode, compartment because oxygen inhibits electricity generation. In cathode compartment oxygen is supplied which act as an electron acceptor [7]. At anode biodegradation takes place where organic matter is biochemically oxidized and as a result carbon dioxide is liberated, and the resulted protons are diffused to cathodic chambers. Electrical current is produced when electrons are brought to flow in circuit. To maintain this current an external resistance is required [8].

2. ENERGY FROM WASTEWATER THROUGH MFC

It has now become a universal truth that energy is the currency, which will drive the global economy in the future. According to the estimation made by Lewis, energy consumed by humans in terms of the number of joules in a typical year and dividing them by the number of seconds in a year results in an average burn rate of about 13 trillion watts (13 TW) [9]. This is the amount of power which is consumed all around the world to maintain energy balance of human activities. The economic activities are directly and indirectly

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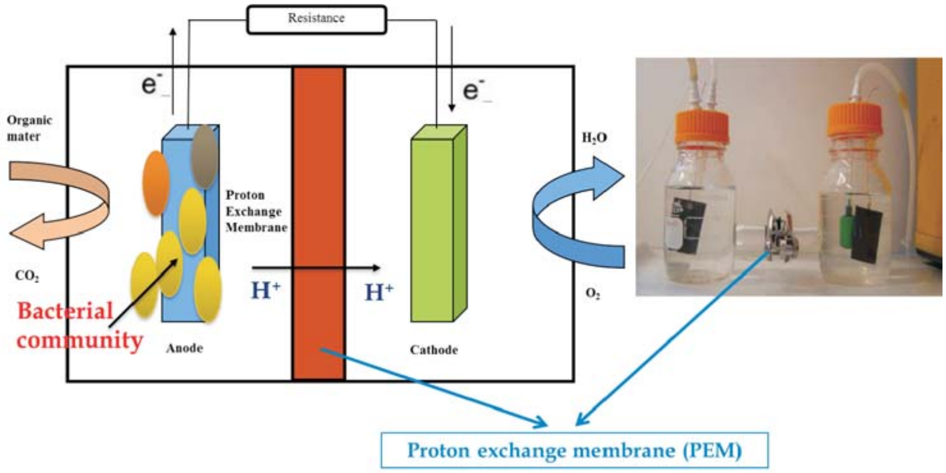

Figure-1: Graphical Representation of Microbial Fuel Cells [Ref. 27]

affected by the energy supply. Without compromising the needs of developing world, an enormous increase in energy supply is required to encounter the challenges and demands of the overall growing world population and to reduce poverty.

In order to harvest electrical energy from organic matter, MFCs are expected to provide a bio-electrochemical power option. MFC can also utilize the waste-water as a source of organic substrate to remove contaminants and simultaneously produce electricity. This can also reduce the operational budget of the waste-water treatment.

Chemical reaction:

MFCs have received more attention in the recent

$$\text{Wastewater} + H_2O \rightarrow nH^+ + yCO_2 + ne^-$$

$$\underline{\tfrac{1}{2}\,O_2 + 2H^+ + 2e^- \rightarrow H_2O}$$

$$\text{Wastewater} + O_2 \rightarrow 2H_2O + CO_2$$

years. Wide range of studies were conducted on different biodegradable organics substrates in waste-water, such as glucose, acetate, sucrose, domestic waste-water, brewery waste-water and waste-water containing starch from pulp and paper industries. But there are only a few reports published on *bio-refractory compounds*, i.e., for instance fuels, furfural, phenol, pyridine, and *p*-nitrophenol, etc. These reports indicate that if the MFC technology is used in practical applications, organic material in the waste-water might be suitable resource for electricity generation [10].

3. ELECTRON TRANSFER MECHANISMS

In MFCs, there are mainly two ways by which the electrons are transferred from bacterial culture in anodic chamber to electrodes. It may be of either direct transfer (mediatorless) or indirect electron transfer (mediator MFC) [11].

3.1 Direct Electron Transfer

There are several microorganisms that can transfer electrons from inside the cell to extracellular acceptors through c-type cytochromes, biofilms and highly conductive pili (nano-wires or nano-tubes), i.e., *Shewanella putrefaciens*, *Geobacter sulferreducens, G. metallireducens* and *Rhodoferax ferrireducens* (Figure-2). These microorganisms possess high Coloumbic efficiency and can result biofilms formation on the anode surface, which then act as electron acceptors and shift electrons directly to the anode, after which more energy is harvested [12].

3.2 Electron Transfer by Own /Artificial Mediators

In this type of electron transfer, the electrons from microbial carriers are shifted to the electrode (anode) either by a microorganisms (i.e. *Shewanella oneidensis*, or *Geothrix ferementans*) or through their own mediators or sometimes by adding mediators, which in turn result in the extracellular electron transfer.

The MFCs that operate on mediators for electron transfer are called mediator-MFCs. Mediators offer a platform for the microorganisms to generate electrochemically active reduced-products. Cell

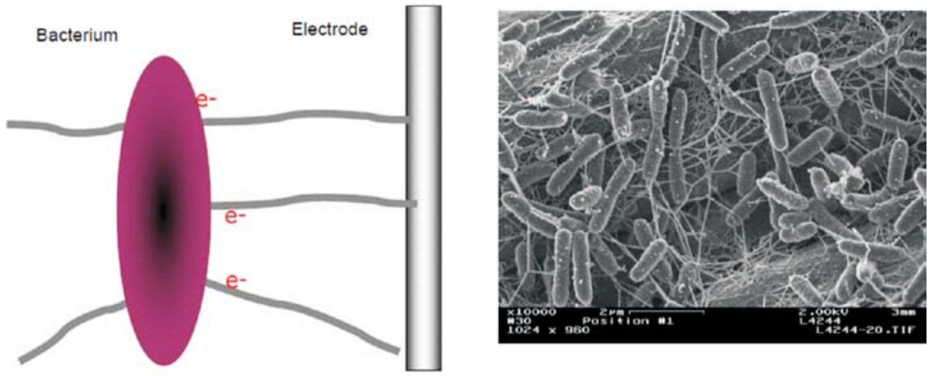

Figure-2: Bacteria Use Nanowires that can Transfer Electrons Directly to the Electrode [Ref. 28]

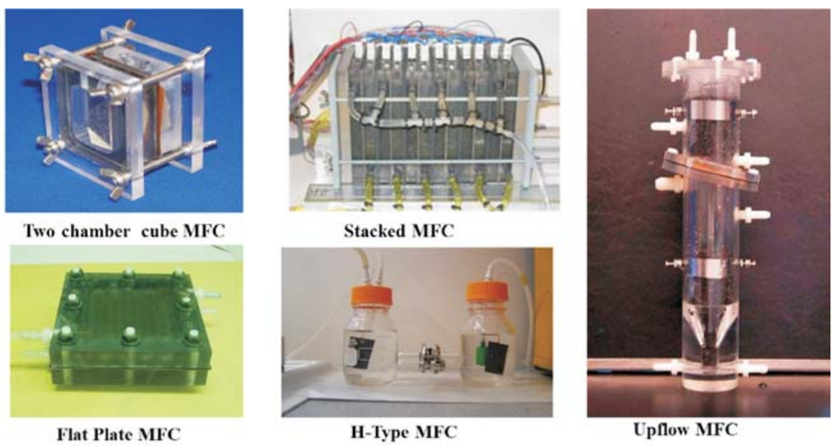

Figure-3: Different Types of Microbial Fuel Cells [Ref. 27]

Permeable is the reduced form of the mediators that can accept electrons from the electron carrier and transfer them to the surface of electrode [13]. Usually the chemicals like neutral red, methylene blue, thionine, 6-disulfonate, anthraquinone-2, phenazines and iron chelates are added to the MFCs as redox mediators [14]. MFCs that contain bacteria like *Proteus vulgaris*, *Escherichia coli*, *Streptococcus lactis*, and *Pseudomonas* require mediators because these bacteria cannot transfer electrons outside the cell. For effective working, the mediator must be able to penetrate easily in the cell membranes to grip the electrons from the electron carriers of the electron-transport chains. These should increase the electron transfer from the metabolites during long periods of redox cycling and must be non-toxic to the microbial community [15].

4. MFC DESIGNS

All MFCs have same operating principle but due to different substrates and power options, they have different modifications in their shapes (Figure-3). Using a diversity of materials, different configurations of MFCs are being established. To enhance performance, they are used under different conditions to get more power output and to reduce the overall cost [16]. There are different kinds of MFCs that are usually exploited in scientific research projects, such as:

Two chamber MFC: This is the most widely and commonly applicable and acceptable design, which consists of two chambers with the anode and cathode compartments separated by a proton-exchange membrane (PEM). The anode chamber is supplied with anaerobic environment consisting of diverse anaerobic microbial communities depending on the substrate selectivity. This design is generally applied in basic research. Literature proposes that the power output from these systems are usually low due to their high internal resistance, complex design and electrode based electron losses [5, 17].

Single chamber MFC: This design has only one chamber that contains both the anode and the cathode inside the compartment. Variably the anode is either placed close or away from the cathode, which are separated by PEM. It has been reported that after combining, the two chambers can increase the power density because if the anode is closer to the cathode, it will decrease the internal ohmic resistance by escaping the use of catholyte [18]. As compared to the two chamber MFC, it appears to be simple, cost effective and produces more power in more efficient manners [18]. However, there are a few major drawbacks in single chamber MFC, i.e., the membrane-less configuration, microbial contamination and backward diffusion of oxygen from cathode to anode with no presence of PEM [19].

Up-flow MFC: These are cylinder shaped MFCs which comprise of anode at the bottom and the cathode at the top of the container and both electrodes are separated from each other by glass wool or with layers of glass beads. The substrate is supplied from the bottom of the anode chamber, whereas the upper cathodic chamber at the top is supplied with oxygen. For proper operation of the MFCs the diffusion barrier between the electrodes provides a gradient. It is suitable for waste-water treatment because there is no physical separation as such and no problems for proton transfer in this design. However, some times the mixing of anolyte and catholyte tends to be a major drawback of this design [20].

Stacked MFC: In this design to achieve high current outputs, many single-celled MFCs are connected to each other in series or in parallel combinations. Parallel connection can generate more energy as compared with series connection due to higher electrochemical reaction rate. Parallel connections are more subjected towards the higher short circuiting when operated at the same volumetric flow, as compared to a series connection. But there are more problems of internal resistance in it because of the involvement of increased volume of microbes and zeta-potential [21].

5. ELECTRODE MATERIALS IN MFC

The performance of MFC is affected by the choice of electrode materials. Different materials have been tested as electrodes to enhance the performance and increased power outputs from MFCs. To make anode, different materials have been investigated, i.e., carbon felt, carbon cloth, carbon mesh, graphite felt and graphite fiber brush are frequently employed due to their stable nature, high electrical conductance and large surface area [5]. For making cathodes, materials like platinum (Pt), platinum black, graphite based cathodes, activated carbon (AC), and bio-cathodes have been used [22]. Though platinum coated electrodes are not cost-effective, they are more efficient and superior in power production due to higher catalytic activity with oxygen as compared with other electrodes. Different compounds have been used instead of platinum as an alternative catalysts, i.e., manganese oxides, ferric iron, iron and cobalt based compounds. Ferricyanide ($K_3(Fe(CN)_6)$ is often

Table-1: Microbial Community Analysis [Ref. 27]

Inoculum	Community	Reference
River sediment (glucose+glutamic acid)	α-Proteobacteria (mainly Actinobacteria)	Phung, et al. (2004)
River sediment (river water)	β-Proteobacteria (related to Leptothrix spp.)	Phung, et al. (2004)
Marine sediment (cysteine)	γ-Proteobacteria, 40% Shewanella affinis KMM, then Vibrio spp. and Pseudoalteromonas sp.	Logan, et al. (2006)
Waste-water (starch)	36%=unidentified, 25%=β- and 20%=α-Proteobacteria, and 19%= Cytophaga+Flexibacter+Bacterioides	Kim, et al. (2004)
Waste-water (acetate)	24%=α-, 7%=β-, 21%=γ- , 21%= δ-Proteobacteria; 27%=others	Lee, et al. (2003)

Table-2: Different Substrates with their Power Production Potentials [Ref. 27]

Substrate	Power production (mW/m^2)
Glucose	494
Acetate	506
Butyrate	309
Protein	269
Domestic wastewater	146

employed as an electron acceptor in the MFC due to its low over-potential and good performance. Bio-cathodes increase the power productions by reducing the over-potential [23]. Alternatively, the bio-cathode can contain oxygen and therefore it is given priority, due to increased cell operation and it is more commonly applied as electron acceptor in MFC.

5.1 Proton Exchange Membrane

The proton transfer from anode to cathode affects the power outputs. As the transfer of protons from anolyte to catholyte is a slow process that can result in high internal resistance. In most of the designs, MFCs need a salt bridge or PEM to separate the anode and cathode chambers. The PEM is commonly made up of polymers like Ultrex and Nafion. Although membrane-less, single chamber MFCs are reported to produce higher power density, membrane absence would increase oxygen to the anode and thus lower the coulombic efficiency and bioelectrocatalytic activity of the microbes [20].

5.2 Microbes in MFC

A wide range of bacteria have the ability to oxidize organic matter and transfer electrons to the anode along with the production of protons and carbon dioxide. In MFC, both the mixed cultures and pure bacterial cultures can be utilized [24]. It was reported that the mixed cultures have higher performance rate and more resistance towards process disturbances.

The electrochemically active bacteria in MFCs may be aerobes or facultative anaerobes, and the reaction temperature in MFCs depends on the bacterial tolerance to temperature (mesophilic/thermophilic) [25]. Not only the electrochemically active, iron-reducing bacteria (*Shewanella* and *Geobacter*), but also other group of bacteria (*Klebsiella pneumonia, Rhodopseudomonas palustris, Dessulfobulbus propionicus*) that are isolated from the waste-water showed great potential to be used in MFCs [26].

5.3 Substrate in MFC

Substrate provides not only energy for the bacterial cells to grow in the MFCs, but also influences the economic viability and overall performance, such as power density and columbic efficiency of MFCs. The composition, concentration and type of the substrate also affect the microbial community and power production. Many organic substrates including carbohydrates, proteins, volatile acids, cellulose and wastewater have been used as feed in MFC studies. It can range from simple, pure, low molecular sugars to complex organic matter containing waste-water to generate electricity. In most of the MFCs, acetate is commonly used as a substrate due to its inertness towards alternative microbial conversions (fermentation and methanogenesis) that lead to high coulumbic efficiency and power output [26]. Power generated with acetate is found to be higher, when compared with other substrates.

6. CONCLUSION

Energy harvesting from waste-water using microbial fuel cells (MFC) appears to be an attractive option for sustainable energy. The major advantages are treatment of waste-water by reducing biological oxygen demand (BOD) and chemical oxygen demand (COD). From the perspective of electric current and power production, applicability of MFCs has expanded the use of novel materials, and new cell designs are being studied for waste-water treatment. MFCs with modified treatment technologies seem to be more realistic, cost-effective and feasible for waste-water treatment. MFCs can be more realistic option for waste-water treatment as they oxidize organic matter, thus reducing pollution load in wastewater. Subsequently, through electrogenic process, electrons are generated that travel through external circuit and produce electrical power at the same time. In future perspective, MFCs are suitable option to overcome the waste-water problems and energy crises.

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