International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:11, No:9, 2017

A Review on Electrical Behavior of Different Substrates, Electrodes and Membranes in Microbial Fuel Cell

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Abstract**—**The devices, which convert the energy in the form of electricity from organic matters, are called microbial fuel cell (MFC). Recently, MFCs have been given a lot of attention due to their mild operating conditions, and various types of biodegradable substrates have been used in the form of fuel. Traditional MFCs were included in anode and cathode chambers, but there are single chamber MFCs. Microorganisms actively catabolize substrate, and bioelectricities are produced. In the field of power generation from non-conventional sources, apart from the benefits of this technique, it is still facing practical constraints such as low potential and power. In this study, most suitable, natural, low cost MFCs components are electrodes (anode and cathode), organic substrates, membranes and its design is selected on the basis of maximum potential (voltage) as an electrical parameter, which indicates a vital role of affecting factor in MFC for sustainable power production.

Keywords**—**Substrates, electrodes, membranes, microbial fuel cells, voltage.

I. Introduction

TODAY'S world is facing a serious problem that is the energy crisis. Traditional sources such as coal and oil are getting reduced in the last few decades. The scientists around the world are engaged in developing some new sources of energy from non-conventional energy sources [1], [2].

Continuous use of conventional sources of energy is harmful to the environment due to global warming, reduction of fossil fuels, energy supply security and risk, etc. [3]. It is a primary need to replace conventional source with the non-conventional source of energy, which makes people happy and healthy environment [4]. This review discusses the progress of low cost and the suitable components of MFCs, affecting factor voltage for sustainable power production.

II. MFC and Its Operation

MFC is an innovative alternative technology which generates renewable energy from organic wastes and also is helpful for removing organic pollutant from atmosphere/ surroundings [5]. The characteristics of MFCs can be defined in simple words, i.e. microbially catalyzed electrons liberated at the anode and subsequent electrons consumption at the cathode, when both processes are at suitable characteristics of MFCs [6], [7]. In this technology, microorganisms oxidize organic matter in the anode chamber (anaerobic conditions) where electrons, protons, and the electron acceptor (mainly oxygen) combine to produce water. The produced electrons by the bacteria (in anaerobic condition) from organic substrates are transferred to the anode (negative terminal) via the external circuit and flow to the cathode (positive terminal). Anode and cathode are linked to a conductive material connecting with a resistor or are operated under load [8]-[10].

III. Design of MFCs

An appropriate design is an important feature in MFCs, and researchers have come up with several designs of MFCs over the years with improved performance. Figs. 1 and 2 show in detail the mode of operation and components of a typical two-chamber (TC) and a single-chamber (SC) MFC. In a TC setup, the anode and cathode compartments are separated by an ion-selective membrane or salt bridge [4], [7], [11], [10], [5], allowing proton transfer from the anode to cathode and preventing oxygen diffusion to the anode chamber [10]. Although H-type or two (dual)-chamber MFC is the most common fuel cell in laboratory, it is the most challenging to scale up due to the practical configuration [12], [13]. The second one is a type of MFC; the researchers have given much attention on SC MFC, this type of MFC does not require separate cathodic chamber for generation of electricity because the cathode is exposed directly to the air. Apart from these two common designs, many variations have been made in the MFC design and structure [10], [14], [15].

IV. Electrode Materials

It is a great critical challenge for the researchers to find out choosing the proper electrode for MFC. The materials used in MFC can affect the potential of MFCs [11]. The surface of an electrode is responsible for flow of electron and provides greater electron (current), while narrower electrodes provide lesser electrons (current) [19].

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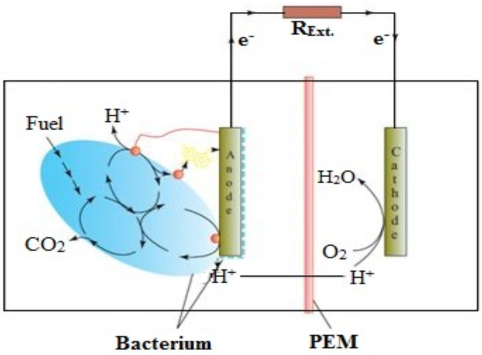

Fig. 1 Schematic diagram of the dual-chamber MFC structure (represents the mediator) [6], [16]

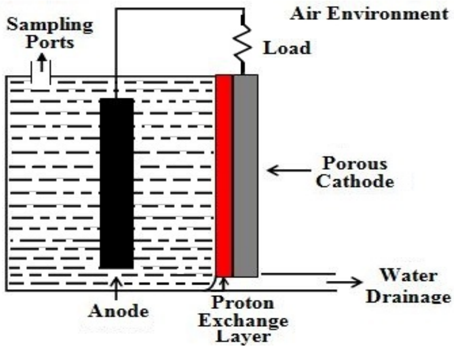

Fig. 2 Schematic diagram of the single-chamber MFC structure [10], [17], [18]

A. Electrode as an Anode

There are many materials which can be used as an anode in MFC [19]. The electrode used in fabricating an MFC must be non-corrosive and cost effective. It also should be a good conductor, bio-compactable, and chemically stable in an electrolyte [6], [20]. The carbon electrode is a widely used as anode electrode because it is inexpensive, higher surface area, highly conducting [11]. Many studies have attempted to increase the anode performance by adapting chemical and physical modification as shown in Table I.

B. Electrode as a Cathode

Design structure of cathode and selection of material plays a major role in the commercialization of MFC. In the selection of cathode material, it contains possible reduction of cost due to its flexibility in using low-cost material and increasing the potential. Catalyst is used in cathode electrode which improves the performance of MFC [19], [21]. Presently, the common cathode type of electrode materials is graphite, carbon cloth, carbon paper, carbon felt, zinc, aluminum, copper and magnesium, etc. To improve performance, modifying the cathode with a highly active catalyst, e.g. platinum (Pt), which has been the most popular one to try, is supposed to reduce the cathodic reaction activation energy and to increase the reaction rate. But, Pt is an expensive metal, and this limits its practical application [22].

V. Membranes/Mediators Used in MFCs

MFC power output is affected by proton exchange system. However, in spite of the considerable developments in the past decades, the commercialization of MFCs technology is delayed as a result of several barriers such as low power performance [23], [24], the high cost of materials including high-priced proton exchange membranes (PEM) and costly metallic catalysts used in the electrodes [25]. Until today, several researches have been done to bring this technology even closer to real world applications by engineering or technical approaches. Among them, finding appropriate and economic separators attracted great attentions [26], [27]. Nafion is the most popular membrane because of its highest selective permeability for protons. Nafion is the best choice but it is very costly [28].

In addition to high price, ion exchange membranes, i.e. cation exchange membranes (CEM) and anion exchange membranes (AEM), caused other problems including pH splitting, biofouling, high oxygen and substrate diffusion.

Today's researchers are trying to find less expensive and more durable substitutes. Therefore, the cheaper and more effective alternatives such as porous cloths, J-cloth, glass fiber, composite/polymer membranes, CMI-7000, AMI-7001, and etc. were examined as separators in MFCs [29], [27], [30].

Recently researchers are using ceramics instead of conventional membranes in their study with the focus on practical. Scalable materials (i.e. air breathing, non-platinum based cathodes) are an ideal material for advancing. MFC is ceramic with different types of ceramic membranes (Clayware [31] Mfensi Clay, Terracotta and Earthenware [32]) was investigated to find a low-cost alternative of commercially available proton exchange membranes. Ceramic provides a natural and stable environment for the bacteria and also enables a more efficient system for energy harvesting [32], [33].

There are many different types of microbial cells that are not active. There is an electron transfer of one type that goes from the microbial cells straight into the electrode. Due to this cyclic process, the electron accelerates the transfer rate, and thus, the power generation increases. These will be made possible by different types of mediator. These different types of specific synthetic exogenous mediators include dyes, and metallono-organic include methylene blue, methyl viologen, thionine, humic acid, toluidine blue, as well as neutral red. It is rare to be able to find one of these types of mediators that are not toxic or expensive. Electron transfer capacity in MFC can be improved if more suitable electron mediators were used [34].

An ideal electron mediator for converting metabolic reducing power into electricity should form a reversible redox couple at the electrode, and it should link to NADH and a high negative E_0value in order to maximize electrical energy production [35]-[37]. Good mediators should have the following features [37], [35]: (1) low cost;(2) able to cross the cell membrane easily; (3) nontoxic and non-biodegradable to microbes; (4) having high reaction rate of electrodes; (5) having a good solubility in anolyte; (6) able to grab electrons from the electron carries of the electron transport chains.

The salt bridge is the external mediator which is used in dual chamber MFC; it is much less expensive than others [38].

Unfortunately, the toxicity and instability of synthetic mediators limit their applications in MFCs. Korea Institute of Science and Technology is going to experiment on this special type of fuel cells. There is no need for a mediator to transfer the electrons with mediator-less MFCs. There is an active bacterium that is electrochemically transferred from the electron into the electrode. These specific electrons are actually carried in the electrode directly from the enzyme in the bacterial respiratory [34].

VI. Substrates in MFCs

In MFC, there are various substrates that have been used for generation of electricity from waste treatment with improved output in term of power generation, and waste treatment newer substrates are brought under these systems. Simple substrates like acetate and glucose were commonly used in the initial years of manufacturing of MFCs, but in recent years, researchers are mostly using non-conventional substrates for the use of waste biomass or treating waste water on one hand to improving MFC output on the other. Electricity from renewable and waste biomass through MFCs has higher potential in terms of bio-energy with sufficiently [10].

TABLE I
ELECTRICITY PRODUCTION USING VARIOUS COMPONENT OF MFC

Substrate	Design	Concentration	Anode	Cathode	Membrane /Mediator	Maximum Voltage (V)	Reference
Cow's Urine	SC	625mg/L	Carbon Rod	Zinc Rod	-	1.35	[39]
DairyWastewater	TC	4500mg/L	Graphite Plate	Graphite Plate	Toludine Blue	1.13	[40]
Cow Dung + Urine	TC	2 L	Copper	Magnesium	Natural Red	1.100	[35]
Cow Urine	TC	3 kg COD/m^3	Carbon Felt	Carbon Felt	Clayware Pot	0.947	[31]
Cow's Urine	TC	625mg/L	Carbon Rod	Zinc Rod	Salt Bridge	0.878	[39]
Waste Water	SC	4385 mg/L	Zinc	Aluminum	Mfensi Clay	0.863	[41]
Cow Dung	TC	500 g	Copper Plate	Copper Plate	Salt Bridge	0.825	[42]
Cow Dung	TC	100mg/L	Graphite Plate	Graphite Plates	Salt Bridge	0.804	[43]
Food Processing Wastewater	TC	8920mg/L	Toray Carbon Paper	Toray Carbon Paper	Nafion-117	0.776	[44]
Coconut Water	TC	1500mg/L	Graphite	Graphite	CMI-7000	0.762	[45]
Wheat Straw Hydrolysate	TC	1000mg/L	Toray Carbon Paper	Toray Carbon Paper	Nafion-117	0.730	[46]
Furfural	SC	6.68 mM	Carbon Cloth	Carbon Cloth	Nafion-212	0.710	[47]
Acetate	SC	125mg/L	Graphite Plates	Ss Mesh	-	0.700	[48]
Waste Water	TC	6358mg/L	Carbon Rod	Zinc Rod	Salt Bridge	0.700	[39]
Sewage Sludge	TC	510mg/L	Graphite Fiber Brush	Titanium Wire	Nafion-112	0.687	[49]
SyntheticWastewater	SC	3000 mg/L	L-Shaped Stainless Steel	Rectangular-Stainless Steel Mesh	-	0.670	[50]
Waste Water	TC	500 g	Graphite Plates	Graphite Plates	Salt Bridge	0.645	[51]
Glucose–Phenol Mixture	TC	58.0 mL	Carbon Paper	Carbon Paper	Nafion-212	0.635	[52]
Waste Water	TC	500 g	Graphite Plates	Graphite Plates	Salt Bridge	0.625	[51]
Ferricyanide	SC	4.316mg/L	Graphite Plates	Graphite Plates	Nafion-117	0.586	[53]
Aerated	SC	4.316mg/L	Graphite Plates	Graphite Plates	Nafion-117	0.572	[53]
Acetate	SC	1 g/L	Carbon Fibers	Carbon Cloth	-	0.570	[54]
Starch Processing Wastewater	SC	4852mg/L	Carbon Paper	Carbon Paper	Nafion-117	0.490	[55]
Acetate	SC	0.007 M	Carbon Cloth	Carbon Cloths	AMI-7001	0.480	[56]
Ethanol	SC	70mg/L	Plain Porous Carbon Paper	Carbon Paper	-	0.476	[57]
Cellulose	TC	1 g/L	Graphite Plates	Carbon Paper	Nafion-117	0.470	[58]
Cellulose	TC	1.0 g/L	Carbon Paper	Carbon Paper	Nafion-117	0.470	[59]
Glucose	TC	30 g/ L	Graphite Plates	Graphite Plates	Nafion-117	0.440	[60]
Sugar Derivates	SC	480 mg /L	Carbon Cloth	Carbon Cloths	Nafion	0.440	[61]
Domestic Wastewater	SC	1.6 g/L	Carbon Paper	Carbon Paper	Nafion-117	0.428	[62]
Waste Water	SC	6358mg/L	Carbon Rod	Zinc Rod	Nafion	0.420	[39]
Cellulose	SC	100 Mm	Graphite-Fiber Brush	Carbon Cloth	-	0.420	[63]
Potato	SC	7.7mg/L	Graphite Fiber Brush	Carbon Cloth	-	0.400	[64]
Textile Wastewater	SC	250 mg/L	Carbon Brush	Carbon Rod	Salt Bridge	0.390	[65]
Glucose	SC	95 ml	Carbon Granular	Carbon Cloth	-	0.385	[66]
Polyalcohol	SC	298 mg/L	Carbon Cloth	Carbon Cloths	Nafion	0.340	[67]
Bovine Serum Albumin	SC	1100 mg/L	Toray Carbon Paper	Toray Carbon Paper	-	0.331	[68]
Meat Wastewater	SC	1420 mg/L	Toray Carbon Paper	Toray Carbon Paper	-	0.325	[68]
Rice Mill Waste Water	TC	400 g	Stainless Steel Mesh	Graphite Plate	Nafion-117	0.304	[69]

VII. Discussion and Future Scope

In Table I, various components of MFCs like as organic substrates, electrodes, membranes/mediators and design used by researchers are categorized. These components of MFCs are selected on the basis of maximum potential (voltage) as an electrical parameter for power generation. The voltage against an electrode with a known potential can be determined by measuring the voltage, consisting the survival phases of composition and constant potential [6]. The potential of electrodes appears to vary with the use of different electrodes, membranes/mediators and substrates in the table, the voltage 0.8 to 1.35 V was recorded maximum and sufficient for the MFCs with its used components on the basis of suitability. But, magnesium electrode is very costly that is not suitable for MFC. It is also reported the use of proton exchange membrane (PEM) in the cell led to an increase in the cost of the cell [25]. But, the membrane made up of ceramic material is proven to enhance the efficiency the cell. The ceramic membrane provides low production cost, availability, very good stability and high structural strength compared to other [33], [70], [71]. Mediator-less MFC are advantageous because most available mediators are expensive and toxic.

Cow excreta (dung, urine) and waste water produce the maximum voltage if used as substrates. Substrates like cow excreta (dung and urine) are an easily available resource of bio-energy that holds maximum potential for sustainable development of MFCs in current days.

Due to the elimination of the cathodic chamber, the future of single chamber MFC will be more attractive and advanced and will provide more power generation. They can run without artificial aeration and can reduce internal ohmic resistance by avoiding the use of catholyte [13], [72], [73]. The advancement in potential for digital electronic devices, cost reductions of materials in electricity generation may be performed. In the field of power generation from non-conventional sources, if this unit of electricity production is integrated, it may be useful and very important for sustainable power generation.

VIII. Conclusion

The future of MFCs critically depends on the long-standing accessibility of energy from sources that are reasonable, reachable and biodegradable with the help of alternative sources of energy. The usage of organic substrates, electrodes and membranes or mediators in various type of MFC is discussed with the cost reduction and maximum potential of the electrode by replacing low-cost material with compromising MFC performance. Cow excreta (dung and urine) are a cheap and easily available bio-resource on our planet. Nowadays, MFCs are alternative energy devices based on bio-electro catalysis of natural substrates. This paper focuses on recent findings made on natural and low-cost components of MFC that can be used for a green technology.

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