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Microbial Fuel Cell: Generating Electricity from Organic Waste – A Review

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ABSTRACT

In the recent decades, there has been a huge energy demand due to the exponential increase of the human population and consequently, the depletion of non-renewable energy sources. This creates the need to explore alternate routes for renewable energy resources. Recently, the microbial fuel cell (MFC) technology is being considered a promising alternative due to their mild operating conditions and the ability to use variety of biodegradable substrates as fuel. This environment-friendly process converts chemical energy of organic waste into electricity through electroactive microbes. The review covers various aspects like the anodic/cathodic materials and select microbial/enzymatic electrochemical cathodic reactions. The critical review of different classes of wastes that can be employed for bio-energy generation, power output, challenges and the limitations are also described.

Keywords: Microbes, Fuel cell, Non-renewable energy, Substrate, *Saccharomyces cerevisiae, Clostridium butyricum*

1. INTRODUCTION

Energy generation to meet the demand is a very big issue, and almost 10-15% of the total economic expenditures in the world are used for meeting this supply and demand [1]. The total resources which can be used for energy generation in the world can be broadly categorized into

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fossil fuels, renewable sources and nuclear resources. The fossil fuels and nuclear sources comes under the category of non-renewable sources further [2] out of these three sources of energy, fossil fuels are the conventional sources which are used to meet the major portion of the energy requirements in the world but they are depleting with time and also have adverse consequences such as global warming. Nuclear sources are also harmful for the living beings. This lead to shift towards renewable sources which is the best promising alternative of energy generation as compared with the above two categories of energy sources.

The renewable energy source includes solar energy, wind energy, hydel energy and energy generated by microbes. Out of these solar, wind and hydel energy require a very huge area to collect the energy and also they are intermittent in nature. Considering this in view, the microbial fuel cell (MFC) technology is emerged recently which is the best alternative for all the energy sources because of their mild operating conditions and their ability to use variety of substrates [3] which are biodegradable as fuel Focus has been given in this review to compare this special type of fuel cell called microbial fuel cell. MFC uses the chemical energy which is generated by the metabolic activities of electro active microbes which are present in the organic waste to produce electricity. Since the energy is generated from a natural process, this technology can be called as green and clean technology as it does not produce any toxic by-product.

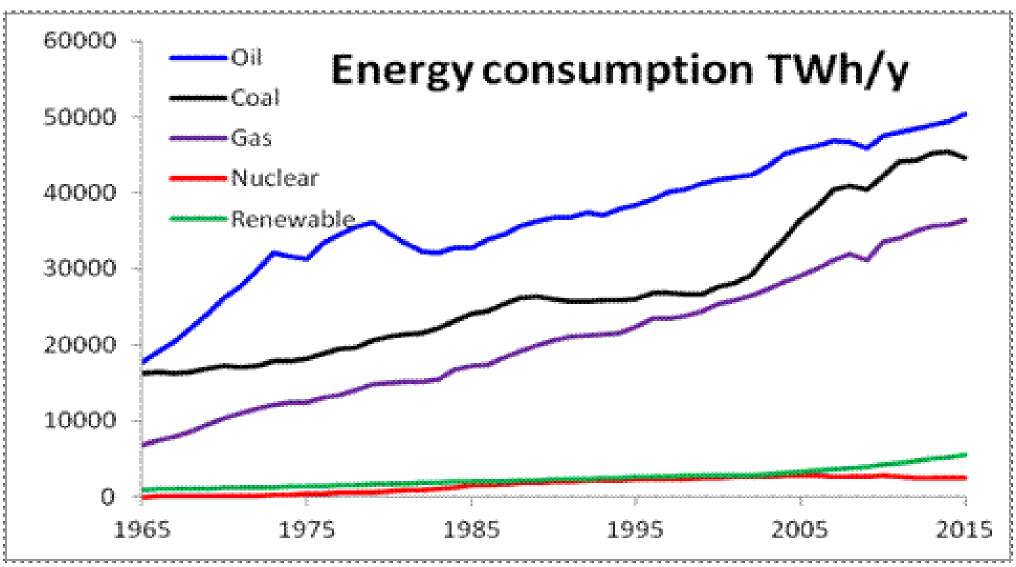

Figure 1. The world's energy consumption (2015 data) [4]

1. 1. History

The research on MFCs starts from the early twentieth century and credit goes to M.C. Potter [5] as the microbial activity of *Saccharomyces cerevisiae* (a species of yeast [6]) is used for the generation of electricity. Further in 1931, B. Cohen [7] created microbial half fuel cells, connected in series; which results in producing 35 volts with a current of 2 mA. Delduca et al. [8] performed a study in which they used hydrogen produced by the fermentation of glucose by *Clostridium butyricum* as the biocatalyst at the anode of a hydrogen and air fuel cell. This cell was functioning but was not reliable because of the unstable nature of hydrogen produced by the microbes. This problem was resolved by Karube et. al. [9] investigation in 1976, after which they designed a successful MFC in the following year [10]. Later on in the 80-90s, studies by Bennetto et. al. [11] on synthetic mediators and the earlier research works mentioned results in the formation and development of MFCs which are still in use.

2. MICROBIAL FUEL CELL

2. 1. How bio-energy is generated?

The configuration of most of the MFCs which are existing, includes anode chambers, cathode chambers, and a proton exchange membrane (PEM) for separating the anode and cathode chambers [12] along with an external electrical circuit as shown in

Figure 2. The microbes, working as a biocatalyst in the chamber of anode, oxidizes the substrate i.e., organic waste and thus produce electrons and protons in the process [13]. The protons which were produced in anodic chamber move to the cathodic chamber through proton exchange membrane while the electrons starts moving through the external circuit. The reaction takes place between protons and the electrons in the chamber of cathode where simultaneous reduction of oxygen to water [14] takes place continuously. The anode chamber should be premeditative designed anaerobic, so that the microbes should be kept air-sealed in the chamber [15] as in aerobic condition (oxygen presence) the production of electricity will be inhibited. The reactions given below are involved in the process in an MFC. [16]

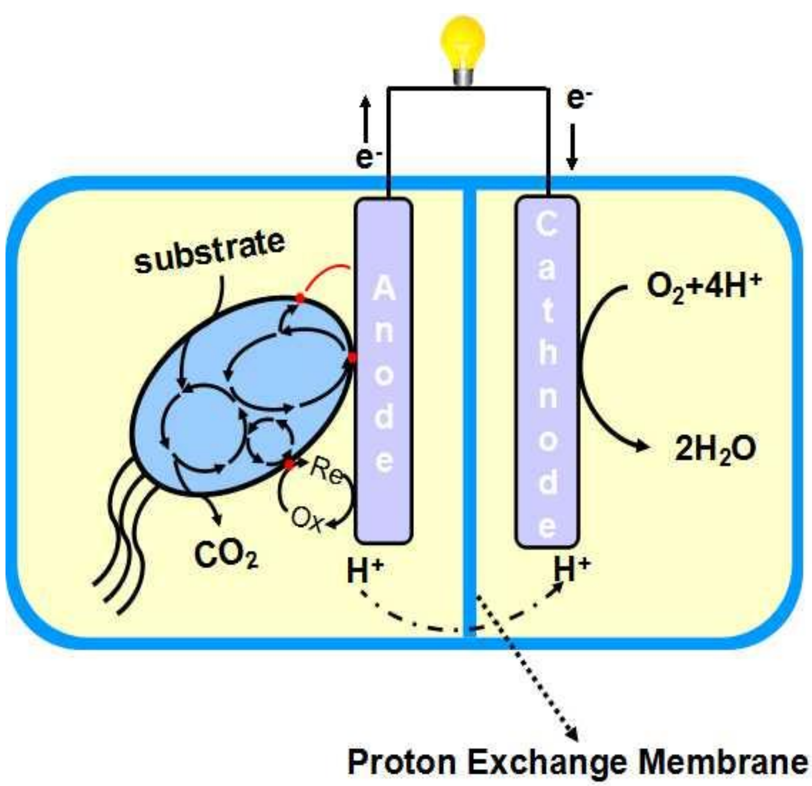

Figure 2. Schematic representation of MFC [17]

Half reaction (Oxidation)

$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^-$

Half reaction (Reduction):

$24H^+ + 24e^- + 6O_2 \rightarrow 12H_2O$

Overall oxidation/reduction reaction:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

2. 2. Classification of MFCS

2. 2. 1. Classification on the basis of design of chamber

MFCs can be classified on the basis of chamber designed: Single-chambered MFCs and Dual-chambered MFCs. Ina single-chamber MFC, only one chamber is there and both anode and cathode are placed in the same chamber as shown in Fig. 3.

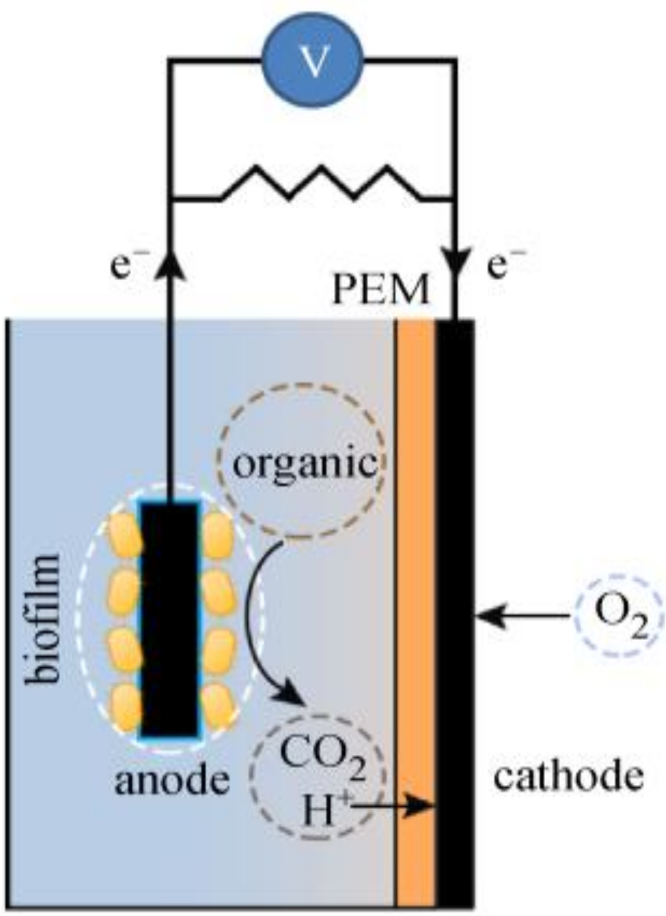

Figure 3. Schematic representation of a single-chamber MFC [18]

Single chamber MFCs (SCMFC) are also called as air-cathode MFCs.

On the other hand, the dual chamber MFC has anode and cathode in the two different chambers. The MFC which is detailed in *Section 2.1* was a dual-chambered MFC (DCMFC) in which the anode and cathode are placed in two different chambers and are separated by a PEM as shown below in Fig. 4.

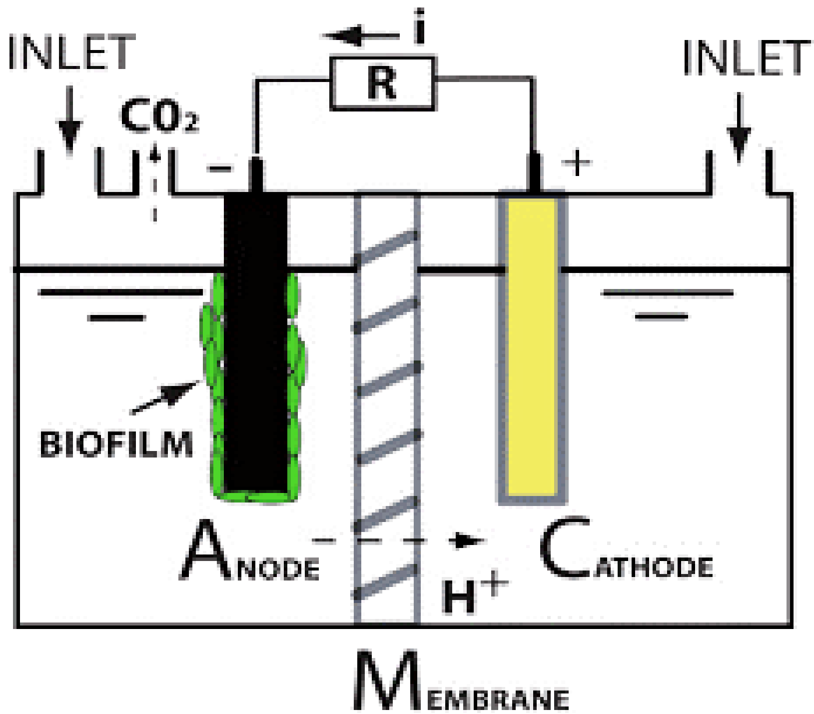

Figure 4. Schematic representation of a dual-chambered MFC [18]

Table 1. Comparison table of single and dual chambered MFC.

Dual Chambered	Single Chambered
1) A dual-chambered MFC (DCMFC) where the anode and cathode are installed in two different chambers demarcated by a proton exchange membrane (PEM).	1) On the other hand, a single chambered MFC has both the anode and cathode in the same chambered with a PEM in between.

2) Dual-chambered provide better performance or efficiency as shown by Luo et al. in 2009	2) Provide lesser performance or efficiency.
3) Despite providing better efficiency, dual chambered MFCs do not attain the amount of power densities as single chambered MFCs do, due to their higher internal resistances.	3) They attain higher power densities due to their lower internal resistances. Power generation as function of chemical oxygen demand (COD) in single chamber MFC showed a Monod-type relationship with P_{max} .

Luo et al. in 2009 [19] showed that DCMFCs gives better performance as compared to SCMFCs. The performance of the MFCs is affected by the effective area of the anode and the proton exchange membrane [19]. Although, the power density generated by single chamber MFCs is higher because of its lesser internal resistances, but the chemical oxygen demand (COD) at the anode increases due to the absence of PEM and thus, the columbic efficiency of single chamber MFCs decreases. Comparison of both the MFCs is shown in Table 1.

2. 2. 2. Classification on the basis of presence of mediator

On the basis of mediator MFCs can be classified as Mediated MFCs and Mediator free MFCs. The microbes in the MFCs are generally electrochemically inactive; the transfer of electron from the MFCs to the external circuit can be boosted with the help of a mediator. Methyl viologen, methyl blue, humicred [20] etc., are the few examples of the Mediator MFCs.

Although the Mediator boosted the electron transfer, but they are not advisable to use as they are toxic in nature. Unlike to the mediated MFCs, the electrochemical bacteria's are used in the mediator-free MFCs for boosting the transfer of electrons to the external circuit. The performance of Mediator-free MFCs depends on the many factors like, strain [21, 22]of the microbes, type of ion-exchange membrane used and many other abiotic conditions like temperature, pH, etc.

The mediator-free MFCs can also be operated through wastewater and hence, energy can directly be extracted from the plants, and thus, it can be called as a plant microbial fuel cell e.g. plant-e technology [23, 24] which provides various ecological advantages credited to the *in situ*-energy production. Comparison of both these MFCs is done in Table 2.

Table 2. Comparison table of Mediated and Mediator free MFC

Mediated MFC	Mediator-free MFC
1) MFCs with electrochemically inactive microbes are mediated with the help of a mediator.	1) Here, electrochemically active bacteria are employed for the operation of MFC.
2) Mediators used such as methyl blue, humic red, methyl viologen can be toxic in nature, therefore mediated MFC stand at an ecological disadvantage.	2) No mediators used and hence no danger of toxification giving mediator-free MFCs, an ecological advantage in terms of use.
3) Mediated MFCs are better characterized.	3) Mediator-free MFCs are less well characterized as they are dependent on a variety of factors such as the microbial strain, type of ion-exchange membrane and other system conditions such temperature, pH etc.

2. 3. Working of anode in MFCs

The basic working of MFC is already explained in *Section 2.1*. The anodic chamber plays an important role in the working of MFC because there only the biomass is degraded (organic/inorganic compound is oxidized into ATP by sequential reactions [25]) and the activity of microbes takes place. Inside the anodic chamber, there are substrates, microbes, mediator (which may be used or may not be used depending upon the type of MFC) and the anode electrode which collects electrons produced by the microbes.

The electron transfer takes place either directly or indirectly as shown in Fig.5. Indirect transfer of electron is performed because of the oxidation of a by-product due to bacterial metabolism as in the case of production of hydrogen by fermentative bacteria which is then oxidized at the surface of the anode [26].

The electron can directly be transferred between the electroactive microbes by making the direct contact between the surface of the anode and the outer membrane of the microbes. The electro-active (EA) biofilms are the microbial electro-catalysts in the system and contain the electro-active microbes inside it [27].To improve this direct transfer mechanism, research is going on and one other direct electron transfer mechanism was discovered in the last decade, where the electron transfer takes place through the extracellular conductive connections called the conductive pili or bacterial nanowires [28].

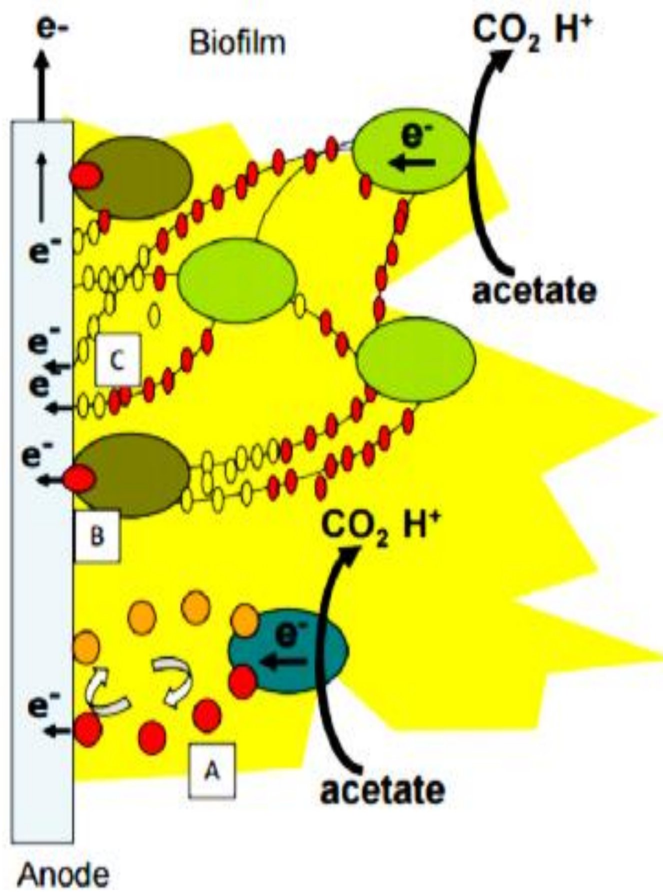

Figure 5. A) Indirect transfer via fermentation or mediators B) Direct transfer via cytochromeproteins C) Direct transfer via conductive pili (C. Santoro et al [27])

2. 3. 1. Different anodic materials and its effects

The performance of MFCs depends on the choice of materials from which electrodes are made as some materials have the tendency to boost the performance of MFC and its power output. The materials which are chosen should be able to improve interactions between the electro-active biofilms and the anodic material surface or in other words, the anodic microbial electron transfer rate [29] should amplify with the choice of material. Along with the material the configuration in which the anodes are installed also affects the performance of the MFC such as stacking the MFCs together [30]. Before choosing the anodic material, factors such as (i) large surface area; (ii) high electrical conductivity (iii) chemical stability; (iv) biocompatibility; (v) toughness and mechanical strength; and (vi) corrosion resistance should be considered [17]. Usually, carbon or any metallic-based materials exhibit all the above properties. Out of the carbonaceous materials one can use carbon cloth, carbon rod, graphite fiber brush, carbon mesh, carbon brush, carbon veil, carbon paper, carbon felt, granular activated carbon, granular graphite, graphite plate, carbonized cardboard and reticulated vitreous carbon (RVC); and for the metal-based materials, stainless steel plate, silver sheet, nickel sheet, copper sheet, gold sheet and titanium plate [31] can be considered.

Because of large surface area, graphite fiber brush, carbon felt, carbon cloth, carbon paper and RVC are few of the most used anodic materials which provide good electrical conductivity and also they are stable in terms of microbial culturing. The anode modification such as granulating graphite [32] or activated also helps in improving the performance and efficiency of MFCs as the carbon leads to high degree of microporosity which enhances the electron microbial transfer rate as the area of interaction between microbes increases. Nanomaterials can also be used to improve the electron transfer rate generated by microbes and also enhances the power density. Carbon Nanotubes (CNTs) is a material popular for its versatile and very wide range of applications and also amplifies the electron transfer rate. Another way to improve the performance of anode is the modification of anodes with the use of conductive polymers such as polyaniline (PANI) which is mostly utilized. To increase the current densities, two variations of PANI — fluorinated PANI and PANI (titanium dioxide composite) is used. List of different anodes and the maximum power density of the MFC system is given in Table 3.

2. 4. Working of cathode in MFCs

In the cathode chamber, the half reduction of the overall chemical reaction takes place. It also considered as the limiting reaction of the Microbial Fuel Cell. The reduction of oxygen in neutral media can be further enhanced by using enzymes, microbes or abiotic catalysts.

2. 4. 1. Different Cathodic materials and its effects

Materials used for cathodes are generally made up of platinum (Pt), platinum black, activated carbon (AC), graphite[33] based or bio cathodes. The electrodes are coated with platinum and they produce a very much efficient power because of the high catalyst factor with oxygen than other electrodes. Although, they are having these advantages, but they are expensive. Ferric iron [34], manganese oxides, iron and cobalt based compounds are act as a catalyst. Ferricyanide ($K_3(Fe(CN)_6)$) is the another acceptor of electron which is used in the Microbial Fuel Cell because of its better performance and low over-voltage. Bio-cathodes decrease the over-voltage and thus, increase the power. Alternately, oxygen is contained by the cathode and as it simplifies the operation of the cell, it is mostly preferred. It is also the commonly used electron acceptor in MFC. The proton transfer which takes place from anode to cathode defines the power output of MFC. Proton transfer is a very slow process which causes high internal resistance.

2. 5. Substrate

Table 3. Effect of different substrates

Substrates	Concentra tion	Current Density (mA/cm^2)
Acetate	1 g/L	0.8
Lactate	18 mM	0.005
Glucose	6.7 mM	0.7

Sucrose	267 mg/L	0.19
Phenol	400 mg/L	0.1
Starch	10 g/L	1.3
Cellulose	4 g/L	0.02
Xylose	6.7 mM	0.74
Domestic wastewater	600 mg/L	0.06
Brewery Wastewater	2240 mg/L	0.2

In the construction of an MFC, substrate is considered as one of the most important biological factors which affect electricity generation [35-37]. The energy is provided by the substrate to the bacterial cells for their growth in the MFCs and. The substrate also effect the economical factor, power density and current efficiency of the Microbial Fuel Cells [38]. The list of different substrates with its effect is shown in Table 3&4.

3. LIMITATIONS & CHALLENGES

As compare to the pure carbon sources like glucose, we get a very low power density with xenobiotics. This is one of the main hindrance in its application in generation of electricity from waste for our daily purposes. Although, the carbon sources provides the better results, but they cannot be easily employed because they are more costly in comparison to the wastes. The commercialization of MFC is also hindered by the costly material used for cathode, anode and membrane. So, presently to obtain the cost efficient system to generate the required and better output is the major challenge in front of the researchers.

4. CONCLUSION

The technology and sciences involved in MFCs are a step in the right direction when it comes to production of electricity from metabolism of abundant microbes. A large number of microbes and waste material has been used to produce electricity and it has also demonstrated its use in waste management and pollution control. Despite the major advantages of this technology, there is still work to be done on the problems such as commercialization, increasing the power output and make MFCs reliable and capable of meeting energy requirements on a wider level (Table 4).

Table 4. List of various anodes with their configurations and power density output [35-37]

Substrate	Anode	Bacteria	System Configuration	Maximum Power Density (mW/m^2)
Glucose	Carbon paper	*Geobacter* SPP (Firmicutes)	Dual-chamber	40.3 ± 3.9
Glucose	Graphite	*Saccharomyces cerevisiae*	Dual-chamber	16
Acetate	Carbon Paper	*G. sulfurreducens*	Dual-chamber	48.4 ± 0.3
Cyctenin	Carbon Paper	*Gammaproteo* and *Shewanella affinis* (KMM3586)	Dual-chamber	36
Marine sediment reached in acetate	Graphite	*Deltaproteo bacterium*	Dual-chamber	14
Marine sediment	Non-corroding graphite	*Desulfurmonas* SPP and ...	Dual-chamber	25.4—26.6
Sewage Sludge	Graphite with Mn^{4+}	*Escherichia coli*	Single chamber	91
Sewage Sludge	Graphite with neutral red (NR)	*Escherichia coli*	Single chamber	152
Sewage sludge	Platinum and polyaniliniecо-modified	*Escherichia coli*	Single chamber	6000
Glucose	Composite electrode (graphite/PTFE)	*Escherichia coli*	Single chamber	760
Glucose	Teflon treated carbon fiber paper	Electrochemically active bacteria	Dual-chamber (H-type MFC)	15.2
Glucose	Graphite Plates	*Mixed culture*	2-chamber air-cathode MFC	283

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