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Microbial Fuel Cells- A Boon or a Ban

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Review Article

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ABSTRACT

Microbial fuel cells utilises waste carbohydrates as fuel. It has the property of not utilising a catalyst or proton exchange membrane and it is thus eco-friendly for treating wastes. Biological fuel cell converts chemical energy directly into electrical energy. They are in light because they act in very mild conditions such as ambient temperature, pressure, and inexpensive catalysts i.e. microorganisms or enzymes. The cell uses manure sludge in the anode compartment and aqueous salt solutions which contain dissolved oxygen. The position of both anode and cathode highly influences fuel cell power performances. There are two types of microbial fuel cell i.e. mediated fuel cell and mediator less fuel cells. The maximum power densities obtained with the cell was 4.21 W/m^2. Researchers have also reported of a mediated fuel cell utilising a yoghurt bacteria and methylene blue as mediator. A maximum power density of more than 13 W/m^2 is generated. Enriched anodic biofilms have generated power densities of as high as 6.9 W/m^2. A drawback with redox enzymes in MFCs is that they cannot take part in direct transfer of electrons with conducting supports hence use mediator are used for the electrical connection of the biocatalyst and the electrode. Several methods are utilised to functionalise the electrode surface with layers consisting of redox enzymes, electro catalysts and biocatalysts that promote electrochemical transformation at the electrode interface. Microorganisms that require a mediator do not have electrochemically active surface proteins to transfer electrons to anode electrode. MFCs that do not use mediator require some more carbohydrates to functions. Metal reducing bacteria example Geobacteraceae family and shewanella genus are mainly used for this type of mediator less fuel cell.

INTRODUCTION

Microbial Fuel Cell (MFC) is a promising technology where microbes are used in the oxidation of organic substances for the production of electricity [1]. The idea of using microbial cells in an attempt to produce electricity was first conceived at the turn of the nineteenth century. M. C Potter was the first to perform work on this subject in 1911. Being a professor of botany at the University of Durham potter generated electricity from E. coli to some extent. In 1931, further discovery in this field with certain modifications was done by Barnet Cohen. He created a number of microbial half fuel cell connected in series produced over 35 volts with a current consumption of only 2 milliamps. Delduca et al. in 1963 used hydrogen produced by fermentation of glucose by clostridium butyricum as the reactant at the anode of a hydrogen and air fuel cell. It was found to be unreliable due to unstable nature of hydrogen production by microorganisms. Current design concept of an MFC came into existence a year later with work by Suzuki. First detailed study was done by M.J Allen and H. Peter Bennetto from King's College, London. They saw the fuel cell as a method for generation of electricity for third world countries and thus helped to build an understanding of how fuel cells operate. Microbial fuel cells (MFCs) operate in a galvanic mode: they employ microbial catalysts to extract oxidation current from waste organic matter in the anodic half-cell [2]. It is now know that electricity can be produced directly from degradation of organic matter in a MFC. Biological Fuel Cells (BFCs) use biological catalysts (e.g. microbes, enzymes) for the catalysis of electrochemical reactions [3]. The single-chamber MFC with an air-cathode had great advantage in terms of the structure, power density, and aeration [4]. MFC has both cathode and anode chamber. The working principle of MFC is similar to that of an electrochemical cell. Micro-organisms anaerobically oxidize biomass in the anodic chamber thereby reducing anode [5]. The MFC anode served as the working electrode and the cathode served as both the counter electrode and the reference electrode [6]. The anaerobic anode chamber is connected internally to the cathode chamber by an ion exchange membrane the circuit is complete by an external wire. Literally biological fuel cells are those cells that can produce chemical energy of wastes into usable electrical energy. Therefore they are in trend because of their property of generating electricity that is very much required in this era of globalisation. Biological fuel cells are of two types i.e. microbial fuel cells and enzymatic fuel cells. The Microbial Fuel Cell (MFC) technology can potentially be a part of the bioenergy solution. MFCs are capable of utilizing low-grade organic carbons in various types of wastewater such as municipal and industrial wastewaters as fuels to produce bioelectricity that can offset the energy needed for wastewater treatment [7]. Microbial fuel cells require only ambient temperature, pressure, and microorganisms. MFCs or microbial fuel cells can be further divided into mediator MFCs and mediator less MFCs. Among these mediators less MFCs are superior because of cost effective and absence of undesirable toxic mediators.

MFCs are now considered to be a promising sustainable technology to meet emerging energy needs especially by utilising wastewater as substrates to generate energy and also accomplish wastewater treatment. The efficiency and economic viability converting organic wastes to bioenergy depend on characteristics and components of the waste materials. Different substrates used in MFCs are acetate, glucose, lignocellulosic biomass, landfill leachates, brewery biomass and starch processing biomass, cellulose and chitin, dye wastewater and other organic and inorganic substrates. The production of current in MFCs is directly linked to the ability of bacteria to oxidise a substrate and transfer electrons resulting from this oxidation to the anode electrode. A MFC produced 506 mW/m2 with acetate, but 261 mW/m2 with swine wastewater and 146 Mw/m2 with domestic wastewater. The maximum power density produced appears to be related to the complexity of the substrate. Substrates like meat processing waste water and peptone containing many different aminoacids and proteins produced lower power than achieved using single compound like bovine serum albumin [8].

Working principle in MFCs

Working principle in MFCs is related to microorganisms oxidise organic matter in the anode chamber (anaerobic conditions) producing electrons and protons [9-15]. Electrons transfer via the external circuit to the cathode chamber where electrons, protons, and electrons acceptor (mainly oxygen) combine to produce water. In a two chamber set up, the anode and cathode compartments are separated by an ion selective membrane allowing proton transfer from anode to cathode and preventing oxygen diffusion to the cathode chamber. In the single chamber MFC the cathode is exposed directly to air. Despite of this there are also mediator MFCs and mediator less MFCs, microorganisms that require a mediator do not have electrochemically active surface proteins to transfer electrons to the anode electrode [16-25]. Whether the fuel cells are single culture or not MFCs that don't use mediators still require some form of carbohydrate to function. In comparison to mediator MFCs, mediator less MFCs is more important. Example of mediator less MFCs is marine environment have created a fuel cell using the different sediments on the sea floor [25-27].

A mediated MFC cell

Most of the microbial cells are electrochemically active. The transfer of electron from microbial cell to the electrode is facilitated by mediators such as thionine, methyl viologen, humic acid, methyl blue, neutral red and so on. Most of the mediators available are expensive and toxic. Therefore it is assumed to be less efficient then mediator less MFCs [27-32]. All MFCs are having a pair of battery like terminals i.e an anode and a cathode electrode connected by an external circuit and an electrolyte solution to conduct electricity. Therefore electricity is generated by the difference in voltage between anode and cathode along with electric between circuits. The anode respiring bacteria breaks down organic wastes to carbon dioxide and transfers the electrons released to the anode [33-37]. The electrons travel from the anode via electrical circuit to generate electrical energy. Finally the electron reaches cathode and are taken up by oxygen and hydrogen ions to form water. Another aspect is that bacteria in the biofilm produce a matrix of material so that they stick to anode which contains proteins, sugars and bacterial cells. It may also contain tiny conducting nanowires to conduct electrons.

A non-mediated MFC cell

A mediator less fuel cell does not require a mediator but uses electrochemically active bacteria to transfer electrons to the electrodes as they are directly transferred by respiratory enzymes of bacteria. Some of the electrochemically active bacteria are shewanella putrifaciens and aeromonas hydrophilla. Some bacteria have pilli and are able to transfer electrons via them [37-42]. Non mediated fuel cells can also work upon aquatic plants i.e. reed sweet grass, lupines, rice, cord grass, tomatoes and algae. The objective of various treatment processes is to remove pollutants from waste streams before their safe discharge to the environment. The emphasis of today's waste management is on reuse and recovery of energy, which has led to new views on how MFCs can be dealt with waste management [43-46].

Chemical energetics involved for production of electrical energy

Microorganisms consume substrates like sugar and release co_2 and o_2 in aerobic conditions. In anaerobic conditions it releases co_2, protons and electrons [47-50].

In a microbial cell the anode is the final terminal electron acceptor. Therefore microbial activity strongly depends upon redox potential of anode. Therefore a Michealis-Menten curve can be obtained between anodic potential and power output on acetate driven microbial cell [51].

DISCUSSION

Science can never remain untouched it's every nook and corner is discovered for the betterment of human race. Many eminent scientists have led this path with glorified results. Discussing about the topic of MFC it is also undergoing an era of recent development and scope of future researches. Showing results on the different types of substrates used in MFCs one of which is acetate. Acetate is a simple substrate that is why it is used as a carbon source to induce electro active bacteria [52-55]. Another fact is that it is used because it is inert to fermentations and methanogenesis at room temperature. Using a single chambered MFC the power generated is reported with acetate 506 m W/m^2, 800 mg/L was up to 66% higher than that produced with butyrate 305m W/m^2, 1000mg/L. Acetate fed MFC showed highest power output 72.3%, followed by propionate 36%, butyrate 43% and glucose 15% [55-58]. Glucose is another commonly used as substrates. It was reported that a maximum power density of 216 w/m^3 was obtained from glucose fed-batch MFC using 100 mM ferric cyanide as cathode oxidant. In a baffle chamber membrane less MFC, anaerobic sludge added very limited substrate and a limited power 0.3 mW/m^2 was generated. However with glucose in the same system a maximum power of 161 mW/m^2 was generated. The ECE (energy-conversion efficiency) was 42% with acetate and only 3% with glucose which lead to a low current and power density. In a recent study, glucose fed MFC generated the lowest PE as a result of electron loss by fermentation and methanogenesis by competing bacteria [59-60].

The abundance and renewability of lignocellulosic materials from agricultural residues renders a promising feedstock for cost effective energy production. Polysaccharides like Lignocellulosic biomass cannot be directly utilized by microorganisms in MFCs for generation of electricity. So it has to be converted into mono saccharides or other low molecular weight compounds. When cellulose is used as the substrate for electricity generation it requires a microbial community with both cellulolytic and exoelectrogenic activities. A PD of 69mW/m2 was reported using xylose at 10 mM concentration which was less than the PD for glucose indicating that xylose is more difficult to utilize power generation than glucose [61-64].

The May lab microbial processes in microbial fuel cells and microbial electrolysis cells. Recently, the main focus of the group has been studying the specialized microorganisms responsible for bio

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catalysis in thermophilic microbial fuel cells. A community of thermophilic microorganisms enriched from Charleston Harbor sediment proved to be a good source of electrochemically active bacteria. Studying the microbe-electrode interactions of these and other similar bacteria is of special interest to the group [64-68].

The Environmental Bioengineering Laboratory of the Biotechnology Research Institute, National Research Council of Canada is focused on developing high-rate microbial electrolysis cells (MECs) and microbial fuel cells (MFCs) through a combination of knowledge in the areas of mathematical modelling, microbiology, and electrochemistry. Research includes further understanding of the development of non-Pt catalysts, microbial kinetics, and exploring various carbon sources for their potential in electricity and hydrogen production in stackable MFCs and MECs [68-73].

A microbial fuel cell made in collaboration of micro fluids, micro/Nano technology, and bioenergy. It focuses on the developing scalable microbial fuel cell array that enables parallel analysis of electricigens, microbes that can directly produce electricity. The MFC array functions as multiple independent miniaturized MFCs. Micro fabrication technologies are used to develop the MFC array, which is a compact and user-friendly platform for the identification and characterization of electrochemically active microbes in parallel [73-76]. The current MFC array consists of 24 integrated anode and cathode chambers that function as 24 independent miniature MFCs, and supports direct and parallel comparisons of microbial electrochemical activities. The MFC array demonstrates highly repeatable results and can be used as a reliable high throughput screening tool for different MFCs.

Microbial fuel cells (MFCs) are not yet commercialized but they show great promise as a method of water treatment and as power sources. The power produced by these systems is currently limited, high internal (ohmic) resistance. However, improvements in the system will result in power generation dependent on the capabilities of the microorganisms. The bacterial communities are full of diversity, ranging from primarily -Proteobacteria that predominate in sediment MFCs to communities composed of α-, β-, - or -Proteobacteria, Firmicutes and uncharacterized clones in other types of MFCs There are very much research left to be discovered about the physiology of these bacteria capable of exocellular electron transfer, collectively defined as a community of exoelectrogens [77-83].

Studies suggests that in a mediator less fuel cell bacterial communities can be grown to produce electricity on electron beam platinum deposited electrodes. The content of a bacterial consortium found on an electron beam (e-beam) Pt-deposited electrode in a mediator-less microbial fuel cell (MFC) using glucose and glutamate as fuel is reported here. The e-beam Pt-deposited electrode along with electrochemically active bacteria (EAB) consortium was developed to improve the mediator-less MFC performance. Restriction fragment length polymorphism (RFLP), Denaturing gradient gel electrophoresis (DGGE), and 16S rRNA sequencing were used to identify the Electron Active Bacteria (EAB) consortia [83-85]. Sequencing results showed that clone ASP-31 was predominant and was similar to Aeromonas hydrophila, and a Fe(III)-reducing EAB. The phylogenetic tree analysis disclosed the presence of γ-proteobacteria groups such as Aeromonas genus, Klebsiella oxytoca, and Enterobacter asburiae. These results suggest that MFC performance of the e-beam Pt-deposited electrode with Aeromonas genus consortia is dominated by A. hydrophila. With the e-beam Pt-deposited electrode and Aeromonas genus consortia in the mediator-less MFC, it is possible to increase the efficiency of electron transfer between the bacteria and the electode. A potential microbial fuel cell was reported from Rhodoferax ferrireducens a potential iron reducing microorganism, isolated from subsurface sediments in Oyster Bay, Virginia, USA. It reduce Fe(III) during the oxidation of glucose to CO_2 transfering electrons directly to the graphite electrodes. The advantages of using Rhodoferax ferrireducens is that it grows at 4 to 30°C (optimum is 25°C), growth is supported in various substrates like ranging from organic acids to simple carbohydrates, this reducing organism is able to generate 80% of electricity efficiency by oxidization of glucose, a best example of mediator less MFC and finally it can reduce all type of sugar unlike family Geobacteraceae which cannot metabolise sugars [86-88]. The cells in mediator less type of MFCs are grown under strict anaerobic conditions in a bicarbonate-buffered defined medium, under N_2/CO_2 (80% and 20%, respectively) at 25°C. For growth on Fe(III), 10 mM Fe(III) chelated with nitrilotriacetic acid (FE(III)-NTA) is provided.

A company Lebone solutions which is a startup based in Cambridge is bringing fuel cells to Africa so that poor people can get more help because they generate such a small amount of power that is not sufficient to charge electronic devices so people of Africa can use it as they are now in off the grid. In some areas of Africa, a small amount of energy is enough for a few hours of lamp light in the evening, or for charging the cell phones. This project was headed by Harvard University alumini and current students from African country. With the funding from the Harvard Institute for Global Health, a pilot study was successfully completed by the team in Tanzania, where members brought six basic microbial fuel cells and taught residents how to use them by organizing village meetings where Stephen Lwendo et al. explained how to make the fuel cells. Other pioneers from Japan are focusing in generating electricity by using microbial fuel cell batteries from soil and waste water that can be used by Africans to charge mobile phones and light small LED [89-90,1-5]. An amount of 800 million yen funding is raised for this project from by New Energy and Industrial Technology Development Organization (NEDO). In May 2007, the University of Queensland Australia completed a prototype MFC in association with Foster's brewing company. The prototype that is a 10 L design can convert the brewery wastewater into clean water, carbon dioxide and electricity. With the success of prototype plans are made to produce 660 gallon version for the brewery, which is estimated to produce 2 Kw of power. While it is a negligible amount of power the production of clean water is of utmost important to Australia which is experiencing its worst drought in over 100 years.

Despite of the fact that MFCs are very efficient in power generation and have also reached primary level of power target at least in small lab-scale systems, its scaling up is still a big issue. Also the high cost of cation exchange membrane the potential for bio fueling and associated high internal resistance restrain the power generation and limit the practical application of MFCs. In case of phototrophic MFCs the need for artificial illumination exerts extra energy input for the system and thus raises cost [91-93]. One major drawback with MFCs is the start-up time which varies from 4 to 103 days depending on factors like reactor design, inoculums and electrode materials, operating conditions such as substrate used temperature, and external loading. Another impediment in scaling up is lack of buffer capacity of electrolytes. It is also admitted that power output of MFCs is too low in some of the cases. Besides high cost of metal catalyst such as platinum is also used on a cathode which causes a hindrance in its scaling up. Open air bio cathodes can be used as a solution and use of non-platinized cathodes are also suggested. The use of manganese dioxide as an alternative cathode catalyst in MFCs is also recently developed to commercialize the aspect of using MFCs [93-97]. Wastewater from canning of fruits and vegetables, whey waste and wastewater from livestock industry are all potential substrates for MFCs. The effluent from cane molasses are rich in organic load and produced in enormous volume could be a potential substrate for MFCs. Despite of present slow rate of substrate conversion to electricity in MFCs there can be potential application for microbe-electrode technology such as in the form of implanted medical devices using blood sugar as fuel, microbial transistors, circuits and electronic computing devices. Reactions at the bio anode can be directed towards the production of valuable compound from inexpensive substrates. The organic matter in waste can be used to produce PHB (poly hydroxyl butyrate). Carbon dioxide capture and production of other useful compounds in MFCs is another lucrative approach. It is also used for treatment of recalcitrant compounds at the bio anode or cathode side. MFCs performing de nitrification by microorganisms in the cathode using electrons supplied by microorganisms oxidizing acetate or glucose is also reported [98-100].

CONCLUSION

It is genuine that in forthcoming years with the expected improvement in this technology and lower costs, more variety of substrates will be used leading to a sustainable and economical bioenergy. The various substrates that have been used in MFCs for current production and waste treatment are numerous but there is also scope of production or utilization of newer substrates along with improved outputs both in terms of power generation as well as waste treatment. Substrates being used in both MFCs have grown in complexity and strength. Several new substrates can be used under the MFC set ups such as the wastewaters from molasses based distilleries rich in organic matter and produced in large volumes, wastewater from large number of pharmaceutical industry with recalcitrant pollutants, waste plant biomass (agriculture residue) which is burnt at this moment, etc. Other potential ways to use MFC are in areas like desalination, pollution remediation, remote sensing and hydrogen production. The process of removing salt i.e. desalination from sea and brackish water which needs lot of external power to be supplied, an MFC can be used for desalination without the supply of external power. MFCs can be used for generating hydrogen which is an alternative fuel. For hydrogen production, the MFC is supplemented by an external power source so as to get over the energy barrier of converting all organic material into carbon dioxide and hydrogen gas. The standard MFC is changed with both anaerobic chambers and the MFC is supplemented with 0.25 volts of electricity. Hydrogen bubbles are collected from the cathode for use as fuel source. This method of producing hydrogen uses electricity but is very efficient because more than 90% of the protons and electrons generated by the bacteria at the anode are turned into hydrogen gas. Hydrogen produced by conventional process consumes 10 times of more energy. MFCs can also run some low power sensors for collecting data from remote areas. For example, scientists have replaced a traditional wireless thermometer in the Palouse River in Washington with one powered by a MFC. Current is generated by placing the anode in the anaerobic sediment of a river or ocean and placing the cathode in the aerobic water right above the sediment. Anaerobic bacteria growing naturally in the sediment produce the small current is used to charge a capacitor to store energy for whenever the sensor needs it. One major advantage of microbial fuel cell in remote sensing over traditional battery is that the bacteria can reproduce, providing the MFC a longer lifetime than traditional batteries. The sensor thus does not require maintenance for years. Another development in the field of utilizing microbial fuel cells is that we can think of power our house with sewage or can charge our pacemaker with household sewage rather than using conventional source of energy as it is not only eco-friendly but also can increase GDP or gross domestic production of a nation. As the whole world is depended on conventional source of energy this field is emerging to be a reusable, nonconventional and renewable and bio friendly source of energy. By combining MFC with electro dialysis one can overcome the drawbacks of MFCs. A current report from Penn state suggests that this concept generated 0.9 kilowatt-hours of electricity per kilogram of organic waste.

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