

MICROBIAL FUEL CELLS: A NEW DIMENSION OF SUSTAINABLE DEVELOPMENT

Uma Maheswari¹, Juveria Anjum Z.², Adil Pasha N.³ and Geetika Pant^{*4}

Department of Biotechnology, Indian Academy Degree College, Bangalore-560043, India.

* Corresponding Author: Dr. Geetika Pant

Department of Biotechnology, Indian Academy Degree College, Bangalore-560043, India.

Article Received on 07/07/2016

Article Revised on 27/07/2016

Article Accepted on 17/08/2016

ABSTRACT

Bioenergy is a renewable energy that plays an important role in meeting today's ever increasing energy needs. Unlike biofuels, microbial fuel cells (MFCs) convert energy harvested from redox reactions directly into bioelectricity with the help of micro-organisms. Electrons produced by bacteria from their substrates are transferred to the anode and flow to the cathode linked by a conductive material containing a resistor. The anodes of a MFCs behave as bacteria's typical electron acceptor and thus, the movement of the electrons to the cathode of the MFC through a resistor, generate electricity. MFCs as a source of bioenergy production have accelerated the research worldwide and the technical aspects of MFCs have been reviewed extensively. This paper briefly focuses on the working principle of MFC technology, chamber design and construction, future outlook and the key players involved in research of MFC.

KEYWORDS: MFC, bioenergy, electron transport, PEM.

INTRODUCTION

Microbial Fuel Cells (MFCs) is an emerging field that uses bacteria to generate electricity from waste. Production of electrical energy using microorganisms through microbial fuel cells (MFC) is one such renewable and sustainable technology that is considered to be the most efficient^[1,2] and carbon neutral energy sources.^[3] Microbial fuel cells (MFCs) can provide an answer to several of the problems which traditional wastewater treatment faces. They enable the recovery of energy out of the wastewater, while limiting both the energy input and the excess sludge production.^[4] The role of bacteria is, in oxidizing the substrates to produce electricity which makes MFCs an ideal solution for wastewater treatment and domestic energy production.^[5] MFCs can generate power densities as much as 1kW/m³ of reactor volume.^[6]

MFC TECHNOLOGY AND MICROBIAL SYSTEM

A typical microbial fuel cell consists of anode and cathode compartments. In the anode compartment, fuel is oxidized by microorganisms, generating electrons and protons. Electrons are transferred to the cathode compartment through an external electric circuit (multimeter) and the protons are transferred to the cathode compartment through a separator. Electrons and protons are consumed in the cathode compartment, combining with oxygen to form water.

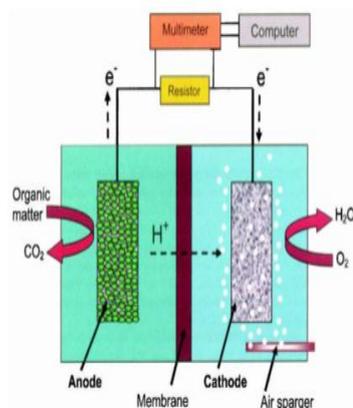
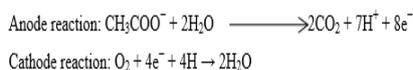


Fig 1: Graphical representation of microbial fuel cells.^[7]

Based on type of bacteria used there can be two types of microbial fuel cells: mediator dependent MFCs and mediator independent MFCs. Such microbial fuel cells are involved in the usage of glucose and methanol from the bio-waste and in turn convert it into hydrogen and food source for bacteria in the system. The electrons obtained from this oxidation are transferred into anode chamber where they get departed through an electrical circuit before entering into cathode region. Here they are transferred to a high potential electron acceptor such as oxygen. As current flows over a potential difference, power is generated directly from microbial fuel by the catalytic activity of bacteria.

The microorganisms have the ability to produce electrochemically active substances that may be either metabolic intermediaries or final products of anaerobic respiration.^[8] When microorganisms consume a substrate such as sugar in aerobic conditions they produce carbon dioxide and water. However when oxygen is not present, they produce carbon dioxide, protons and electrons.^[9]

General reaction



MECHANISMS FOR ELECTRON TRANSPORT TO ELECTRODES

Electricity is generated in microbial fuel cells when the electrons are liberated from the organic matter and are transferred to electrodes which acts as a key mechanism for the efficient conversion of waste to electricity generation. There are four primary mechanisms proposed for microorganisms to transfer electrons to electrodes.

1. INDIRECT ELECTRON TRANSPORT

Researchers in earlier days, used fermentation microorganisms like yeast for power generation in MFCs. It was suggested that reduced products of microbial fermentation were abiotically oxidized at the anode surface to provide electrons. These products might include hydrogen, alcohols or ammonia. However, there were no studies that directly quantified which reduced products were oxidized at the anode. Since fermentation products include organic acids reacting very slowly with electrodes, electricity production was inefficient. Increasing the reactivity of anode with some metabolic end products these electrodes were tend to foul with oxidation products.^[10]

2. DIRECT ELECTRON TRANSFER

Microorganisms might be able to transfer electrons to an electrode surface. Likewise *Shewanella putrefaciens* produced electricity while metabolizing lactate. This was prior to the discovery, discussed above, that *Shewanella* species produce an electron shuttle. It was proposed that electrons might be directly transferred from the cell to the electrode through outer-membrane c-type cytochromes⁴⁸, but there was no direct evidence. Furthermore, it is now recognized that outer-membrane cytochromes are important in electron shuttle reduction in *Shewanella*.^[11] This demonstrates the potential for microbial cultures to generate electricity and have greatly advanced understanding in this field. Furthermore, microbial growth that is fuelled by the generation of energy derived from electron transfer to electrodes has not been shown, which is an important consideration in the long-term sustainability of microbial fuel cells.

3. ELECTRON TRANSPORT BY ARTIFICIAL MEDIATORS

In this mechanism electrons are transported by artificial mediators, also referred to as electron shuttles. This

chemical materials make the possibility for microorganisms to generate reduced products that are more electrochemically active than most fermentation products. These artificial mediators 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. Mediators are important in MFCs 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.^[12] Artificial mediators includes thionine, benzylviologen, 2,6-dichlorophenolindophenol, 2-hydroxy-1, 4-naphthoquinone and various phenazines, phenothiazine, phenoxazines, iron chelates and neutral red. Neutral red was considered to be one of the most effective mediators that can accept electrons from NADH and can be enzymatically reduced by hydrogenase, and possibly formate dehydrogenase^[13, 14 & 15]. For efficient electron transportation the mediators should be able to cross the cell membrane easily, able to grab electrons from the electron carriers of the electron transport chains, should possess a high electrode reaction rate, should have a good solubility in the anolyte, non-biodegradable and non-toxic to microbes and cost effective.

4. ELECTRON TRANSPORT BY MICROORGANISM'S OWN MEDIATOR

Some microorganisms can produce their own mediators to promote extracellular electron transfer. Organisms such as *Geothrix fermentans*^[16] and *Pseudomonas* species also produce electron shuttles.^[11] It is expensive to biosynthesize an artificial mediators and therefore an electron shuttle must be recycled many times in order to recoup this energy investment. Electron shuttles were produced in a microbial fuel cell that was sequentially fed glucose over time, but without substantial medium replacement.^[17] *Pseudomonas* species isolated from this fuel cell and *Pseudomonas aeruginosa*, produce phenazine electron shuttles that could aid in electron transfer to electrodes.^[16]

TYPES OF MFC DESIGNS

There are mainly 3 types of MFCs sharing similar operating principle and they were operated under various conditions mainly to increase power output and performance.

a. Double chamber MFC

It is the most widely used MFC design which consists of two compartments with anode and cathode inturn separated by ion exchange membrane which allows transfer of protons across to the cathode and prevents the diffusion of cathodic electrolyte to the anode. Two-chamber MFCs can be further classified according to the different shapes of the two chambers.^[18] The typical systems are salt bridge MFC, cylindrical MFC, rectangular and flat MFC, miniature MFC and up-flow tubular MFC (Fig 2). But the function of these designs in

producing electricity is found to be less due to their complexity, high internal resistance and electrode based losses.^[18,19,20]

b. Single chamber MFC

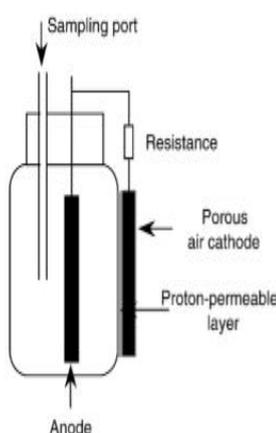
One-chamber MFCs typically possess only an anode chamber without aeration in a cathode chamber. In the typical one-chamber MFC, the anode and cathode electrodes are placed on either side in a system. A flat plate is put against the anode and one side of the cathode is exposed to air directly while the other side faces to water.^[21] If the anode is closer to the cathode, it reduces internal ohmic resistance by avoiding the use of catholyte as a result of combining two chambers and thus increases the power density.^[22] Compared to the double chambered MFC, it offers simple, cost effective design and produces power in a more efficient way.^[23] However, in the membrane-less configuration, microbial contamination and back diffusion of oxygen from cathode to anode without PEM are the major drawbacks.^[24]

c. Multi-chamber/stacked MFC systems

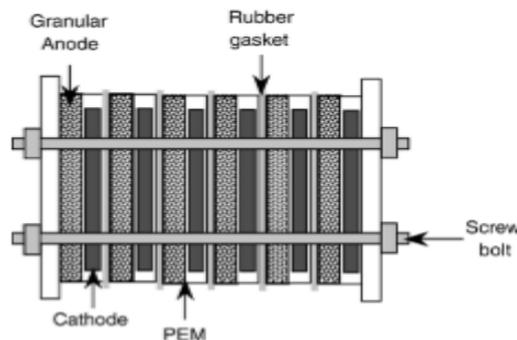
To increase the overall system voltage or current, MFCs can be connected in series or parallel as a stacked system. Connecting several MFCs in parallel adds the current, while one common voltage applied to each cell. In case several MFCs are connected in series, the voltage is added. Therefore, any desired current or voltage could be obtained by parallel and series stacking the appropriate number of MFCs. Due to higher electrochemical reaction rate, a parallel connection can generate more energy than a series connection when operated at the same volumetric flow but is prone to higher short circuiting compared to a series connection.^[25]



a. Two chamber MFC



b. One chambered MFC



c. Stacked MFC

Fig 2: Examples of different MFC configurations.^[26]

❖ **MATERIALS USED IN MFC**

a. Electrode Material

There are different types of electrode material used for increasing the efficiency for the MFC. Platinum and Platinum black electrodes are superior to graphite, graphite felt and carbon-cloth electrodes for both anode and cathode constructions. A current of 2–4 mA could be achieved with platinumized carbon-cloth anode in an agitated anaerobic culture of *E. coli* using a standard glucose medium at 0.55 mmol/L. Pt also has a higher catalytic activity with regard to oxygen than graphite materials.^[14] Alternate catalysts for platinum include ferric iron, manganese oxides, iron and cobalt based compounds. Electrodes can be replaced if they are corroded or saturated and it doesn't affect the conditions much if the microbes are non-film making and are present in liquid anolyte.

2. pH Buffer and Electrolyte

In MFC chamber, pH difference will be seen between anodic and cathodic chamber in the absence of buffer solution but theoretically there will be no pH shift since 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 latter transport through the membrane is slower than its production rate in and its consumption rate in the anode and cathode chambers respectively at initial stage of MFC operation.^[27] Thus brings a pH difference leading to proton diffusion from anode to cathode system and thereby attains the form of equilibrium in system. Addition of NaCl to MFCs improved the power output because NaCl has the capacity in enhancing anolyte and the catholyte conductivity.

3. PEM system

The Proton exchange system acts as a permeable membrane for the transfer of protons between anodic and cathodic chamber. Nafion (DuPont, Wilmington, Delaware) is most popular because of its highly selective permeability of protons. The power output depends on the ratio of PEM surface area to system volume. As the surface area of PEM increases, there is a decrease in the internal resistance created in MFCs.

4. Substrate in MFC

Substrates provide energy to the microbes present in the MFCs, influencing with the power density and coulombic efficiency (current efficiency- the efficiency with which electrons are transferred in a system facilitating an electrochemical reaction) of MFCs. The composition, concentration and type of the substrate also affect the microbial community and power production.^[28,29,30] Substrates like carbohydrates, proteins, volatile acids, cellulose and wastewater have been used as feed in MFC studies. Acetate is the best used substrate due to its efficiency in microbial conversions like fermentations and methanogenesis which leads to high power output and coulombic efficiency.^[30]

APPLICATIONS OF MFCs: It has a very wide range of application in various fields including:

- **Electricity generation:** The most important application of microbial fuel cells is the generation of electricity from the organic waste with the help of micro-organisms which has the ability in transferring electrons under anaerobic conditions.

Electricity obtained can be utilized mostly in rural sector and urban sectors. Though till now the efficiency of electricity generation via fuel cells is found to be low in small scale but usage in large scale can yield better efficiency. These have conversion efficiency of fuel to electricity of an order of 70% and above. Higher electricity recovery of 80% to 97% have been reported by.^[31,32,33] The best way to utilize is to store the electricity in rechargeable battery.

- **Bio hydrogen production**

The production of Biohydrogen at Cathode of MFCs were previously reported in some of the studies. Even though the process is not thermodynamically feasible but it can overcome by increasing anodic potential with the additional voltage of 0.2V and complete removal of oxygen from the cathodic chamber. A potential as low as 110 mV can produce hydrogen which is far less than the 1210 mV required to break water to hydrogen and oxygen via electrolysis.^[34] Thus apart from producing electricity, MFCs were adjusted to harvest bio hydrogen and hydrogen gas. Therefore MFCs provide renewable hydrogen source in order to face a demand in hydrogen economy.

- **Wastewater treatment**

Generation of electricity and simultaneous treatment of waste water is one of the most beneficial applications in MFC. Solid wastes were reduced by completely breaking down most of the acetate and carbon compounds to CO₂ and water. Meanwhile electricity produced was used to aerate the sludge. Therefore it can be considered as one of the self-powered treatment facility. The up flow mode MFCs and Single chambered like constructions are favoured because of large scale implementation.^[13,35]

Huge amount of excess sludge are produced in waste water treatment plant which is then converted to biogas by means of microbial fuel cells with the help of anaerobic bacteria. They enable the recovery of energy out of the wastewater, while limiting both the energy input and the excess sludge production.

- **Bioremediation**

Bioremediation using electrodes as electron donors has several advantages over traditional methods including positive selection of bacterial strains and reduced competition for electron donor.^[36] Current production is not only the major advantage, but wastewater treatment or bioremediation using a cathode or anode maybe much more promising than the electrical production of the MFC itself.

- **Biosensors for pollution analysis**

MFCs with anaerobic consortium could be used as a biosensor for on line monitoring of organic matter.^[37] *Shewanella* species acts as a sensor in quantifying BOD in waste water but most of them are not suitable for online monitoring in controlling biological waste water processes. A linear correlation between coulombic yield of MFC and strength of organic matter in waste water makes MFC a possible BOD sensor.^[38,39] This sensor technology is applied in detecting various compounds acting as an electron donor in electricity generation as aromatic compounds.

- **Other applications**

Low power wireless systems can also be powered with MFCs. There has been reported study of using the MFC to utilize the body glucose to power implanted medical devices.^[40] Robotics has also high usage of MFCs for sustaining self-sustainable autonomous robots.

LIMITATIONS IN MFCs

The major limitation of MFCs were found to be its low power density. The current generation is only 14mA, which could power only small devices.^[2] By using similar biocatalyst and substrate showed differences in the power density.^[24] The power obtained from MFCs is about 300 Wm⁻³ which is low for commercial applications.^[41] The another limitation of MFCs is that it will not work out at extreme low temperature due to the fact that microbial reactions get slow at low temperature.^[18]

FUTURE OUTLOOK IN MFCs

MFCs were considered to be one of the most evident technologies in bioelectricity generation and waste water treatment. Discovery of new organisms that can directly transfer electrons to or from an electrode might be exploited to remediate polluted waters or soils while concurrently generating electrical power. More fundamental studies might lead to an understanding of which proteins and cellular structures are responsible for electron transport across the cell membrane. Higher power densities were achieved by using efficient MFC

designs with cost effective materials. In the long term more dilute substrates, such as domestic sewage, could be treated with MFCs, decreasing society's need to invest substantial amounts of energy in their treatment. A varied array of alternative applications could also emerge, ranging from biosensor development and sustained energy generation from the seafloor, to bio-batteries operating on various biodegradable fuels.^[7]

CONCLUSIONS

MFCs is the promising technology in generation of electricity from organic waste using anode respiring bacteria. The discovery and usage of new anodophilic microbes that vastly enhance the electron transport rate from the biofilm covering an anode to the anode are much needed to improve the power density output in MFCs. At present, microbial fuel cells are not commonly considered a part of the energy portfolio for the future, i.e., microbial fuel technology is not yet sufficiently well developed to produce substantial quantities of power in a cost-effective manner. Further development of MFC applications, a greater focus on understanding the microbial processes in MFC systems is required and thus can be made available for commercialization.

REFERENCES

- HaoYu, E., Cheng, S., Scott, K. and Logan, B. Microbial fuel cell performance with non-Pt cathode catalyst. *Journal of power sources*, 2007; 171: 275-281.
- Salgado, C.A. Microbial fuel cells powered by geobacter sulfurreducens. *Basic Biotech*, 2009; 5, 5: 1.
- Lovely DR. Microbial fuel cells: novel microbial physiologies and engineering approaches. *Curr Opin Biotech*. 2006; 17: 327–32.
- Rabaey K, Verstraete W. Microbial fuel cells: novel biotechnology for energy generation. *Trends Biotechnol*. 2005; 6: 291–298.
- Schwartz, K. Microbial fuel cells: Design elements and application of a novel renewable energy sources. *Basic biotech. ells. Enzyme and Microbial Technology*, 2007; 47: 179-188.
- Logan BE, Murano C, Scott K, Gray ND, Head IM. Electricity generation from cysteine in a microbial fuel cell. *Water Res*. 2005; 39: 942–52.
- Logan, B.E. *Microbial fuel cells*. Wiley-Interscience. 2008; ISBN: 978-0-470-23948-3.
- Katz E, Shipway A N, Wilner I. in. Vielstich, W., Lamm, A. & Gasteiger, H.A eds. *Handook of Fuel Cells-Fundamentals, Technology, and Application*, 2003; 355–382.
- Bennetto, H. P., *Electricity Generation by Micro-organisms*, *Biotechnology Education*, 1990; 1(4): 163-168.
- Yan-ping, X.M.-y.S. Preliminary Study on E. coli Microbial Fuel Cell and On-electrode Taming of the Biocatalyst[J]. *Chinese Journal of Process Engineering*, 2008; 8: 179-1184.
- Nevin K. P, Lovley D. R. Mechanisms for accessing insoluble Fe (III) oxide during dissimilatory Fe (III) reduction by *Geothrix fermentans*. *Appl. Environ. Microbiol*. 2002; 68: 2294–2299.
- Davis F, Higon SPJ. Biofuel cells—recent advances and applications. *Biosens Bioelectron*, 2007; 22: 1224–35.
- Park D.-H. Zeikus J. G. Improved fuel cell and electrode designs for producing electricity from microbial degradation. *Biotechnol. Bioeng*. 2003; 81: 348–355.
- Schroder U, Niessen J, Scholz F. A generation of microbial fuel cells with current outputs boosted by more than one order of magnitude. *Angew. Chem. Int. Ed. Engl*. 2003; 42: 2880–2883.
- McKinlay J. B, Zeikus J. G. Extracellular iron reduction is mediated in part by neutral red and hydrogenase in *Escherichia coli*. *Appl. Environ. Microbiol*. 2004; 70: 4367–4374.
- Newman D. K, Kolter. A role for excreted quinones in extracellular electron transfer. *Nature*, 2000; 405: 94–97.
- Lies D. P. et al. *Shewnaella oneidensis* MR-1 uses overlapping pathways for iron reduction at a distance and by direct contact under conditions relevant for biofilms. *Appl. Environ. Microbiol*. 2005; 71: 4414–4426.
- Du, Z., Li, H. and Gu, T. A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy. *Biotechnology Advances*, 2007; 25: 464-482.
- Logan. E, Regan. M. Microbial challenges and microbial fuel cells application. *Environmental Science & Technology*. 2006; 40: 5172-5180.
- Nwogu, N.g. Microbial fuel cells and parameters affecting performance when generating electricity. *Basic Biotech*, 2007; 73-79.
- Liu H, Grot S, Logan BE. Electrochemically assisted microbial production of hydrogen from acetate. *Environ. Sci. Technol.*, 2005; 4317–4320
- Liang, J.B., Chen, Y.Q., Lan, C.Y., Tam, N., Zan, Q.J., Huang, L.N., Recovery of novel bacterial diversity from mangrove sediment. *Mar. Biol.*, 2007; 150(5): 739-747.
- Du, Z., Li, H. and Gu, T. A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy. *Biotechnology Advances*, 2007; 25: 464-482.
- Kim, K.-J.C., Mi-Jin Choi (2008). *Microbial fuel cells: Recent advances, bacterial communities and application beyond electricity generation ENVIRONMENTAL ENGINEERING RESEARCH* 1.
- Aelterman, P., Rabaey, K., Pham, H.T., Boon, N., and Verstraete, W. Continuous Electricity Generation at High Voltages and Currents Using Stacked Microbial Fuel Cells. *Environmental Science & Technology*, 2006; 40: 3388-3394.
- Zhuwei, Du A., H.A. Li and Gu B. Tingyue A state of the art review on microbial fuel cells: A

- promising technology for wastewater treatment and bioenergy. *Biotechnol. Advan.*, 2007; 25: 464-468.
27. Gil GC, Chang IS, Kim BH, Kim M, Jang JY, Park HS, et al. Operational parameters affecting the performance of a mediatorless microbial fuel cell. *Biosens Bioelectron.* 2003; 18: 327-334.
 28. Chang I S, Moon H, Jang J K & Kim B H. Improvement of a microbial fuel cell performance as a BOD sensor using respiratory inhibitors, *Biosens Bioelectron*, 2005; 20: 1856-1859.
 29. Logan, B., Cheng, S. Increasing power generation for scaling up single-chamber air cathode microbial fuel cells. *Bio resource technology*, 2011; 102: 4468-4473.
 30. Pant Deepak, Van Bogaert, Gilbert, Diels, Ludo, Vanbroekhoven, Karolien, "A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production ", *Bioresource Technology*. 2010; 101: 1533-1543.
 31. Chaudhuri, S.K. and Lovley, D.R. Electricity generation by direct oxidation of glucose in mediatorless microbial fuel cells. *Nature biotechnology*, 2003; 21: 1229-1232.
 32. Lovley DR. Bug juice: harvesting electricity with microorganisms. *Nat Rev/Microbiol.* 2006; 4: 497-508.
 33. Oh SE, Min B, Logan BE. Cathode performance as a factor in electricity generation in microbial fuel cells. *Environ Sci Technol.*, 2004; 38: 4900-4944.
 34. Logan B.E. Hydrogen and electricity production from a food processing wastewater using fermentation and microbial fuel cell technologies. *Water Res.* 2005; 39: 4673-4682.
 35. D.Hyun Park and J. Gregory Zeikus. Electricity generation in microbial fuel cells using neutral red as an electrophore. *Applied and environmental microbiology.* 2000; 66: 1292-1297.
 36. Gregory KB, Lovley DR: Remediation and recovery of uranium from contaminated subsurface environments with electrodes. *Environment science technology*, 2005; 39: 8943-8947.
 37. Kumlaghan A, Liu J, Thavarungkal P, Kanatharana P & Mattiasson B, Microbial fuel cell-based biosensor for fast analysis of biodegradable organic matter, *Biosens bioelectron*, 2007; 22: 2939-2944.
 38. Kim H J, Hyun M S, Chang I S & Kim B H, A microbial fuel cell type lactate biosensor using a metal-reducing bacterium, *shewanella putrefaciens*, *J Microbiol Biotechnol*, 1999; 9: 365-367.
 39. Cheng, S., Liu, H. and Logan, B.E. Power Densities Using Different Cathode Catalysts (Pt and CoTMPP) and Polymer Binders (Nafion and PTFE) in Single Chamber Microbial Fuel Cells. *Environmental Science & Technology*, 2005; 40: 364-369.
 40. Ieropoulos I, Greenman J, Melhuish C. Imitation metabolism: energy autonomy in biologically inspired robots. *Proceedings of the 2nd International Symposium on Imitation of Animals and Artifacts*, 2003; 191-194.
 41. Abhijith Bhusare, Rahul Ghalme, Vrajesh Modi. Design of Microbial Fuel cell: A green technology of waste water treatment with Bio electricity Generation. *Biotech for biofuels.*, 2009; 24: 2-7.