Indian Journal of
Advances in Chemical Science

Review Article

Recent Developments and Challenges in Microbial Fuel Cell's for Bioelectricity Production

Devanand Maski[1], J. Neeraja[1], Siddaramaiah[2]

[1]Department of Renewable Energy Engineering, College of Agricultural Engineering, University of Agricultural Sciences, Raichur, Karnataka, India, [2]Department of Polymer Science & Technology, Sri Jayachamarajendra College of Engineering, JSS Science & Technology University, Mysuru, Karnataka, India

ABSTRACT

With ever-increasing demand in the energy needs along with the growing population, there is a greater thrust for the sustainable energy production. Recently, there is a growing interest in microbial fuel cell (MFC) technology across the world for the production of bioenergy from biowastes. An MFC is a device that converts chemical energy from the substrate into electrical energy by the action of microorganisms. A typical MFC consists of anode and cathode chambers, physically separated by a proton-exchange membrane, and substrate. Anode chamber is made completely anaerobic, whereas cathode chamber is made aerobic. It uses an active microorganism as a biocatalyst in an anaerobic anode compartment for the production of bioelectricity. The energy conversion efficiency in MFC is far better than conventional fossil fuels, which is around 60%. MFCs operate well in mild conditions, 20–40°C and also at a pH of 7. Mainly the MFCs can be used to generate bioelectricity, to produce biohydrogen, used in wastewater treatment, and also used in biosensors. Recently, the feasibility of using composite metal-carbon, metal-polymer, polymer-carbon, polymer-polymer, and carbon-carbon materials in MFCs has been investigated. Some of the materials such as carbon nanotube (CNT)/polyaniline composite, and polypyrrole-coated CNTs composite for anode play a major role in producing maximum power density, maximum current density, and max voltage. This paper mainly deals with the recent developments and their interrelated challenges including the use of polymers in MFCs for producing bioelectricity from various biowastes.

Key words: Microbial fuel cell, Applications of microbial fuel cell, Bioelectricity production, Waste to energy, Polymers in microbial fuel cell.

1. INTRODUCTION

Fossil fuels (coal, petrol, and natural gas) contribute more than 80% of the world total energy. Excessive consumption and overdependence on fossil fuels have made them to deplete completely in near coming future and also negatively influence the nature owing to the emission of greenhouse gases as well as severely imperilled human life through its drastic aftermaths such as global warming and atmospheric pollution. Currently, petroleum fuels are facing the challenges of unreliability due to global price fluctuations, and stringent environmental regulations have also been set to reduce the contribution of fossil fuels to emission of the greenhouse gases in the process of addressing climate change [1].

Hence, to find a piece of cogent solution for the challenges caused by fossil fuels, one of the clean, reliable, and efficient latterly proposed alternative energy sources is fuel cell (FC) [1]. An FC is a device that converts chemical energy from fuel into electricity by the action of catalyst. Microbial fuel cell (MFC) generates electricity from organic substrate using microorganism as a catalyst. Hence, the FCs are also referred as an alternative renewable energy source. In actual fact, FC is of plethora advantages over other kinds of energy sources, for example, no greenhouse gas emissions except CO_2, higher energy conversion efficiency, no existence of mobile parts, as a result, lack of sonic pollution, and so forth. In contrast, high cost and high mass generation are the only disadvantages of these new energy sources.

2. MFC

An MFC is a device that converts chemical energy from the organic substrate into electrical energy by the action of microorganisms. Hence, MFC is also called as biological FC, and the electricity which is generated is called as bioelectricity. These cells are constructed using an anode and cathode. Most MFCs contain a membrane to separate the compartments of the anode (where oxidation takes place) and the cathode (where reduction takes place). Hence, the anode acts as an electron donor, whereas cathode acts as an electron acceptor. The electrons produced during oxidation are transferred directly to an electrode or to a redox mediator species. The electron flux is moved to the cathode. The charge balance of the system is compensated by ionic movement inside the cell, usually across an ionic membrane (Figure 1).

***Corresponding author:**
E-mail: dmaski@gmail.com

ISSN NO: 2320-0898 (p); 2320-0928 (e)
DOI: 10.22607/IJACS.2018.603002

Received: 28th March 2018;
Revised: 02nd May 2018;
Accepted: 02nd June 2018

3. CONSTRUCTION OF MFC

A typical MFC is made of the following core components such as: (a) Anode, (b) cathode, (c) proton-exchange membrane (PEM), and (d) substrate. Properties of core components are briefly described below.

3.1. Properties of Anode

Anodic material must be conductive, biocompatible, and chemically stable in the substrate. The most versatile material used for the construction of anode is carbon, available as compact graphite plates, rods, or granules. The carbon material is also available as fibrous material (felt, cloth, paper, fiber, and foam) and as glassy carbon. So among them, the simplest material for anode construction is graphite rods as they are relatively inexpensive and easy to handle and have a defined surface area [1]. Effect of different anodes on MFC performance is tabulated in Table 1.

3.2. Properties of Cathode

The choice of the cathode material greatly affects the performance of MFC. The most popular material used for the construction of cathode is ferricyanide. The greatest advantage of ferricyanide is the low overpotential and its greatest disadvantage is the insufficient reduction. The other alternative material used for cathode construction is carbon, available as compact graphite plates, rods, or granules [1]. Effect of different cathodes on MFC performances is presented in Table 2.

3.3. Properties of PEM

The PEM must be impermeable to chemicals such as oxygen, substrate, and other ions except H_2 ions. The most commonly used material for the construction of PEM is Nafion [1]. Nafion is a sulfonated tetrafluoroethylene copolymer discovered in the late 1960 by Walther Grot of DuPont de Nemours. It is the first class of synthetic polymers with ionic properties which are called ionomers. MFCs are typically designed as a two-chamber system with the bacteria in the anode chamber separated from the cathode chamber by a polymeric PEM [21].

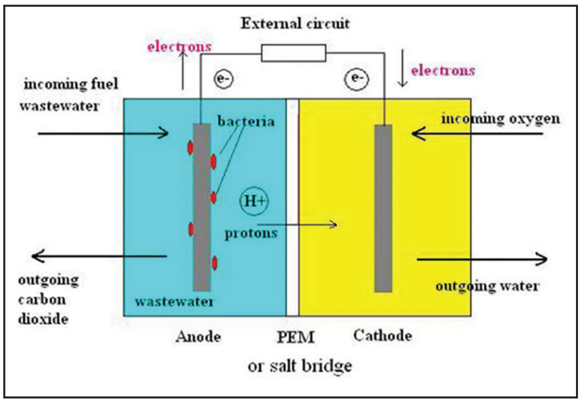

Figure 1: Representative diagram of microbial fuel cell.

3.4. Properties of Substrate

The substrate is the most significant component is MFC because it serves as energy source for microorganisms present in it. It must essentially harbor optimum populations of microbial colonies that effectively bring about greater movement of electrons in the circuit. It must also be flexible and adaptable to changes made in any ancillary components added to the substrate to modify the medium, ecosystem to favor the growth of specific populations that are found to produce better result in the MFC. Wastewater harbors have varied range of microorganisms, which include aerobes and anaerobes. Essentially for aerobes present in wastewater should have a good chemical oxygen demand value because more the oxygen for microbes, then more the flow of electrons. Substrates can be broadly classified into three types, namely: (a) Non-fermentable substrates such as acetate and butyrate; (b) fermentable substrates such as glucose, sucrose, and xylose; and (c) complex substrates such as domestic, municipal, and industrial wastewater.

4. ROLE OF POLYMER MATERIALS IN MFC

The major drawback in MFCs are low power density and hence to overcome the issue, researchers have recently identified new class of nano-materials called carbon nano-tubes (CNTs) coated with polymers including polypyrrole (PPy) and polyaniline (PANI) which are used as anode material.

4.1. CNT

A CNT is a tube-shaped material, made of carbon, having a diameter measuring on the nanometer scale. CNTs are unique because the bonding between the atoms is very strong, and the tubes can have extreme aspect ratios. They have many structures, differing in length, thickness, and number of layers. The characteristics of CNT can be different depending on graphene sheet has rolled up to form the tube causing it to act either metallic or as a semiconductor [22].

4.2. Anode Modification using PPy-coated CNTs

Recently, conducting polymer composites such as PPy-coated CNTs have significantly higher electrical conductivity than that of CNTs. Its electrical conductivity ranges from 2 to 100 S/cm. Among all the

Table 1: Effect of different anodes on MFC performances [1].

Anode	Bacteria	MFC design	Max. power density (mW/m^2)	References
Carbon paper	*Geobacter* spp. (Firmicutes)	Two-chamber	40.3±3.9	[2,3]
Graphite	*Geobacter* spp. (Firmicutes)	Two-chamber	16	[4]
Carbon paper	*G. sulfurreducens*	Two-chamber	48.4±0.3	[2,3]
Carbon paper	*Gammaproteo* and *Shewanella affinis*	Two-chamber	36	[5,6]
Graphite	*Deltaproteobacterium*	Two-chamber	14	[7,8]
Non-corroding graphite	*Desulfuromonas* spp.	Two-chamber	25.4–26.6	[9,10]
Graphite with Mn4+	*Escherichia coli*	Single chamber	91	[11,12]
Platinum and Polyaniline comodified	*Escherichia coli*	Single chamber	6000	[13,14]
Composite electrode (CCN-PPy)	*Escherichia coli*	Single chamber	228	[15,16]

MFC: Microbial fuel cell

Table 2: Effect of different cathodes on MFC performance [1].

Cathode	Max. power density	Max. current density	Max. voltage (mV)	References
ACFF	315 mW/m^2	1.67×10^{-3} mA/m^2	679	[17]
Air-cathode with graphite	283 mW/m^2	1210 mA/m^2	440	[15]
Carbon felt	77 mW/m^2	6×10^{-3} mA/m^2	575	[17]
Plain carbon	67 mW/m^2	1.5 mA/m^2	598	[17]
Pt-coated carbon paper	0.3 W/m^3	4.69 mA/m^2	644	[17]
Tubular ACFF	784 mW/m^2	3.17 A/m^2	716	[17]
ACFF granules (1 cm)	667 W/m^3	3.34 A/m^2	658	[17]
Biocathode	19.53 W/m^3	41.78 A/m^3	432	[18]
Graphite felt	539 mW/m^2	3145 mA/m^2	742.3	[19]
Air-cathode with Carbon cloth	50 W/m^3	363 A/m^3	710	[20]

MFC: Microbial fuel cell, ACFF: Activated carbon fiber felt

conducting polymers studied up to date, PPy can be considered as one of the most attractive materials due to its excellent conductivity, stability, and biocompatibility even in neutral pH solution [23].

4.3. Anode Modification using PANI-coated CNTs

Recently, conductive polymers have attracted intensive research in different electrochemical devices. PANI is an important conducting polymer due to its relatively facile processability and environmental stability. Conductive PANI used in the MFC not only provides a protective function for bacteria but also directly contributes to electrocatalysis to give a high current density. On the other hand, the lower conductivity and poor electron transfer of PANI limit its application in MFCs [24].

5. CONCLUSIONS

The demands of energy in the world continue to accelerate and which triggers the global energy crisis and environmental pollution. Recently, great attentions have been paid to MFCs due to their mild operating conditions and using variety of biodegradable substrates as fuel. It has a very significant application in bioelectricity generation and also used to produce biohydrogen, used in wastewater treatment, and biosensors. Besides, the advantages of this technology, it still faces practical barriers such as low power and current density. To overcome this barrier, the researchers have identified new class of nanomaterials called CNTs coated with polymers such as PPy and PANI is used as anode material. Among these two polymers, PPy is considered as one of the most attractive materials due to its excellent conductivity, stability, and biocompatibility even in neutral pH solution compared to PANI. Whereas, PANI gives high current density compared to PPy. However, still, there is a scope for increase in the current density of MFCs by increasing the surface area of anode and also using the genetically modified microorganisms to form highly reducing recombinant strains producing more available electrons at anode.

6. REFERENCES

1. M. Rahimnejad, A. Adhami, S. Darvari, A. Zirepour, S. U. Oh, (2015) Microbial fuel cell as new technology for bioelectricity generation: A review, ***Alexandria Engineering Journal*, 54(3):** 745-756.
2. C. Bettin, (2006) ***Applicability and feasibility of incorporating microbial fuel cell technology into implantable biomedical devices, Honours' Undergraduate Thesis submitted to the College of Engineering Honours' Committee***. Hitchcock Hill: College of Engineering, The Ohio State University.
3. S. Jung, J. M. Regan, (2007) Comparison of anode bacterial communities and performance in microbial fuel cells with different electron donors, ***Applied Microbiology and Biotechnology* 77:** 393-402.
4. M. Rahimnejad, N. Mokhtarian, G. Najafpour, W. Daud, A. Ghoreyshi, (2009) Low voltage power generation in a biofuel cell using anaerobic cultures, ***World Applied Science. Journal*, 6:** 1585-1588.
5. M. Zhou, T. Jin, Z. Wu, M. Chi, T. Gu, (2012) Microbial fuel cells for bioenergy and bioproducts. ***Sustainable Bioenergy and Bioproducts.*** London: Springer. p. 131-171.
6. N. D. Grayc, I. M. Headc, (2005) Electricity generation from cysteine in a microbial fuel cell, ***Water Research*, 39:** 942-952.
7. M. Zhou, J. Yang, W. Wang, T. Jin, D. J. Hassett, T. Gu, (2013) Bioelectrochemistry of microbial fuel cells and their potential applications in bioenergy. ***Bioenergy Research: Advanced Applied***. Amsterdam: Elsevier. p. 131-153.
8. D. R. Bond, D. E. Holmes, L. M. Tender, D. R. Lovley, (2002) Electrode-reducing microorganisms that harvest energy from marine sediments, ***Science*, 295:** 483-485.
9. G. C. Gil, I. S. Chang, B. H. Kim, M. Kim, J. K. Jang, H. S. Park, H. J. Kim, (2003) Operational parameters affecting the performance of a mediator-less microbial fuel cell, ***Biosensors and Bioelectronics*, 18:** 327-334.
10. L. M. Tender, C. E. Reimers, H. A. Stecher, D. E. Holmes, D. R. Bond, D. A. Lowy, K. Pilobello, S. J. Fertig, D. R. Lovley, (2002) Harnessing microbially generated power on the seafloor, ***Nature Biotechnology*, 20:** 821-825.
11. K. P. Nevin, H. Richter, S. F. Covalla, J. P. Johnson, T. L. Woodard, A. L. Orloff, H. Jia, Z. Zhang, D. R. Lovley, (2008) Power output and columbic efficiencies from biofilms of Geobacter sulfurreducens comparable to mixed community microbial fuel cells, ***Environmental Microbiology*, 10:** 2505-2514.
12. D. H. Park, J. D. Zeikus, (2002) Improved fuel cell and electrode designs for producing electricity from microbial degradation, ***Biotechnology. Bioengineering*, 81:** 348-355.
13. A. E. Franks, K. Nevin, (2010) Microbial fuel cells a current review, ***Energies*, 3:** 899-919.
14. U. Schroder, J. Niesen, F. Scholz, (2003) A generation of microbial fuel cells with current outputs boosted by more than one order of magnitude, ***Angewandte Chemie International***

***Edition*, 42:** 2880-2883.
15. M. Rahimnejad, A. A. Ghoreyshi, G. Najafpour, (2011) Power generation from organic substrate in batch and continuous flow microbial fuel cell operations, ***Applied Energy*, 88:** 3999-4004.
16. T. Zhang, Y. Zeng, S. Chen, X. Ai, H. Yang, (2007) Improved performances of *E. coli*-catalyzed microbial fuel cells with composite graphite/PTFE anodes, ***Electrochemical Communication*, 9:** 349-353.
17. Q. Deng, X. Li, J. Zuo, A. Ling, B. E. Logan, (2009) Power generation using an activated carbon fiber felt cathode in an upflow microbial fuel cell, ***Journal of Power Sources*, 195:** 1130-1135.
18. G. W. Chen, S. J. Choi, T. H. Lee, G.Y. Lee, J. H. Cha, C. W. Kim, (2008) Application of biocathode in microbial fuel cells: Cell performance and microbial community, ***Applied Microbiology Biotechnology,* 79:** 379-388.
19. A, T. Heijne, H. V. M. Hamelers, V. D. Wilde, R. A. Rozendal, C, J. N. Buisman, (2006) A bipolar membrane combined with ferric iron reduction as an efficient cathode system in microbial fuel cell, ***Environmental Science & Technology,* 40:** 5200-5205.
20. S. You, Q. Zhao, J. Zhang, H. Liu, J. Jiang, S. Zhao, (2008) Increased sustainable electricity generation in up-flow air-cathode microbial fuel cells, ***Biosensors and Bioelectronicsg,* 23:** 1157-1160.
21. S. Gottesfeld, T. A. Zawodzinski, (1997) Polymer electrolyte fuel cell, ***Advanced Electrochemical Science*, 5:** 195-301.
22. Anonymous, (2017) Available from: http://www.nano-science.com. [Last accessed on 2017 Aug 23].
23. Y. Zou, C. Xiang, L. Yang, L. Sun, F. Xu, Z. Cao, (2008) A mediatorless microbial fuel cell using polypyrrole coated carbon nanotubes composite as anode material, ***International Journal of Hydrogen Energy*, 33:** 4856-4862.
24. Y. Qiao, C. M. Li, S. J. Bao, Q. L. Bao, (2007) Carbon nanotube/polyaniline composite as anode material for microbial fuel cells, ***Journal of Power Sources*, 170:** 79-84.

***Bibliographical Sketch**

Dr. Devanand Maski has remarkable professional experience in teaching, research and extension in the field of Agricultural Engineering. He has earned M. Tech. and Ph.D. degrees from Tamil Nadu Agricultural University and Postdoctoral Research Fellow from Kansas State University, USA. Presently, he is working as Assistant Professor in the College of Agricultural Engineering, University of Agricultural Sciences-Raichur. He has authored several papers in reputed international and national journals, conference proceedings, research bulletins, book chapters, reports and popular articles. He has developed, taught, and evaluated various theory courses and laboratory sessions to Postgraduate, Undergraduate, and Diploma students. He is a recipient of three travel grant awards to attend ASABE conferences in USA, Young Scientist Fellowship from DST, Senior Research Fellowship from CSIR, Junior Research Fellowship from ASPEE Foundation. He is a Life Member of the Indian Science Congress Association; Life Member of the Karnataka Vijnyana Parishat; Life Member of the Indian Society of Agricultural Engineers; Life Member of the Karnataka State Agricultural Engineers Association; Member of The Institution of Engineers (India).

Er. Neeraja, J., has earned her B. Tech (Ag. Engg.) degree from the College of Agricultural Engineering, Raichur. She is presently pursuing her Master's degree in the Department of Farm Machinery and Power Engg., in the College of Agricultural Engineering, Raichur from the University of Agricultural Sciences-Raichur, Karnataka.