A Review on Microbial Fuel Cell

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Abstract:

Microbial fuel cell (MFC) is the device which can convert chemical energy stored in the organic compounds to the electrical energy using metabolic activity of microorganism. In MFCs various types of a substrate can be used as fuel. MFCs can treat the wastewater and simultaneously produced electricity. One of the most useful applications of MFC is used as a biosensor which can monitor biological oxygen demand (BOD) of wastewater. The output from the MFCs are low because of that it is not commercialized yet. Current and power output from the MFCs are low at present but it is expected that with improvements in research and technology, the amount of electric current and power will increase. The performance of MFCs affected by selection of Electrode, proton exchange membrane, substrate, operating conditions and cost. This review article presents the recent improvement in the MFC technology so far, that will help to increased current and power output from the MFCs.

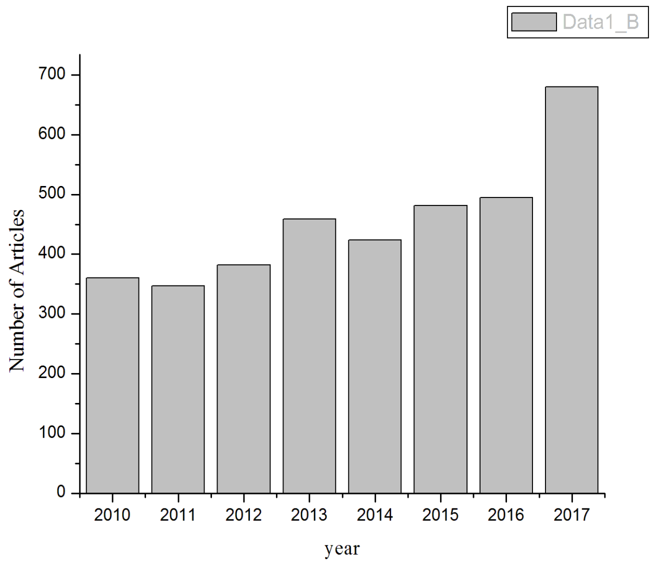
Keywords: Microbial Fuel Cell, Proton Exchange Membrane, Wastewater Treatment, Biosensor. Light

I. Introduction

Past few decades introduces us a variety of alternate energy sources. Some of which are, geothermal energy, wind energy, hydroelectricity, tidal energy, solar energy and many more. still, these energies couldn't fulfill our energy requirements[1]. A similar source of energy invented that is the Microbial Fuel Cell. In1911, Potter developed the first Microbial fuel cell (MFC) [2]. Different types of substrate can be used as feed for bacteria such as glucose, acetate, brewery wastewater etc. in which various types of bacteria are present. Bacteria oxidized the substrate and converted it into electricity through the metabolic activity of the microorganisms. The microbial fuel cell is a renewable and sustainable technology. MFCs can simultaneously treat industrial and domestic wastewater and also generate the electricity but operational cost of MFC is the offset [3]. The current output from the MFCs has increased over the recent years. Bacteria present in the Substrate oxidized the organic compounds and generate the electrons and protons[4]. Generated electrons moved on the surface of anode electrode through nanowires or using mediators and flow through external circuit towards the cathode electrode and protons transfer through proton exchange membrane (PEM), cation exchange membrane(CEM) or salt bridge where proton, electron and electron acceptor (oxygen, Fe_2O_3) combine to produce water[5].

MFC is a device which can be produced energy with low or zero emission of greenhouse gases but it has some drawbacks so that it is not commercialized yet. The reason behind that is microbial fuel cell produced very less amount power output because electrons produced by microbes are not captured by the electrodes[1]. Performance of MFCs can be enhanced using the nanocomposite material as the electrode, using different polymers as proton exchange membrane (PEM) which has highest proton conductivity and cheaper to use, used of inexpensive catalyst which can increased the rate of reaction. This review article gives information about alternate sources which help to increase the current and power density of MFCs and also decreased the cost of MFC.

Fig. 1 shows that 'Google Scholar' search engine shows the number of articles published over 7 year ago (2010-2017) on the Microbial Fuel Cell. Furthermore, the reported electric current output from the MFCs has also increased tremendously over the recent years. More and more researchers are interested to do the research on the microbial fuel cell.



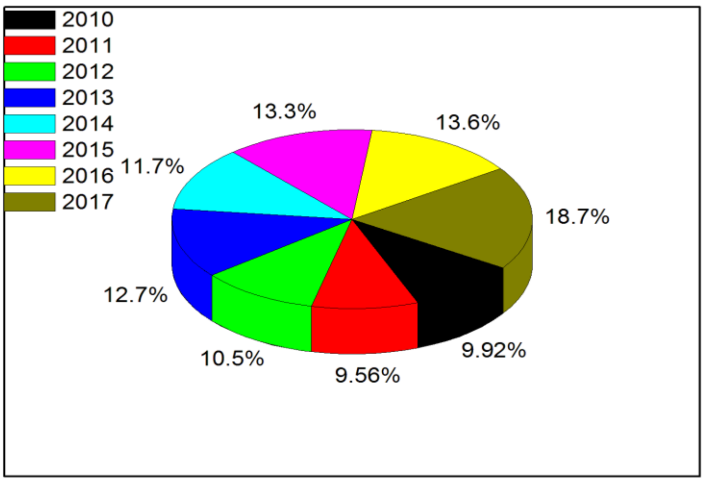


Fig. 1 Representation of the Number of articles published over seven years on MFCs.

II. Microbial Fuel Cell

Li He *et al.* reported that it is very critical part of MFCs is to metabolize substrate and exchange electrons with an electrode using electrochemically active microorganisms. In anode compartment, anaerobic respiring bacteria oxidize organic matter into carbon dioxide as the end product and simultaneously produced electrons and protons. The produced electrons are transferred from anode compartment to the cathode compartment through an external circuit. Generated electrons and protons move through the electrodes to maintain electroneutrality and produced current in mA. The conventional microbial fuel cell is normally half biotic since only the anode side contains electrochemically-active microorganisms while the cathode is abiotic. In cathode, oxygen, ferricyanide, and hydrogen peroxide are primarily used as the terminal electron acceptor. Out of that, oxygen is the most suitable terminal electron acceptor mostly due to its sustainability and availability, especially for the air cathode MFCs. The air-cathode normally consists of the catalyst layer, electrode, and separator. In addition, separator plays a progressively leading role in MFCs as compared with catalytic and electrode materials, which do not only increase the internal resistance but also decreases the MFCs' performances because of that practical MFC is not commercialized yet [6]. To Improve the current and power output from the MFCs biocathode is used, in which bacteria act as a biocatalyst on cheap carbon cathodes. it gives better performance than the abiotic cathode.

III. Design and Operation of MFCs

A typical MFCs consist of the anodic and cathodic chamber which is separated by salt bridge or PEM. There are three types of MFC- single chamber, dual chamber and stack MFCs. Single chamber MFCs are cost effective and have a simple design. They have only an anodic chamber, no need to have the cathodic chamber. In single chamber MFCs, the anode is attached to porous air-cathode that is exposed directly to the air. Protons are transferred from the anolyte solution to the porous air-cathode[7].The anode was made up of carbon paper and the cathode was made-up of rigid carbon paper only without PEM, bonding of PEM or it can be also made up of a flexible carbon-cloth electrode or bonding the PEM on a carbon electrode assembly. Air cathode can be made up of graphite, carbon paper, fibers [7],[8],[9].

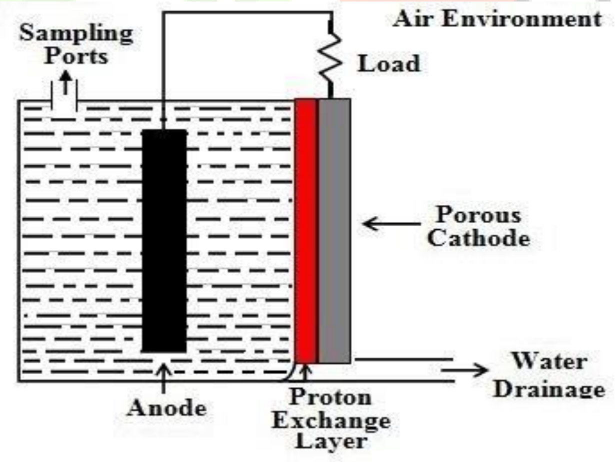


Fig. 2 Schematic diagram of the Single-chamber MFC structure [3],[10],[11].

Dual chamber MFCs also called a two compartment MFCs in which two chambers are connected by the salt bridge or PEM through which protons can flow towards the cathode chamber. It can block the diffusion of oxygen into the anode chamber. Dual chamber MFCs are used often in batch mode and for laboratory research because of complex design. It is very difficult to scale up.

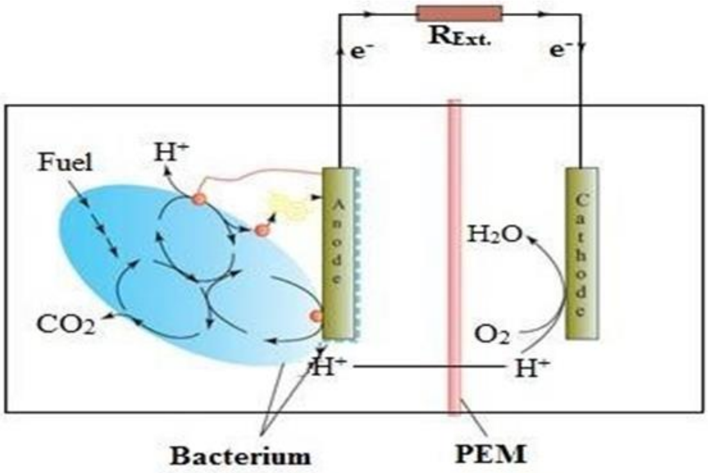


Fig. 3 Schematic diagram of the dual-chamber MFC structure (represents the mediator) [12],[13].

Stack MFCs in which various MFCs are connected in series or in parallel to enhance voltage or current output. Coulombic efficiency means how many electrons produced from the electron-rich substrates such as acetate and transferred towards the electrodes. There are two types of stack MFCs, one with the parallel type of stack MFCs and another is the series type of stack MFCs. The parallel connection gives six times higher efficiency than series connection was operated at the same volumetric flow rate. The chemical reaction rate for the parallel type of stack MFCs is higher than the series type of stack MFCs. Therefore, parallel type of stack MFCs are used to remove the Chemical Oxygen Demand (COD) of wastewater [14].

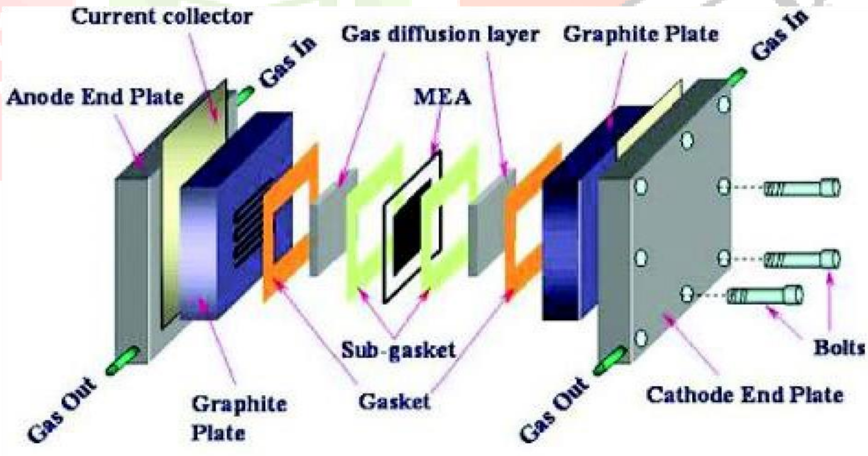


Fig. 4 Schematic of Polymer Electrolyte Membrane Fuel Cell showing different components [15].

IV. Advance Research to Improve the Performance of MFCs

A. Anode material

The anode is the crucial part of MFCs which can act as support for bacteria. The bacteria formed the biofilm on the surface of the anode which can directly transfer electrons to the anode. Basically, nanosize materials provide a large surface area on which biofilm form to a large extent, so that maximum electron produced from the substrate. The substrate used such as carbon nanotube. Commonly used anode materials are carbon paper[16], carbon cloth[17], graphite felt (GF), tungsten carbide[18], graphite foil[19]. Anode materials should be anticorrosive, chemically inert, nontoxic. It should have high electrical conductivity with low resistance, high mechanical strength, toughness such as Stainless steel, conducting polymers, metal oxides, and electrolytes. Following Table I represents the different anode material was used in previous research. Y.Hindatu *et al*. stated that nowadays conventional anode electrode (CAE) materials functionalized with nanostructure material such as carbon nanotube (CNT)[14],[15], graphene (GR)[22],[23] and conducting polymers such as polyaniline (PANI)[24] and Poly-N-isopropylacrylamide (PNIPAm)[25]. Using Chemical Vapor Deposition method graphite felt was modified with carbon nanofiber which gave maximum current density than bare graphite felt used as anode[26].

B. Cathode material

Aerobic biocathode are an excellent and stable alternative for the chemical catalyst used in oxidation-reduction reaction. Strike *et al.* made a bio-cathode using cation exchange membrane and graphite felt. The newly found the cathodic bio-electrode achieved the power density value of 3.1 mW m^{-2} with a 384Ω, in the same way, the anodic bio-cathode produces the maximum power density value of 41 mW m^{-2} with a 102 Ω internal resistance[27]. Cultured group of Gammaproteobacteria is gram negative bacteria responsible for the oxygen reduction activity. They developed the biofilm on the cathode surface called as cathodic bio-electrode. E.M. Milner *et al.* stated that performance of an operation of MFC with a plain carbon felt electrode, a carbon paper electrode and one with a biocathode biofilm of the same geometric area with Pt loading was compared with both the anolyte and catholyte buffered pH 7. it was observed that a peak power density operated with a biocathode was higher than the plain carbon felt electrode, and carbon paper electrode loaded with Pt. Using biocathode, the peak power density was increased as compared to plain carbon felt

upto 89% with a Pt cathode. This indicates that the different cathodes gives different power output [28].

Table I

Basic Components and Material Used in Microbial Fuel Cells [29].

Items	Material used	Remarks
Anode	Graphite, graphite felt, carbon paper, carbon-cloth, Pt, Pt black, reticulated vitreous carbon (RVC)	Necessary
Cathode	Graphite, graphite felt, carbon paper, carbon-cloth, Pt, Pt black, reticulated vitreous carbon (RVC)	Necessary
Anodic chamber	Glass, polycarbonate, Plexiglas	Necessary
Cathodic chamber	Glass, polycarbonate, Plexiglas	Necessary
PEM	Nafion, Ultrex, polyethylene. Poly-(styrene-co-divinylbenzene); salt bridge, porcelain septum, or solely electrolyte	Necessary
Electrode	Pt, Pt black, MnO_2, Fe^{3+}, polyaniline, electron mediator immobilized on anode	Necessary

C. Proton Exchange Membrane(PEM)

S. Zinadini *et al.* developed the high-performance commercial blended polyethersulfone proton exchange membrane. Four composites of sulfonated polyethersulfone (SPES) produced using wet phase inversion method. The efficiency of SPES was compared with Nafion 117. Adding SPES into the PES solution that led to mitigation of biofouling in MFC system. SPES solution added into casting solution that led to the formation of PEMs with low roughness and high anti-biofouling. Maximum current and power generated with new SPES were higher than the commercial Nafion 117 in the same experimental condition. It was observed that at a same current density, SPES gives power output higher than Nafian 117. The oxygen mass transfer coefficient (Ko) for the prepared SPES was also higher than Nafion 117, resulting in increased in the coloumbic efficiency, COD removal and decreased the substrate loss for the SPES membrane. The cost of MFC is reduced and improve the performance of MFC[30]. Using the alternate sources such as Porous ceramic and Clayware membranes are widely used in microbial fuel cells (MFCs) as separators. They have Chemical, mechanical and thermal stability, low-cost as compared to another membrane. In the batch mode, continuous hydration of cathode surface needed when Ceramic membranes are used as ion exchange membrane in MFCs[31],[32]. Winfield *et al.* stated that applying one hydrophobic gas diffusion layer (GDL) like polyurethane or PTFE [33] on the cathode would help to counter this problem when working in a batch operation. In continues operation of anolyte, moisture would be evenly contributing through the ceramic due to electro-osmotic drag force for the more efficient wastewater treatment [31]. More practical application of ceramic-based MFCs has been done by assembling 288 MFC reactors feeding with urine to directly power the indoor lighting in which cylindrical terracotta used as a separator and an internal cathode[34]. This stack MFC contains eight MFCs serially connected and thirty-six MFCs are connected in parallel (Fig. 4A, B). It produces power around 400 mW when directly connected to the lights. During the music festival for more than 1000 audiences per day, assembling 432 MFCs together which produces 800 mW power when directly connected [34]. (Fig. 4C, D).

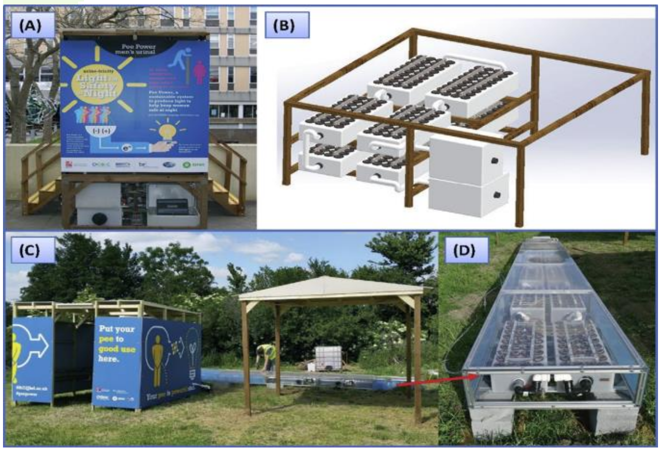


Fig. 5 Stacking the ceramic-based MFCs applied for indoor lighting; (A) 288-MFC stack trial in the UWE campus, (B) 3-D representation of 288-MFC stack with the inlet and outlet tanks underneath the urinal, (C) 432-MFC stack trial in Glastonbury Music Festival, (D) 432-MFC stack arranged in 12 modules [35].

D. Separator electrode assembly (SEA)

M. Oliot *et al.* stated that the performance of MFCs can also enhanced by using Separator electrode assembly (SEA) with 3-dimensional bioanode and removable air-cathode. A. Bergel *et al.* developed the SEA is used to decrease the anode-cathode distance in order to reduce the internal resistance. Reducing the distance between anode and cathode the ions must cover to carry the current through the electrolyte is a major objective, generally electrolyte that is used in MFCs having low ionic conductivity. The bioanode cannot be placed too close to an air-cathode because the flux of oxygen that passes through the air-cathode deteriorates the bioanode. Anaerobic electroactive bacteria blocked in presence of oxygen and the electroactive bacteria diverted from using the anode as the electron acceptor[36]. The bioanode microbial community favours the growth of non-electroactive bacteria in presence of oxygen. The presence of oxygen on the bioanode is harmful to its performance. To protect bioanode from oxygen and reduced distance between cathode and anode SEA is used. The high-power densities obtained by using the SEA. Maintain around 4 mm grid distance between anode and cathode to avoid short-circuiting[37]. SEA gave better result because of well pH balance, mitigate acidification of bioanode and alkalinisation of the air-cathode, remove the presence of oxygen. Anaerobic biofilm form on the cathode surface because of removable cathode improve the performance of MFC. Plastic grid (Grid-SEA) produced high power densities than J Cloth- SEAs and Paper-SEAs.

V. Recent Developments in the Applications of MFCs

A. Biosensor

The most important application of MFC technology is to use as a sensor for the analysis of pollutant and BOD of wastewater. It has a linear relationship between the Coulombic yield and the strength of the wastewater for a wide BOD concentration range. since, a high BOD concentration requires a long response time because unless the BOD has been depleted, the Coulombic yield can't be calculated [38]. Jon Chouler *et al.* stated that MFCs can treat the wastewater and simultaneously monitor BOD using biosensor with response times ranging from 3 to 120 minutes but operational stability is poor and small measuring range because of limited organic compounds present in the substrate. Two different low-cost of membrane materials such as a natural polymer (eggshell membrane), and a synthetic polymer (polydimethylsiloxane, PDMS) are also used. The energy generating from this system compare with membrane less device and Nafion membrane. It is observed that the power density generating from PDMS is same as expensive Nafion. The electrode spacing affected the output power but it had a negligible or small effect on the BOD sensing capability of the devices. Especially, in case of the eggshell membrane and the membrane-less devices, higher the electrode spacing better will be the power performance. Eggshell membranes have low internal resistance and highest sensitivity[39].

B. Wastewater treatment

Habermann and Pommer *et al.* stated that the MFC was used for treating wastewater early in 1991[40]. Total amount of electricity produced by conventional process required half of the electricity to operate conventional wastewater treatment plant. Certain microbes have a special ability to remove sulfides as required in wastewater treatment [41]. Peng Dub et.al. stated that five benefits make MFCs more sustainable when applied in wastewater treatment: (1) The direct conversion of organic substrate energy to electricity (2) Small amount of activated sludge compared to the processes of Anaerobic digester (AD) and conventional aerobic activated sludge (CAAS) treatment (3) Even at low temperatures, impermeable to operation environment, (4) Without any treatment of the gas (5) No energy supply for aeration (6) An extensive application in locations with insufficient electrical organizations[6].

Various types of wastewater-

a. Municipal or domestic wastewater
b. Agricultural wastewater
c. Industrial wastewater
d. Food processing wastewater
e. Dye wastewater

Municipal or domestic wastewater contains high levels of organics (about 66%). Continuous flow and single-compartment MFCs and membrane-less MFCs are used for wastewater treatment for commercialization purpose [42] [43]. Integrating conventional wastewater and MFC process, the COD removal efficiency increased in the range of 80.0% to 90.0% in stabilization period. Integrating anaerobic treatment and MFCs gives the final result of the removal efficiencies of COD, sulfat and the colour was respectively achieved 53.2%, 52.7%, 41.1%. Another combination is to integrate the MFC into an anaerobic reactor.

Cheng *et al.* improved the up-flow membrane-less microbial fuel cell (UMLMFC) through installing the immobilized biological aerated filters at the top, to remove COD and NH_3-N from the reactor with removal efficiencies higher than 96.5% and 93.6% respectively [44].

Huang *et al.* designed a system to treat alcohol distillery wastewater by combining an anaerobic fluidized bed (AFB) and an MFC. Anode and cathode chamber, external resistor merged in the AFB-MFC system a Nafion 117 used as a proton exchange membrane which can separate anode and cathode chamber. The COD removal efficiency in this system ranged from 80.0% to 90.0% in stabilization period and the maximum power density observed as 124.03 mW/m^2 under an external resistance of 120 Ω and a variety of system operational settings[45].

Mohan *et al.* designed a small floating macrophyte based ecosystem by combining ecological treatment technologies with sediment type microbial fuel cell (SMFC), which was used to generate bioelectricity from domestic sewage and fermented distillery wastewater. Results presented that Increasing the organic load of wastewater increase both power generation as well as removal efficiencies of COD and VFA respectively[46].

Xie *et al.* implanted an MFC into the anaerobic– anoxic–oxic (A2/O) process. A2/O represents the anaerobic–anoxic–oxic process. This process is one of the most useful processes to treat wastewater which can simultaneously remove nitrogen and phosphorous from the water. For solving the problems of substrates competition and high energy consumption, this integrated system was used to generate electricity[47].

VI. Future Perspectives

In the future, it would be essential to look for cheap and effective electrode materials such as biocathode. In the future developing the new alternative source for proton transfer that would be cheap and effective which can improve the performance of MFCs. Secondly, using integrated reactors such as the combination of MFCs and Conventional process that can increase the current and power density. Thirdly, sustainable electrochemically active bacteria should be cultured and adapted for wastewater treatment. For the commercialization of MFCs, the output from the MFCs has to be increased using low cost and good performance of MFCs such as used of biocathode, Sediment MFCs.

VII. Conclusion

This review summarizes the recent development in the Microbial fuel cell to increase the electricity. The alternative sources are used to reduce the cost of MFC and improved the performance of MFC. In the initial years, electricity was produced from convential microbial fuel cell such as single chamber, dual chamber, but in the recent years researchers are using integrated type of reactor which can produced maximum amount of electricity. The power produced from MFCs till now, that can be increased by 6.4 W/m^2 using separator electrode with the 3-dimensional bioanode. Integrating the processes of conventional wastewater and MFC leads to increase the chemical oxygen demand removal efficiency. The electricity also boosts using biocathode than the plain carbon cathode electrode. It is hoped that the coming years gives the new renewable energy source with this improvement in this technology.

References

[1] S. Singh, S. Suresh, Review on Microbial Fuel Cell Energy Enhancement Using Nano Materials, Biofuels and Bioenergy,. (2017) 321–327.

[2] P. MC., Electrical effects accompanying the decomposition of organic compounds., Proc R Soc London Ser B Contain Pap Biol Charact. 84 (1911) 260–76.

[3] D. Pant, G. Van Bogaert, L. Diels, K. Vanbroekhoven, A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production, Bioresour. Technol. 101 (2010) 1533–1543. .

[4] H.-L. Song, Y. Zhu, J. Li, Electron transfer mechanisms, characteristics and applications of biological cathode microbial fuel cells – A mini review, Arab. J. Chem. (2015).

[5] N.K.. Lovley DR, Holmes DE, Dissimilatory Fe(III) and Mn(IV) reduction, Adv Microb Physiol. 49 (2004) 219–86.

[6] L. He, P. Du, Y. Chen, H. Lu, X. Cheng, B. Chang, Z. Wang, Advances in microbial fuel cells for wastewater treatment, (2016).

[7] Z.J. Park DH, improved fuel cell and electrode designs for producing electricity from microbial degradation., Biotechnol. Bioeng. 81Biotechn (2003) 348–55.

[8] L.B. Liu H, Cheng S, Production of electricity from acetate or butyrate using a single-chamber microbial fuel cell., Env. Sci Technol . 39 (2005) 658–

62.

[9] H. Liu, H. Liu, R. Ramnarayanan, R. Ramnarayanan, B.E. Logan, B.E. Logan, Production of electricity during wastewater treatment using a single chamber microbial fuel cell., Environ. Sci. Technol. 38 (2004) 2281–5.

[10] M.F.C. 19. A. Parkash, A Source of Bioenergy, Microb. Biochem. Technol. 2016 (83AD) 247–255.

[11] K.V. 20. D. Pant, A. Singh, G.V. Bogaert, Y.A. Gallego, L. Diels, An introduction to the life cycle assessment (LCA) of bioelectrochemical systems (BES) for sustainable energy and product generation: Relevance and key aspects, Renew. Sustain. Energy. 15 (2) (2011) 1305–1313.

[12] B.E. Logan, B. Hamelers, R. Rozendal, U. Schröder, J. Keller, S. Freguia, P. Aelterman, W. Verstraete, K. Rabaey, Microbial fuel cells: Methodology and technology, Environ. Sci. Technol. 40 (2006) 5181–5192.

[13] A. 18. M. Zhou, M. Chi, J. Luo, H. He, T. Jin, overview of electrode materials in microbial fuel cells, J. Power Sources. 196 (2011) 4427–4435.

[14] Z. Du et al., A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy, Biotechnol. Adv. 25 (2007) 464–482.

[15] S. Basu, Proton Exchange Membrane Fuel Cell Technology : India ' s Perspective, (2015) 865–890.

[16] L.B. et al. Santoro C, Guilizzoni M, Baena JC, Pasaogullari U, Casalegno A, The effects of carbon electrode surface properties on bacteria attachment and start up time of microbial fuel cells., Carbon N. Y. 67 (2014) 128–39.

[17] S.H. Yu Y-Y, Guo CX, Yong Y-C, Li CM, Nitrogen-doped carbon nanoparticles enhanced extracellular electron transfer for high-performance microbial fuel cells anode., Chemosphere. 140 (2015) 26–33.

[18] K.S.U. of J. Yuan Y, Jeon Y, Ahmed J, Park W, carbon nanoparticles for bacteria immobilization in microbial fuel cells for high power output., Electrochem Soc. 156 (2009) B1238–B1241.

[19] Oyedepo SO., Energy and sustainable development in Nigeria: the way forward, Energy Sustain Soc. 2 (2012) 1–17.

[20] L.F. et al. Ren H, Pyo S, Lee J-I, Park T-J, Gittleson FS, A high power density miniaturized microbial fuel cell having carbon nanotube anodes., J Power Sources. 273 (2015) 823–30.

[21] H.Z. Ci S, Wen Z, Chen J, Decorating anode with bamboo-like nitrogen-doped carbon nanotubes for microbial fuel cells., Electrochem Commun. 14 (2012) 71–4.

[22] L.C. Liu J, Qiao Y, Guo CX, Lim S, Song H, Graphene/carbon cloth anode for high-performance mediatorless microbial fuel cells., Bioresour Technol. 114 (2012) 275–80.

[23] Z.Y. Hou J, Liu Z, Yang S, Three-dimensional macroporous anodes based on stainless steel fiber felt for high-performance microbial fuel cells., J Power Sources. 258 (2014) 204–9.

[24] C.P. Yong Y-C, Dong X-C, Chan-Park MB, Song H, Macroporous and monolithic anode based on polyaniline hybridized three-dimensional graphene for high- performance microbial fuel cells., ACS Nano. 6 (2012) 2394–400.

[25] S.F. Hashmi S, Karthikeyan C, GhavamiNejad A, Vatankhah-Varnoosfaderani M, Graphene oxide/carbon nanotube composite hydrogels—versatile materials for microbial fuel cell applications., Macromol Rapid Commun. 35 (2014) 1861–5.

[26] Y. Hindatu, M.S.M. Annuar, A.M. Gumel, Mini-review : Anode modi fi cation for improved performance of microbial fuel cell, 73 (2017) 236–248.

[27] C.J.N.B. D.P.B.T.B. Strik, H.V.M. Hamelers, No Title, Environ. Sci. Technol. 44 (2010) 532–537.

[28] E.M. Milner, D. Popescu, T. Curtis, I.M. Head, K. Scott, E.H. Yu, Microbial fuel cells with highly active aerobic biocathodes, J. Power Sources. 324 (2016) 8–16.

[29] Z. Du, H. Li, T. Gu, A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy, Biotechnol. Adv. 25 (2007) 464–482.

[30] S. Zinadini, A.A. Zinatizadeh, M. Rahimi, V. Vatanpour, Z. Rahimi, High power generation and COD removal in a microbial fuel cell operated by a novel sulfonated PES/PES blend proton exchange membrane, Energy. (2017).

[31] I.I. Winfield J, Greenman J, Huson D, Comparing terracotta and earthenware for multiple functionalities in microbial fuel cells., Bioprocess Biosyst

Eng. 36(12) (2013) 1913–21.

[32] G.M. Chatterjee P, Design of clayware separatorelectrode assembly for treatment of wastewater in microbial fuel cells., Appl Biochem Biotechnol. 173(2) (2014) 378–90.

[33] L.B. Santoro C, Agrios A, Pasaogullari U, Effects of gas diffusion layer (GDL) and micro porous layer (MPL) on cathode performance in microbial fuel cells (MFCs)., Int J Hydrog. Energy. 36(20) (2011) 13096–104.

[34] et al. Ieropoulos IA, Stinchcombe A, Gajda I, Forbes S, MerinoJimenez I, Pasternak, microbial fuel cell technology field trials in the context of sanitation., Pee Power Urin. -. (n.d.).

[35] V. Yousefi, D. Mohebbi-kalhori, A. Samimi, ScienceDirect Ceramic-based microbial fuel cells (MFCs): A review, Int. J. Hydrogen Energy. (2016).

[36] A. Bergel, M. Oliot, L. Etcheverry, A. Mosdale, R. Basseguy, M. D, Separator electrode assembly (SEA) with 3-dimensional bioanode and removable air-cathode boosts microbial fuel cell performance, (2017) 1–11.

[37] B.E.L. Y. Ahn, A multi-electrode continuous flow microbial fuel cell with separator electrode assembly design., Appl. Microbiol. Biotechnol. 93 (2012) 2241–2248.

[38] C. et al. Chang IS, Jang JK, GilGC, KimM, KimHJ, Continuous determination of biochemical oxygen demand using microbial fuel cell type biosensor., Biosens Bioelectron. 19 (2004) 607–13.

[39] J. Chouler, I. Bentley, F. Vaz, A.O. Fee, P.J. Cameron, M. Di, Electrochimica Acta Exploring the use of cost-effective membrane materials for Microbial Fuel Cell based sensors, Electrochim. Acta. 231 (2017) 319–326.

[40] P.E. Habermann W, Biological fuel cells with sulphide storage capacity., Appl Microbiol Biotechnol. 35 (1991) 128–33.

[41] A.P. Rabaey K, Van De Sompel K, Maignien L, Boon N, et al. Clauwaert P, Microbial fuel cells for sulfide removal., Env. Sci Technol . 40 (2006) 5218–24.

[42] C.K. et al. Jang JK, Pham TH, Chang IS, Kang KH, Moon H, Construction and operation of a novel mediator-and membraneless microbial fuel cell., Process Biochem. 39 (2004) 1007–12.

[43] K.B. generation. Moon H, Chang IS, Jang JK, Residence time distribution in microbial fuel cell and its influence on COD removal with electricity, Biochem Eng J. 27 (2005) 59–65.

[44] B.A. Cheng J, Zhu XP, Ni JR, Palm oil mill effluent treatment using a twostage microbial fuel cells system integrated with immobilized biological aerated filters., Bioresour Technol. 101 (2010) 2729–34.

[45] Z.K. Huang JS, Yang P, Guo Y, Electricity generation during wastewater treatment: an approach using an AFB-MFC for alcohol distillery wastewater., Desalination. 276 (2011) 373–8.

[46] C.P. Mohan SV, Mohanakrishna G, Sustainable power generation from floating macrophytes based ecological microenvironment through embedded fuel cells along with simultaneous wastewater treatment., Bioresour Technol. 102 (2011) 7036–42.

[47] L.H. Xie BZ, Dong WB, Liu BJ, Enhancement of pollutants removal from real sewage by embedding microbial fuel cell in anaerobic-anoxic-oxic wastewater treatment process., J Chem Technol Biotechnol. 89 (2014) 448–54.