Chapter 13
The Performance of Microbial Fuel Cells in Field Trials from a Global Perspective

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13.1 Microbial Fuel Cells (MFC): A Sustainable Solution for Energy Demand

The global energy demand is exponentially increasing everyday, and it has been currently managed by the consumption of fossil fuels and their products. It is a well-known fact that the persistent utilisation of the fossil fuels has made awful damage to our environment. In this context, from last few decades, the motivation towards the development of sustainable energy is strongly driven due to growing demand for global requirement of energy to meet the technological, economical and social welfare needs of the community. The rapid depletion of fossil fuels and emerging environmental awareness on global warming have given impetus to search for the alternative energy sources with sustainable supply, which has become one of the major research objective in many countries. Hence, the energy gleaned especially from renewable resources or cost-effective resources would pave a plausible way for the sustainable energy development (Carla Jones and Stephen 2016; Ravinder and Pradeep 2017).

The wastes generated from agricultural or plant-based byproducts are termed as 'biomass' which can be effectively converted into biofuels. Unlike the chemical fuel cells, the chief compositions of these biomass wastes are carbohydrates and proteins. Microorganisms consume these wastes and degrade them into harmless materials (Elizabeth et al. 2011; Ritu and Sanjeev 2017). The basis for the construction of microbial fuel cells (MFCs) relies on the conversion of chemical energy stored in

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the form of chemical bonds suitably into electrical energy through redox reactions catalysed by microorganisms (Bruce Logan et al. 2006; Frank and Higson 2007; Rachnarin and Roshan 2017).

The microorganisms, viz. *Shewanella* sp. and *Geobacter* sp., have been used for the construction of MFCs that degrade the inorganic and organic compounds such as sugars, proteins, cellulosic materials and polyphenols through oxidation-reduction reactions (Padma and Dirk Hays 2012; Zhuwei et al. 2007). The MFCs are one among the cost-effective renewable energy sources, where the electricity is generated from domestic and industrial effluents. More than two decades, the development of MFCs not only has contributed to the energy sector but also augment in efficiently converting industrial and domestic wastes into electricity through microbes. Many reviews, monographs and book chapters pertaining to MFCs are published in the reputed journals by several scientific researchers (Carlo et al. 2017; Mostafa et al. 2015; Oliveira et al. 2013).

13.2 Why Microbial Fuel Cells (MFCs)?

The awareness on the protection of environment since the dawn of the twenty-first century has purported the search for alternative fuels around the world with attention focusing on the MFCs because of its greener and bioenergy production. The main objective of the MFC development is to treat the industrial and domestic effluents in a cost-effective manner by using microbes, which are capable of producing electricity from these wastes through the oxidation and reduction reactions catalysed by them (Kim et al. 2008; Yi-Chi et al. 2015). For instance, the complete oxidation of one glucose molecule to CO_2 in the presence of air/O_2 produces 24 electrons, which can be utilised for the generation of electrical energy. Thus, any energy source obtained from various biomasses, which are rich in carbohydrates, proteins, alcohols, hydrocarbons and organic acids, could be used as a fuel for the MFCs. In addition, the polymeric carbohydrates such as cellulose and starch can also be utilised for fuel. The organic matter present in theses wastes could be oxidised by these self-replicating bacteria also known as *exoelectrogens* through electron transfer reactions to produce the bioenergy.

The major advantage of MFCs is not only providing electrical energy but also to treat wide range of agricultural wastes such as cornhusks, rice husks, whey and also animal or human sewage. For instance, the wastewater sludges containing carbohydrates especially glucose, sucrose, glucoronic acid, starch and xylose generate current density in the range of 0.7 and 1.3 mA/cm^2 at the concentration of 6 to 7 mM/L (Pant et al. 2010).

Further, MFCs also succour to continuous monitoring of quality of wastes and minimal investment on the fuels. Accordingly, there has been tremendous efforts made across globe which can be clearly observed through the huge number of research articles published in the last few years (2010–2016) dealing with the various aspects of the MFCs (Carlo et al. 2017; Ravinder et al. 2017b). Figure 13.1

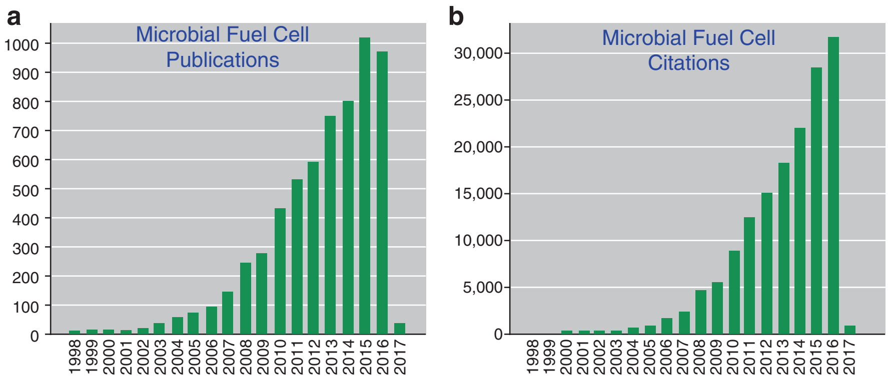

Fig. 13.1 (**a**) Number of publications appeared during 1998–2017. (**b**) Number of citations on MFCs during 1998–2017. (Credit: Carlo et al. 2017)

summarises the number of research articles published on MFCs since 1998 till 2017(Carlo et al. 2017). A major breakthrough in the year 1998 was the construction of mediator-less MFC that made a greater contribution in the advancement of the MFCs (Kim et al. 1999a, b). The development of MFCs has enormous opportunities in various domains for sustainable energy production.

13.3 From Laboratory to Pilot Scale: In Nutshell

Galvani was the pioneer who identified the relationship between electricity and bioactivity (bioelectromagnetics). He observed the muscle of dead frog's leg twitched when an electric spark was applied to it. In 1911, Chesse Potter noted that when platinum electrode was in contact with the *E. coli*, potential difference was generated. This observation led Cohen to construct the first microbial battery, which generated potential of 35 V (Cohen 1931). Lower efficiency and the higher construction costs were the major issues confronted with the development and manufacturing of MFCs at the commercial level in earlier 1990s. However, there have been tremendous efforts undertaken to solve the issues associated with efficiency and life cycle of the MFCs. From the dawn of the twenty-first century, the focus on improving the efficiency with low construction cost has gained the highest priority among the research community working in the various domains of sustainable energy-related fields. The progress of innovation in MFCs from laboratory level to pilot scale largely depends on the design of reactor, proton exchange membrane and low-cost electrode materials. On the other hand, the innovations made at laboratory level should be successfully adopted for pilot-scale MFC plants.

For the pilot scale, the maximum current density has to be generated with reduced cost of the electrode materials. Though the electrode materials such as platinum and graphite showed high performance, they are expensive, and hence they must be replaced with low-cost metals like iron or cobalt and carbon materials like carbon felts, carbon cloth and carbon brushes (Bruce Logan 2010). Thus, the electrode materials cumulatively contribute to the current density as well as commercial feasibility. Issues related to the generation of maximum current density can be resolved by adopting air-cathode model using efficient microorganism and suitable fuel materials. The electrode designs also equally contribute to the efficiency of the MFCs. They must be designed in such a way to cover the large surface area to volume ratio which can be achieved by tubular cathodes coated with conducting or catalytically active materials and should be closely packed. For successful commercialisation of MFCs, adoption of suitable reactor designs, viz. mediator-less design, air-cathode model, stacked MFCs, continuous flow MFCs, upflow tubular model and flat-pad MFCs in addition to single- and double-chamber designs, is desirable. One of the predominant techniques adopted for the treatment of wastewater relies on the commercialisation or construction of pilot plant of MFCs (Kelly and John 2009).

13.4 Qualities of MFCs

The MFCs are often referred to as bioelectrochemical cells and have seen many obstacles since its inception. Consequently, numerous innovations have been appearing periodically in the form of research articles, reviews and patents (Fig. 13.1) to improve the quality of MFCs. Primarily, MFCs operate through the biochemical redox reactions catalysed by the microorganisms that involve transfer of exogenous electrons from the organic matter chiefly from the domestic or industrial effluents and trapping of these electrons in an external circuit (Ravinder et al. 2016; Prashant et al. 2016). Both in laboratory and at pilot-scale level, MFCs offer to fulfil the energy demand by generating the electricity from wastes and also provide an excellent solution for treating the wastewater or waste materials (Rene Rozendal et al. 2008; Micheal and Thomas 2013; Minghua et al. 2013; Oliveira et al. 2013; Tonia and Giorgia L 2017).

MFCs are sustainable source of energy in terms of economical and environmental perspectives with superior performance than the ordinary electrochemical cells. The advantages of the MFCs are as follows:

(i) Electroactive bacteria or microorganism that acts as a catalyst for redox reactions.
(ii) These fuel cells work in the temperature range of 15–45 °C, which is in the level of ambient conditions.
(iii) MFCs are neither acidic nor basic; thus, they can efficiently work under neutral pH conditions.
(iv) Utilisation of large volume of organic biodegradable mass fuels for MFCs, which efficiently manages the solid wastes or effluents that are generated from the domestic and industrial activities. The bioelectrochemical cells have been

classified based on their applications and the products generated during the reactions (Ravinder et al. 2017a).

13.5 Source of Green Energy

The demand for energy is satisfied by renewable energy sources such as hydropower, wind, geothermal and solar which are commonly referred to as ‘green energy sources’. However, in the current scenario, the energy demand may not be fully supplied by the above resources. Thus, the quest for the alternative energy sources has gained much momentum. The renewable energy sources derived from biomass such as wood waste, municipal solid waste, landfill biogas, ethanol and biogas are also capable of producing ‘green energy’. Among the biomass that is utilised for the energy production, municipal solid wastes together with wastewater containing organic and inorganic components can be successively employed as a replacement for fossil fuels. Apart from the usual treatment of wastes with physical and chemical methods, the biological treatment of wastes proves to be more of an energy efficient process. The typical biological treatment involves the degradation of organic matter by the microorganism under the ambient conditions. However, most of the biological degradation processes proceed through oxidation-reduction reactions. Thus, the idea of MFCs emerged from the use of exogenous electrons released during the redox degradation of the organic matter (Heming and Zhiyong 2013).

More interestingly, *Enteromorpha prolifera*, a green alga that causes serious environmental issues in southern region yellow sea, has been utilised as an energy source for the MFCs (Min et al. 2013). The algae have the ability to grow rapidly both in freshwater and seawater and cause green tide. This rapid growth of alga created huge biomass that has found varied applications. The alga is composed of 50% carbohydrate, and the hydrolysed biomass of *E. prolifera* is used as a good source of energy for the construction of MFCs. In this study, the MFC has been constructed using carbon cloth as anode and air cathode and single cylindrical chamber as the reactor. The fuel cell showed power density value of 1027 mW m^{-2}, and the chemical oxygen demand (COD) has been significantly reduced to 71%. It is quite evident that the biomass generated by *E. prolifera* could be successfully used for the generation of the electricity using MFC technology.

13.6 Generating Power While Treating Wastes

The advancement of MFCs at commercial level generally depends on the effective degradation of various kinds of organic/inorganic wastes. The redox biochemical reactions of microorganisms are pivotal to construct the fuel cells to generate electricity using organic wastes derived from domestic and industrial sources (Rene Rozendal et al. 2008; Pant et al. 2010; Hai-Liang et al. 2015; Quanguo et al. 2016).

The microorganisms present in the wastes effectively catalysed the electrochemical oxidation of the organic impurities or pollutants. The typical working principle of the MFCs involves the oxidation of organic and inorganic components by the microorganisms and the electrons generated in the process transferred to the anode and protons (H^+) to the cathode thereby completing the electrical circuit. After the organic and inorganic wastes have been completely degraded or utilised, fresh wastes can be replenished or can be percolated to the MFCs for the continuous generation of electricity. Besides the power generation, the quality of wastewater from domestic or industrial activities could also be effectively monitored by the use of MFCs. The investment incurred on the construction of MFCs should be minimised for the pilot or commercial scale process (Bruce Logan et al. 2006).

The utilisation of MFC technology is of great benefit for the wastewater treatment and could be an inexpensive way of monitoring the quality of the wastewater or ground water regularly (Zhuwei et al. 2007; Abilasha Singh 2016; Valesquez-orta et al. 2017). Substantially, the wastewater generated from dairy industries (Xiaonan et al. 2011; Ana Faria et al. 2017), agro-food industries (Daniele et al. 2017), textile industries (Anam et al. 2014), microbreweries industries (Ellen et al. 2016), removal of heavy metal from wastewater (Syed Zaghum et al. 2017), winery industry (Cusick et al. 2011), beer brewery industry (Parawira et al. 2005), domestic wastewater (Shijia et al. 2016), municipal wastes, food wastes, animal wastewater (Jeffery et al. 2010) and urine (Couler et al. 2016) can be utilised as a source of fuel for the MFC technology (Fig. 13.2).

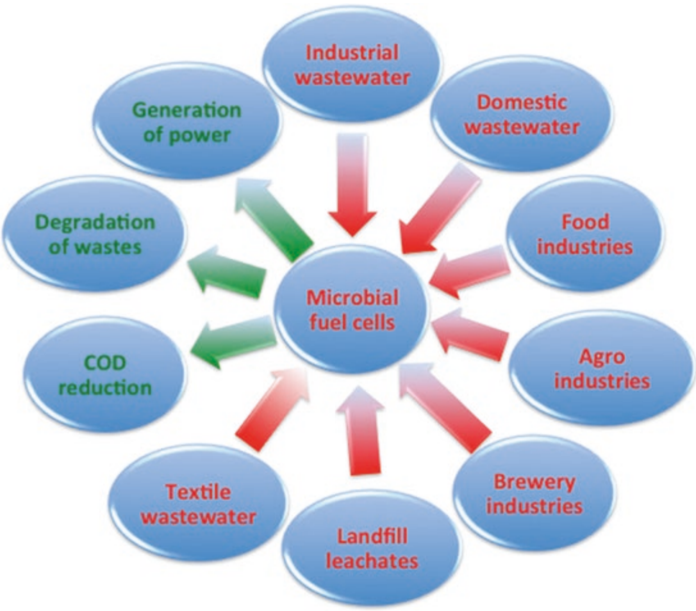

Fig. 13.2 MFC is a source of green energy

The use of landfill leachate is explored as a source material for MFC. An air-breathing cathode and carbon felt anode-based MFCs have been fabricated using landfill leachate as a fuel. The cell is constructed at laboratory-scale level and showed maximum open circuit volt of about 1.29 V over the study period of 17 days. The maximum power density was achieved up to 1513 mW m^{-2}, and it was the highest value reported so far for any MFCs using landfill leachate as an energy source (Jayesh Sonawane et al. 2017). *Mesophilic* bacteria were found to be the catalyst for the redox reaction of the organic wastes. The optimised cell parameters and use of cost-effective electrodes in the present study are prerequisite for the commercial or pilot-scale investigations. However, intensive research on the composition of wastes and exploration of the various species of microbes are necessary for better construction of the MFCs.

In addition to the wastewater or municipal solid wastes, the farm or agricultural wastes, such as humus, cattle manure (Haugen et al. 2015), peat moss, saw dust, rice husk and whey etc., could also be used as a biodegradable source for the MFC applications (Pant et al. 2010). Using sawdust, a single-chamber MFC has been constructed using carbon felt as anode and air-breathing cathode. It showed stable power generation as compared to the other solid wastes over the period of 40 days (Ademola et al. 2017). On the other hand, the MFC using humus as carbon source showed excellent power density but showed poor performance after 40 days. Interestingly, the combination of humus and sawdust increased the life span of the MFC up to 9 months. Similarly, rice bran, which is a waste product generated during the milling process, could also be used as carbon source for the MFC (Takahashi et al. 2016). The study showed that a single-chamber MFC was constructed with a capacity of 15 mL at laboratory-scale level using graphite felt as anode and polytetrafluoroethylene (PTFE) coated with platinum catalyst as cathode. The MFC showed maximum power density from 360 to 520 mWm^{-2} in the presence of pure water and mineralised water. These studies revealed that there are plenty of carbon sources available for the construction of the MFCs at commercial-scale level.

13.7 Reactor Design for Pilot-Scale Process

Many of the pilot-scale MFCs have been constructed for the wastewater treatment either from domestic or industrial sources (Micheal and Thomas 2013; Bruce Logan 2010; Nastro 2014). The design of MFCs would affect the efficiency of the generation of sufficient current density for the commercial implementation. Currently, there are various designs of MFCs, viz. single-chamber, double-chamber, upflow cylindrical−/tubular-type, flat bed-type (FPMFC), stacked-type (Oliveira et al. 2013; Prashant et al. 2016) and sediment microbial fuel cells (Atieh et al. 2015, Valeria et al. 2017), developed for the large-scale applications. With respect to the nature and type of land and the composition of the wastewater, the appropriate model of the reactor has to be chosen for the better performance of the MFCs (Carlo et al. 2017). The laboratory trials of MFCs showed considerable amount of current density at 10 A m^{-2} surface area of electrode, which is sufficient for the construction of MFCs for commercial-scale power production (Rene Rozental et al. 2008). Several studies have been reported on the MFCs for laboratory levels, but scaling up or commercial process would be successful if the MFCs with high power density are constructed for the real-time applications like wastewater treatment. In this section, various models of MFCs constructed for the pilot scale is discussed.

13.7.1 Single-Chamber MFCs

Although many designs of MFCs have been reported, one of the most widely used MFCs are the membraneless single-chamber (MLSC) MFCs. These MFCs owing to its simple reactor constructions and least expensive membranes are extensively employed for the large-scale applications. A single-chamber MFC (SCMFC) with carbon cloth as both anode and cathode, coated with platinum catalyst, utilises brewery wastewater as a fuel source (Yujie et al. 2008). The cell showed maximum power density up to 205 mW/m^2 at 30 °C with COD removal efficiency up to 37%. Further, addition of phosphate buffer at 50 mM and 200 mM concentration increased the power density to 438 and 528 mW/m^2, respectively.

Daqian and Baikun (2009) reported single-chamber MFC (SCMFC) made of granular activated carbon (GAC) chamber containing graphite rod as anode and platinum-coated carbon cloth as air cathode. The wastewater collected from the University of Connecticut having COD value of 200 mg/L and pH 7.2 served as fuel. Excess of sodium acetate was added to achieve the desired COD value of 1500 mg/L, and the MFC was operated at 30 °C. The SCMFC containing four sets of multiple anode and cathode was also constructed to achieve the maximum power density. The SCMFC generated maximum power density up to 7 W/m^2 at electrode distance of 2 cm, and COD level (100–200 mg/L) reduced up to 89%. The multiple anodes and cathodes containing GAC-SCMFC generated 3.25 mA current, while single-anode GAC-SCMFC showed output of 3 mA current. However, the overall performance of MFCs greatly depends on the work ability of the cathode. The power density of MFCs has been increased by the use of MFC containing multi-anode and cathode (Baikun et al. 2011). Daqian et al. (2011) reported the increment in the power density when multi-anode/cathode containing MFC were used for the treatment of wastewater. The MFCs were constructed and evaluated at a domestic wastewater treatment plant in the Gloversville Johnson Joint Wastewater Treatment Facility (GJJWWTF) (New York, USA) (Fig. 13.3). The study revealed that the power density increased from 300 to 380 mW m^{-2} by using the MFC containing 12 anodes and cathodes. In this study, an attempt has been made to replace the expensive platinum electrode by metal-doped MnO_2 cathode. With respect to platinum electrode, Cu- and Co-doped MnO_2 showed higher power density up to 465 and 500 mW/m^2, respectively. Though the cathode showed advantage, gradually the decrease in power density was observed due to the cathode fouling by the precipitation of calcium and sodium.

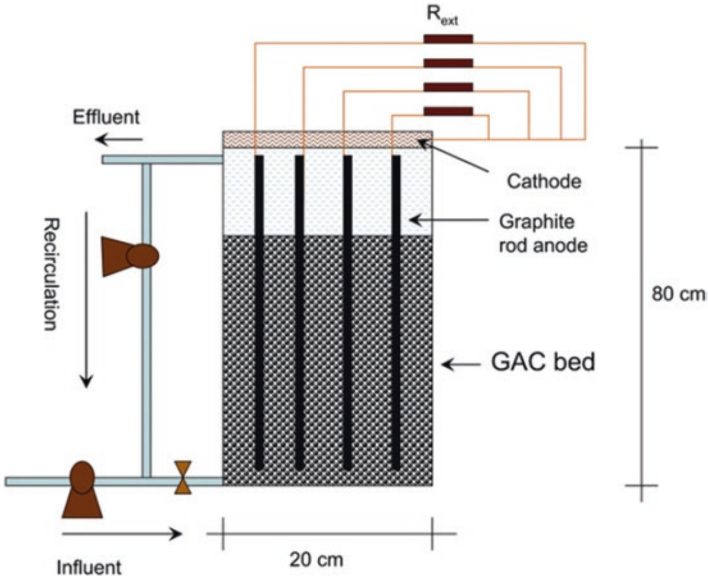

Fig. 13.3 Schematic view of MAC-MFC at pilot scale. (Credit: Daqian et al. 2011)

A single-chamber air-cathode MFC has been developed for the continuous wastewater treatment containing variable COD values. A synthetic wastewater containing 0.1 to 0.4 g/L of glucose was treated with novel submerged-air-cathode MFC (SE-AMFC) with working volume of 5.7 L (Yu et al. 2012). The study revealed that while increasing COD values from 100 to 400 mg/L, the power density of SE-MFC increased from 191 to 754 mW m^{-2}. However, the increasing COD values declined the COD removal efficiency.

Yongwon et al. (2013) developed a single-chamber hexagonal-shaped large-scale MFC for the treatment of activated sludge from the Jungnang Sewage Treatment Centre, Seoul, Korea. The performance of the cell was evaluated by the COD removal efficiency and current density, and the durability of the MFC was tested for more than 5 months. The cell constructed with a capacity of 1.29 L consists of 30 wt% wet-proofed carbon cloth as air cathode and 20% Pt/C-coated carbon cloth as anode. The cell was operated at neutral pH in 30, 35 and 40 °C. The cell showed 94% COD removal efficiency at 40 °C, and this study uncovered that the efficiency of COD removal could be increased from 88.5% to 94% by increasing the operating temperature from 30 to 40 °C. In addition, the columbic efficiency also increased from 3% to 21% by increasing the operating temperature. The study unearthed the fact that the power density greatly depends on the reactor size and its efficiency could be reduced with an increasing size which may be due to an increase in internal resistance in larger size reactor. Thus for the successful implementation of the MFCs for the larger-scale applications, the internal resistance has to be controlled.

A pilot-plant MFC with 45 L capacity has been constructed and combined with the effluent from wastewater treatment plant operated by Emschergenossenschaft, a non-profit organisation in Germany mainly working on the river basin management (Heinz et al. 2016). For the real-time application, a membraneless single-chamber MFC (SCMFC) was connected to the primary treatment plant. 45 L capacity was achieved by successively connecting four individual chambers with a capacity of 11.2 L. Each compartment was connected with the platinum-coated PTFE as air cathode and graphite fibre brush as anode. The performance of the MFC was evaluated by the removal efficiency of COD, total nitrogen (TN) and total suspended solids (TSS). The COD value of the wastewater was found to be 130 mg/L, which is very low due to the dilution by the river water, and conductivity between 3.0 and 4.2 S/cm was established.

13.7.2 Two-Chamber MFCs

The usual construction of MFCs contains two chambers, and the chambers are separated by proton exchange membrane (PEM). In one chamber, the oxidation of organic materials occurs on carbon cloth or platinum-based electrodes, which serve as anode. Electrons generated are transferred to the external circuit. The electrons are collected by another chamber where oxygen get reduced (cathode) to O^{2-} and combine with proton to form water as byproduct (Booki and Bruce Logan 2004) (Fig. 13.4).

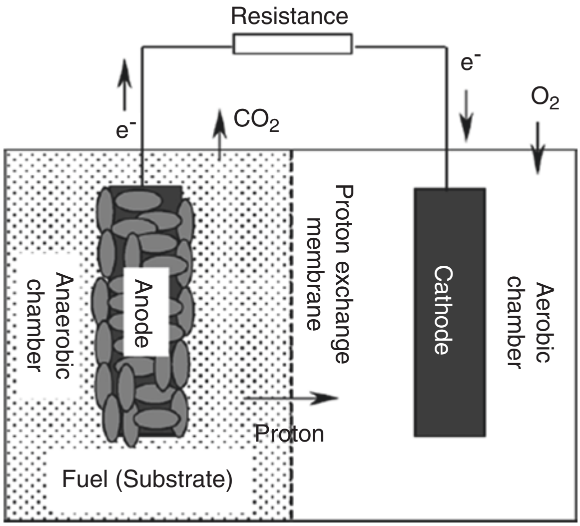

Fig. 13.4 Typical two-chamber microbial cells. (Credit: Zhuwei et al. 2007)

The dairy wastewater is treated by using dual chamber as reported by Daniele et al. (2017). The chambers are filled with granular graphite material and connected with electrodes made of graphitic rods. The reactor was operated for 2.5 months and supplied with raw dairy effluent. The COD value of the dairy industries was found to be in the range of 650–3000 mg L^{-1}. The DCMFC showed COD removal efficiency up to 80–90% with columbic efficiency achieved up to 60%. The study showed excellent organic matter removal efficiency with maximum recovery of energy in the form of power density up to 27 Wm^{-3}.

13.7.3 Vertical or Upflow Chamber MFCs

Upflow anaerobic sludge bed (UASB) reactors are mainly constructed for the biogas production or for the purpose of preparing composite from the organic waste material like cow and dairy wastes (Hina et al. 2015). In Lahore, Pakistan, the domestic wastewater obtained from the Garden Town wastewater-pumping agency was treated using UASB. The UASB is a cylindrical-type reactor built with a capacity of 4.6 L at the top, and in the bottom is a gas-liquid-solid separator built with the volume of 11.2 L. At 25 °C both cow dung manure and dairy wastewater showed 77% and 68% COD reduction, respectively, after 120 days. Since, the reactor design showed effective biogas and biomass production, it could be successfully adopted for making the MFCs. Another usage of UASB has been explored for the treatment of opaque beer brewery waste sludge collected from the largest brewery industry in Harare, Zimbabwe (Parawira et al. 2005). The reactor with a capacity of about 500 m^3 was built for treating the wastes having COD value of 6 kg/m^3 per day. Before treating the wastes, the digester chamber was seeded with active municipal sludge and acclimatised for 3 months and the brewery waste sludge fed at hydraulic retention time of 24 h. The performance of the reactor was assessed by examining the parameters such as pH, COD, total dissolved solids (TDS), TSS and settleable solids. The study showed that the anaerobic treatment of the wastes using the microbes efficiently reduced the COD in the average range of 30–70% (initial COD value from 16 to 4 g/L) over the study period of 2 years.

Thus based on the COD removal efficiency from the sludge, a series of cylindrical-type longitudinal MFCs with a total internal volume of 1 L have been constructed for the treatment of sucrose wastes as model substrate (Jung Rae et al. 2011). The MFCs consist of 0.5 mg m^{-2}-coated membrane as air cathode and carbon veil as anode, and it was operated for more than 7 months. The active microbes cultured from the sludge were obtained from Cog Moors Sewage Treatment Works, Cardiff, UK, and were acclimatised for more than 3 weeks in the digester compartment. Independently connected MFC modules showed maximum power density up to 6% and 36% at 0.8 and 0.08 g/L of sucrose containing wastes, respectively, as compared to parallel connected MFC modules. The study emphasised that the increasing number of tubular MFC modules would maximise the organic removal as well as power generation efficiency. The tubular design MFCs has higher possibility for the scaled-up process.

Haugen et al. (2015) has reported the use of computer modelling for the full-scale pilot plant optimal design of anaerobic digestion reactor (UASB) for the treatment of dairy farm wastes especially dairy manure produced from herd. The planned full-scale pilot plant has the volume of 250 L, and solid particles removed were 25% wet dairy wastes. The reactor has produced more than 70% of methane gas. The mathematical optimisation of the reactor design and optimisation of parameters revealed that at the reactor temperature of 36 °C, the maximum power surplus up to 49.8 MWh/y with the hydraulic retention time of 6.1 days was achieved.

In another instance, the use of upflow reactor design coupled with ionic liquid-type membrane for the continuous electricity production from the treatment of industrial wastewater has been investigated. In this study, the reactor with 1.7 L was built containing a single-chamber air-cathode electrode coated with 0.5 mg/cm^2 platinum, and the combination of graphite bar and carbon granules was used as anode (Salar-Garcia et al. 2016). Instead of the usual Nafion membrane, ionic liquid based on the triisobutyl(methyl)phosphonium tosylate and methyl trioctylammonium chloride was used for the preparation of polymer inclusion membranes.

13.7.4 Stacked MFCs

Reaching the maximum power density of the MFCs is a major task for the commercial or large-scale applications. Besides the single-chamber, dual-chamber, upflow tubular MFCs, the development of stackable MFCs is proved to be a successful design to achieve the maximum power density (Ravinder et al. 2017a, b). By definition, the stacked MFCs are constructed by joining multiple SCMFC, DCMFC, and UCMFC in series or in parallel to increase the output of the MFCs. Thus, in the stacked MFCs, the multiplication of the power output of single MFCs is possible with respect to the number of MFCs connected together. In addition to the power generation, the maximum reduction in COD values can be achieved because of the efficient degradation of the organic matters present in the wastewater.

For instance, six single continuous MFCs showed power output up to 258 W m^{-2} in the stacked configuration and when the MFCs connected in parallel or in series showed an increase in voltage up to 2.02 V at 228 W m^{-2} (Peter et al. 2006) (Fig. 13.5). Both anode and cathode materials consist of graphite granules and graphite rod, and the rod was operated for more than 7 months. By connecting six individual units of MFCs, the total volume of 360 mL was achieved. Based on the open circuit voltage (OCV) output, the individual MFCs showed 693 mV, and nearly sixfold increase in the OCV was achieved when the MFCs were connected in series, whereas the parallel connection showed 668 mV OCV.

In another example, 10 units of single MFCs were connected in parallel to generate OCV of up to 13.03 V using the activated sludge as the fuel and were operated in continuous mode (Pablo et al. 2013). The stack was designed to power the

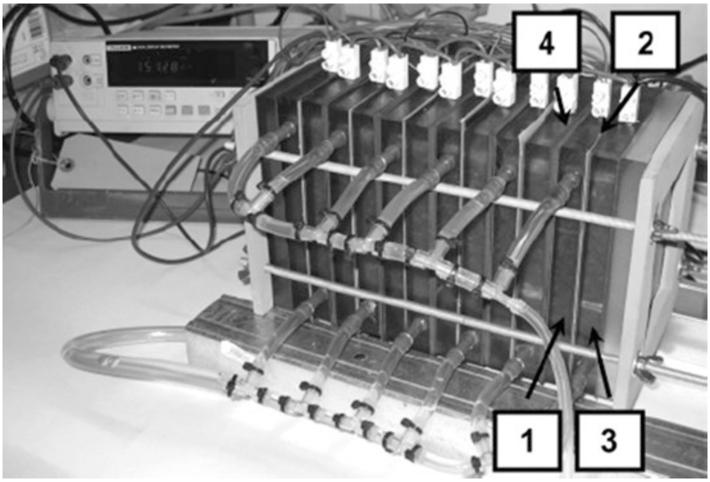

Fig. 13.5 Parallel connected stack microbial fuel cell (MFC) consisting of six individual microbial fuel cells (MFCs) with (1) a granular graphite anode, (2) an Ultrex cation exchange membrane and (3) a 50 mM hexacyanoferrate cathode separated by (4) a rubber sheet. (Credit: Peter et al. 2006)

microcontroller, and it is programmed for self-monitoring as a self-sustainable model. On the other hand, the stacks of the MFCs showed more than 96% reduction in the COD value using the continuous operation mode. Similarly, Yujie et al. (2014) have constructed a stacked MFC for the real-time application to treat the municipal wastewater collected from Harbin Institute of Technology, Harbin, China. A single horizontal MFC with a capacity of 250 L has been built and connected with 0.25 mg/cm^2 platinum-coated carbon mesh as air cathode and carbon brush combined with titanium wire as the anode. Four of the above individual modules were connected independently without affecting the other module performance or operation. The maximum power output up to 116 mW was generated by the above model, and in addition to that, a maximum COD reduction up to 79% was observed. However, the development of internal resistance is the limiting factor in the large-scale applications.

A 90 L pilot-scale stackable MFC has been constructed for the treatment of brewery wastewater (Yue Dong et al. 2015). In this study, five individual modules were slotted in the 100 L reactor, and each module is connected with activated carbon-coated PTFE as cathode and carbon brush woven with titanium wire as anode, and the system was operated at 25 °C (Fig. 13.6). Brewery wastewater collected from Harbin Brewery Co., Harbin, China, was used as the influent with hydraulic retention time of 3 days, and the performance of the MFC was evaluated for 6 months.

The above design effectively reduced the suspended solids (SS) up to 81.7 and 86.3% in the diluted sewage (stage 1) and raw sewage water (stage 2), respectively. Likewise, tremendous reduction in COD values were also observed up to 84.7 and

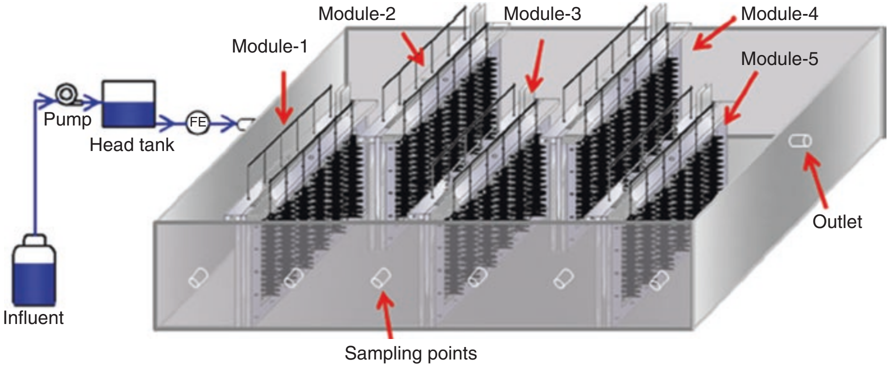

Fig. 13.6 Schematic drawing of the 90 L stackable baffled microbial fuel cell. (Credit: Yue Dong et al. 2015)

87.6% in the stage 1 and stage 2 processes. In addition, the system proved to be self-sustained since it generated 0.097 kWh m^{-3} that is capable of powering the pumping system (0.027 kWh m^{-3}). The results are encouraging, and the above design could be successfully adopted for the larger-scale or commercial applications.

By using stacked MFC design, Byung-Min et al. (2016) developed the stacked MFC for the treatment of ethanolamine containing synthetic wastewater at pilot-scale level. The working volume of the reactor was set in 1 L in which the reactor is equally divided into five parts using the baffles and connected to two sets of electrodes to improve the efficiency of the cell. The system utilised wettable carbon cloth as anode and 30% wet proof carbon cloth as air cathode. The air-facing side of the electrode was coated with activated carbon/PTFE and 10% platinum-coated side used for solution-facing side. The anodic chamber is filled with the synthetic wastewater containing 1000 mg/L of ethanolamine. The performance of the cell was evaluated based on the COD reduction and power-generating efficiency at 25 °C. The use of dual anode and cathode in the stacked MFC design has generated power up to 0.86 W m^{-2} with maximum carbon and ammonia removal efficiency up to 95.30 and 95.70%, respectively.

Since the reactor designs have the major role on the performance of the MFCs, the development of novel designs would be always beneficial for the improvement of the power-generating as well as waste-treating efficiency. Also, each design has its own flaws, which limits their application in the commercial-scale or pilot-scale level and in turn affects the practicability of the MFCs. For instance, the anode fouling affecting the biofilm on the anode is a major issue in SCMFC, and proton accumulation is a shortcoming of DCMFCs. So far, the stacked MFC design includes either SCMFC or DCMFC or baffled designs were investigated. But the hybrid of SCMFC and DCMFC in the stacked design has so far not been investigated. However, recently hybrid fuel cell stacks have been constructed at the laboratory level for the treatment of synthetic wastewater using single and dual chamber (Wei et al. 2016). The hybrid design showed improvement in the power generation of

0.8 V with operational stability up to 16 h, which is comparatively stable than the stacked SCMFC and DCMFC alone.

13.7.5 Flat-Plate Microbial Fuel Cells (FPMFCs)

The raise in internal resistance is a major issue in the large-scale application of MFCs. Thus, the FPMFC design is mainly developed to overcome the internal resistance to ease the pilot-scale operation of the MFCs with continuous operation. In the FPMFC model, the anode and cathode are kept very close and separated by a cation exchange membrane. For instance, wastewater that is consistently generated either from domestic or industrial process is required for the continuous treatment in order to maintain the equality of groundwater. Also, using MFCs for the treatment of wastewater can continuously generate the electricity. The typical FPMFC is constructed using single electrode consisting of platinum- or carbon-based electrodes separated by proton exchange membrane (Fig. 13.7) (Booki and Bruce Logan 2004). The domestic water or fresh organic materials can be employed as energy sources. The FPMFC, with total cell volume of 22 cm^3 is constructed with two chambers separated by Nafion membrane, in which carbon paper connected to one chamber act as anode and 10% platinum coated electrode connected to other chamber acts as cathode. For the real-time application, the domestic wastewater collected from Pennsylvania State University water treatment plant used as fuel and also carbon sources such as glucose, acetate, dextran, starch and butyrate

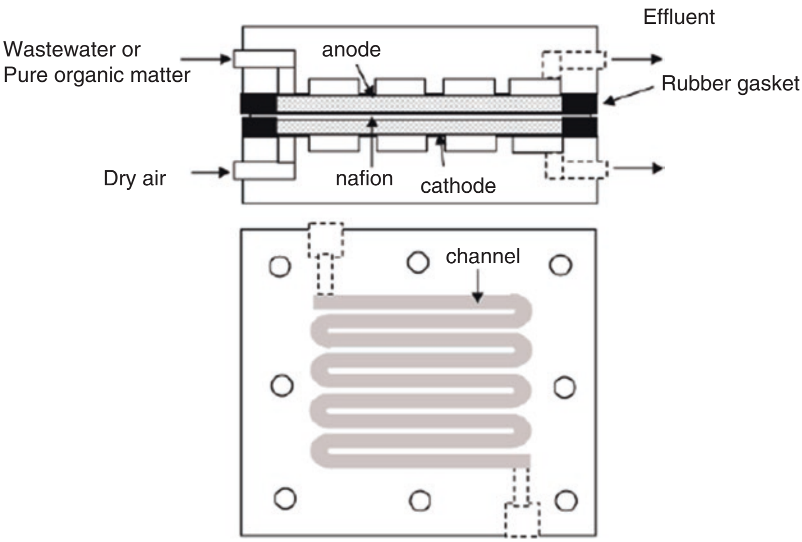

Fig. 13.7 Schematic view of FPMFC. (Credit: Booki and Bruce Logan 2004)

were added to make up the final COD value of 1000 mg/L. The FPMFC was operated at 30 °C.

Marjolein et al. (2012) reported a plant-based FPMFC using *Spartina anglica* as a plant source. The design of FPMFC uses graphite felt as both anode and cathode, and the electrodes are separated by cation exchange membrane. The working volume of the MFC is about 650 mL. The performance of the FPMFC was monitored for nearly 2 years. The study revealed that the use of FPMFC model reduced the internal resistance considerably as compared to the tubular model. The performance of membrane used for the separation of the electrodes is of great importance for the effective functioning of the FPMFC. The performance of FPMFC constructed using various commercially available membranes has been evaluated (Sona et al. 2016). In this study, the membrane having high coefficients of oxygen and ethanol mass transfer showed lower power density when the electrodes were kept in close proximity. However, the Nafion 117 showed high performance as compared to other separators used in the study. For instance, the cell constructed with Nafion 117 with electrodes spacing of 2 mm showed the OCV up to 0.75 V and 10.7 ± 0.5% columbic efficiency when compared to other MFCs. In addition, a marginal increment was observed in OCV and columbic efficiency when the electrode spacing was increased from 2 mm to 4 and 8 mm.

Unless the issues such as expensive electrodes, internal resistance and electrode fouling are resolved, the continuous operation at the larger scale would not be commercially viable. The presence of proton exchange membrane (PEM) in the FPMFC model would possibly eliminate the biomass as well as oxygen that would enhance the MFC efficiency to generate the maximum power during the continuous operation. Adoption of the FPMFC model made of graphite felt electrodes along with air-breathing cathode could solve the issues related to the electrodes. For instance, the FPMFC is constructed using graphite felt anode, platinum-coated carbon cloth as air cathode separated by PEM containing activated sludge collected from Howe Sound Pulp and Paper Mill, British Columbia, Canada, for the treatment of synthetic wastewater at batch process as well as a continuous process (Sona et al. 2015). In the batch mode process, the cell has produced maximum power density up to 40 mW m^{-3}, and the same has showed better performance by producing 95 mW m^{-3} during 250 h. The COD removal efficiency was achieved up to 60% during the continuous operation of the MFC.

The anaerobic fluidised bed microbial fuel cells (AFB-MFCs) have been developed for the continuous operation using air cathode. The synthetic wastewater circulated through the column of carbon particles, and the wastewater was continuously pumped through a peristaltic pump from the storage tank (Xuyun et al. 2015). In this model the cell was capable of generating 900 mV by gradual increment up to 80 h, and after that the power steeply increased to 900 mV and stabilised up to 120 h.

Thus, based on the application and the requirement, various MFCs model can be chosen for the further development. Among the several designs, cylindrical-type, FPMFC and combined stacked model MFCs have tremendous opportunities for the larger-scale applications. Several instances on the construction design of various types of MFCs and its effective operation at pilot scale have been discussed above. The majority of the large-scale applications of MFCs largely dealt with treatment of wastewater together with the generation of power successfully. It would be a worthy option to discuss the various types of wastewater treated using the MFC technology.

13.8 Field Trials of MFCs

The commercialisation of MFCs has much complexity since the efficiency of MFC is still under development when working with real industrial effluents (Padma and Hays 2012; Escapa et al. 2016). Firstly, effluents containing various kinds of organic wastes have been used as fuel for anode in MFC, but the mechanism of interaction between the electroactive microorganism and fuel could not be clearly established, and still it remains a challenging task for investigators (Ganesh et al. 2017; Hai-Liang et al. 2015). Secondly, MFCs generate relatively lower energy when compared with electrochemical cells though they offer many advantages over the latter. In addition, the knowledge on the nature and type of the effluents generated from industries and anthropogenic activities is necessary, and feasibility of treating them with electroactive microbes should also be checked for the construction of MFCs.

Thus this section focuses on the contribution on the treatment of the wastewater using MFCs which has been summarised in a nutshell. In addition, the problems associated with the commercialisation and solutions are also discussed at the end of the chapter as solutions at laboratory level. Further, the latest reports on economical cathode material development are also discussed.

13.8.1 Application of MFC for Wastewater Treatment

The uses of microbial fuel cell technology have immense potential for the wastewater treatment, and it has the history more than a decade (Dan et al. 2015; Dimou et al. 2014). Based on the origin and availability, one of the MFC designs may be adopted for the continuous or batch process applications. A number of reviews appeared frequently that deal with the advancements and challenges in the treatment of various kinds of wastewater (Zhuwei et al. 2007; Rene Rozendal et al. 2008; Bruce Logan 2010; Micheal and Thomas 2013; Minghua et al. 2013; Oliveira et al. 2013; Haishu et al. 2016; Prashant et al. 2016; Iwona et al. 2016; Gude 2016a, b; Carlo et al. 2017), and MFC technology is used to enhance the removal efficiency of organic matters to restore the sediments (Henan et al. 2017)

13.8.2 Constructed Wetlands

Constructed wetlands (CWs) are best known as artificial wetlands that are created mainly for the treatment of wastewater of domestic, industrial and agricultural sources generated from small communities (Wu et al. 2014). The wastewater generated from the anthropogenic activities may contain various kinds of organic wastes that could be a viable source for the generation of electricity if the microbial fuel cell technology is successfully implemented. The installation of MFC at pilot scale in the CW would treat the wastes as well as the system would become self-sustainable. In addition, it would help in monitoring the quality of wastewater influent and effluent. The construction of wetlands majorly uses the model of horizontal subsurface flow (HSSF-CW) at 0.3–0.6 m depth. The performance of the HSSF-CW is evaluated based on the design parameters. The efficiency of the treatment depends on the percentage removal of COD, nitrogen content and sulphate (Corbella and Puigagut 2015). An added advantage for the construction of the MFC in CW is to provide redox gradient of about 0.5 V between the upper and lower layers.

For instance, as shown in Fig. 13.8, a pilot-scale HSSF-CW combined with MFC model has been constructed in the Institute of Chemical and Environmental Technology, Castilla La Mancha University, Spain (Villasenor et al. 2013). The above CW combined MFC system to a 150 L wastewater tank and peristaltic pump to supply wastewater at variable flow rate. The graphite material is used as cathode and anode connected to the upper and lower layer, respectively. The CW-MFC system was operated with respect to variable COD and organic loading rate by continuous mode for about 6 months. The above system showed average power density up to 15.6 mW m^{-2} and maximum power density up to 43 mW m^{-2} with COD removal efficiency up to 90–95% during 110–130 days of the overall study period.

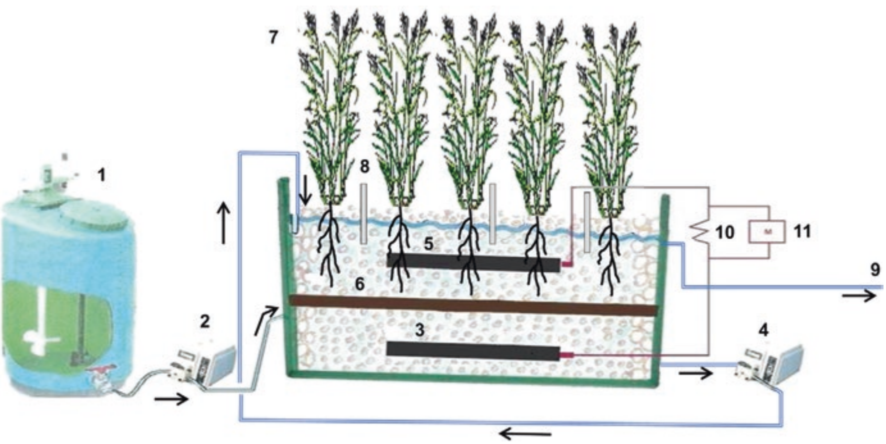

Fig. 13.8 Experimental installation. (1) Wastewater tank; (2) peristaltic pump; (3) anode; (4) peristaltic pump; (5) cathode; (6) bentonite layer; (7) reed plants; (8) sampling points; (9) treated effluent; (10) resistance; (11) multimeter. (Credit: Villasenor et al. 2013)

Doherty et al. (2014) has reported the CW based on alum sludge combined with MFC for the treatment of swine slurry. The performance of the system has been evaluated with respect to the electrode spacing, sludge flow rate and ammonia, COD and phosphate removal efficiency. The maximum power density achieved up to 0.268 W m^{-3} with 75% ammonia and 64% COD removal efficiency by upflow-downflow regime. On the other hand, continuous upflow operation delivered 80% boost in power density with 79% ammonia and 81% COD removal efficiency.

Two small-scale CW-MFC systems with a capacity of 3.7 L have been constructed for the treatment of swine wastewater dedicated for operation at batch and continuous mode (Zhao et al. 2013). The continuous upflow mode of operation showed improved performance by 76.5% average COD removal efficiency with maximum power density of 9.4 mW m^{-2}, whereas batch mode operation showed 71.5% removal efficiency with maximum power density of 12.83 μW m^{-2}.

Very limited investigations have been made in the evaluation of MFC combined with constructed wetlands. However, some interesting preliminary results showed MFC has potential application in CWs as treating the wastes as well as generating power.

13.8.3 Small Island

Kiran and Praneet (2015) reported the performance of the pilot-scale MFCs built in Trinidad and Tobago, which are small-island developing states. Generation of wastewater and shortage of groundwater quality seriously affect these small islands. Thus, the states require the state-of-art MFC technology, which can generate power by using wastewater stream as a fuel. The above system is specially designed for small island countries like Caribbean islands. The construction of MFC consists of two major chambers separated by proton exchange membrane (Fig. 13.9). The domestic wastewater collected from various sources is flown to the anodic chamber after thorough screening of wastewater. On the other hand, the seawater collected from the Atlantic Ocean and Gulf of Paria is taken in the cathodic chamber. The microbes present in the domestic wastewater are attached to anode. The study revealed that the constructed MFC showed decrease in biological oxygen demand (BOD) and increase in chemical oxygen demand (COD) from 30% to 75%. Both the systems delivered power density up to 84 and 96 mW/m^2.

The above system is advantageous since it generates power from the domestic wastewater while treating them with the microbes. Thus, the above MFC could be economically viable as well as offers solution for wastewater treatment.

Bruce Logan (2010) reported that the power density of MFCs could reach up to 1 KW/m^3 and 6.9 W/m^2 per surface area of anode at the laboratory level. The main obstacle is applying the laboratory parameters to the production at pilot scale, and it required further modification of the laboratory parameters. Novel and economically feasible electrodes viz., cathodes, membranes and separators are crucial to achieve better performance at the commercial scale. Currently, the fabrication of air-cathode

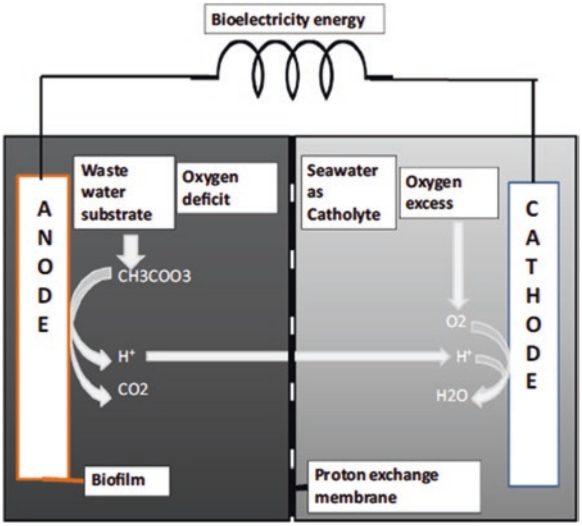

Fig. 13.9 Two-chamber MFCs constructed at Trinidad and Tobago. (Credit: Kiran and Praneet 2015)

design could be successfully implemented for large systems like wastewater treatment using the MFC technology.

Padma and Dirk (2012) have reported the possible types of MFC construction and development of electrode materials. The MFCs are mainly classified into four types. The first type is the two-chamber MFC, where anode and cathode are kept in different chamber and separated by proton exchange membrane. The second type is the single-chamber MFC, in which anode and cathode are kept in the same chamber and separated by proton exchange membrane. It's construction is simple when compared to other types and is therefore, less expensive. However, it has drawbacks like microbial contamination and short circuit. The third type is a vertical-type MFC, where anode is kept at the bottom and cathode at the top. Glass wool and glass beads were used to separate the electrodes. This system can be employed for large-scale wastewater treatment and power production. In the fourth type, a series of single-chamber MFC were connected to form stacked MFCs. By using the stacked-type MFC, high power density can be achieved. In addition to the usual designs, flat-plate microbial fuel cell design can also be used for the treatment of wastes and could also be successfully operated in the small islands. However, optimisation on the design parameters such as reactor size, membrane and electrode materials is necessary as well as thorough understanding of wastewater parameter would help to choose the design and construction of suitable MFCs.

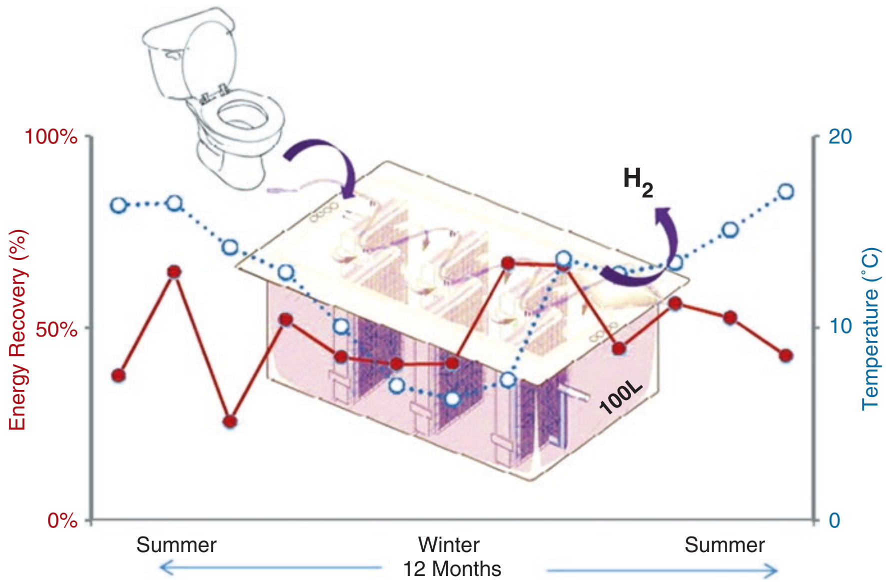

Fig. 13.10 Construction of microbial electrochemical cells (MEC) using domestic wastewater. Also, the plot of energy recovery and temperature is included in the image. (Credit: Elizabeth et al. 2014)

13.8.4 Domestic Wastewater

The organic and inorganic wastes generated in water due to day to day human activities has to be regularly monitored for their qualities (Valesquez-Orta et al. 2017). Waste water generated from different sources has to properly treated prior its entry into the river or main water stream. By using MFC technology, domestic wastewater can be treated while generating power, and the system may become self-sustainable, and in addition, this technology also avoids expensive and non-energy recoverable treatment methods (Booki and Bruce Logan 2004; Jeffrey et al. 2010; Castro 2014; Cotteril et al. 2017; Elizabeth et al. 2013)

Elizabeth et al. (2014) reported on the pilot-scale microbial electrolysis cell (MEC), which is performed on domestic wastewater as a fuel. The wastes generated from anthropogenic activities have been used to generate electricity by constructing the MEC with a capacity of 100 L (Fig. 13.10). The performance of the MEC was continuously monitored for 12 months in temperature range of 1–22 °C. The cell can be capable of producing 0.6 L of hydrogen per day, and the hydrogen production was found to be decreasing with respect to increase in time. However, nearly 48% on average electrical energy was recovered with an efficiency of 41.20%. On the other hand,

Castro (2014) developed a large-scale MFC system for the treatment of human wastes (The Green Latrine) in Ghana. The construction of MFC for the human faeces and urine is expected to deliver treated effluent, compost as well as energy recovery. In this investigation, hydraulically separated three-chamber MFC has been built. The performance of the MFC was evaluated by nitrogen and organic matter removal efficiency. By using the above model, the COD removal efficiency achieved was 90% and nitrogen removal efficiency achieved was 76.8 ± 7.1% and delivered maximum power production was 3.4 ± 0.01 nW m^{-2}.

A 200 L pilot-scale MFC system is constructed for the treatment of municipal wastewater collected from primary clarifier, Pepper's Ferry wastewater treatment plant, Radford, VA, USA (Zheng et al. 2015). The system consists of 2 L tubular reactor connected in series by various arrangements to make 100 L effective working volume as well as to achieve the maximum power recovery efficiency. The MFC system consists of cathode made of nitrogen-doped activated carbon with an HRT of 18 h. The system showed maximum conversion efficiency up to 80% with 11.4 mW power output.

Cotteril et al. (2017) developed a large-scale MEC for the treatment of domestic wastewater in collaboration with Northumbrian Water Ltd., Northwest England, UK. The large-scale MEC module with an area of 1 m^2 has been built to treat wastewater having an average COD value of 340 mg L^{-1} without the addition of any acetate or phosphate buffers. The MEC system consists of 316 stainless steel mesh as cathode (total surface area 0.8 m^2) and graphite felt as anode (anodic area 1 m^2 × 3 modules) with a tank volume of 175 L, and the MEC is operated for the span of 217 days. The large MEC has generated hydrogen of about 0.8 L per day. The COD removal efficiency was found to have an average value of 63.5%. However, the rise of pilot-scale MEC to commercial scale needs process optimisation in terms of reactor design, electrode materials and thorough understanding of the wastewater.

13.8.5 Brewery and Winery Industries

The wastewater generated from winery and brewery industries is rich in various kinds of sugars, proteins and other organic matters, which led to the rise in COD value of wastewater and wastes being non-toxic in nature (Prashant et al. 2016). Because of the high COD value, the winery and brewery wastewater could be an excellent recoverable energy source if they are properly treated using suitable MFC design.

Parawira et al. (2005) reported on the large-scale anaerobic treatment using upflow anaerobic sludge blanket (USAB) reactor for the treatment of organic matter collected from the opaque beer brewery wastewater. The system was installed close to the beer brewery effluent plant, and the study continued for about 2 years. The study is intended for the degradation of organic matter and focused on the COD removal efficiency and other wastewater parameters. The use of USAB effectively reduced the COD value up to 57%. However, the study is not extended to energy recovery using MFC technology.

A prototype upflow single-chamber MFC has been constructed for the treatment of diluted brewery wastewater (1:20 by volume) collected from Hexham Municipal Sewage Treatment Plant, Northumberland, UK (Krishna and Scott 2010). The COD value of the wastewater is around 430 mg L^{-1}, and the MFC was operated in batch mode for 455 h. The cell showed stable maximum density up to 330 mW m^{-2}.

Cusick et al. (2011) evaluated the pilot-scale MFC constructed for the treatment of winery wastewater using continuous mode of operation. The wastewater generated from winery industry is rich in various types of carbohydrates and is the major source of energy. A single-chamber MEC design is used for the field study with reactor working volume of 1000 L and graphite felt and SS304 as anode and cathode, respectively. The electrolysis cell delivered an average COD removal efficiency up to 62 ± 20% with hydraulic retention time of 1 day. The current generation reached up to 7.4 A m^{-3} at the end of 100 days of study.

As discussed earlier in this chapter, Yue dong et al. (2015) constructed a 90 L single-chamber MFC containing five modules of electrodes fixed in the stacked design for the treatment of brewery wastewater. The study revealed that this pilot-scale MFC produced power while degrading the organic wastes present in the effluent by efficiently reducing the COD up to 88% without any energy input. The use of MEC for the treatment of wastewater collected from the craft brewery, Ontario, Canada, has been explored by Ellen et al. (2016). The wastewaters generated from the microbreweries are rich in organic matters and have the highest COD value up to about 2250 mg L^{-1}. A two-chamber MFC has been developed for the treatment of 84 L per day of wastewater. The system has achieved 91.9% COD removal efficiency with the generation of 26.4 mWh electricity.

Based on the studies above, the carbohydrate-rich wastewater collected from brewery, winery and also sugar industries, which are naturally having higher COD value, would be a viable source for the operation of MFCs.

13.8.6 Agro-Food and Dairy Industries

The use of MFC technology has been explored for the treatment of the wastewater generated from food-processing industries such as rice mills, cassava mills, palm-oil mills and mustard tuber mills as well as from the dairy industry wastes such as cheese whey, milk wastes and yoghurt wastes. Among the food industry wastes, dairy wastewater contains the highest COD values because of the presence of sugar as a major constituent. The performance of the MFC has been evaluated based on the reduction of COD. In addition, various designs of the MFC have been explored for the treatment of agro-food industry wastewater (Prashant et al. 2016; Wen-wei et al. 2013).

Daniele et al. (2017) discussed on the energy recovery from the dairy wastewater using dual chamber MFC (DCMFC). The DCMFC reduced the COD value up to 90% with generation of 27 W m^{-3} power density. XiaoNan et al. (2011) explored on the possibility of using continuous flow MLMFC for the treatment of cow manure, milk wastes, cow slurry wastes and feed wastes. The use of MLMFC effectively reduced the COD values up to 98% under continuous mode of operation and recovered more than 80% of energy as hydrogen from the wastes.

A laboratory-level single-chamber MFC using the rice bran wastes as carbon has been reported by Takahashi et al. (2016). The capacity of MFC is 15 mL and equipped with graphite felt as anode and PTFE coated with platinum catalyst as air cathode. The mineral solution containing paddy soil and rice bran was used as anolyte, and the cell was operated at 30 °C. The power output increased from 0.1 V to 0.5 V after 30 days of acclimatisation. The study revealed that *Trichococcus* and *Geobacter* are specifically responsible for the oxidative degradation of the organic matter such as rice bran. Instead of rice bran, other agricultural wastes like whey could also be used as a carbon source.

13.9 Problems Associated with Pilot-Scale Studies

The major challenges which remain in the construction of commercial- or pilot-scale MFCs are expensive electrode material, screening the complexity of fuels, type of microbes, operating temperature, power density and longevity. The upscaling of MFCs using the parameters as developed in the laboratory mainly depends on the operating conditions such as temperature, pH, wastewater type and operation time. In addition to the above, the properties of the electrode materials, surface area of the electrode, electrode-microorganism interaction and the reactor size has to be considered for the successful development of MFCs. The cost of the electrode materials should be minimised substantially, and more economically viable electrode without losing the efficiency of the power generation would be commercialised effortlessly (Bruce Logan et al. 2006). On the other hand, the clear understanding of the nature and composition of the wastewater is essential for establishing the mechanism of electron transfer. In addition, the thorough investigation on the microorganisms present in the wastewater should be made (Vinay and Kundu 2010; Venkata Mohan et al. 2014).

13.10 Solutions at Laboratory Level

The efficient anode is necessary for the upscaling of MFCs. The characteristics of the anode should possess good electrical conductivity, stronger adhesion towards microorganisms, larger surface area, excellent stability towards severe weathering condition/continuous operation and low-cost materials. The development of low-cost anodic materials would tremendously reduce the construction investment of the MFCs. Subsequently, the carbon cloth or nitrogen doped gra phene aerogel that are low-cost carbon based materials can be used.

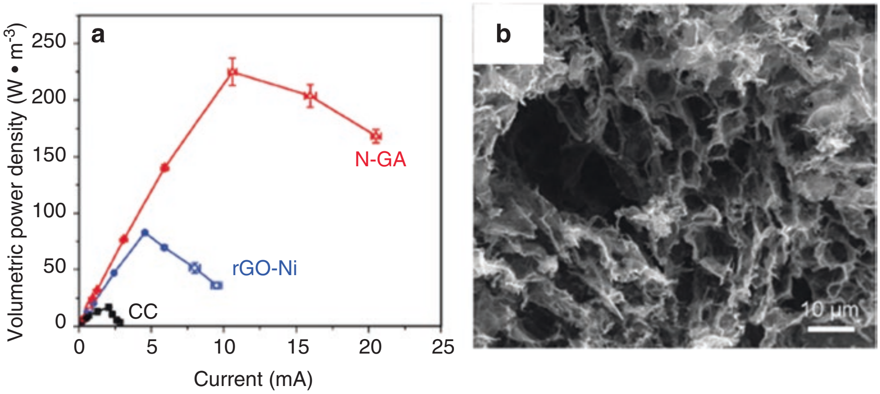

Fig. 13.11 (**a**) Volumetric power density, (**b**) SEM image of N-GA. (Credit: Yang et al. 2016b)

The graphene oxide doped with nitrogen (N-GA) has been successfully adopted as the anodic material for the development of microfluidic MFC (Fig. 13.11). The microfluidic MFCs are useful for the design of biosensor and micropower generators. The N-GA containing MFCs generated power density of 1181.4 ± 135.6 Wm^{-3} in the continuous mode and 690.2 ± 62.3 Wm^{-3} in batch mode process (Yang et al. 2016a). The presence of nitrogen doping on a low-cost material like carbon considerably reduces the cost of the MFC construction. Further, the above report added that the nitrogen doping acts as catalytic sits that enhanced the power density by oxygen reduction rate (ORR). The nitrogen-doped graphene porous aerogel anode electrode showed a power density of 225 ± 12 W m^{-3} using the dual-chamber MFC (Yang et al. 2016b). According to the report, the presence of nitrogen doping tremendously reduced the charge transport resistance and enhanced the power density of the MFCs. The porous nature of the aerogel electrode design can enhance the adhesion capacity and facilitate the cultivation of the bacterial communities. Based on the report, the generation of the power density was found to be higher for the laboratory (chamber capacity 25 mL)-level investigation. As per report, the N-GAMicrobial fuel cells (MFCs): was obtained by the reaction of ammonium hydroxide with acid-treated graphene oxide at 180 °C under hydrothermal conditions (Yang et al. 2016b).

Hanyu et al. (2013) developed the 3D reduced graphene oxide deposited Ni foam (3D rGO-Ni foam) as an anodic material for the construction of MFC (Fig. 13.3). The anode material has been obtained by the controlled deposition of graphene oxide over the Ni foam using reduction process. The power density up to 661 W m^{-3} was achieved using 3D rGO-Ni foam as anode under batch mode process. As per report, the power density achieved using the above electrode was found to be higher as compared to the anode materials derived from carbon-based materials such as carbon felt, carbon cloth and carbon paper. The uniform porous nature of Ni foam provided effective diffusion of microorganism, and more surface area offered space for the microorganism to colonise to the large extent. The MFC has been worked

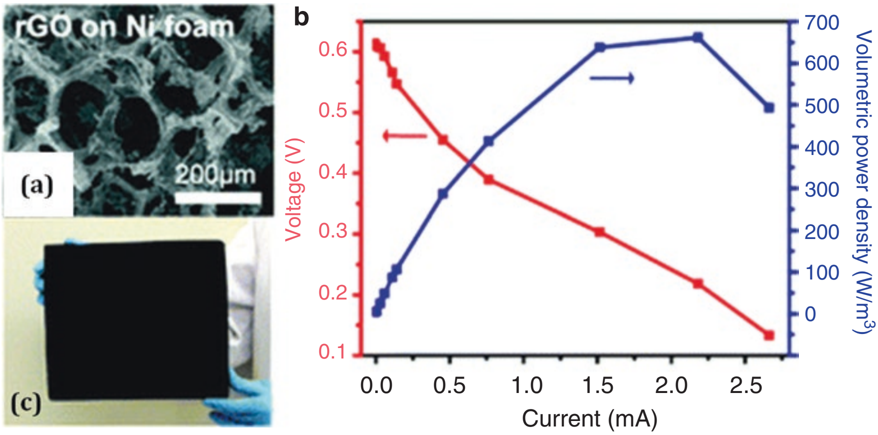

Fig. 13.12 (**a**) SEM picture of rGO on Ni foam, (**b**) polarisation and power curves collected for a MFC device with rGO-5-Ni anode. (**c**) Digital picture of a 25 cm X 20 cm rGO-Ni foam. (Credit: Hanyu et al. 2013)

more efficiently under bat-mode process using the pure strain of *Shewanella oneidensis MR-1* bacterial culture (Fig. 13.12).

The use of conducting polymer-coated carbon felt as an anode material for the evaluation of MFCs has been investigated by Chao et al. (2011). The two-chamber MFC has been constructed using carbon felt anode material coated with polyaniline (PANI) and polyaniline-co-*o*-aminophenol (PAOA). The PANI-coated anode containing MFC showed a power density of 27.4 mWm^{-2}, and the cell was found to effectively work in the presence of *Hippea maritima* bacterial culture, whereas the PAOA-coated anode material showed a power density value of 23.8 mWm^{-2} under *Clostridiales* bacterial strain. Further, the investigation stated that the power density produced by MFCs containing surface-modified anode is higher as compared to the pure counterpart. The nanographene sheets doped with nitrogen using plasma-enhanced chemical vapour deposition (CVD) have been utilised as an anode for the construction of the MFCs (Joseph Kirubakaran et al. 2015). The N-doped nanographene sheets showed porous and cross-linked framework structure as observed from electron microscope techniques. The MFC was constructed using the above as the biocompatible anode, glucose as energy source and *Escherichia coli* as redox biocatalyst. According to the report, the MFC has capacity of producing a power density of 1008 mW m^{-2}.

13.11 Future Perspectives

Based on the numerous reports, the many types of carbon electrodes have placed an ambitious focus for the development of novel low-cost electrodes for the MFC applications. The use of carbon materials would be cost-effective replacement for the expensive metal-based electrodes. Apart from the economical perspective, the carbon-based materials are biocompatible, and thus it can be suitable for wide range of microorganisms. On other hand, they can also be obtained from carbon biomass waste using suitable process. The carbon materials such as carbon cloth, carbon felt, carbon foam, graphene sheets, microporous and mesoporous carbon materials have tremendous opportunities for the fabrication of microbial fuel cells at the pilot-scale level or commercial-scale level. In addition to the electrode fabrication, the appropriate selection of the chamber design and size should be considered based on the location, type of waste to be treated, mode of operation (whether continuous or batch mode process) and source of energy.

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