Chapter 17
Microbial Fuel Cells: The Microbial Route for Bioelectricity

Mridul Umesh and Hanish Mohammed Coppath Hamza

Abstract The quest for sustainable energy sources serves as the essential pillar for development of humans since the dawn of civilization. The alarming increase in demand of energy, especially electricity propelled the need to screen for alternative sources of energy over the conventional fossil based non-renewable counterparts. Electricity generation through microbial route functions by the fundamental phenomena of electron transport chain and the microbes operate as the source of energy production utilizing the substrate. Since its initiation, microbial fuel cell has gained a lot of research focus from all over the world. The integration of waste treatment with power generation was highlighted as the most productive and sustainable part of microbial fuel cells. Over the past few decades, a lot of research and development was done on improving the design of fuel cells, searching for cost-effective electrodes and membranes for commercialization. Despite tremendous research done on this domain, its commercialization still faces a lot of hurdles especially once it comes to the overall maintenance and production cost. This chapter summarizes the basic architecture of different microbial fuel cells and the challenges that need to be addressed for making microbial fuel cells a sustainable route for the bioelectricity generation from microorganisms.

Keywords Bioelectricity · Energy · Electrodes · Membranes · Microbial fuel cells

---

M. Umesh (✉)
Department of Life Sciences, CHRIST (Deemed to be University), Bangalore, Karnataka, India
e-mail: mridul.umesh@christuniversity.in

H. M. C. Hamza
Department of Environmental Sciences, Bharathiar University, Coimbatore, Tamil Nadu, India

P. Kumar, C. Kuppam (eds.), *Bioelectrochemical Systems*,
https://doi.org/10.1007/978-981-15-6868-8_17

17.1 Introduction

Energy is the basic element for the functioning of every single action pursuit, need for energy is multiplying with the advancement of life and population increase. Energy is gained from different sources broadly from renewable and non-renewable sources. In 2018, the demand for energy hiked by 2.3% globally. Forty-five percent demand for natural gas and seventy percent for fossil fuel and energy from the renewable sources also escalated (EIA Industrial Sector Energy Consumption 2016). Non-renewable energy sources are mainly from coal, petroleum, and natural gas; they do not replenish and are relatively inexpensive to extract but contribute largely for CO_2 emission. Renewable energy sources are from the renewable sources, namely from sun, wind, hydropower, geothermal and biomass. They are replenishable, less polluting but relatively expensive to extract. A productive economy utilizes more resources and has greater energy output as an influencing factor for the fulfilment of energy requirement by the growing population (Tang et al. 2018). Global energy consumption the energy extracted from all the resources are consumed by mankind through industrial and economy sectors and depends upon the consumerism in each country it varies. As the population increases energy consumption also increases consequently population turns as the major consumer of energy with a great importance in the socio-economic and political spheres since world energy consumption is the measure of civilization. Manufacturing sectors and industries consume the major portion of total consumption of energy in developing countries (Farjana et al. 2018). The economical development activity and technological development intensify fuel consumption; it varies over countries and regions (IEA 2019). According to International Energy Agency (IEA) global energy demand from non-renewable sources augmented to 4.6%, 1.3%, 0.7% and 3.3% by gas, oil, coal and nuclear energy respectively. The renewable energy from all these resources contributed to a 4% growth from the previous years by 2018 (IEA 2018). This implies the need of energy from any resources to meet the demand for the future but the growing global warming concerns demand much from the alternative renewable resources.

17.1.1 Energy from Renewable Resources

Globally energy crisis and global warming are the critical issues concerned with the multiplying population and depleting the non-renewable energy sources (Kadier et al. 2016a). Excessive energy consumption by humans augments environmental pollution, climate change impacts and the greenhouse effect (Saratale et al. 2017). Industrialization and technological developments raising the demand for energy ever and pressurize the environment with climate change and pollution issues (Kumar et al. 2017). The large-scale industrial developments are based on fossil fuel depending energy leading to the depletion of the natural resources and impacting the global climate change emitting greenhouse gases (Chandrasekhar et al. 2015a). The effect of pollution damaging the environment has accelerated the concern for energy from alternative source (Enamala et al. 2018). It increased the interest of using renewable energy from different sources (Kadier et al. 2017) so energy from renewable resources is given high preference that has lower environmental issues (Kadier et al. 2016b). Also production of energy from renewable resources is gaining more attraction internationally due to the depletion of fossil fuel and overcoming global warming problems (Kadier et al. 2015). Attaining WHO guidelines and Paris agreement for clean air and stable climate requires swift phase change. Energy from renewable sources is gaining importance worldwide for attaining a sustainable development and positive environmental quality. Renewable energy decreases the dependence on the non-renewable energy and sustaining economic condition in energy prices from volatility (Zafar et al. 2019). Renewable energy can profit the public health and climate replacing emissions caused by electricity generation using fossil fuels (Buonocore et al. 2016). Globally less carbon emission and sustainable development energy system are focusing on a sustainable future (Zhang et al. 2018). Study on CO_2 emission nexus between renewable energy and non-renewable energy of 128 countries from 1990 to 2014 ensued that renewable energy can reduce CO_2 emission (Zhang et al. 2018). Petroleum formation in nature is 105 times lagging behind its current consumption. Thus natural petroleum cannot meet the future energy demands and the greenhouse gas emission from their combustion leading to global warming has become more challenging, thus urging for development of green clean energy alternatives (Shuba and Kifle 2018). Hydropower, solar, wind, biomass and geothermal such renewable energy sources do have certain barriers to pass with environmental impacts and few are consequential. The potency of environmental impact variants rely upon the geographical location, technology employed and other factors, but understanding the issues associates with renewable energy effective measures are taken to avoid, to upkeep the supply. Escalating global energy consumption and depletion of conventional energy resources are addressing the insufficiency to meet the energy demand igniting energy crisis where renewable energy utilization becomes significant (Guo et al. 2018). Thermal, photovoltaic and wind generated energy require special medium or storage facility for later use (Gude 2015). Despite the few flaws renewable can substantiate the need of the green and cleaner energy for a better tomorrow.

17.1.2 Waste Management

Waste generation and disposal are an integral part of the society (Reddy et al. 2011a, b). The management of waste becoming a great environmental and public health concern due to rapid urbanization (Mohan and Chandrasekhar 2011b). Waste generation is gravely a global problem; the degree of waste generation depended on economic development, reducing, reusing and recycling efficacious tool for solving the waste issue (Minelgaitė and Liobikienė 2019). As the population increases the waste generation increases and waste management become a difficult process (Ayeleru et al. 2018). Municipal solid waste projected to reach over 2.2 billion tons per year by 2025 globally; landfilling and incineration are the most commonly used conventional techniques impacting public health negatively (Indrawan et al. 2018). In developing countries more than 70% of the municipal waste consist of degradable materials; these play a considerable part in greenhouse gas production. Only 60% of the municipal wastes are disposed at authorized sites and the remaining disposed at unauthorized sites (Ramachandra et al. 2018). A low carbon energy system of alternative resources and novel technologies to improve efficiency of the energy sector for a resource endowed future are the need of population (Kumar and Pandey 2019). Achieving greener growth efficient waste management and waste treatment are essential (Ghasemi et al. 2013). Waste collection, transport and disposal are the challenges in developing countries and developed countries are generating electricity, heat, biofuel and compost as by-products with the emerging technologies (Moya et al. 2017). Rapid growth of industries generates a vast amount of waste as solids and liquids such as food processing, distillery, dairy, tannery, slaughter houses, Sugar, poultries, sago paper and pulp industries, etc. Composting, recycling and energy recovery in waste management implementation have a great scope minimizing the waste disposed as landfill (Palanivel and Sulaiman 2014). Limitation in availability of land area for waste disposal along with infections associated with careless discharge of waste trigerred the waste management organizations to focus on technologies for recovering sustainable energy alternatives through waste valorisation (Fetanat et al. 2019). The current scenario vitalizes researchers to thrive new different waste to energy alternatives (Beyene et al. 2018). Food and beverage industries are huge consumers of energy and produces substantial amount of biowaste. These biowaste generated offer a promising potential for the recovery of sustainable energy alternatives there by enhancing the overall efficiency of integrated production process (Siqueiros et al. 2019). Paper and pulp industries every year utilize a large quantity of resources such as wood and water, creating a huge amount of solid waste and wastewater; these wastes are not treated properly and discharged, eco-friendly treatment and extracting energy from these wastes are the necessity of the day (Gopal et al. 2019). Slaughterhouse, agriculture and livestock produce large quantities of waste and are potential sources for generating electricity (Shirzad et al. 2019). Waste to energy technologies provide scope to recycle organic waste materials into renewable energy counterbalancing the disposal and environmental costs (Milbrandt et al. 2018). Bioelectrical systems and anaerobic digesters are expanding technologies as renewable energy from waste (Beegle and Borole 2018). Domestic and industrial wastewaters are generated hugely across the world, causing water crisis and environmental downturn, hence sustainable and energy efficient wastewater system is the solution for the issue (Rathour et al. 2019). Wastewater with a high organic load is contemplated as a valuable energy resource (Chandrasekhar et al. 2015b).

17.1.3 Microbial Fuel Cell

Trending shift from "waste to wealth" in the past few decades' vests considerable interest in organic biotic waste due to its high organic content, consequently comparing to conventional treatment technique electro-fermentation gains much interest (Kumar and Pandey 2019). The microbial fuel cell (MFC) is a promising technique for wastewater treatment and simultaneous electricity generation. MFC technology has gained the attention of researchers in the past two decades due to the possibility of utilizing organic waste as a cost effective substrate for energy production through microbial metabolism (Santoro et al. 2017). Climatic change and need for alternative energy are increasing concern and MFC qualifies as a solution of both the need (Slate et al. 2019). MFC is attaining scientific and technological significance considering the global scenario of meeting renewable energy and treatment of waste, the major advantage of MFC (Neto et al. 2018). The increasing demand for elctricity, scarcity of renewable resources for power generation coupled with high cost associated with waste water treatment propelled the need for integrating these domains for the sustainable production of electicity from MFCs using waste water as substrate for microbial growth (He et al. 2017). MFC generates bioenergy from waste reducing environmental pollution and the treatment cost (Gajda et al. 2018). The ability of MFC to utilize broad range of substrates makes MFC a promising and interesting fuel presently (Marks et al. 2019). Bioenergy generation and wastewater treatment advantages of MFC are comprised of energy saving and sludge volume reduction (Zhang et al. 2019). MFC as an alternative energy generation provides sustainable energy from biodegradable compounds; its applications include electricity generation, wastewater treatment, biohydrogen production and biosensors (Goswami and Mishra 2018). Hamza et al. (2017) unveiled the promising potential of MFC in application of heavy metal reduction from the wastewater distillery effluent apart from wastewater treatment and electricity generation. MFC is a susatinable and ecofriendly aternative for generation of energy in tune with wastewater treatment (Chandrasekhar and Mohan 2014b).

17.1.4 Types of MFC

Depending on the design and functioning facility of MFC, different types of MFCs are applied in studies. They are dual chamber MFC, single chamber MFC, up-flow MFC and stacked MFC.

17.1.4.1 Dual Chamber MFC

Double-chamber MFC (see Fig. 17.2) is the simplest design among all MFCs (Niessen et al. 2004; Phung et al. 2004; Kumar et al. 2016). In a typical design, one bottle (can be of different designs) is used as anode while the other one as cathode, separated by PEM. Usually in a two-chamber MFC, defined medium (or substrate) in the anode and defined catholyte solution are used to generate energy. In other words, the double-chamber MFC is often operated in batch mode. The double-chamber MFC may be in the shape of bottles or cube. The choice of catholyte in the MFC can define the nomenclature of the design. For example, if the air is used in the cathode to provide the electron acceptor, i.e. oxygen, then the MFC can be called as a two-chamber air cathode MFC (Ringeisen et al. 2006; Shantaram et al. 2005). Such MFCs may prove valuable to generate electricity in remote sensing regions. Dual chamber MFC is one of the simplest designs in MFCs (Niessen et al. 2004; Phung et al. 2004). Dual chamber MFC consists of two chambers; they are anode and cathode separated either using salt bridge or proton exchange membrane (PEM). The substrate is used in anode chamber and catholyte water or other catholytes are used in cathode chamber, salt bridge or proton exchange membrane separates the anode and cathode chamber, which helps in the proton transport between the two chambers (Fig. 17.1). The appellation of MFC is also defined by the catholyte or cathode chamber configuration. If air (oxygen) is the electron acceptor for the cathode in the cathode chamber, MFC will be termed as air cathode MFC (Ringeisen et al. 2006; Shantaram et al. 2005).

This design although applied for basic research generally produces low power output due to the intricate design, high internal resistance and electrode based losses

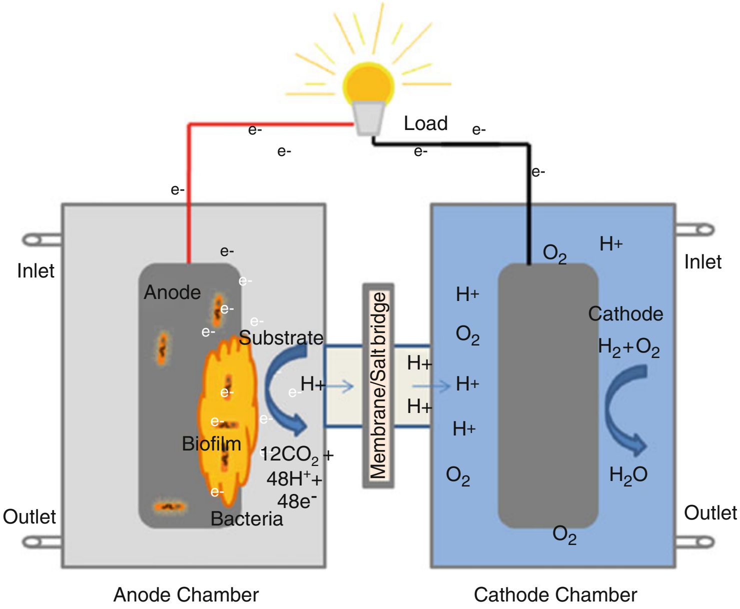

Fig. 17.1 Dual chamber microbial fuel

(Du et al. 2007; Logan and Regan 2006a, b). Hamza et al. (2017) reduced the distance between the anode and cathode as two distinct chambers from the conventional “H” type reactor even using the salt bridge as a separator.

17.1.4.2 Single Chamber MFC (SCMFC)

Single chamber MFC (SCMFC) consists of a single chamber incorporating both the anode and cathode configuring to a single chamber by design, introduced by Park and Zeikus (2003). The anode is placed close or afar to the cathode separated by PEM, decreasing the electrodes spacing aids the reduction in internal Ohmic resistance of the MFC. Combining the two chambers by avoiding catholyte increases the power density (Fig. 17.2). Such MFC is simple, economical and produces much power in rival to double-chamber MFC (Chaudhuri and Lovley 2003; Ringeisen et al. 2006). The major problems such as microbial adulteration and reverse passage of oxygen from cathode to anode occur normally. SCMFCs propose simpler and economic designs. Such MFCs generally have simply an anodic chamber with no requisite of air in a cathodic chamber (Rabaey et al. 2004, 2005).

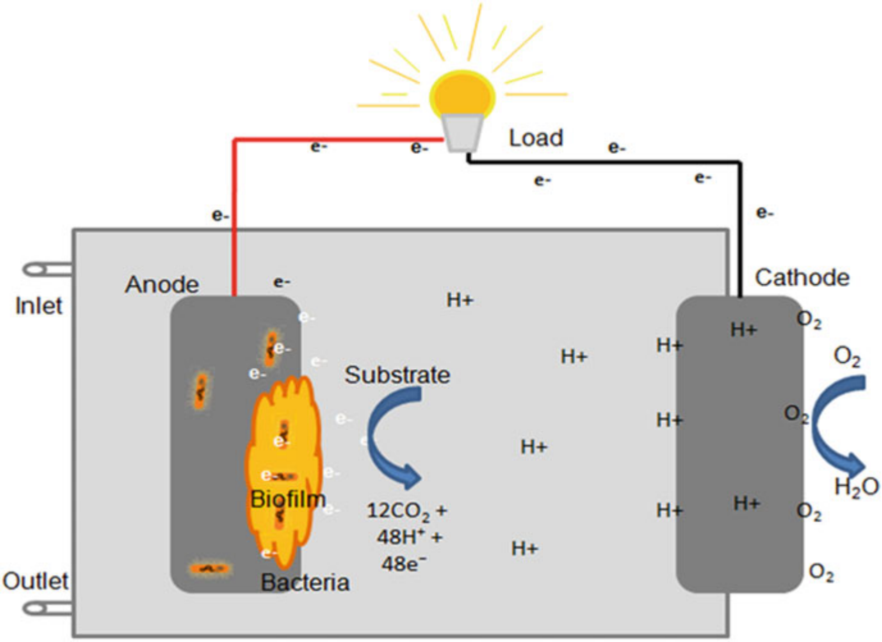

Fig. 17.2 Single chamber microbial fuel cell

17.1.4.3 UP-Flow Tubular MFC

Jang et al. (2004) advanced MFC design working in continuous flow mode. The up-flow MFC is cylindrical shaped (He et al. 2006); assembling the cathode chamber on top above the anode chamber and the anode chamber as the bottom chamber (Fig. 17.3); both the chambers are allocated with glass wool and glass bead layers as separator. Tartakovsky and Guiot (2006) devised a rectangular up-flow MFC separation using polyester pad apart from glass wool and glass beads. The substrate provided from the bottom of the anode that moves upward to the cathode and leaves at the top (Moon et al. 2005). Gradient formed between the electrodes which also help in the favourable action of the fuel cell (Cheng et al. 2006). In up-flow MFC design the anolyte and catholyte are not distinct and lack physical parting consequently the proton transmission associated impediments are reduced (Mohan et al. 2014).

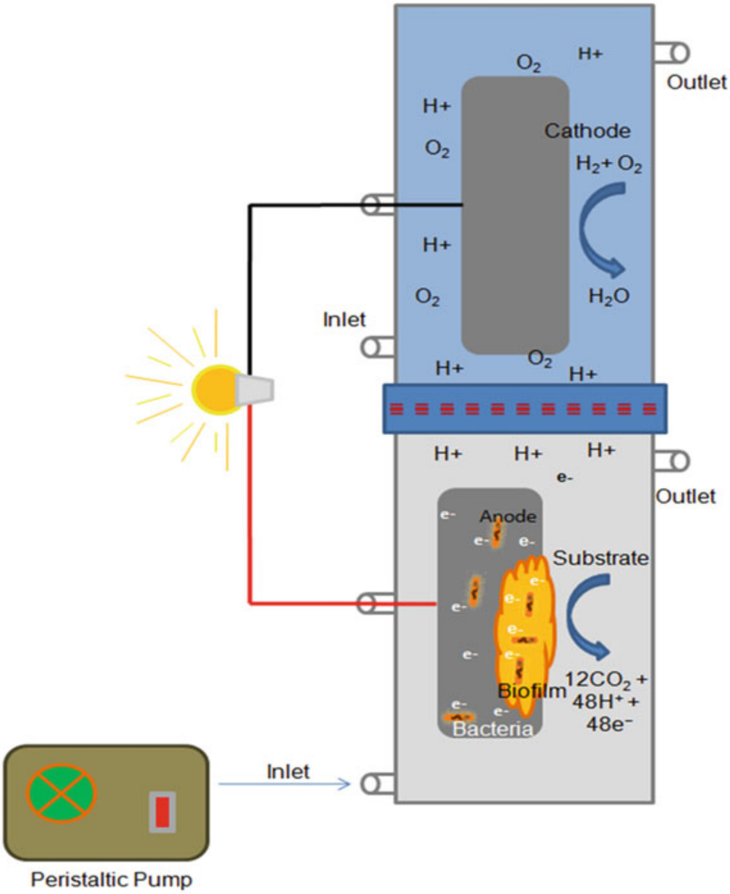

Fig. 17.3 Up-flow MFC

Up-flow MFC's scaling up is ease comparatively with other MFC designs. Substrate pumping is the prime disadvantage of up-flow MFC. Substrate pumping from the anode to cathode assembled at the top requires higher power than the power output generated by the MFC (Zhou et al. 2013). Wastewater treatment is the typical purpose apart from electricity generation from up-flow MFC (Brutinel and Gralnick 2012).

17.1.4.4 Stacked MFC

A stacked MFC comprises several MFCs connected in series or parallel (Fig 17.4) (Logan and Regan 2006a, b; Sun et al. 2012). Stacking increases the MFC output by multiplying individual MFC units power or current output (Logan et al. 2005). This design was observed to enhance the voltage/current output. MFCs stacked in parallel connection do not influence the single unit MFC maximum power output adversely and give six times higher efficiency than the series, parallel-connected stack has higher short circuit current than the series connected stack. The maximum bioelectrochemical reaction rate was recorded in the connection of MFCs in parallel than in the series. Maximizing the chemical oxygen demand (COD) removal, a

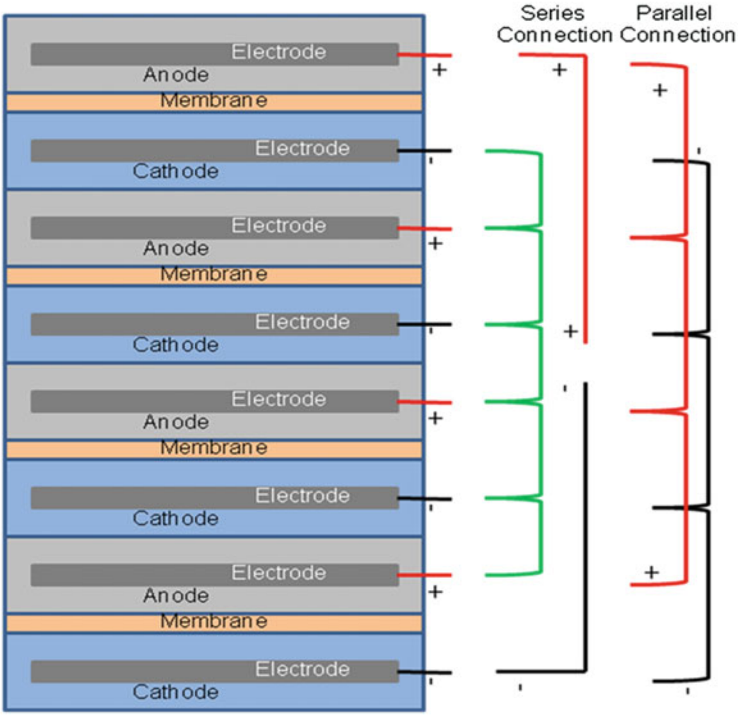

Fig. 17.4 Stack MFC (connecting MFC series/parallel)

parallel connection is preferred if MFC units are not independently operated (Aelterman et al. 2006).

17.1.5 Factors Affecting MFC Performance

The success of MFC depends on the efficiency of the microbial population to transfer electrons generated through the catabolism of organic matter towards the anode portion. This in turn depends on the electrochemical reactions taking place in cathode (Rabaey and Verstraete 2005). The chief factors influencing MFC performance are the type of substrate used, electrode material, nature of the microorganism, proton exchanger, resistance, catholyte, pH and temperature (Du et al. 2007).

17.1.5.1 Substrates Used in MFC

Substrate is regarded as an important factor affecting electricity generation in MFC (Liu et al. 2009). Simple substrates like acetate are effective in more electricity generation due to simpler degradation pathways that could require less energy in breaking the compound by microbes (Ge et al. 2014). The immense potential of MFC in using different wastewater as substrate made researchers to experiment with different streams of wastewater and waste. Wastewaters used in the MFCs are acetate, glucose, lignocellulosic biomass, brewery wastewater, starch processing wastewater, synthetic/chemical wastewater, dye wastewater, landfill leachates, cellulose, chitin, distillery effluent, inorganic and other substrates.

17.1.5.2 Electrode Material

Electrode material oxidation and thereby release of electrons takes place in the anode. In the cathode electrons enter the cell and reduction occurs. Electrodes are alternative electron acceptor promoting the organic contaminants degradation (Mohan and Chandrasekhar 2011a).

Anode

An anode used in MFC should be conductive, non-corrosive, non-fouling, high porosity, high surface area, less expensive and offers provision for an easy scale of the process. Usually carbonaceous materials are preferred as anodes due to their low internal resistance. In dual chambered MFC increasing the size of anode observed to accelerate the power generation substantially as surface area increases with the increase in size of anode (Oh and Logan 2006). The commonly used anode materials and their characteristics are summarized in Table 17.1.

Table 17.1 Anode materials and its characteristics

Anode material	Characteristics	Reference
Carbon paper	Brittle and plain paper	Yuan and Kim (2008)
Carbon cloth	Flexible, high porosity	Cheng and Logan (2007)
Carbon foam	Thick, confers more space for bacterial growth	Reimers et al. (2006)
Reticulated vitrified carbon (RVC)	High porosity and conductivity, effective pore size control	Yuan and Kim (2008)
Graphite rods	Highly conductive, defined surface area and high electrochemical properties	Hamza et al. (2017)
Graphite sheet	Less porous, low power generation	Gao et al. (2013)
Graphite granules	Effective to be used for packed bed reactors	Feng et al. (2010)
Graphite fibres and brushes	High surface area, highly effective	Logan et al. (2007)

Cathode

The scalability of MFC depends on cathode design, this serves as the important factor for its commercialization. The chemical reaction occurring in cathode is quite complex as it involves a tri phase reaction between solid catalyst, air and water. The catalyst should be coated on to the conductive surface and must be exposed to water and air. The most commonly used cathode material includes carbon paper coated with the platinum catalyst in such a way that the catalyst faces water whereas uncoated side faces air (Cheng et al. 2006). Non-precious metals like iron based catalyst were used as alternative to platinum catalyst and observed to produce 3.8 times as much power as graphite cathodes (Park and Zeikus 2003). Plain carbon cathodes without catalyst can also be used in MFC but their power production was found to be greatly reduced. The power generation in catalyst-less MFC can be accelerated by increasing the surface area of catalyst (Reimers et al. 2006). The use of tubular carbon coated cathodes has gained much attention for MFC construction using due to their high porosities and the improved surface area (Zuo et al. 2007). Cathode limitations also include expensive precious metal as cathode to yield higher voltage and current density (Sivagurunathan et al. 2018).

17.1.5.3 Microbes in MFC

Microbes play a vital role in MFC generating electricity and simultaneous wastewater treatment. Microbes convert renewable biomass and waste organic matter into electricity by oxidation of organic compounds and transfer electrons generated by them to electrodes (Lovley 2006). Electrons generated by the microbes in the anode are utilized in cathode as electron acceptors passing through the external circuit (Rahimnejad et al. 2015). Electrogenic microbes are electrochemically active microbes that are capable of accepting and donating electrons from an external source to an external source like electrodes (Loan and Regan 2006b). The conductive nanowires, C type cytochromes connected with the bacterial outer membrane and pili like functional organelle help in the direct electron transfer to the anode electrode surface through a direct physical contact (Xu and Gu 2011). Some microbes require mediators to transfer electrons to the anode electrode, some microbes are capable to exude mediators by themselves and for some microbes mediators are need to be provided. These mediators' help in shuttling the electron transfer between the microbes and electrodes (Rabaey et al, 2005; Freguia et al. 2009; Deng et al. 2010; Keck et al. 2002). Fermentation process boosts the microbial metabolism (Kumar et al. 2018), elutriation helps in production of readily biodegradable organic acids used directly by anodic biocatalysts for bioelectrogenesis (Chandrasekhar and Ahn 2017) and anaerobic culture bioaugmentation to anodic microflora enhances the electrogenic activity of microbes (Chandrasekhar and Mohan 2012). Substrate degradation consists of oxidation process by bacterial metabolic activity, obtaining energy from the substrate as carbon source (Kumar et al. 2012). Enzymes are involved in the oxidation reduction process releasing protons and electrons during substrate degradation. A mixed microbial consortium is preferred in wastewater and biomass because of its lower cost (Chandrasekhar and Mohan 2014a).

17.1.5.4 Proton Exchange

Oxidation of organic material produces both protons and electrons, the electrons are removed instantaneously via biofilm and the electrical circuit of the MFC. The larger protons have to migrate out of the biofilm to the cathode. This occurs at a much slower rate and may cause a bottleneck inhibiting power production. Every electron produced in the form of current, a proton is also produced within the biofilm (Franks and Nevin 2010).

Salt Bridge

Salt bridge and selective permeable membranes are used for proton exchange in MFCs between the anode and cathode. Salt bridges are the one of the cheapest and easiest proton exchangers in MFC. High salt concentration facilitated the transfer of more protons from the anode to the cathode chamber which reduced the activation loss (Sevda and Sreekrishnan 2012).

Membranes

A membrane in MFC acts as an integral component as it serves as a separator and promotes the transfer of protons between the anode and cathode, hence called as the proton exchange membrane. Membranes can be either cation exchange type or anion exchange type. The use of membranes in MFC, although widely reporeted in literature, has raised some controversies as well, especially with regard to net power generation. In some of the research studies membrane-less MFC was observed to produce more power than an MFC with membrane bound, to indicating membrane can adversely affect power generation (Liu and Logan 2004). Over the last decade the use of bipolar membrane consisting of an anion and cation membrane joined in a series has gained significant attention. The use of salt bridge instead of the membrane-based system was also devised in certain research works. Impedance spectroscopy studies revealed a low power output in MFC with the salt bridge and that could be correlated directly to their higher internal resistance (Min et al. 2005).

The ability of the membranes to help in better performance than conventional salt bridge makes membranes as an advanced version of proton exchangers in MFCs. Proton exchange membrane fuel cells (PEMFCs) are considered to be a promising technology for a clean and efficient power generation in the twenty-first century. Proton exchange membranes (PEMs) are one of the key components in a fuel cell system. Researchers are focusing to reach the proton exchange membrane with high proton conductivity, low electronic conductivity, low permeability to fuel, low electro-osmotic drag coefficient, good chemical/thermal stability, good mechanical properties and low cost. Table 17.2 describes the performance of different types of membranes used in MFCs.

17.1.5.5 Resistance

Internal resistance is the fundamental element limiting the power output of the microbial fuel cell. Ohmic resistance, charge transfer and diffusion resistance are the factors causing internal resistance in MFC like in any other electrochemical cell (Larminie et al. 2003). Internal resistance includes the anode, cathode, electrolyte and membrane resistances are the other limiting factors influencing the MFC power output performance (Logan and Regan 2006a, b). Resolving them will enhance the performance of MFC. Increasing the surface area of anode and cathode helps in the reduction of internal resistance (Logan et al. 2007; Oh and Logan 2006) as well as increasing the proton exchange membrane surface area and electrolyte ionic strength can help in the internal resistance reduction bound to membrane and electrolyte limiting factor (Oh et al. 2004; Liu et al. 2012, 2018).

17.1.5.6 Catholyte

The electrons generated at the anode through oxidation or breaking the wastewater contents are transferred to cathode and oxidized by electron acceptors eventually (Logan and Regan 2006a, b). Oxygen is predominantly used cathodic terminal acceptor for proton reduction enabling the production of water (Kadier et al. 2018). Oxygen is a quintessential terminal acceptor in MFC cathode due to its strong oxidation potential, low cost and formation of water as the end product

Table 17.2 Membranes used in the MFC and its performance

Membrane types	Type of fuel cell	MFC performance	Reactor volume	Substrate	Cathode	References
Cation exchange membranes (Nafion 117 (Dupont Corp.)	Dual chamber MFC	395 mV	180 mL	Acetate	Phosphate buffer	Choi et al. (2011)
Anion exchange membranes Ralex AEM	Dual chamber MFC	0.729 V	225 mL	Luria broth	Phosphate buffer	Pandit et al. (2012)
Bipolar membrane (anion and a cation membrane joined)	Flat pate MFC	679 mV	785 mL	Acetate	Ferric iron chloride	Ter Heijne et al. (2006)
Ultrafiltration membrane (DIVFLO ultrafiltration)	Cube shaped MFC	320 mV	14 mL	Acetate	Air cathode	Kim et al. (2007)
Microporous filtration membranes (polysulphone membrane on a composite polyester carrier)	Tubular MFC	403 mW/m^2	32 mL	Domestic wastewater	Phosphate buffer	Zuo et al. (2007)
Nanocomposite membrane Activated carbon nanofibre and nafion Sulphonated Tio2	H Shaped MFC Cylindrical Single Chamber MFC	57.64 mW/m^2 1345 mW/m^2	1690 mL 28 mL	Synthetic Wastewater Sewage wastewater	Phosphate buffer Air cathode	Ghasemi et al. (2012) Ayyaru and Dharmalingam (2015)
SPEEK (sulphonated poly(ether ether ketone) ion exchange membrane)	Cube shaped MFC Single chamber MFC	77.3 mW/m^2 670 mW/m^2	420 mL 28 mL	Palm oil mill effluent Dairy wastewater	Phosphate buffer solution Air cathode	Ghasemi et al. (2013) Ayyaru and Dharmalingam (2015)
SPSEBS (sulphonated form of polystyrene–ethylene–butylene–polystyrene tri-block polymer. polystyrene-ethylene-butylene-polystyrene)	Single chamber MFC	600 mW/m^2	28 mL	Glucose	Air cathode	Ayyaru and Dharmalingam (2011)

(Jang et al. 2004; Franks and Nevin 2010). Catholyte impacts in the enhancement of MFC power output, but the nature of catholyte does not influence in the substrate degradation efficiency of MFC (Raghavulu et al. 2009). In order to improve the MFC performance different catholytes are experimented, such as ferricyanide (Oh et al. 2004; Venkata Mohan et al. 2008), permanganate (You et al. 2006), phosphate buffer (Sangeetha and Muthukumar 2011) regardless the higher power production achieved from the catholytes experimented they are considered to be unsustainable in practicability after all it require chemicals and cause environmental related issues (Logan and Regan 2006a, b).

17.1.5.7 pH

pH has a direct correlation with MFC performance. Generally, neutral pH is ideal for the MFC performance. Pre-fermentation of wastewater can make the pH to near neutrality and can speed up the MFC power generation (Guerrini et al. 2013). Alkaline pH condition 8.3 is optimal for anodic reaction in MFC (Deval et al. 2017), MFC performed better at anodic pH 8 compared with pH 6 (Yuan et al. 2011). Anolyte pH in acidic condition influences the bacterial activity at the anode inhibiting the power production thereby affecting the overall performance of the MFC (Behera and Ghangrekar 2009; Puig et al. 2010). The standard procedure in anaerobic digestion for the development of methanogenic bacteria cannot improve the performance of MFC (Jannelli et al. 2017). Anode feed acidification and catholyte alkalization result in the overall poor performance of MFC (Zhuang et al. 2010).

17.1.5.8 Temperature

Temperature also plays a vital role in the performance of MFC in COD removal and electricity generation (Behera et al. 2011; Larrosa-Guerrero et al. 2010) Temperature controls the metabolic activity of the microorganism of the anodic chamber in the MFC through enzymatic reactions (Clauwaert et al. 2008). Higher temperature contributes to higher power density in MFC (Min et al. 2005). Increase in temperature lowers the current generation and columbic efficiency whereas lowering of temperature increases the current and columbic efficiency during the MFC performance (Jadhav and Ghangrekar 2009). MFC, the anodic biofilm development establishes at lower temperature and aids yielding constant voltage from MFC (Liu et al. 2009). The performance of MFC varies depending on the microbial consortium and type of wastewater used. It renders the optimum performance at room temperature.

17.1.6 Challenges in Commercialization

Despite the rapid progress of electromicrobiology emphasizing the development of electricity using the microorganism as sustainable approach to meet the increasing demand for power globally, widespread commercialization of MFCs still faces a lot of constraints once it comes to a scale up study (Chandrasekhar et al. 2018). The major concerns to be addressed while scaling up MFC to a commercial scale bioelectricity unit include:

- Cost effectiveness and molecular design that can be effectively and safely handled should be developed (He et al. 2017; Do et al. 2018).
- Provisions for high power densities and energy efficiencies are limited in existing models and require development.
- Improving catalytic properties of electrode materials while maintaining their performance (Santoro et al. 2017).
- The voltage generated in MFC is generally less and needs to be accelerated to be applied for commercial scale.
- Proper time dependent study on MFC performance should be done to ensure their reproducibility for commercial scale application due to constraints associated with long time changes in enzyme activity, electrode fouling, membrane blockage, build up of metabolites and break down of products (Choi et al. 2011; Xu et al. 2012).
- Maintaining a steady state of electron transport from bacteria to the electrode through the mediator is crucial.
- The development of immobilization technique for microbial enzymes used in MFC and using nano structured substrates although found effective in improving MFC performance should tackle out the issues associated with practicality and cost effectiveness.

References

Aelterman, P., Rabaey, K., Pham, H. T., Boon, N., & Verstraete, W. (2006). Continuous electricity generation at high voltages and currents using stacked microbial fuel cells. *Environmental Science & Technology, 40*(10), 3388–3394. https://doi.org/10.1021/es0525511

Ayeleru, O. O., Okonta, F. N., & Ntuli, F. (2018). Municipal solid waste generation and characterization in the City of Johannesburg: A pathway for the implementation of zero waste. *Waste Management, 79*, 87–97. https://doi.org/10.1016/j.wasman.2018.07.026

Ayyaru, S., & Dharmalingam, S. (2011). Development of MFC using sulphonated polyether ether ketone (SPEEK) membrane for electricity generation from waste water. *Bioresource Technology, 102*(24), 11167–11171. https://doi.org/10.1016/j.biortech.2011.09.021

Ayyaru, S., & Dharmalingam, S. (2015). A study of influence on nanocomposite membrane of sulfonated TiO_2 and sulfonated polystyrene-ethylene-butylene-polystyrene for microbial fuel cell application. *Energy, 88*, 202–208. https://doi.org/10.1016/j.energy.2015.05.015

Beegle, J. R., & Borole, A. P. (2018). Energy production from waste: Evaluation of anaerobic digestion and bioelectrochemical systems based on energy efficiency and economic factors. *Renewable and Sustainable Energy Reviews, 96*, 343–351. https://doi.org/10.1016/j.rser.2018.07.057

Behera, M., & Ghangrekar, M. M. (2009). Performance of microbial fuel cell in response to change in sludge loading rate at different anodic feed pH. *Bioresource Technology, 100*(21), 5114–5121. https://doi.org/10.1016/j.biortech.2009.05.020

Behera, M., Murthy, S. S. R., & Ghangrekar, M. M. (2011). Effect of operating temperature on performance of microbial fuel cell. *Water Science and Technology, 64*(4), 917–922. https://doi.org/10.2166/wst.2011.704

Beyene, H. D., Werkneh, A. A., & Ambaye, T. G. (2018). Current updates on waste to energy (WtE) technologies: A review. *Renew Energy Focus, 24*, 1–11. https://doi.org/10.1016/j.ref.2017.11.001

Brutinel, E. D., & Gralnick, J. A. (2012). Shuttling happens: Soluble flavin mediators of extracellular electron transfer in Shewanella. *Applied Microbiology and Biotechnology, 93*(1), 41–48. https://doi.org/10.1007/s00253-011-3653-0

Buonocore, J. J., Luckow, P., Norris, G., Spengler, J.D., Biewald, B., Fisher, J., et al. (2016). Health and climate benefits of different energy-efficiency and renewable energy choices. *Nature Climate Change, 6*, 100–105. https://doi.org/10.1038/nclimate2771

Chandrasekhar, K., & Ahn, Y. H. (2017). Effectiveness of piggery waste treatment using microbial fuel cells coupled with elutriated-phased acid fermentation. *Bioresource Technology, 244*, 650–657. https://doi.org/10.1016/j.biortech.2017.08.021

Chandrasekhar, K., Lee, Y. J., & Lee, D. W. (2015a). Biohydrogen production: strategies to improve process efficiency through microbial routes. *International Journal of Molecular Sciences, 16*(4), 8266–8293.

Chandrasekhar, K., Amulya, K., & Mohan, S. V. (2015b). Solid phase bio-electrofermentation of food waste to harvest value-added products associated with wasteremediation. *Waste Management, 45*, 57–65. https://doi.org/10.1016/j.wasman.2015.06.001

Chandrasekhar, K., Kadier, A., Kumar, G., Nastro, R. A., & Jeevitha, V. (2018). Challenges in microbial fuel cell and future scope. In *Microbial fuel cell* (pp. 483–499). Cham: Springer. https://doi.org/10.1007/978-3-319-66793-5_25

Chandrasekhar, K., & Mohan, S. V. (2012). Bio-electrochemical remediation of real field petroleum sludge as an electron donor with simultaneous power generation facilitates biotransformation of PAH: Effect of substrate concentration. *Bioresource Technology, 110*, 517–525. https://doi.org/10.1016/j.biortech.2012.01.128

Chandrasekhar, K., & Mohan, S. V. (2014a). Induced catabolic bio-electrohydrolysis of complex food waste by regulating external resistance for enhancing acidogenic biohydrogen production. *Bioresource Technology, 165*, 372–382. https://doi.org/10.1016/j.biortech.2014.02.073

Chandrasekhar, K., & Mohan, S. V. (2014b). Bio-electrohydrolysis as a pretreatment strategy to catabolize complex food waste in closed circuitry: Function of electron flux to enhance acidogenic biohydrogen production. *International Journal of Hydrogen Energy, 39*(22), 11411–11422. https://doi.org/10.1016/j.ijhydene.2014.05.035

Chaudhuri, S. K., & Lovley, D. R. (2003). Electricity generation by direct oxidation of glucose in mediatorless microbial fuel cells. *Nature Biotechnology, 21*(10), 1229–1232. https://doi.org/10.1038/nbt867

Cheng, S., Liu, H., & Logan, B. E. (2006). Increased performance of single-chamber microbial fuel cells using an improved cathode structure. *Electrochemistry Communications, 8*(3), 489–494. https://doi.org/10.1016/j.elecom.2006.01.010

Cheng, S., & Logan, B. E. (2007). Ammonia treatment of carbon cloth anodes to enhance power generation of microbial fuel cells. *Electrochemistry Communications, 9*(3), 492–496.

Choi, M. J., Chae, K. J., Ajayi, F. F., Kim, K. Y., Yu, H. W., Kim, C. W., et al. (2011). Effects of biofouling on ion transport through cation exchange membranes and microbial fuel cell performance. *Bioresource Technology, 102*(1), 298–303. https://doi.org/10.1016/j.biortech.2010.06.129

Clauwaert, P., Aelterman, P., De Schamphelaire, L., Carballa, M., Rabaey, K., & Verstraete, W. (2008). Minimizing losses in bio-electrochemical systems: The road to applications. *Applied Microbiology and Biotechnology, 79*(6), 901–913. https://doi.org/10.1007/s00253-008-1522-2

Deng, L., Li, F., Zhou, S., Huang, D., & Ni, J. (2010). A study of electron-shuttle mechanism in Klebsiella pneumoniae based-microbial fuel cells. *Chinese Science Bulletin, 55*, 99–104. https://doi.org/10.1007/s11434-009-0563-y

Deval, A. S., Parikh, H. A., Kadier, A., Chandrasekhar, K., Bhagwat, A. M., & Dikshit, A. K. (2017). Sequential microbial activities mediated bioelectricity production from distillery wastewater using bio-electrochemical system with simultaneous waste remediation. *International Journal of Hydrogen Energy, 42*(2), 1130–1141. https://doi.org/10.1016/j.ijhydene.2016.11.114

Do, M. H., Ngo, H. H., Guo, W. S., Liu, Y., Chang, S. W., Nguyen, D. D., et al. (2018). Challenges in the application of microbial fuel cells to wastewater treatment and energy production: A mini review. *Science of the Total Environment, 639*, 910–920. https://doi.org/10.1016/j.scitotenv.2018.05.136

Du, Z., Li, H., & Gu, T. (2007). A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bio-energy. *Biotechnology Advances, 25*, 464–482. https://doi.org/10.1016/j.biotechadv.2007.05.004

EIA Industrial Sector Energy Consumption. (2016). Retrieved 15 June, 2019, from https://www.eia.gov/outlooks/ieo/pdf/industrial.pdf

Enamala, M. K., Enamala, S., Chavali, M., Donepudi, J., Yadavalli, R., Kolapalli, B., et al. (2018). Production of biofuels from microalgae-A review on cultivation, harvesting, lipid extraction, and numerous applications of microalgae. *Renewable and Sustainable Energy Reviews, 94*, 49–68. https://doi.org/10.1016/j.rser.2018.05.012

Farjana, S. H., Huda, N., Mahmud, M. P., & Saidur, R. (2018). Solar process heat in industrial systems–A global review. *Renewable and Sustainable Energy Reviews, 82*(3), 2270–2286. https://doi.org/10.1016/j.rser.2017.08.065

Feng, Y., Lee, H., Wang, X., Liu, Y., & He, W. (2010). Continuous electricity generation by a graphite granule baffled air–cathode microbial fuel cell. *Bioresource Technology, 101*(2), 632–638. https://doi.org/10.1016/j.biortech.2009.08.046

Fetanat, A., Mofid, H., Mehrannia, M., & Shafipour, G. (2019). Informing energy justice based decision-making framework for waste-to-energy technologies selection in sustainable waste management: A case of Iran. *Journal of Cleaner Production, 228*, 1377–1390. https://doi.org/10.1016/j.jclepro.2019.04.215

Franks, A. E., & Nevin, K. P. (2010). Microbial fuel cells, a current review. *Energies, 3*(5), 899–919. https://doi.org/10.3390/en3050899

Freguia, S., Masuda, M., Tsujimura, S., & Kano, K. (2009). Lactococcus lactis catalyses electricity generation at microbial fuel cell anodes via excretion of a soluble quinone. *Bioelectrochemistry, 76*(1–2), 14–18. https://doi.org/10.1016/j.bioelechem.2009.04.001

Gajda, I., Greenman, J., & Ieropoulos, I. A. (2018). Recent advancements in real-world microbial fuel cells applications. *Current Opinion in Electrochemistry, 11*, 78–83. https://doi.org/10.1016/j.coelec.2018.09.006

Gao, X., Zhang, Y., Li, X., & Ye, J. (2013). Novel graphite sheet used as an anodic material for high-performance microbial fuel cells. *Materials Letters, 105*, 24–27. https://doi.org/10.1016/j.matlet.2013.04.044

Ge, Z., Li, J., Xiao, L., Tong, Y., & He, Z. (2014). Recovery of electrical energy in microbial fuel cells: Brief review. *Environmental Science & Technology Letters, 1*(2), 137–141. https://doi.org/10.1021/ez4000324

Ghasemi, M., Shahgaldi, S., Ismail, M., Yaakob, Z., & Daud, W. R. W. (2012). New generation of carbon nanocomposite proton exchange membranes in microbial fuel cell Systems. *Chemical Engineering Journal, 184*, 82–89. https://doi.org/10.1016/j.cej.2012.01.001

Ghasemi, M., Daud, W. R. W., Ismail, A. F., Jafari, Y., Ismail, M., Mayahi, A., et al. (2013). Simultaneous wastewater treatment and electricity generation by microbial fuel cell: performance comparison and cost investigation of using Nafion 117 and SPEEK as separators. *Desalination, 325*, 1–6. https://doi.org/10.1016/j.desal.2013.06.013

Gopal, P. M., Sivaram, N. M., & Barik, D. (2019). Paper industry wastes and energy generation from wastes. In *Energy from toxic organic waste for heat and power generation* (pp. 83–97). Cambridge: Woodhead Publishing. https://doi.org/10.1016/B978-0-08-102528-4.00007-9

Goswami, R., & Mishra, V. K. (2018). A review of design, operational conditions and applications of microbial fuel cells. *Biofuels, 9*(2), 203–220. https://doi.org/10.1080/17597269.2017.1302682

Gude, V. G. (2015). Energy storage for desalination processes powered by renewable energy and waste heat sources. *Applied Energy, 137*, 877–898. https://doi.org/10.1016/j.apenergy.2014.06.061

Guerrini, E., Cristiani, P., & Trasatti, S. P. M. (2013). Relation of anodic and cathodic performance to pH variations in membraneless microbial fuel cells. *International Journal of Hydrogen Energy, 38*(1), 345–353. https://doi.org/10.1016/j.ijhydene.2012.10.001

Guo, S., Liu, Q., Sun, J., & Jin, H. (2018). A review on the utilization of hybrid renewable energy. *Renewable and Sustainable Energy Reviews, 91*, 1121–1147. https://doi.org/10.1016/j.rser.2018.04.105

Hamza, H. C., Duraisamy, P., Periyasamy, S., Pokkiladathu, H., & Muthuchamy, M. (2017). Simultaneous electricity generation and heavy metals reduction from distillery effluent by microbial fuel cell. *Indian Journal of Science and Technology, 10*(13), 1–13. https://doi.org/10.17485/ijst/2017/v10i13/111203

He, L., Du, P., Chen, Y., Lu, H., Cheng, X., Chang, B., et al. (2017). Advances in microbial fuel cells for wastewater treatment. *Renewable and Sustainable Energy Reviews, 71*, 388–403. https://doi.org/10.1016/j.rser.2016.12.069

He, Z., Wagner, N., Minteer, S. D., & Angenent, L. T. (2006). An upflow microbial fuel cell with an interior cathode: Assessment of the internal resistance by impedance spectroscopy. *Environmental Science & Technology, 40*(17), 5212–5217. https://doi.org/10.1021/es060394f

IEA. (2018). *Global energy and CO2 status report*. Retrieved 15 June, 2019, from https://www.iea.org/geco/

IEA. (2019). Retrieved 15 June, 2019, from https://www.iea.org/newsroom/news/2019/march/global-energy-demand-rose-by-23-in-2018-its-fastest-pace-in-the-last-decade.html

Indrawan, N., Thapa, S., Bhoi, P. R., Huhnke, R. L., & Kumar, A. (2018). Electricity power generation from co-gasification of municipal solid wastes and biomass: Generation and emission performance. *Energy, 162*, 764–775. https://doi.org/10.1016/j.energy.2018.07.169

Jadhav, G. S., & Ghangrekar, M. M. (2009). Performance of microbial fuel cell subjected to variation in pH, temperature, external load and substrate concentration. *Bioresource Technology, 100*(2), 717–723. https://doi.org/10.1016/j.biortech.2008.07.041

Jang, J. K., Pham, T. H., Chang, I. S., Kang, K. H., Moon, H., Cho, K. S., et al. (2004). Construction and operation of a novel mediator-and membrane-less microbial fuel cell. *Process Biochemistry, 39*(8), 1007–1012. https://doi.org/10.1016/S0032-9592(03)00203-6

Jannelli, N., Nastro, R. A., Cigolotti, V., Minutillo, M., & Falcucci, G. (2017). Low pH, high salinity: Too much for microbial fuel cells. *Applied Energy, 192*, 543–550. https://doi.org/10.1016/j.apenergy.2016.07.079

Kadier, A., Chandrasekhar, K., & Kalil, M. S. (2017). Selection of the best barrier solutions for liquid displacement gas collecting metre to prevent gas solubility in microbial electrolysis cells. *International Journal of Renewable Energy Technology, 8*(2), 93–103. https://doi.org/10.1504/IJRET.2017.086807

Kadier, A., Kalil, M. S., Abdeshahian, P., Chandrasekhar, K., Mohamed, A., Azman, N. F., et al. (2016a). Recent advances and emerging challenges in microbial electrolysis cells (MECs) for microbial production of hydrogen and value-added chemicals. *Renewable and Sustainable Energy Reviews, 61*, 501–525. https://doi.org/10.1016/j.rser.2016.04.017

Kadier, A., Simayi, Y., Chandrasekhar, K., Ismail, M., & Kalil, M. S. (2015). Hydrogen gas production with an electroformed Ni mesh cathode catalysts in a single-chamber microbial electrolysis cell (MEC). *International Journal of Hydrogen Energy, 40*(41), 14095–14103. https://doi.org/10.1016/j.ijhydene.2015.08.095

Kadier, A., Kalil, M. S., Chandrasekhar, K., Mohanakrishna, G., Saratale, G. D., Saratale, R. G., et al. (2018). Surpassing the current limitations of high purity H2 production in microbial electrolysis cell (MECs): Strategies for inhibiting growth of methanogens. *Bioelectrochemistry, 119*, 211–219. https://doi.org/10.1016/j.bioelechem.2017.09.014

Kadier, A., Simayi, Y., Abdeshahian, P., Azman, N. F., Chandrasekhar, K., & Kalil, M. S. (2016b). A comprehensive review of microbial electrolysis cells (MEC) reactor designs and configurations for sustainable hydrogen gas production. *Alexandria Engineering Journal, 55*(1), 427–443. https://doi.org/10.1016/j.aej.2015.10.008

Keck, A., Rau, J., Reemtsma, T., Mattes, R., Stolz, A., & Klein, J. (2002). Identification of quinoide redox mediators that are formed during the degradation of naphthalene-2-sulfonate by Sphingomonas xenophaga BN6. *Applied and Environmental Microbiology, 68*(9), 4341–4349. https://doi.org/10.1128/AEM.68.9.4341-4349.2002

Kim, J. R., Cheng, S., Oh, S. E., & Logan, B. E. (2007). Power generation using different cation, anion, and ultrafiltration membranes in microbial fuel cells. *Environmental Science & Technology, 41*(3), 1004–1009. https://doi.org/10.1021/es062202m

Kumar, P., Chandrasekhar, K., Kumari, A., Sathiyamoorthi, E., & Kim, B. S. (2018). Electro-fermentation in aid of bioenergy and biopolymers. *Energies, 11*(2), 343–363. https://doi.org/10.3390/en11020343

Kumar, S., & Pandey, A. (2019). Current developments in biotechnology and bioengineering and waste treatment processes for energy generation: An introduction. In *Current developments in biotechnology and bioengineering* (pp. 1–9). London: Elsevier. https://doi.org/10.1016/B978-0-444-64083-3.00001-4

Kumar, A. K., Reddy, M. V., Chandrasekhar, K., Srikanth, S., & Mohan, S. V. (2012). Endocrine disruptive estrogens role in electron transfer: Bio-electrochemical remediation with microbial mediated electrogenesis. *Bioresource Technology, 104*, 547–556. https://doi.org/10.1016/j.biortech.2011.10.037

Kumar, G., Sivagurunathan, P., Pugazhendhi, A., Thi, N.B.D., Zhen, G., Chandrasekhar, K., et al. (2017). A comprehensive overview on light independent fermentative hydrogen production from wastewater feedstock and possible integrative options. *Energy Conversion and Management, 141*, 390–402. https://doi.org/10.1016/j.enconman.2016.09.087

Larminie, J., Dicks, A., & McDonald, M. S. (2003). *Fuel cell systems explained* (Vol. 2, pp. 207–225). Chichester: J. Wiley.

Larrosa-Guerrero, A., Scott, K., Head, I. M., Mateo, F., Ginesta, A., & Godinez, C. (2010). Effect of temperature on the performance of microbial fuel cells. *Fuel, 89*(12), 3985–3994. https://doi.org/10.1016/j.fuel.2010.06.025

Liu, Z., Liu, J., Zhang, S., & Su, Z. (2009). Study of operational performance and electrical response on mediator-less microbial fuel cells fed with carbon-and protein-rich substrates. *Biochemical Engineering Journal, 45*(3), 185–191. https://doi.org/10.1016/j.bej.2009.03.011

Liu, H., & Logan, B. E. (2004). Electricity generation using an air-cathode single chamber microbial fuel cell in the presence and absence of a proton exchange membrane. *Environmental Science & Technology, 38*(14), 4040–4046. https://doi.org/10.1021/es0499344

Liu, L., Tsyganova, O., Lee, D. J., Su, A., Chang, J. S., Wang, A., et al. (2012). Anodic biofilm in single-chamber microbial fuel cells cultivated under different temperatures. *International Journal of Hydrogen Energy, 37*(20), 15792–15800. https://doi.org/10.1016/j.ijhydene.2012.03.084

Liu, S. H., Lai, C. Y., Ye, J. W., & Lin, C. W. (2018). Increasing removal of benzene from groundwater using stacked tubular air-cathode microbial fuel cells. *Journal of Cleaner Production, 194*, 78–84. https://doi.org/10.1016/j.jclepro.2018.05.138

Loan, B. E., & Regan, J. M. (2006). Electricity-producing bacterial communities in microbial fuel cells. Trends in Microbiology, 14 (12), 512–518. https://doi.org/10.1016/j.tim.2006.10.003

Logan, B. E., Murano, C., Scott, K., Gray, N. D., & Head, I. M. (2005). Electricity generation from cysteine in a microbial fuel cell. *Water Research, 39*(5), 942–952. https://doi.org/10.1016/j.watres.2004.11.019

Logan, B. E., & Regan, J. M. (2006a). Microbial fuel cells—challenges and applications. *Environmental Science & Technology, 40*(17), 5172–5180. https://doi.org/10.1021/es0627592

Logan, B. E., & Regan, J. M. (2006b). Electricity-producing bacterial communities in microbial fuel cells. *Trends in Microbiology, 14*(12), 512–518. https://doi.org/10.1016/j.tim.2006.10.003

Logan, B. E., Cheng, S., Watson, V., & Estadt, G. (2007). Graphite fiber brush anodes for increased power production in air-cathode microbial fuel cells. *Environmental Science and Technology., 41*, 3341–3346. https://doi.org/10.1021/es062644y

Lovley, D. R. (2006). Microbial fuel cells: Novel microbial physiologies and engineering approaches. *Current Opinion in Biotechnology, 17*(3), 327–332. https://doi.org/10.1016/j.copbio.2006.04.006

Marks, S., Makinia, J., & Fernandez-Morales, F. J. (2019). Performance of microbial fuel cells operated under anoxic conditions. *Applied Energy, 250*, 1–6. https://doi.org/10.1016/j.apenergy.2019.05.043

Milbrandt, A., Seiple, T., Heimiller, D., Skaggs, R., & Coleman, A. (2018). Wet waste-to-energy resources in the United States. *Resources, Conservation and Recycling, 137*, 32–47. https://doi.org/10.1016/j.resconrec.2018.05.023

Min, B., Cheng, S., & Logan, B. E. (2005). Electricity generation using membrane and salt bridge microbial fuel cells. *Water Research, 39*(9), 1675–1686. https://doi.org/10.1016/j.watres.2005.02.002

Minelgaitė, A., & Liobikienė, G. (2019). Waste problem in European Union and its influence on waste management behaviours. *Science of the Total Environment, 667*, 86–93. https://doi.org/10.1016/j.scitotenv.2019.02.313

Mohan, S. V., Babu, V. L., & Sarma, P. N. (2008). Effect of various pretreatment methods on anaerobic mixed microflora to enhance biohydrogen production utilizing dairy wastewater as substrate. *Bioresource Technology, 99*(1), 59–67. https://doi.org/10.1016/j.biortech.2006.12.004

Mohan, S. V., & Chandrasekhar, K. (2011a). Self-induced bio-potential and graphite electron accepting conditions enhances petroleum sludge degradation in bio-electrochemical system with simultaneous power generation. *Bioresource Technology, 102*(20), 9532–9541. https://doi.org/10.1016/j.biortech.2011.07.038

Mohan, S. V., & Chandrasekhar, K. (2011b). Solid phase microbial fuel cell (SMFC) for harnessing bioelectricity from composite food waste fermentation: influence of electrode assembly and buffering capacity. *Bioresource Technology, 102*(14), 7077–7085. https://doi.org/10.1016/j.biortech.2011.04.039

Mohan, S. V., Velvizhi, G., Modestra, J. A., & Srikanth, S. (2014). Microbial fuel cell: Critical factors regulating bio-catalyzed electrochemical process and recent advancements. *Renewable and Sustainable Energy Reviews, 40*, 779–797. https://doi.org/10.1016/j.rser.2014.07.109

Moon, H., Chang, I. S., Jang, J. K., & Kim, B. H. (2005). Residence time distribution in microbial fuel cell and its influence on COD removal with electricity generation. *Biochemical Engineering Journal, 27*(1), 59–65. https://doi.org/10.1016/j.bej.2005.02.010

Moya, D., Aldás, C., López, G., & Kaparaju, P. (2017). Municipal solid waste as a valuable renewable energy resource: A worldwide opportunity of energy recovery by using waste-to-energy technologies. *Energy Procedia, 134*, 286–295. https://doi.org/10.1016/j.egypro.2017.09.618

Neto, S. A., Reginatto, V., & De Andrade, A. R. (2018). Microbial fuel cells and wastewater treatment. In *Electrochemical water and wastewater treatment* (pp. 305–331). London: Butterworth-Heinemann Elsevier. https://doi.org/10.1016/B978-0-12-813160-2.00012-2

Niessen, J., Schröder, U., & Scholz, F. (2004). Exploiting complex carbohydrates for microbial electricity generation–a bacterial fuel cell operating on starch. *Electrochemistry Communications, 9*, 955–958. https://doi.org/10.1016/j.elecom.2004.07.010

Oh, S., Min, B., & Logan, B. E. (2004). Cathode performance as a factor in electricity generation in microbial fuel cells. *Environmental Science & Technology, 38*(18), 4900–4904. https://doi.org/10.1021/es049422p

Oh, S. E., & Logan, B. E. (2006). Proton exchange membrane and electrode surface areas as factors that affect power generation in microbial fuel cells. *Applied Microbiology and Biotechnology, 70*(2), 162–169.

Palanivel, T. M., & Sulaiman, H. (2014). Generation and composition of municipal solid waste (MSW) in Muscat, Sultanate of Oman. *APCBEE Procedia, 10*, 96–102. https://doi.org/10.1016/j.apcbee.2014.10.024

Pandit, S., Ghosh, S., Ghangrekar, M. M., & Das, D. (2012). Performance of an anion exchange membrane in association with cathodic parameters in a dual chamber microbial fuel cell. *International Journal of Hydrogen Energy, 37*(11), 9383–9392. https://doi.org/10.1016/j.ijhydene.2012.03.011

Park, D. H., & Zeikus, J. G. (2003). Improved fuel cell and electrode designs for producing electricity from microbial degradation. *Biotechnology and Bioengineering, 81*(3), 348–355. https://doi.org/10.1002/bit.10501

Phung, N. T., Lee, J., Kang, K. H., Chang, I. S., Gadd, G. M., & Kim, B. H. (2004). Analysis of microbial diversity in oligotrophic microbial fuel cells using 16S rDNA sequences. *FEMS Microbiology Letters, 233*(1), 77–82. https://doi.org/10.1016/j.femsle.2004.01.041

Puig, S., Serra, M., Coma, M., Cabré, M., Balaguer, M. D., & Colprim, J. (2010). Effect of pH on nutrient dynamics and electricity production using microbial fuel cells. *Bioresource Technology, 101*(24), 9594–9599. https://doi.org/10.1016/j.biortech.2010.07.082

Rabaey, K., Boon, N., Höfte, M., & Verstraete, W. (2005). Microbial phenazine production enhances electron transfer in biofuel cells. *Environmental Science & Technology, 39*(9), 3401–3408. https://doi.org/10.1021/es048563o

Rabaey, K., Boon, N., Siciliano, S. D., Verhaege, M., & Verstraete, W. (2004). Biofuel cells select for microbial consortia that self-mediate electron transfer. *Journal of Applied & Environmental Microbiology, 70*(9), 5373–5382. https://doi.org/10.1128/AEM.70.9.5373-5382.2004

Rabaey, K., & Verstraete, W. (2005). Microbial fuel cells: Novel biotechnology for energy generation. *Trends in Biotechnology, 23*(6), 291–298. https://doi.org/10.1016/j.tibtech.2005.04.008

Raghavulu, S. V., Mohan, S. V., & Goud, R. K. (2009). Effect of anodic pH microenvironment on microbial fuel cell (MFC) performance in concurrence with aerated and ferricyanide catholytes. *Electrochemistry Communications, 11*(2), 371–375. https://doi.org/10.1016/j.elecom.2008.11.038

Rahimnejad, M., Adhami, A., Darvari, S., Zirepour, A., & Oh, S. E. (2015). Microbial fuel cell as new technology for bioelectricity generation: A review. *Alexandria Engineering Journal, 54*(3), 745–756. https://doi.org/10.1016/j.aej.2015.03.031

Ramachandra, T. V., Bharath, H. A., Kulkarni, G., & Han, S. S. (2018). Municipal solid waste: Generation, composition and GHG emissions in Bangalore, India. *Renewable and Sustainable Energy Reviews, 82*, 1122–1136. https://doi.org/10.1016/j.rser.2017.09.0

Rathour, R., Kalola, V., Johnson, J., Jain, K., Madamwar, D., & Desai, C. (2019). Treatment of various types of wastewaters using microbial fuel cell systems. In *Microbial electrochemical technology* (pp. 665–692). London: Elsevier. https://doi.org/10.1016/B978-0-444-64052-9.00027-3

Reddy, M. V., Chandrasekhar, K., & Mohan, S. V. (2011b). Influence of carbohydrates and proteins concentration on fermentative hydrogen production using canteen based waste under acidophilic microenvironment. *Journal of Biotechnology, 155*(4), 387–395. https://doi.org/10.1016/j.jbiotec.2011.07.030

Reddy, M. V., Devi, M. P., Chandrasekhar, K., Goud, R. K., & Mohan, S. V. (2011a). Aerobic remediation of petroleum sludge through soil supplementation: Microbial community analysis. *Journal of Hazardous Materials, 197*, 80–87. https://doi.org/10.1016/j.jhazmat.2011.09.061

Reimers, C. E., Girguis, P., Stecher, H. A., Tender, L. M., Ryckelynck, N., & Whaling, P. (2006). Microbial fuel cell energy from an ocean cold seep. *Geobiology, 4*(2), 123–136.

Ringeisen, B. R., Henderson, E., Wu, P. K., Pietron, J., Ray, R., Little, B., et al. (2006). High power density from a miniature microbial fuel cell using Shewanella oneidensis DSP10. *Environmental Science & Technology, 40*(8), 2629–2634. https://doi.org/10.1021/es052254w

Sangeetha, T., & Muthukumar, M. (2011). Catholyte performance as an influencing factor on electricity production in a dual-chambered microbial fuel cell employing food processing wastewater. *Energ Source Part A: Recovery, Utilization, and Environmental Effects, 33*(16), 1514–1522. https://doi.org/10.1080/15567030903397966

Santoro, C., Arbizzani, C., Erable, B., & Ieropoulos, I. (2017). Microbial fuel cells: From fundamentals to applications. A review. *Journal of Power Sources, 356*, 225–244. https://doi.org/10.1016/j.jpowsour.2017.03.109

Saratale, R. G., Kuppam, C., Mudhoo, A., Saratale, G. D., Periyasamy, S., Zhen, G., et al. (2017). Bioelectrochemical systems using microalgae–A concise research update. *Chemosphere, 177*, 35–43. https://doi.org/10.1016/j.chemosphere.2017.02.132

Sevda, S., & Sreekrishnan, T. R. (2012). Effect of salt concentration and mediators in salt bridge microbial fuel cell for electricity generation from synthetic wastewater. *Journal of Environmental Science and Health, Part A, 47*(6), 878–886. https://doi.org/10.1080/10934529.2012.665004

Shantaram, A., Beyenal, H., Veluchamy, R. R. A., & Lewandowski, Z. (2005). Wireless sensors powered by microbial fuel cells. *Environmental Science & Technology, 39*(13), 5037–5042. https://doi.org/10.1021/es0480668

Shirzad, M., Panahi, H. K. S., Dashti, B. B., Rajaeifar, M. A., Aghbashlo, M., & Tabatabaei, M. (2019). A comprehensive review on electricity generation and GHG emission reduction potentials through anaerobic digestion of agricultural and livestock/slaughterhouse wastes in Iran. *Renewable and Sustainable Energy Reviews, 111*, 571–594. https://doi.org/10.1016/j.rser.2019.05.011

Shuba, E. S., & Kifle, D. (2018). Microalgae to biofuels: 'Promising' alternative and renewable energy, review. *Renewable and Sustainable Energy Reviews, 81*, 743–755. https://doi.org/10.1016/j.rser.2017.08.042

Siqueiros, E., Lamidi, R. O., Pathare, P. B., Wang, Y., & Roskilly, A. P. (2019). Energy recovery from brewery waste: Experimental and modelling perspectives. *Energy Procedia, 161*, 24–31. https://doi.org/10.1016/j.egypro.2019.02.054

Sivagurunathan, P., Kuppam, C., Mudhoo, A., Saratale, G. D., Kadier, A., Zhen, G., et al. (2018). A comprehensive review on two-stage integrative schemes for the valorization of dark fermentative effluents. *Critical Reviews in Biotechnology, 38*(6), 868–882. https://doi.org/10.1080/07388551.2017.1416578

Slate, A. J., Whitehead, K. A., Brownson, D. A., & Banks, C. E. (2019). Microbial fuel cells: An overview of current technology. *Renewable and Sustainable Energy Reviews, 101*, 60–81. https://doi.org/10.1016/j.rser.2018.09.044

Sun, M., Reible, D. D., Lowry, G. V., & Gregory, K. B. (2012). Effect of applied voltage, initial concentration, and natural organic matter on sequential reduction/oxidation of nitrobenzene by graphite electrodes. *Environmental Science & Technology, 46*(11), 6174–6181. https://doi.org/10.1021/es300048y

Tang, E., Peng, C., & Xu, Y. (2018). Changes of energy consumption with economic development when an economy becomes more productive. *Journal of Cleaner Production, 196*, 788–795. https://doi.org/10.1016/j.jclepro.2018.06.101

Tartakovsky, B., & Guiot, S. R. (2006). A comparison of air and hydrogen peroxide oxygenated microbial fuel cell reactors. *Biotechnology Progress, 22*(1), 241–246. https://doi.org/10.1021/bp050225j

Ter Heijne, A., Hamelers, H. V., De Wilde, V., Rozendal, R. A., & Buisman, C. J. (2006). A bipolar membrane combined with ferric iron reduction as an efficient cathode system in microbial fuel cells. *Environmental Science & Technology, 40*(17), 5200–5205. https://doi.org/10.1021/es0608545

Xu, D., Gu, T. (2011). Bioenergetics explains when and why more severe MIC pitting by SRB can occur. Corrosion/2011 Paper (11426).

Xu, J., Sheng, G. P., Luo, H. W., Li, W. W., Wang, L. F., & Yu, H. Q. (2012). Fouling of proton exchange membrane (PEM) deteriorates the performance of microbial fuel cell. *Water Research, 46*(6), 1817–1824. https://doi.org/10.1016/j.watres.2011.12.060

You, S., Zhao, Q., Zhang, J., Jiang, J., & Zhao, S. (2006). A microbial fuel cell using permanganate as the cathodic electron acceptor. *Journal of Power Sources, 162*(2), 1409–1415. https://doi.org/10.1016/j.jpowsour.2006.07.063

Yuan, Y., & Kim, S. H. (2008). Improved performance of a microbial fuel cell with polypyrrole/carbon black composite coated carbon paper anodes. *Bulletin of the Korean Chemical Society, 29*(7), 344–1348. https://doi.org/10.5012/bkcs.2008.29.7.1344

Yuan, Y., Zhao, B., Zhou, S., Zhong, S., & Zhuang, L. (2011). Electrocatalytic activity of anodic biofilm responses to pH changes in microbial fuel cells. *Bioresource Technology, 102*(13), 6887–6891. https://doi.org/10.1016/j.biortech.2011.04.008

Zafar, M. W., Shahbaz, M., Hou, F., & Sinha, A. (2019). From nonrenewable to renewable energy and its impact on economic growth: The role of research & development expenditures in Asia-Pacific Economic Cooperation countries. *Journal of Cleaner Production, 212*(1166), 1178. https://doi.org/10.1016/j.jclepro.2018.12.081

Zhang, X., Li, H. Y., Deng, Z. D., Ringler, C., Gao, Y., Hejazi, M. I., et al. (2018). Impacts of climate change, policy and Water-Energy-Food nexus on hydropower development. *Renewable Energy, 116*, 827–834. https://doi.org/10.1016/j.renene.2017.10.030

Zhang, Y., Liu, M., Zhou, M., Yang, H., Liang, L., & Gu, T. (2019). Microbial fuel cell hybrid systems for wastewater treatment and bioenergy production: Synergistic effects, mechanisms and challenges. *Renewable and Sustainable Energy Reviews, 103*, 13–29. https://doi.org/10.1016/j.rser.2018.12.027

Zhou, M., Wang, H., Hassett, D. J., & Gu, T. (2013). Recent advances in microbial fuel cells (MFCs) and microbial electrolysis cells (MECs) for wastewater treatment, bioenergy and bioproducts. *Journal of Chemical Technology and Biotechnology, 88*(4), 508–518. https://doi.org/10.1002/jctb.4004

Zhuang, L., Zhou, S., Li, Y., & Yuan, Y. (2010). Enhanced performance of air-cathode two-chamber microbial fuel cells with high-pH anode and low-pH cathode. *Bioresource Technology, 101*(10), 3514–3519. https://doi.org/10.1016/j.biortech.2009.12.105

Zuo, Y., Cheng, S., Call, D., & Logan, B. E. (2007). Tubular membrane cathodes for scalable power generation in microbial fuel cells. *Environmental Science & Technology, 41*(9), 3347–3353. https://doi.org/10.1021/es0627601