Microbial Fuel Cell Technology as Advanced Sewage Sludge Treatment

Muhammad Najib Ikmal Mohd Sabri, Nur Atiqah Mohd Abdul Rasik, Kavita Pusphanathan, Muaz Mohd Zaini Makhtar, and Hafiza Shukor

Abstract The microbial fuel cell (MFC) has emerged as an innovative and sustainable renewable energy technology, offering a potential alternative to address the global energy crisis. Operating through electrochemical processes, MFCs harness the power of electrogenic bacteria (EB) as biocatalysts to generate electricity. This chapter highlights the untapped potential of sewage sludge, derived from wastewater treatment, as a valuable fuel source within the MFC system. Extensive research has demonstrated the abundance of organic components present in sewage sludge, making it highly amenable to degradation through microbiological pathways within the MFC. Despite the lack of large-scale commercial utilization of MFC technology in wastewater treatment plants, the significant progress and promising findings indicate its effectiveness in addressing the challenges associated with sewage sludge management. The MFC system not only facilitates the simultaneous generation of energy but also contributes to bioremediation efforts. The redox potential inherent in MFCs enables this dual functionality, effectively integrating energy production with the treatment of sewage sludge. This chapter sheds light on the potential of MFC technology as an advanced approach for sewage sludge treatment. By harnessing the capabilities of electrogenic bacteria and capitalizing on the rich organic composition of sewage sludge, MFCs offer a sustainable solution that can simultaneously address energy needs and promote efficient waste management in wastewater treatment plants. The abundant and promising data accumulated thus far underscore the viability and potential of MFCs in mitigating the challenges associated with sewage sludge waste.

M. N. I. Mohd Sabri · N. A. Mohd Abdul Rasik · K. Pusphanathan ·
M. Mohd Zaini Makhtar (✉) · H. Shukor
School of Industrial Technology, Bioprocess Technology Division,
Universiti Sains Malaysia, Penang, Malaysia

M. Mohd Zaini Makhtar
Centre for Innovation and Consultation (CIC), Universiti Sains Malaysia,
Penang, Malaysia

H. Shukor
Faculty of Chemical Engineering & Technology, Universiti Malaysia Perlis, Kangar, Malaysia

M. Mohd Zaini Makhtar et al. (eds.), *Microbial Fuel Cell (MFC) Applications for Sludge Valorization*, Green Energy and Technology,
https://doi.org/10.1007/978-981-99-1083-0_6

Keywords Sewage sludge · Biomass conversion · Microbial fuel cell · Affordable and clean energy · Renewable energy

1 Introduction

Dewatering process is the middle process that happens in sewage sludge management after being pre-treated by digestion or conditioning, thickening before any further processing occurs such as incineration, landfill and composting. Generally, centrifuge involves in dewatering process hence about 20%–25% commonly a good dewatering performance practice in industrial scale [1]. In addition, total cost for managing through the process was estimated about US$ 0.33 billion per year [2]. Commonly incineration considered as a major solver for the lack of new space for sludge to be dumped in landfill. However, side effect of incineration has been argued as approximately 30% of solids from the sludge remain as ash [3]. There are several losses could be found from sludge process in which possible for power generation through biogas production. Data from Bunus Centralized Sewage Treatment Plant (Kuala Lumpur) highlighted the possible of biogas generation up to 2500 m^3/days hence 15,000 kWh/m^3 of power losses statistically [4].

Various types of energy recovery technique that had been through by recent researchers such as thermal hydrolysis, pyrolysis and water extraction through hydrate formation [5]. An attempt of several research to apply thermal hydrolysis onto dewatered sludge for improvement in anaerobic digestion performance which solid content from 10 to 20 wt% unfortunately has drawbacks which are high operation cost and large energy consumption [6, 7]. Next combustion–based technologies named as pyrolysis can be applied to dewatered sludge as well for energy recovery [8, 9]. Specifically, research that focuses on the effect of conditioning operation on pyrolysis performance is limited thus study by [10] on minimizing the bio-crude yield of sludge pyrolysis through attempted of $Fe_2(SO_4)_3$ for producing Fe—amended char.

2 Sludge Disposal Techniques

The diverse disposal method of sewage sludge been implemented throughout the years for example thermal drying, wet air oxidation, incineration and landfill. Both thermal drying and incineration are included in the thermal processing of sewage sludge [11]. Thermal drying is an efficient stabilization, dewatering and pathogen removal process, involving short–term high temperatures, through which sewage sludge may reach sterilization. Incineration is a stabilization process that destroys organic substances and pathogenic organisms through combustion obtained in the presence of excess oxygen [12]. These two methods required enormous energy inputs moreover it has been assumed by Oladejo (2019) that the main purpose of incineration

Table 1 Sewage sludge disposal methods

Methods	Remarks	References
Thermal drying	• Produce pellets for agricultural reuse, sanitary landfills disposal and fuel for boilers and industrial heater	[11]
Wet air oxidation	• Suitable for high diluted of effluent • Improve sludge characteristic for anaerobic digestion	[13]
Incineration	• Produce sludge ash; greatest volume reduction • Destroys organic substances and pathogenic organisms through combustion	[13, 17]
Landfill	• Safe disposal and no damage to public health • Emit methane which 20 times more active than carbon dioxide	[15, 16]

is for burning off harmful elements from waste before final disposal not for electric power generation as conventional used. Wet oxidation is a method that is implemented when the effluent is too diluted to be incinerated thus can improve the sewage sludge characteristics for the anaerobic digestion [13]. Meanwhile, landfills are still retained by metropolitan areas directly after mechanical biological treatment of the unsorted waste [14]. The treated organic fraction when buried continues to emit methane, which is known to be a greenhouse gas effect [15, 16]. Lastly, disposal through landfills may become unsustainable in terms of environmental perspective due to a shortage of land in addition to rising health concerns with regards to the suitability of sludge constituents. Table 1 sums up techniques for sludge disposal.

3 Current Usage of Sewage Sludge

Generally,the sewage sludges are used widely as a source of nutrient for vegetables and plants. These sludges play a pivotal role as soil conditioner such reduces toxic levels and amendment raises pH without a doubt to improve the adsorption of nutrients and stimulates microbial activity. The sewage sludge also can be innovated through advance material inform of biochar. Biochar is a versatile carbonaceous porous product derived from various biomass which came with an appealing alternative for environment remediation as it has an enormous surface area and high porosity that empower it to utilize as an catalyst and adsorbent material in the removal of a wide range of organic and inorganic contaminants in wastewaters [18, 19]. Several researchers reported that the derivation of lipids from sewage sludge may use as biofuel production which lipids are converted to biodiesel by means of transesterification or to bio-oil by pyrolysis [20]. Table 2 summarizes the benefit for each usage of sewage sludge.

Microbial fuel cell (MFC) has been considered as one of the efficient alternative renewable bioenergy technologies since 1911 electrical generated by bacteria [24]. Moreover, through degradation of organic matter includes abundant of biomass in dewatered sludge can directly produce electricity [25].

Table 2 Current usage of sewage sludge

Type of usage	Remarks	References
Biochar	• Applicable as a nutrient source in refining soil fertility • Role as restoration of contaminated soils	[21, 22]
Soil conditioner	• Suitable for high diluted of effluent • Suitable for agricultural purposes; increases the shoots and roots	[13, 23]
Biofuel	• Potential feedstock; low cost and abundant accessibility	[20]

4 Microbial Fuel Cell

Microbial fuel cell (MFC) converts chemical energy to electrical energy by certain microorganisms. Regarding to this, MFC is a bio-electrical device that harness the natural metabolism of electrogenic bacteria (EB) to produce electrical energy (Ren, 2014). Involvement of electrochemical interactions between the microorganisms called as electrogenic microbes which the electrons are transferred from the substrate to the anode electrode. Electron transportation phenomenon known as extracellular electron transport (EET) [26]. Later this MFC innovated with non-mediated where both chemical and electron shuttles mediators had been terminated. This MFC device generally configurates through two compartments; anode and cathode separated by an ion-permeable material. The configuration must innovate accordingly as adaptation through times is hence suitable for all different applications. As shown in Fig. 1, both single chambered and double chambered MFC known as basic configuration and been used broadly in various applications [27].

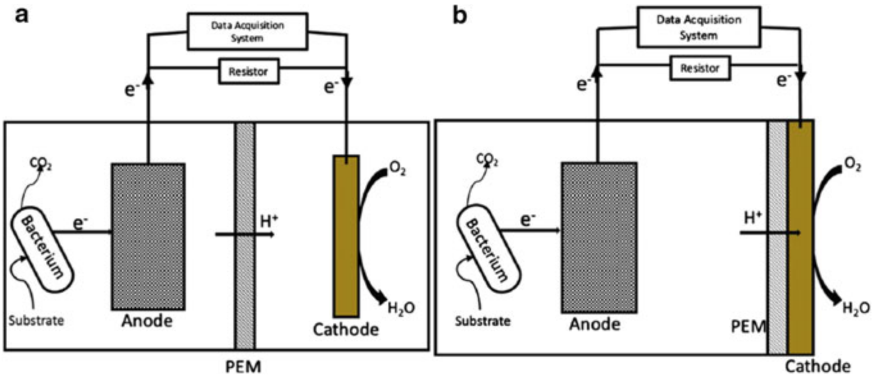


Fig. 1 Basic configuration of MFC; (A) double chambered MFC, (B) single chambered MFC. Reprinted with permission [27] (CC-BY)

4.1 History of Microbial Fuel Cell

Early 1791, researcher named Luigi Galvani examined that current gave a twitching effect on dead frog legs hence there are relation between electric and biological [28]. Back in 1911 which idea for the implementation of microbial fuel cells to produce electricity was first conceived by Potter & Waller (1911). The idea showed that it is possible to generate electricity from cultures of the bacterium *Escherichia coli*. Later 1931, Cohen (1931) added some significant knowledge when he reported that the creation of an assembly of microbial half fuel cells stack connected in series capable of producing over 35 V but the current generated through this stack was only 2 mA. A great impact factor held on early 1980s in the area of MFC research was received by the work of Allen and Peter Bennetto [29], power density improves by the usage of chemical mediators as electron shuttle which meant fuel cell would only function till the mediators were present.

Most recently, MFCs contained various mediators in an oxidized state. These mediators can easily shorten by capturing the electrons from within membrane and released the electrons to the anode and became oxidized again in the bulk solution in the anodic chamber [30]. MFC capacity to clean wastewater and deliver clean drinking water while simultaneously generating electricity, would allow developing countries towards sustainable water treatment [31, 32]. Table 3 summarizes preliminary history of MFC started on 1791 until early 2000.

Table 3 Preliminary history of MFC

Year	Description	References
1791	• Luigi Galvani • Applied current to dead frog legs, the legs twitching • Biological reactions and electric current are closely related	[28]
1911	• Publication by Potter about MFC report on the ability of microorganisms to transform organic substrate (chemical energy) into electricity • The production of electrical energy from living cultures either *Escherichia coli* or *Saccharomyces* • The first MFC proving that biological process produces bioelectricity	[24, 33, 34]
1980	• H. Peter Benneto • Succeed in extracting electric power from MFCs • Employed pure cultures to catalyze the oxidation of organics and utilizing artificial electron mediators; to facilitate electron transfer	[29, 35]
Early 2000s	• Two robots were developed: Chew–Chew and EcoBot I • These two robots are powered by MFCs	[36, 37]

5 Dewatered Sludge as MFC Feedstock

It should be noted that most of the studies on MFC have been focused on wastewater or activated sludge in municipal wastewater treatment plant (MWTP) but have overlooked the end product of MWTP, dewatered sludge. The sewage sludge is commonly taken to landfills or burned in incinerators. Handling sewage sludge is one of the largest contributors to the operational cost of MWTP and it indirectly elevates local environmental problems [4]. Furthermore, there are a few reports on the use of dewatered sludge from MWTPs for energy generation using MFC. There was a huge energy reserve in the sewage sludge without being recognized [38].

There were in the form of biodegradable organic matter and the energy could be recovered. It is reported that there is a conventional wastewater treatment plant in Toronto, Canada, which contained energy about 9.3 times more energy than was used to treat the wastewater. While the study by Logan (2006) stated that the processing of wastewater for domestic, animal and food approximately consist of 17 GW. This amount was equivalent to the energy needed to supply for the whole water infrastructure in the U.S. It is a promising energy and if the energy managed to be recovered that means the treatment plant could be run using its own energy supply [39].

Sewage sludge generated daily from the wastewater in Indah Water Konsortium (IWK) treatment plant were analyzed for its capability to support growth of the EB for the electricity generation. They can be used as value-added substrate instead of polluting the environment. Approximately 3 million cubic meters of sludge was produced annually, and it is also estimated that IWK will be producing 10 million cubic meters of sludge by the year 2035 [4] and make it the most favourable substrate for bioconversion as they are renewable and abundantly available. Their efficiency and economic viability of converting to bioenergy depend on their characteristic and components in it [40].

6 Advantages Compared to Anaerobic Digester

Since the dawn of the twenty-first century, the awareness on the protection environment come out for alternative fuels around the world thus focusing on the MFCs due to greener and bioenergy production. Variety of biomass, rich in carbohydrates, protein, hydrocarbons, alcohols and organic acids, moreover polymeric carbohydrates such as cellulose and starch also could be used as a fuel for the MFC. Accordingly, there also aid to continuous monitoring of quality wastes and minimal investment on the fuels Click or tap here to enter text. Table 4 summarizes the advantages of MFC compared to anaerobic digesters in which MFC directly converted organic substrate into electrical energy and able to treat on low concentration of substrate [41].

Table 4 Advantages of MFC compared to anaerobic digesters

Advantages	Remarks	References
Efficient conversion of substrates to electricity	Roles of electrogenic bacteria (EB) inefficiently convert and consume substrate for electricity generation	[26]
Powerful exoelectrogens oxidize organic matter	Utilization of a wide range of organic and inorganic matter into direct current (DC) electricity	[42, 43]

7 Electrogenic Microorganisms in MFC

Electroactive or electrogenic microorganisms are the core of the MFC technology. Additionally there are various mechanisms of electron transfer such as mediated electron transfer and interspecies electron transfer besides direct electron transfer itself [44]. Electrogenic microorganism can be fractionating into anaerobic and aerobic as described below.

7.1 Aerobic Electrogenic Bacteria

Fundamentally aerobic bacteria can form biocathode which catalyze the reduction of oxygen at the cathodes [45]**.** Research conducted by Qu (2012) highlighted that bacterial diversity and operating environment affect the biodegraded products generation. This phenomenon can be seen on the reductive breakdown of azo bonds been further degraded through aerobic condition by the presence of several oxidoreductases also called as oxidative degradation [46].

7.2 Anaerobic Electrogenic Bacteria

Generation of electricity through microorganism by exchanging electrons with electrodes while oxidizing organic also called as bacterial exocellular electron transfer principle plays a vital role in anaerobic microbial communities that degrade both inorganic electron acceptors; iron- and manganese- oxide and organic matter for growth [45, 47]. Hence these exocellular bacterial can be isolated from anaerobic sludge and municipal effluent thus can be categorized into various functional groups based on types of anaerobic respiration [48]. Via anaerobic respiration, both purple non-sulphur bacteria photosynthetic *Rhodopseudomonas palustris* DX-1 and *Rhodoferax ferrireducens*, non-photosynthetic found to generate electricity in MFC [48, 49].

7.3 Fungi

Fungi belonging to the group of white-rot—well known wood degraders—were found to have an extracellular oxidative ligninolytic enzymatic system; degrade lignin. For the last 10 years, fungi-based MFCs have appeared, their results have revealed the electrogenic potential. In addition enzyme of fungi has proven that been the best catalyst for oxidative reduction that can assure electrogenic activity in MFC activity meanwhile degradation of various xenobiotic compounds and dyes through enzymes of this system [50–51]. Yeast-based is the most intensively studied systems for fungi-based MFCs where direct electron transfer was proved via cytochrome c [52]. MFC that complied with fungi species for treating waste waters from the distillery industries, for example, are *Aspergillusawamori*, *Trichodermaviride* and *Trichodermaatroviride* while *Pleurotusostreatus* used as decolourisation of dye from textile industries effluent [53].

7.4 Algae

Organisms that contain chlorophyll size range from unicellular to multicellular are called as algae. There are two different algal growth types, autotrophic and heterotrophic. Autotrophic termed by the growth system of algae that use carbon dioxide as a carbon source in the presence of light energy while heterotrophic termed as algae that grow in the absence of light, in photobioreactors (PBRs), by utilizing a carbon dioxide source from provided substrates. These two modes can be combined to form a mixed culture (mixotrophic) growth mode, photosynthesis and respiration metabolism simultaneously function to assimilate organic carbon and carbon dioxide [53, 54]

Research outcome by Kruzic reported that metabolism of algae on bicarbonate and oxygen using solar energy may be integrated with aeration system to replace a sustainable photosynthetic one [55]. Subsequently, algae grown in cathode chamber of an MFC, produced electricity by a photosynthetic process [56]. The overall biochemical reaction that happened in both anode and cathode chamber where mediator was used had stated by Zhou (2012) below:

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e \tag{1}$$

$$6CO_2 + 12H^+ + 12e \rightarrow C_6H_{12}O_6\ (\text{biomass}) + 3O_2 \tag{2}$$

7.5 Bacteria

Wastewater is the popular power source of MFC thus at anode chamber should have similar functions to methanogenic anaerobic digesters microbial communities except for microorganisms that are capable of transferring electrons to the electrode. Moreover, there are two mechanisms for electron transport in MFC, firstly direct electron transfer: (a) c-cytochromes, (b) nanowire and (c) electron shuttle. Availability of c-cytochrome in most archaea and eubacteria so a usefully role for electricity generation through electron transfer by electrogenic bacteria. Nanowire by bacteria was studied as a new way of transferring electrons to the electrode by electrically conductive pili (Das 2018). Electron shuttle secreted by most gram-negative bacteria, for example, flavin secretion that can be utilized by the organism as carbon resource although may be limited in field-applied MFC [57]. Secondly mediator electronic transfer; is essential for bacteria that cannot transfer electrons due to enabling of electron shuttle from cell membrane to electrode for example ferricyanide and benzoquinone usage to facilitate electron transfer from bacteria to electrodes [58–60].

8 Microbial Fuel Cell Concept

The concept is a linkage between negative terminal (anode) and positive terminal (cathode). Anode terminal oxidized organic matter such as fuel and released CO_2, electrons and protons while the cathode terminal received the electrons that produced via an external circuit as the result of electrophilic attraction at the cathode electrode. The migration of protons from the anode to the cathode through the separator or called mediated [61]. This mediated generally must possess the quality of high proton transfer rate, low gas permeability, good thermal stability and resistance against biofouling.

8.1 Biological Concept

The basic of molecular diversities are made up of chemical based which mostly of the element carbon. Carbon is unparalleled in its ability to form molecules that are large, varied and complex, making possible the diversity of organisms that evolved on Earth.

Basically, there are seven chemical groups that are most important in biological processes which are carbonyl, hydroxyl, carboxyl, amino, phosphate, sulfhydryl and methyl groups. Major sources of energy in cellular processes are the phosphate group, it complicated name is adenosine triphosphate (ATP) [62]. This ATP will be split off when reacted with water and later becomes adenosine diphosphate (ADP), the reaction released energy then can be used by the cell. In MFCs energy production

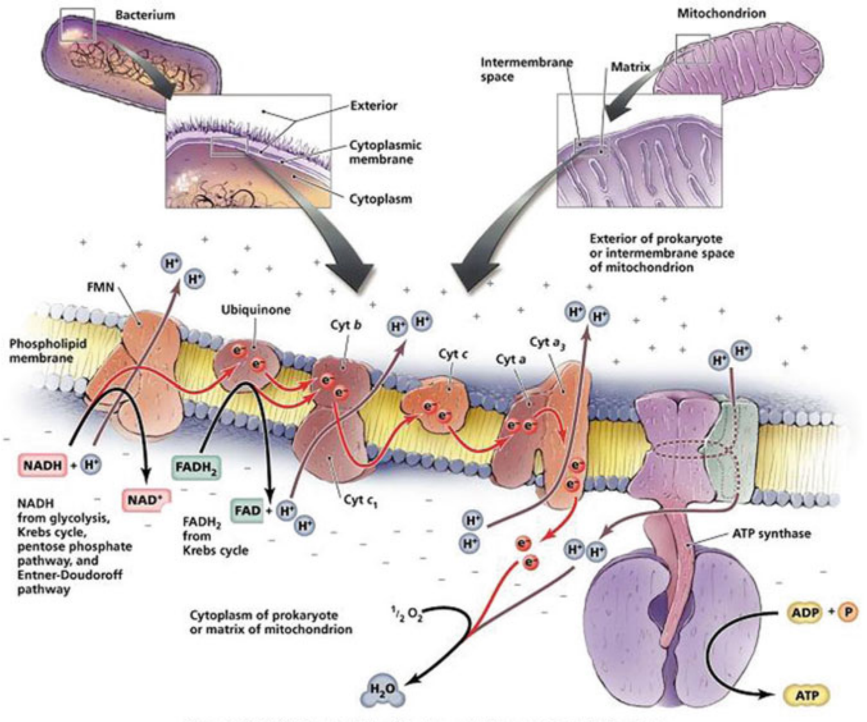


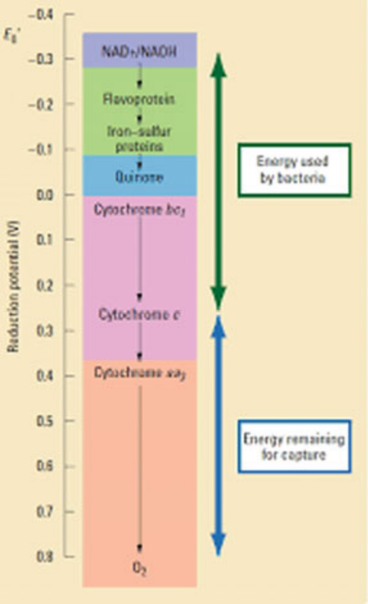
Fig. 2 The schematic diagram of electron transport chain (Reprinted with permission [63] (CC-BY))

occurs when electrons were passed through an electron transport chain (ETC) and protons are translocated across the cell membrane to generate energy in the form of adenosine triphosphate (ATP). Roughly, this ETC mechanism had been illustrated in Fig. 2.

8.2 *Chemical Concept*

Chemical reaction that usually occurs in MFC system is reduction and oxidation popularly called as redox reaction which reduction of oxygen takes place at the cathode resulting in water molecule while oxidation for example hydrogen at the anode was helped by a conductive catalyst; platinum (Pt) [43, 59]. MFC developed as an anode catalyst where microorganism is used as a biocatalyst for the redox reaction. Capability of electrogenic bacteria for generating and transferring electrons through nanowires (*Geobacter sulfurreducens*) and electron shuttle (*Pseudomonas aeruginosa*) [59, 64].

Fig. 3 The schematic diagram of standard redox potential (Reprinted with permission [66] (CC-BY))



Present of lowest redox of mediator theoretically lowest anodic redox thus maximize the redox difference between anode and cathode, affect the voltage different but it would not necessarily be the most efficient at pulling electrons away. A mediator with a higher E^0 redox would give a higher overall power than a mediator with the lowest redox [65]. The schematic of standard redox potential is shown in Fig. 3.

8.3 *Electrical Concept*

In MFCs, bacteria as a living catalyst is used to decompose organic substrates into electricity. Electrical energy yield happened or occurred in MFC when biomass-based materials oxidize by resulting in the generation of free electrons which pass through external circuit [67]. These phenomena occur during microbial metabolism which involved redox reaction. The electrons pass through an electron transport chain (ETC) and protons are translocated across the cell membrane to generate energy in the form of adenosine triphosphate (ATP) (Fig. 4). Production electrical power (W) based on the rate of electrons moving through the circuit; current (amps) besides electrochemical potential difference (V) across the electrodes [68]. Table 5 shows the MFCs with different substrate and the maximum current produced.

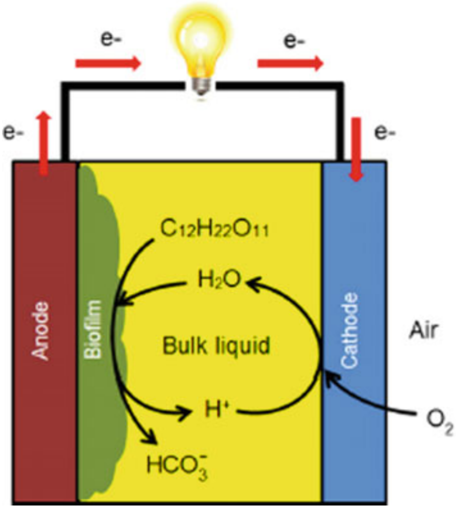


Fig. 4 Schematic diagram of membraneless microbial fuel cell (Reprinted with permission from [69] (CC-BY))

9 Conventional Fuel Cell vs Microbial Fuel Cell

Conventional or typical fuel cell provided with greater control for the designer over operating conditions. The realm of conventional fuel cell is packed with a variety of well-understood technologies that delivers high performance with respect to efficiency and power density. There are reasons where conventional fuel cell may incompetent which were the demand for chemical selectivity and high-cost production correspond with technology and high performance. For example, current densities that produced by Direct Methanol Fuel Cells (DMFCs) are often lower by about 100–300 mA/cm^2. Methanol oxidation owing to the high kinetic resistance as compared to hydrogen oxidation besides performance limited caused by methanol crossover from anode to cathode [67]. Table 6 tabulated the difference between conventional fuel cell and microbial fuel cell.

10 Microbial Fuel Cell Design

Common microbial fuel cell designs consist of an anodic chamber and cathodic chamber separated by proton exchange membrane (PEM) chamber, fundamental for the construction of MFC in a diversity of architecture to produce high power density and coulumbic efficiencies. Power output, coulombic efficiency, stability and longevity are usually evaluated in MFC. Not only the cost of materials but feasibility scaling up also been considered in the real application of MFC. Popular MFCs designs are single chamber, double chamber, tubular membrane, stack design and lastly flat-plat.

Table 5 MFCs with different substrate and the maximum current produced [70]

Types of substrate	Concentration	Source inoculums	Type of MFC	Current density (mA/cm^2)
Starch processing wastewater	10 g/L	Starch processing wastewater	One chamber air cathode MFC with carbon paper anode (25 cm^2)	0.09
Starch	10 g/L	Pure culture of *Clastridiumbutyricum*	Two chambered MFC with woven graphite anode (7 cm^2) and ferricyanide catholyte	1.3
Acetate	1 g/L	Pre-acclimated bacteria from MFC	Cube shape one chamber MFC with graphite fibre brush anode (7170 m^2/m^3 brush volume)	0.8
Corn stover biomass	1 g/L	Domestic wastewater	One chamber membrane-less air cathode MFC with carbon paper anode (7.1 cm^2) and carbon cloth electrode	0.15
Landfill leachate	6000 mg/L	Leachate and sludge	Two chambered MFC with carbon veil electrode (30 cm^2)	0.0004
Domestic wastewater	600 mg/L	Anaerobic sludge	Two chambered mediator-less MFC with plain graphite electrode (50 cm^2)	0.06

The architecture of the optimizations of MFCs aimed to reduce the internal resistance and increase the cell power output. Roughly all of the designs stated above had an addition either PEM or assisted chemical for electron transportation through media. Along the appropriate optimization of architecture, these microbial fuel cells are able to power a wide range of devices such as power sensors for environmental parameters monitoring at various intervals, store energy in external storage device; capacitor and power devices placed under water environment [71]

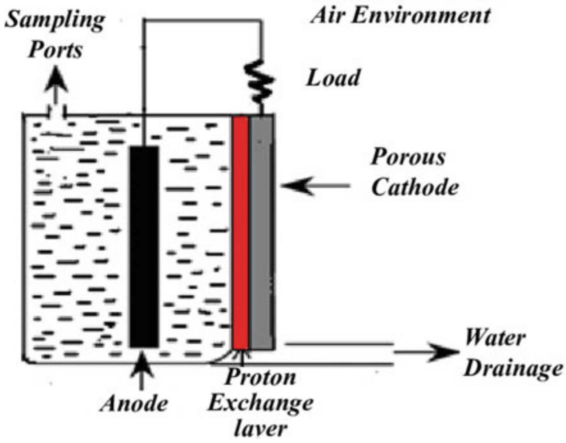
Table 6 Conventional fuel cell and Microbial fuel cell

Subject	Conventional fuel cell	Microbial fuel cell
Mediator	Artificial Abiotic fuel cells Comprise of inorganic catalyst	Natural Biotic fuel cells Assist of microorganism such as *Geobacter sulfurreducens;* nanowires and *Pseudomonas aeruginosa;* electron shuttle
Advantage	Aeration consumes more energy Enhance power generation, short half–life and instability limit	Higher affinity for oxygen with cathode Enhance the chemical oxygen demand removal Inexpensive catalyst and cheap substrate Can operate at ambient temperature and atmospheric pressure
Disadvantage	Expensive catalyst substances	Systematic configuration undetermined
Example	Solid oxide fuel cell and proton exchange membrane fuel cell	Up-flow reactor and stacked MFC *Pseudomonas aeruginosa* and *Geobacter sulfurreducens*

10.1 Single Chamber MFC

This type of MFC design is purposely to solve scale-up problems on two chambers MFCs due to complex design and cost even can be operated in either batch or continuous mode [72]. The design was used to characterize the performance of either anodic or cathodic chambers separately. A common single chamber possessed aeration on an anodic chamber without including a cathodic chamber. The reduction of internal resistance of MFCs thus enhances electricity production [73]. Schematic diagram of the single chamber that is provided with proton exchange membrane (PEM) layered on the cathode (Fig. 5).

Fig. 5 The schematic diagram of single chamber microbial fuel cells (Reprinted with permission from [73] (CCBY))



10.2 Double Chamber MFC

Fundamental or conventional design for microbial fuel cells often run and investigated in batch mode with a defined medium such as acetate or glucose solution to generate electricity. They were built by one cathode chamber and one anode chamber, connected by a bridge and separated by a proton or cation exchange membrane to allow protons to move across to the cathode while blocking the diffusion of oxygen into the anode. Chemically the plain carbon cathode was catalyst and coated in ferricyanide due to platinum expensively [72, 73].

Plain carbon electrode immersed in ferricyanide solution as the electron acceptor and the cathodic reaction is $\mathrm{Fe(CN)}_6^{3-} + \mathrm{e} = \mathrm{Fe(CN)}_6^{4-}$. Reaction in the cathode chamber reduced ferricyanide to ferrocyanide, addition of chemical compulsory after it is depleted. Because of that ferricyanide are not environmentally friendly and not economic to use on cathodes. That is the reason some researcher stated that power densities in two-chamber MFCs are possible to be increased by enhancements of cathode such as concentration increment of dissolved oxygen.

According to He (2005), dual chamber and cylindrical shaped of microbial fuel cells suitable and useful in powering autonomous sensors for long-term because they are relatively easy to scale up. Maximum power generated about 1530 kWh/day of electricity by 24-hour operation perpendicular with 0.204 kWh/m^3 closed to aerobic trickling filter consumed. Schematic diagram of various architecture of dual chambers that provided with PEM as bridge layered on different shapes such as cylindrical, rectangular and miniature (Fig. 6).

10.3 Tubular Membrane MFC

Architecture working of tubular membrane commonly designed in continuous flow mode, initial flow moving through anode chamber and directly up into the cathode chamber in the same column. Although this design has high possibility to be scaled up but there is drawbacks for this design. Based on the implementation of tubular design in wetlands by Wetser (2017) indicated that electricity generation was not optimal due to complication of oxygen crossover from cathode to anode. Practically orientation of anode and cathode tube that been placed as closely as possible inside the reactor developed 112–240 mV higher than outside the reactor. Schematic diagram of tubular membrane built in granular anode that also provided with PEM (Fig. 7).

10.4 Stack MFC

Both parallel and series circuits can be investigated using stack microbial fuel cell. The usage of copper wires in this system is interconnected in series or parallel to

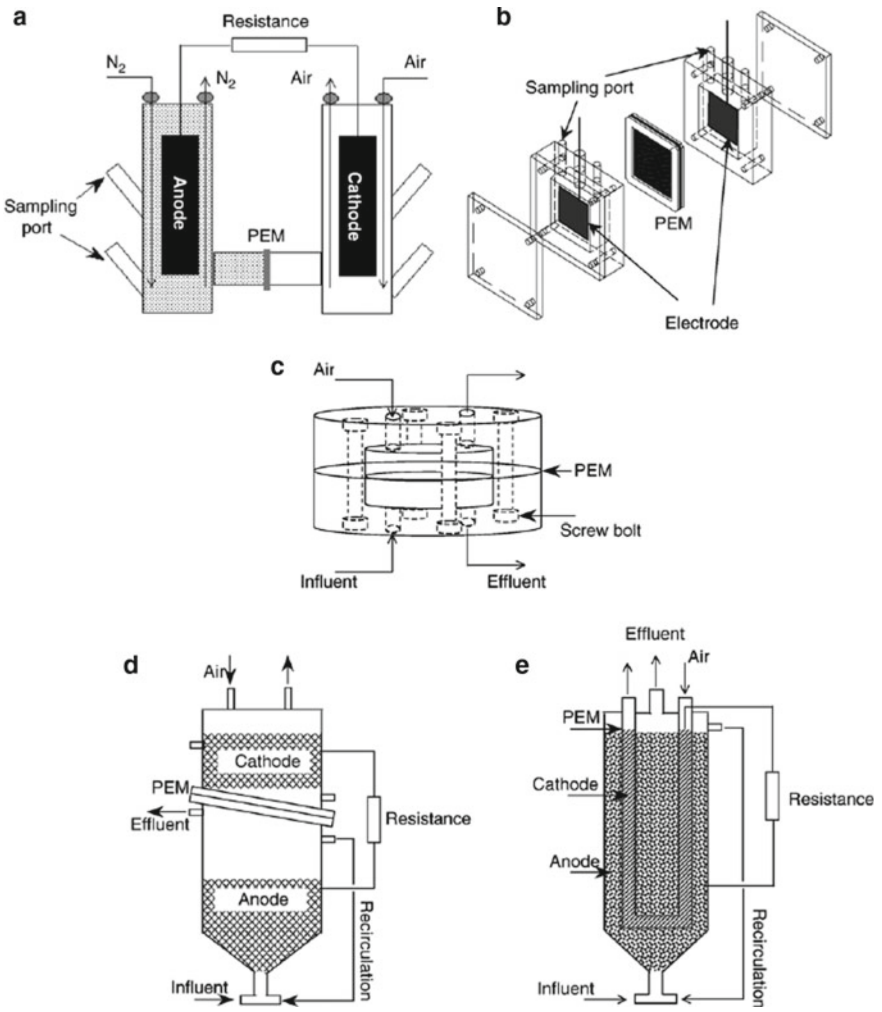


Fig. 6 The schematic diagram of various double chamber microbial fuel cell (Reprinted with permission from [72, 74] (CCBY))

the electrodes and held each other by screw bolts. Both Aelterman (2006) and Li (2008), observed from their research that the effect of maximum power output per MFC unit was no visible adverse which Coulombic efficiency diverged greatly in two arrangements with parallel connection giving about six times efficiency more when both the series were operated at the same volumetric flow rate. Again both research by [75] and [76] supported previous research thus highlighting that the performance of stacked MFC is low caused by voltage reversal in individual cells, increase ohmic, inactive surface area on the cathode, kinetic and transportation resistances. Schematic

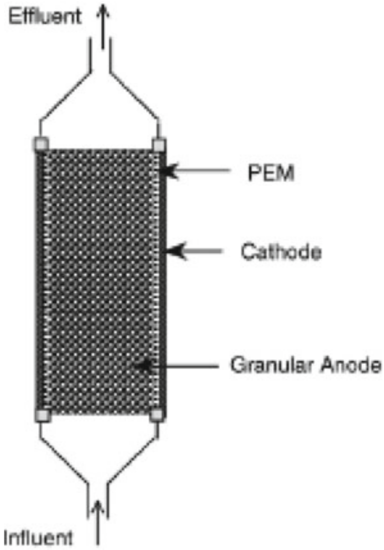


Fig. 7 The schematic diagram of tubular membrane microbial fuel cell (Reprinted with permission from [72] (CCBY))

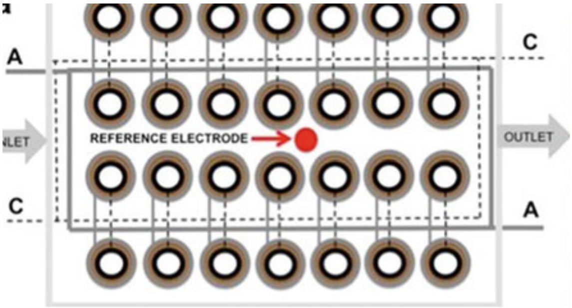


Fig. 8 The schematic diagram of stack microbial fuel cell (Reprinted with permission from [77] (CC-BY))

diagram of stack MFC built in six individual units of granular graphite anode that also provided with PEM (Fig. 8).

10.4.1 Flat–Plat

Basically the structure of flat-plat similar to chemical fuel cell whose designed by [78]. Hot pressed method on cathode with PEM sandwiched between two non-conductive (polycarbonate) plates and placed on top of anode. Coulombic efficiency diverged greatly in two arrangements with parallel connection giving about six times efficiency more when both the series were operated at the same volumetric flow rate. Maximum power density for domestic wastewater obtained was about 72 mW/m^2

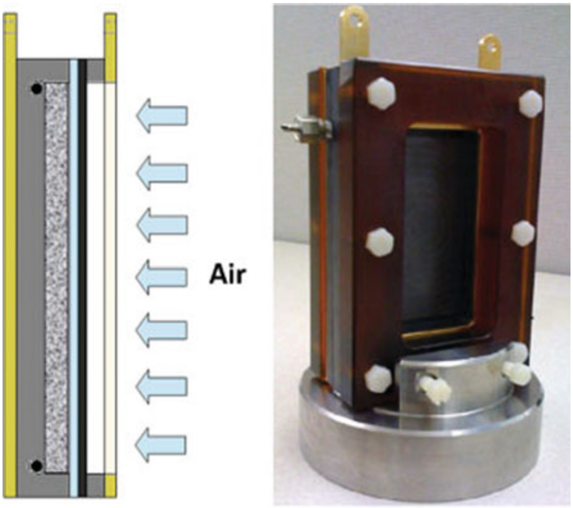


Fig. 9 The schematic diagram of flat-plat microbial fuel cell (Reprinted with permission from [80] (CC-BY))

increment, 2.8 times compared to single chambered MFC. However this design drawback is high in anodic resistance [79]. Schematic diagram (upper, side view; top, lower view) of flat-plat MFC (Fig. 9).

11 MFC Technology: World Energy's Paradigm as a Driven Force

Non-renewable energy sources such as oil, natural gas and coal account for 85 per cent of global energy. Oil provides over 40% of the world's energy [81]. Linearly from 2012, rising transportation fuel consumption and robust industrial demand have resulted in an increase in non-renewable energy usage [81]. About 1.3 billion people in the globe do not have access to electricity, and another three billion rely on traditional fuels, which can have negative consequences for their health, ecosystems and development. According to what is known about global energy demand, it is expected to grow at a pace of 1.6 per cent per year on average from 2008 to 2030 [82].

Non-renewable energy is the most frequently stated problems with constant increment of prices and CO_2 emission which both coal and natural gas is the major impact. Along with this statement is evidence that oil prices are expected to remain between US$ 50.0 and US$ 80.0/barrel until 2030 as stated. Moreover, the increase in the market is due to structural changes and energy efficiency gains in the market. Besides European oil consumption will be reduced by 3.0% over the next 15 years. In addition, oil supply globally is increasing by 14.0 mb/d to 104.0 mb/d by 2040 even though the drift timely expenditure specifically [83].

There is a large volume of published studies describing on greenhouse gases (GHG) which cause by reradiated infrared radiations by CO_2, CH_4, O_3, NO_2 and NO slightly by water vapours thus significantly to maintain Earth's temperature by 33°C (Kumar et al. 2018). Between 2000 and 2010 annual anthropogenic GHG emissions have increased directly coming from energy supply (47%), industry (30%), building (3%) and transport (11%) [83, 84]. Emission of greenhouse gases continuously will cause further warming called as global warming which is irreversible and gives pervasive impacts for people and ecosystems. It has been reported that major drivers of increment in CO_2 emissions are from both fossil fuel combustion and coal impacted by economic and population growth globally [83, 84]. Furthermore, according to Ahmad (2011), Malaysia's petroleum resources are very limited compared to other international areas, at roughly 5.5 billion barrels, with petroleum output peaking in 2004 at roughly 861.8 thousand barrels per day. Nevertheless, these resources will be consumed and become more expensive in the long run.

Effect of oil and natural gas usage can be shown in Fig. 10, CO_2 emission has doubled since early 1970s, accelerating environmental change and climate degradation [83, 84]. Most countries occur a sustained increase due to global economic shift perpendicularly with power consumption clearly world economy is booming which gross domestic product (GDP) growing 2.5 times over the past three decades [85].

Figure 11 explained about the statistic of world's total electricity generation since 1990 and overview of the percentage increase/decrease in world energy, oil, gas, coal, CO_2 emissions and the share of renewable energy in electricity generation respectively. The natural gas, oil and coal cover up to 84% of world's primary energy consumption in 2019 [87]. The increment came from both public and private utilities hence China; Asia significantly contributing almost half of the increase in 2017 due to

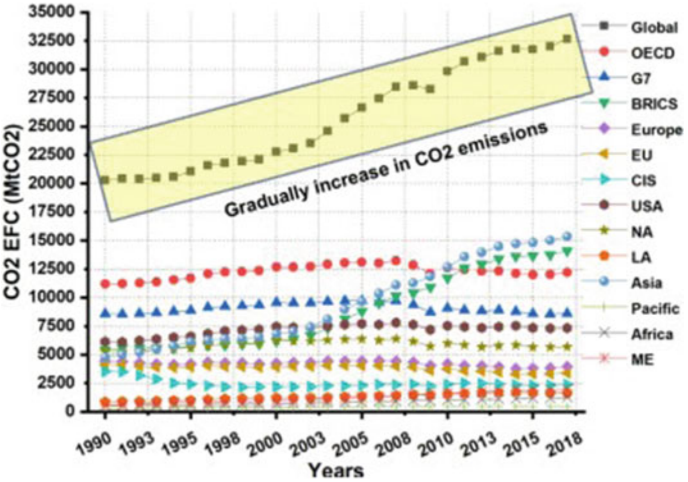


Fig. 10 CO_2 emissions from fuel combustion ($MtCO_2$) (Reprinted with permission from [86] (CC-BY))

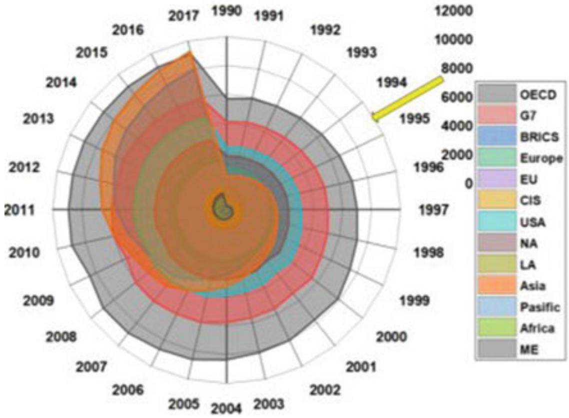


Fig. 11 World's total electricity generation (TWh) (Reprinted with permission from [86] (CCBY))

the high demand for electricity combined to accelerate the development of production capacity (Ahmad and Zhang 2020). According to the New Policy Scenario (NPS), global primary energy requirements increased by 37% between 2012 and 2040 which considers existing government initiatives. As a result, by 2040, oil, coal and natural gas were expected to account for around a third of total demand. Various states declared new initiatives to decrease CO_2 emissions at a long-term climate summit named the Paris Agreement in 2015; nonetheless, emissions continue to rise by 20% (Ahmad and Zhang 2020). Meanwhile, Climate Change Conference 2021 (COP 26) that had been conducted by United Nation (UN) also highlighted on several circumstances that are better than Paris Agreement in which almost 90% had been covered by a net–zero target (Lord, et al. 2021).

In the EU, the United States, India, Japan and China, stringent environmental policies have a significant impact on solar and wind energy development**.** Without a doubt, the share of renewable energy in the entire generation of electricity is gradually increasing daily [86]. As well as that bulk of employment sources is increasing perpendicularly with a large number of renewable energy sources. The major issue arises when non-renewable energy becomes completely reliable, causing prices to skyrocket and as previously stated, negatively impacting the environment. As a result, a new solution with a better conclusion from green energy is required. Microbial fuel cells (MFCs) which convert biochemical energy consisted in the substrate to electrical energy can be a part of it. This green energy technology is capable of utilizing any type of carbon waste that is seen to be impactful on community, government and environment.

12 Conclusion

This chapter summarizes the utilization of sewage sludge in MFCs for electricity production and waste treatment. While simple substrates like acetate and glucose were commonly used in the early years, recent research has focused on utilizing more unconventional substrates, such as sewage sludge, with the aim of both waste utilization and enhancing MFC output. The generation of bioenergy, in the form of electricity, from renewable sources like sewage sludge through MFCs holds significant development potential. It not only contributes to energy self-sufficiency but also addresses concerns about competition with food production that are associated with conventional biofuels. The findings presented in this chapter highlight the evolving landscape of MFC technology and its potential for sustainable sewage sludge treatment and renewable energy generation.

Acknowledgements The authors would like to thank the Universiti Sains Malaysia for the financial support of this study via APEX Era grant (1001/PTEKIND/881004) The authors have declared no conflict of interest for the manuscript.

References

1. To VHP, Nguyen TV, Vigneswaran S, Ngo HH (2016) A review on sludge dewatering indices. Water Sci Technol 74(1):1–16. https://doi.org/10.2166/wst.2016.102
2. Hanum F et al. (2019) Treatment of sewage sludge using anaerobic digestion in Malaysia: current state and challenges. Front Energy Res 7(MAR):1–7. https://doi.org/10.3389/fenrg.2019.00019
3. Kasina M, Kowalski PR, Michalik M (2016) Metals accumulation during thermal processing of sewage sludge—characterization of fly ash and Air Pollution Control (APC) residues. Energy Procedia 97:23–30. https://doi.org/10.1016/j.egypro.2016.10.012
4. Indah Water Konsortium (2013) Indah water cleaning the unseen
5. Wu B, Dai X, Chai X (2020) Critical review on dewatering of sewage sludge: influential mechanism, conditioning technologies and implications to sludge re-utilizations. Water Res 180:115912. https://doi.org/10.1016/j.watres.2020.115912
6. Duan N, Dong B, Wu B, Dai X (2012) High-solid anaerobic digestion of sewage sludge under mesophilic conditions: feasibility study. Biores Technol 104:150–156. https://doi.org/10.1016/j.biortech.2011.10.090
7. Dai X, Duan N, Dong B, Dai L (2013) High-solids anaerobic co-digestion of sewage sludge and food waste in comparison with mono digestions: stability and performance. Waste Manage 33(2):308–316. https://doi.org/10.1016/j.wasman.2012.10.018
8. Tian K, Liu W-J, Qian T-T, Jiang H, Yu H-Q (Sep.2014) Investigation on the evolution of n-containing organic compounds during pyrolysis of sewage sludge. Environ Sci Technol 48(18):10888–10896. https://doi.org/10.1021/es5022137
9. Zhao M, Wang F, Fan Y, Raheem A, Zhou H (2019) Low-temperature alkaline pyrolysis of sewage sludge for enhanced H_2 production with in-situ carbon capture. Int J Hydrogen Energy 44(16):8020–8027. https://doi.org/10.1016/j.ijhydene.2019.02.040
10. Yu G, Chen D, Arena U, Huang Z, Dai X (2018) Reforming sewage sludge pyrolysis volatile with Fe-embedded char: minimization of liquid product yield. Waste Manage 73:464–475. https://doi.org/10.1016/j.wasman.2017.08.004

11. Baru PA, Hassan S (2018) Akademia Baru characterization of Malaysian sewage sludge dried using thermal dryer. J Adv Res Fluid Mech Therm Sci 5(January):24–29
12. Tambo N, Kobayashi M, Thebault P, Haubry A (1982) Sludge treatment and disposal. Water Supply 1(2/3). https://doi.org/10.1142/9781848160798_0015
13. Hii K, Baroutian S, Parthasarathy R, Gapes DJ, Eshtiaghi N (2014) Bioresource Technology: a review of wet air oxidation and thermal hydrolysis technologies in sludge treatment. Biores Technol 155:289–299. https://doi.org/10.1016/j.biortech.2013.12.066
14. Technical EEA (2020) Horizon 2020 Mediterranean report, no. 6
15. Lou XF, Nair J (2009) The impact of landfilling and composting on greenhouse gas emissions—a review. Biores Technol 100(16):3792–3798. https://doi.org/10.1016/j.biortech.2008.12.006
16. Mancini G, Luciano A, Bolzonella D, Fatone F, Viotti P, Fino D (2021) A water-waste-energy nexus approach to bridge the sustainability gap in landfill-based waste management regions. Renew Sustain Energy Rev 137(October 2020):110441. https://doi.org/10.1016/j.rser.2020.110441
17. Oladejo J, Shi K, Luo X, Yang G, Wu T (2019) A review of sludge-to-energy recovery methods. Energies 12(1):1–38. https://doi.org/10.3390/en12010060
18. Sharma M, Singh J, Baskar C, Kumar A (2018) A comprehensive review on biochar formation and its utilization for wastewater treatment. Pollut Res 37:1–18
19. Varjani S, Kumar G, Rene ER (2019) Developments in biochar application for pesticide remediation: current knowledge and future research directions. J Environ Manage 232:505–513. https://doi.org/10.1016/j.jenvman.2018.11.043
20. Bora AP, Gupta DP, Durbha KS (2020) Sewage sludge to bio-fuel: a review on the sustainable approach of transforming sewage waste to alternative fuel. Fuel 259:116262. https://doi.org/10.1016/j.fuel.2019.116262
21. Vijayaraghavan K (Jan 2019) Recent advancements in biochar preparation, feedstocks, modification, characterization and future applications. Environ Tech Rev 8(1):47–64. https://doi.org/10.1080/21622515.2019.1631393
22. Agegnehu G, Srivastava AK, Bird MI (2017) The role of biochar and biochar-compost in improving soil quality and crop performance: a review. Appl Soil Ecol 119:156–170. https://doi.org/10.1016/j.apsoil.2017.06.008
23. Gubišová M et al (2020) Sewage sludge as a soil amendment for growing biomass plant Arundo donax L. *Agronomy* 10(5). https://doi.org/10.3390/agronomy10050678
24. Potter MC, Waller AD (Sep 1911) Electrical effects accompanying the decomposition of organic compounds. *Proc R Soc London Ser B, Contain Pap Biol Character* 84(571):260–276. https://doi.org/10.1098/rspb.1911.0073
25. Shamsuddin NA, Mohd Sabri MNI, Tajarudin HA, Shoparwe NF, Makhtar MMZ (May 2021) Effect of thermal pre-treatments method on sludge degradation process prior usage in membrane-less microbial fuel cell for electricity generation. IOP Conf Ser Earth Environ Sci 76(1):012092. https://doi.org/10.1088/1755-1315/765/1/012092
26. Khoo KS, Chia WY, Tang DYY, Show PL, Chew KW, Chen WH (2020) Nanomaterials utilization in biomass for biofuel and bioenergy production. Energies 13(4):1–20. https://doi.org/10.3390/en13040892
27. Tamboli E, Eswari JS (2019) Chapter 3.2—microbial fuel cell configurations: an overview. Elsevier B.V. https://doi.org/10.1016/B978-0-444-64052-9.00016-9
28. Piccolino M (Jul 1998) Animal electricity and the birth of electrophysiology: the legacy of Luigi Galvani. Brain Res Bull 46(5):381–407. https://doi.org/10.1016/s0361-9230(98)00026-4
29. Bennetto HP, Stirling JL, Tanaka K, Vega CA (Feb1983) Anodic reactions in microbial fuel cells. Biotechnol Bioeng 25(2):559–568. https://doi.org/10.1002/bit.260250219
30. Rezaei F, Richard TL, Logan BE (2008) Enzymatic hydrolysis of cellulose coupled with electricity generation in a microbial fuel cell. Biotechnol Bioeng 101(6):1163–1169. https://doi.org/10.1002/bit.22015
31. Khera J, Chandra A (2012) Microbial fuel cells: recent trends. Proc Natl Acad Sci India Sect A Phys Sci 82(1):31–41. https://doi.org/10.1007/s40010-012-0003-2

32. Logan BE (2012) Essential data and techniques for conducting microbial fuel cell and other types of bioelectrochemical system experiments. Chemsuschem 5(6):988–994. https://doi.org/10.1002/cssc.201100604
33. Bullen RA, Arnot TC, Lakeman JB, Walsh FC (May 2006) Biofuel cells and their development. Biosens Bioelectron 21(11):2015–2045. https://doi.org/10.1016/j.bios.2006.01.030
34. Shukla A, Suresh P, Berchmans S, Rajendran A (Aug 2004) Biological fuel cells and their applications. Curr Sci 87
35. Roller SD, Bennetto HP, Delaney GM, Mason JR, Stirling JL, Thurston CF (Mar 1984) Electron-transfer coupling in microbial fuel cells: 1. comparison of redox-mediator reduction rates and respiratory rates of bacteria. J Chem Technol Biotechnol. Biotechnol 34(1):3–12. https://doi.org/10.1002/jctb.280340103
36. Wilkinson S (2000) 'Gastrobots'—benefits and challenges of microbial fuel cells in food powered robot applications. Auton Robot 9(2):99–111. https://doi.org/10.1023/A:1008984516499
37. Ieropoulos I, Melhuish C, Greenman J (2003) Artificial metabolism: towards true energetic autonomy in artificial life. Adv Artif Life: 792–799
38. Mohd Zaini Makhtar M, Tajarudin HA, Samsudin MDM, Vadivelu VM, Shoparwe NF, Izzah Zainuddin N (Jun 2021). Membrane-less microbial fuel cell: Monte Carlo simulation and sensitivity analysis for COD removal in dewatered sludge. *AIP Adv* 11(6):65016. https://doi.org/10.1063/5.0039014
39. Logan BE et al (2006) Microbial fuel cells: methodology and technology. Environ Sci Technol 40(17):5181–5192. https://doi.org/10.1021/es0605016
40. Pant D, Van Bogaert G, Diels L, Vanbroekhoven K (2010) A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production. Bioresour Technol 101(6):1533–1543. https://doi.org/10.1016/j.biortech.2009.10.017
41. Pham TH et al (2006) Microbial fuel cells in relation to conventional anaerobic digestion technology. Eng Life Sci 6(3):285–292. https://doi.org/10.1002/elsc.200620121
42. Li M et al (2018) Microbial fuel cell (MFC) power performance improvement through enhanced microbial electrogenicity. Biotechnol Adv 36(4):1316–1327. https://doi.org/10.1016/j.biotechadv.2018.04.010
43. Debabrata D (2018) Microbial fuel cell: a bioelectrochemical system that converts waste to watts. Springer International, Switzerland
44. Akiba T, Bennetto HP, Stirling JL, Tanaka K (1987) Electricity production from alkalophilic organisms. Biotech Lett 9(9):611–616. https://doi.org/10.1007/BF01033196
45. Chabert N, Amin Ali O, Achouak W (2015) All ecosystems potentially host electrogenic bacteria. Bioelectrochemistry 106:88–96. https://doi.org/10.1016/j.bioelechem.2015.07.004
46. Danish M et al (2021) Science of the total environment integrated air cathode microbial fuel cell-aerobic bioreactor set-up for enhanced bioelectrodegradation of azo dye Acid Blue 29. Sci Total Environ 756:0–10. https://doi.org/10.1016/j.scitotenv.2020.143752
47. Pous N, Koch C, Colprim J, Puig S, Harnisch F (2014) Extracellular electron transfer of biocathodes: revealing the potentials for nitrate and nitrite reduction of denitrifying microbiomes dominated by Thiobacillus sp. Electrochem Commun 49:93–97. https://doi.org/10.1016/j.elecom.2014.10.011
48. Guang L, Koomson DA, Jingyu H, Ewusi-Mensah D, Miwornunyuie N (2020) Performance of exoelectrogenic bacteria used in microbial desalination cell technology. Int J Environ Res Public Health 17(3):10–12. https://doi.org/10.3390/ijerph17031121
49. Xing D, Zuo Y, Cheng S, Regan JM, Logan BE (Jun.2008) Electricity generation by Rhodopseudomonas palustris DX-1. Environ Sci Technol 42(11):4146–4151. https://doi.org/10.1021/es800312v
50. Martínez ÁT et al (2005) Biodegradation of lignocellulosics: microbial, chemical, and enzymatic aspects of the fungal attack of lignin. Int Microbiol 8(3):195–204. https://doi.org/10.2436/im.v8i3.9526
51. Wesenberg D, Kyriakides I, Agathos SN (2003) White-rot fungi and their enzymes for the treatment of industrial dye effluents. Biotechnol Adv 22(1):161–187. https://doi.org/10.1016/j.biotechadv.2003.08.011

52. Wilkinson S, Klar J, Applegarth S (Oct 2006) Optimizing biofuel cell performance using a targeted mixed mediator combination. Electroanalysis 18(19–20):2001–2007. https://doi.org/10.1002/elan.200603621
53. Sivasankar V, Mylsamy P, Omine K (2018) Microbial fuel cell technology for bioelectricity. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-92904-0
54. Lee Y-K (Nov 2003) Algal nutrition—heterotrophic carbon nutrition. Handb Microalgal Cult :116–124. https://doi.org/10.1002/9780470995280.ch7
55. Kruzic AP, Kreissl JF (May2009) Natural treatment and onsite systems. Water Environ Res 81(10):1346–1360
56. Juang DF, Lee CH, Hsueh SC (2012) Comparison of electrogenic capabilities of microbial fuel cell with different light power on algae grown cathode. Biores Technol 123:23–29. https://doi.org/10.1016/j.biortech.2012.07.041
57. Marsili E, Baron DB, Shikhare ID, Coursolle D, Gralnick JA, Bond DR (2008) Shewanella secretes flavins that mediate extracellular electron transfer. Proc Natl Acad Sci USA 105(10):3968–3973. https://doi.org/10.1073/pnas.0710525105
58. Konovalova EY et al (May 2018) The microorganisms used for working in microbial fuel cells. In: AIP Conference Proceedings, vol 1952. https://doi.org/10.1063/1.5031979
59. Logan BE (2009) Exoelectrogenic bacteria that power microbial fuel cells. Nat Rev Microbiol 7(5):375–381. https://doi.org/10.1038/nrmicro2113
60. Schröder U (2007) Anodic electron transfer mechanisms in microbial fuel cells and their energy efficiency. Phys Chem Chem Phys 9(21):2619–2629. https://doi.org/10.1039/b703627m
61. Feng C et al. (2014) Characterization of exoelectrogenic bacteria enterobacter strains isolated from a microbial fuel cell exposed to copper shock load. PLoS One 9(11). https://doi.org/10.1371/journal.pone.0113379
62. Wu Y et al (2020) Enhanced current production by exogenous electron mediators via synergy of promoting biofilm formation and the electron shuttling process. Environ Sci Technol 54(12):7217–7225. https://doi.org/10.1021/acs.est.0c00141
63. Miriam R, Federico Aulenta, Marianna V, Largus T Angenent (2011) Cathodes as electron donors for microbial metabolism: which extracellular electron transfer mechanisms are involved? Bioresour Technol 102(1):324–333, ISSN 0960-8524. https://doi.org/10.1016/j.biortech.2010.07.008
64. Bond D, Lovley D (2003) Electricity production by geobacter sulfurreducens attached to electrodes. Appl Environ Microbiol 69(3):1548–1555. https://doi.org/10.1128/AEM.69.3.1548
65. Ieropoulos IA, Greenman J, Melhuish C, Hart J (2005) Comparative study of three types of microbial fuel cell. Enzyme Microb Technol 37(2):238–245. https://doi.org/10.1016/j.enzmictec.2005.03.006
66. Kumari S (2012) Studies on marine microbial fuel cell, Doctoral dissertation
67. Barton SC, Gallaway J, Atanassov P (2004) Enzymatic biofuel cells for implantable and microscale devices. Chem Rev 104(10):4867–4886. https://doi.org/10.1021/cr020719k
68. Zhao F, Slade RCT, Varcoe JR (2009) Techniques for the study and development of microbial fuel cells: an electrochemical perspective. Chem Soc Rev 38(7):1926–1939. https://doi.org/10.1039/b819866g
69. Sirinutsomboon B (2014) Modeling of a membraneless single-chamber microbial fuel cell with molasses as an energy source. Int J Energy Environ Eng 5(2–3):1–9. https://doi.org/10.1007/s40095-014-0093-5
70. Roy S, Marzorati S, Schievano A, Pant D (2017) Microbial fuel cells, vol 3. Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.10122-8
71. Logan BE, Regan JM (2006) Electricity-producing bacterial communities in microbial fuel cells. Trends Microbiol 14(12):512–518. https://doi.org/10.1016/j.tim.2006.10.003
72. Du Z, Li H, Gu T (2007) A state of the art review on microbial fuel cells: a promising technology for wastewater treatment and bioenergy. Biotechnol Adv 25:464–482. https://doi.org/10.1016/j.biotechadv.2007.05.004
73. Parkash A (2016 July) Microbial fuel cells: a source of bioenergy. Microbial and Biochemical Technology (July). https://doi.org/10.4172/1948-5948.1000293

74. He Z, Minteer SD, Angenent LT (2005) Electricity generation from artificial wastewater using an upflow microbial fuel cell. Environ Sci Technol 39(14):5262–5267. https://doi.org/10.1021/es0502876
75. Feng C, Tsai C-C, Ma C-Y, Yu C-P, Hou C-H (2017) Integrating cost-effective microbial fuel cells and energy-efficient capacitive deionization for advanced domestic wastewater treatment. Chem Eng J 330:1–10. https://doi.org/10.1016/j.cej.2017.07.122
76. Feng Y, He W, Liu J, Wang X, Qu Y, Ren N (2014) A horizontal plug flow and stackable pilot microbial fuel cell for municipal wastewater treatment. Biores Technol 156:132–138. https://doi.org/10.1016/j.biortech.2013.12.104
77. Santoro C et al. (2018 Feb) Ceramic microbial fuel cells stack: power generation in standard and supercapacitive mode. Sci Rep 8. https://doi.org/10.1038/s41598-018-21404-y
78. Min B, Logan BE (2004) Continuous electricity generation from domestic wastewater and organic substrates in a flat plate microbial fuel cell. Environ Sci Technol 38(21):5809–5814. https://doi.org/10.1021/es0491026
79. Helder M, Strik DP, Hamelers HVM, Buisman CJN (2012) The flat-plate plant-microbial fuel cell: the effect of a new design on internal resistances. Biotechnol Biofuels 5(1):70. https://doi.org/10.1186/1754-6834-5-70
80. Ding HH, Chang S, Liu Y (Nov 2017) Biological hydrolysis pretreatment on secondary sludge: enhancement of anaerobic digestion and mechanism study. Biores Technol 244(Pt 1):989–995. https://doi.org/10.1016/j.biortech.2017.08.064
81. Calderone L (2019) What is the future of non-renewable resources? Other Energy Topics.
82. Kumar A, Ogita S, Yau YY (2018) Biofuels: greenhouse gas mitigation and global warming. Springer, India. https://doi.org/10.1007/978-81-322-3763-1
83. IPCC (2014) Climate change 2014, mitigation of climate change. In: Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, UK
84. IPCC (2014) Climate change. Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. Geneva
85. Kan S, Chen B, Chen G (2019) Worldwide energy use across global supply chains: Decoupled from economic growth? Appl Energy 250:1235–1245. https://doi.org/10.1016/j.apenergy.2019.05.104
86. Ahmad T, Zhang D (2020) A critical review of comparative global historical energy consumption and future demand: the story told so far. Energy Rep 6:1973–1991. https://doi.org/10.1016/j.egyr.2020.07.020
87. Robert R (2020) Fossil fuels still supply 84 % of world energy—and other eye openers from BP's annual review