Biosensors and Bioelectronics 142 (2019) 111576

Contents lists available at ScienceDirect

Biosensors and Bioelectronics

journal homepage: www.elsevier.com/locate/bios

Bioelectrochemical systems: Sustainable bio-energy powerhouses

Mahwash Mahar Gul, Khuram Shahzad Ahmad*

Department of Environmental Sciences, Fatima Jinnah Women University, The Mall, Rawalpindi, 46000, Pakistan

ARTICLE INFO

Keywords:
Microbial fuel cells
Photo MFCs
Plant MFCs
Biophotovoltaics
Bioelectricity

ABSTRACT

Bioelectrochemical systems comprise of several types of cells, from basic microbial fuel cells (MFC) to photosynthetic MFCs and from plant MFCs to biophotovoltaics. All these cells employ bio entities at anode to produce bioenergy by catalysing organic substrates while some systems convert solar irradiation to energy. The current review epitomizes the above-mentioned fuel cell systems and elucidates their electrical performances. Microbial fuel cells have advantages over conventional fuel cells in terms of being sustainable whilst producing impressive power efficiencies without any net carbon emissions. They can be utilized for several environmentally friendly applications including wastewater treatment and bio-hydrogen generation, apart from producing clean and green electricity. Multifarious heterotrophic and autotrophic microbes and plants have been studied for their potential as imperative components of fuel cell technology. MFCs also display some interesting applications, such as integration of plant MFCs into architecture to produce "green" cities. Biophotovoltaic technology is the current hot cake in this field, which aspires to achieve significant electrical efficiencies by light-induced water splitting mechanisms. Furthermore, the utilization of BPVs in space renders it a technology for the future. Compared with other fuel cell systems, this technology is still in its inception and requires further efforts to endeavour its use on commercial or industrial level.

1. Introduction

The aggravating global energy challenge is imposing a limitation on the use of fossil fuels while endorsing the renewable energy resources with infinitesimal repercussion on the environment. The depleting non-renewable energy reserves such as coal and increasing environmental pollution is causing a gradual transformation towards sustainable energy resources, encompassing thermal, hydro and solar (Pospischil et al., 2014; Haldane and Toman, 2015; L. Lu et al., 2015; Rehman et al., 2015; Furlan and Mortarino, 2017). Fossil fuel consumption has a negative impact on the environment culminating in the production of carbon dioxide. The consequence of using non-renewable resources through generations has jeopardized not only human health but also the ecosystem (Machol and Rizk, 2013). Furthermore, climate change and global warming are among the adverse aftermaths of continuous fossil fuel utilization.

A contemplated alternative energy generation method is the fuel cell technology (FC). A fuel cell transforms chemical energy from a fuel into electrical energy (O'hayre et al., 2016). The hydrogen combustion reaction is split into two half electrochemical reactions. Electrons are thus emanated from the fuel because of the spatial separation in these reactions (Spiegel, 2007). These electrons stream into an external circuit causing the generation of electricity (Dicks and Rand, 2018). An FC contains two electrodes in an electrolyte where the two half electrochemical reactions occur. William Grove first invented the fuel cell in 1839 (Appleby, 1990). FCs can be considered as the manufacturing plants that generate electricity until provided with some fuel. They commingle the benefits of batteries and engines. They provide higher energy potential and are rapidly rechargeable than batteries and unlike engines they are highly reliable with minimum toxic emissions (Hoogers, 2002).

One such neoteric energy generating system is the biological entities based electrochemical cells that convert energy either from a substrate or from sunlight into chemical and electrical energy. Biological fuel cell technology emerged as a confluence of microbiology, chemistry and physics (or more specifically the electrochemistry) (Rabaey and Verstraete, 2005; Logan and Elimelech, 2012; Mohan et al., 2014; Dicks and Rand, 2018). Fig. 1 displays a timeline depicting important events that lead to the current emerging technology of next generation green energy production.

2. Microbial fuel cells

The idea of microbial fuel cells dates back to 1911 in the study

* Corresponding author.
E-mail addresses: chemist.phd33@yahoo.com, dr.k.s.ahmad@fjwu.edu.pk (K.S. Ahmad).

https://doi.org/10.1016/j.bios.2019.111576
Received 14 July 2019; Received in revised form 3 August 2019; Accepted 6 August 2019
Available online 07 August 2019
0956-5663/

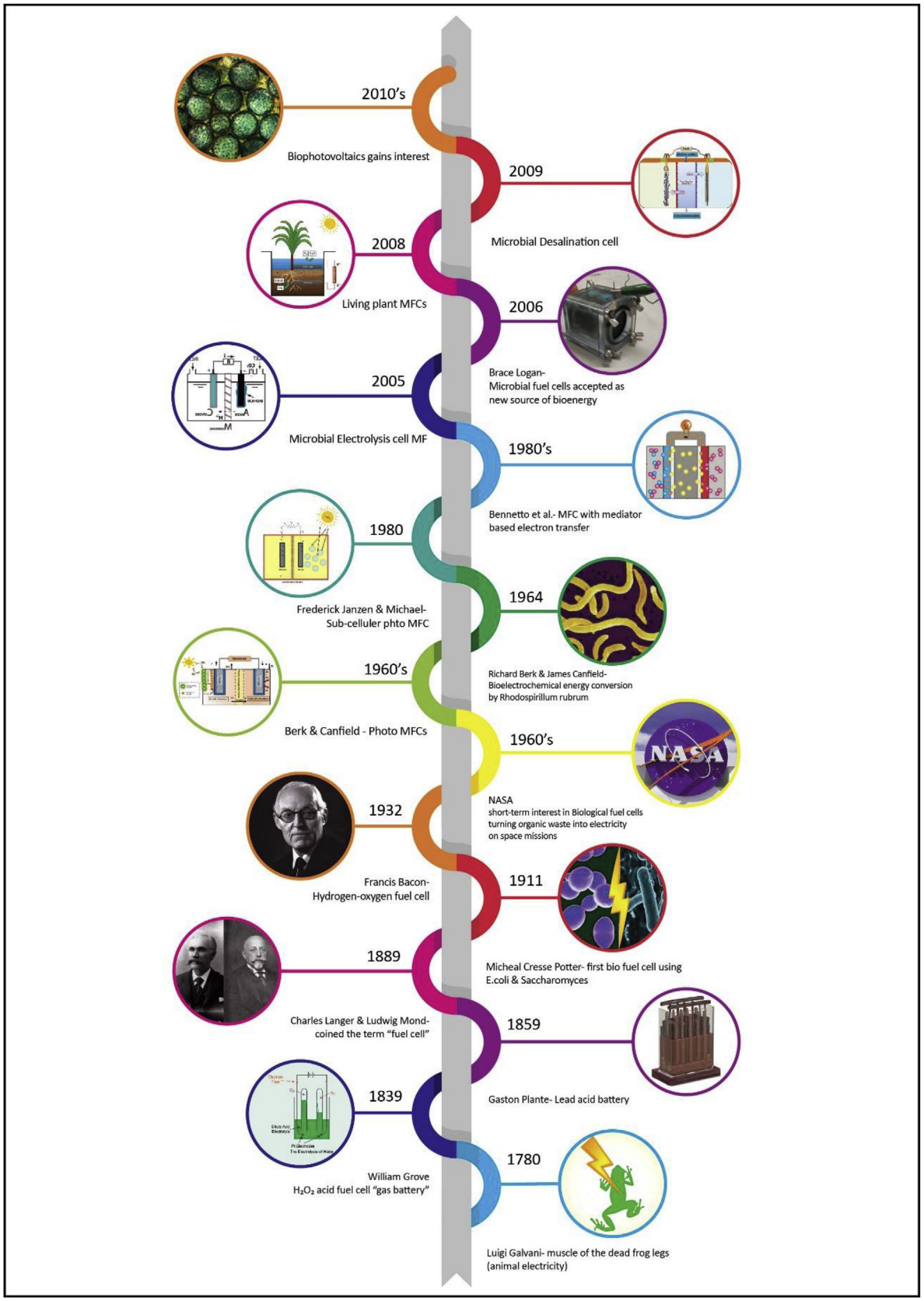

Fig. 1. Timeline displaying some important events during the innovation of fuel cell technology leading to biophotovoltaics.

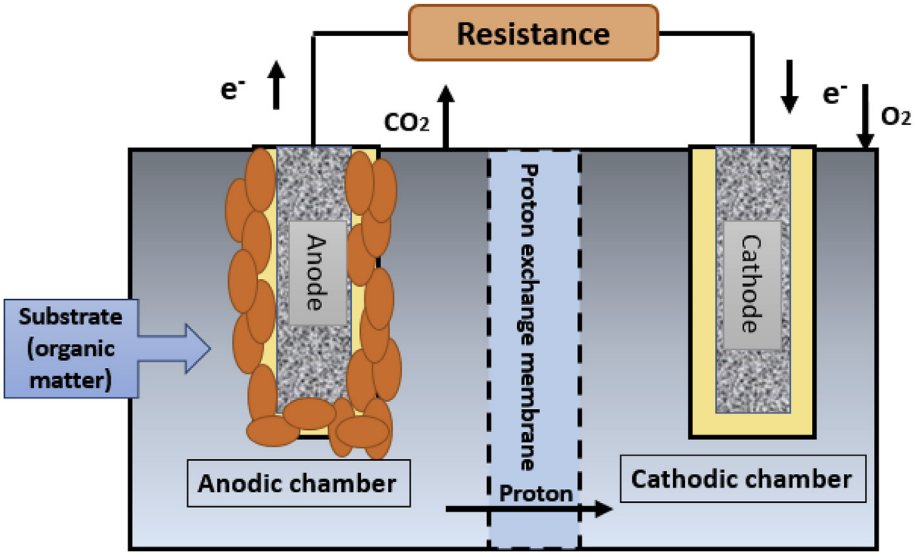

Fig. 2. A basic dual chambered microbial fuel cell.

conducted by Potter (1911). He scrutinized the generation of electricity by insertion of platinum electrode in the *E. coli* suspension. However, the technology became dormant in the following decades and gained prominent spotlight in the late 1990s. The microbial fuel cells (MFCs) convert the chemical energy of a substrate (sometimes wastewater) into electricity by a cascade of catalytic redox reactions of microbes (Fig. 2). The substrate (organic matter) is oxidized at the anode, electrons are generated by the microorganisms that are passed through the cathode to the external circuit resulting in an electrical current (Rabaey and Verstraete, 2005; Ou et al., 2017). MFCs are different from conventional electrochemical cells in the sense that they utilize electrogenic microbes such as bacteria (*Clostridium cellulolyticum* and *G. sulfurreducens*, *Enterobacter cloacae*, *Clostridium butyricum*) and fungi (*Aspergillus awamori* and *Phanerochaete chrysosporium*) (Ren et al., 2008; Rezaei et al., 2009; Kalathil et al., 2011; Ray and Ghangrekar, 2015). These exoelectrogenic bio-agents increase the complexity of the traditional electrochemical cells. The biochemical pathways of the microbial cells convert the chemical energy of fuels to electrical energy (Meunier et al., 2011). However, the low cost-effectiveness of these cells due to high material costs and mediocre power generation impedes the feasibility of this technology at a larger scale (Zhou et al., 2013).

2.1. Basic architecture of MFCs

Although multifarious structures have been built for MFCs yet the basic components and working of all the cells remain consistent. Various components of the MFC produce varying resistance, which collectively account for the cumulative internal resistance of the device. An MFC contains a chamber with anode and cathode separated by a proton exchange membrane (Ghasemi et al., 2012).

2.1.1. Anode

A vital component of MFCs is the anode due to its significance in the growth of microbial cells. It expedites the flow of electrons by the electrochemical reactions of the microbial cells. Carbon is the most prevalent electrode material used in the MFCs. Anodes can be graphite electrodes, carbon nano-tubes, rods and plates (Cheng and Wu, 2013; Erbay et al., 2015; Ahmad et al., 2018; Majid and Ahmad, 2018, 2019). Recently, researchers have worked to revolutionize the anodic material by using nano-technology to increase the efficiency and MFC potential (Zou et al., 2017a,b). An imperative factor of the anode is its congeniality for the microbes in order to facilitate the formation of biofilms. Microbial cells at the anode act as biocatalysts oxidizing the organic substrate thereby generating electrons and protons (Rahimnejad et al., 2012a,b). The anodic chamber of the MFC contains an anode, microbes and a substrate. The microbial electron transfer can be enhanced by the use of electron mediators (also present in the anode chamber) and intensification of the MFC architecture (Aelterman et al., 2006). Furthermore, a quintessential anode should display low resistance and greater chemical stability along with increased surface area (Huggins et al., 2014; Park et al., 2014). Two types of electron transfer occur between the microbe and the anode; direct extracellular electron transfer (DEET) and indirect extracellular electron transfer (IEET). The electron flux in DEET occurs either through direct contact (cytochrome) or through the formation of various extracellular extensions between the outer membrane of microbial cell and the anode (Xiong et al., 2006). Bacteria *Geobacter* spp. forms a biofilm on the anodic material and grow extracellular pilli for the direct electrochemical connection with the electrode (Lovley, 2012). IEET between bacterial cells and anode occurs by the production of redox mediators or the oxidizing of fermentative products formed by the bacterial metabolism such as the generation of hydrogen. The redox mediator involves the endogenous electron mediators (EEM) such as flavins produced by *Shewanella putrefaciens* (Zou et al., 2017b). MFCs dependent upon the IEET generate low power potential as compared with those that rely on DEET (Bonanni et al., 2012; Leang et al., 2013).

2.1.2. Cathode

Cathode in the MFCs are responsible for the oxygen reduction reactions (ORR) (Zhao et al., 2005; Harnisch and Schröder, 2010). The efficiency of MFC power generation depends upon the ORR occurring at the cathode. A high redox potential of the cathode is desirable to catch the protons. The oxygen molecule in the cathode is the usual electron acceptor due to its high oxidation potential (Logan et al., 2006). When the concentration of oxygen at the cathode increases so does the efficiency of electron flux (Larminie and Dicks, 2000). To enhance the cathodic activity for the ORR, it is crucial to apply catalysts at the cathode (Aryal et al., 2017). Platinum is among the preferred cathode material due to its high surface area but its high cost hampers its utilization. To alleviate the issue of expensive cathode material, graphite was utilized by Zhang et al., which also amplified the MFC efficiency due to its large surface area (Zhang et al., 2012a,b). MFC researchers have suggested various economical yet effective cathode catalysts. An effective catalyst significantly reduces the activation energy for the MFCs. These catalysts can be biotic as well as abiotic. Table 1 displays a list of a few abiotic and biotic cathode catalysts from multitudes of

Table 1
List of some abiotic and biotic cathode catalysts utilized in MFCs.

Abiotic catalysts		Biotic catalysts	
Platinum group metal-free catalysts (Fe, N, C, Mn, Co, Ni)	(Santoro et al., 2015, 2018; Kodali et al., 2017a,b)	*Marine algae*	Reddy et al. (2019)
Carbon xerogel doped Fe–N-GO (CXFeNGO)	Thapa et al. (2019)	*Marinobacter* sp.	Debuy et al. (2015)
Rhodium-Activated Carbon	Bhowmick et al. (2019)	*Roseobacter* sp.	Debuy et al. (2015)
Carbon nanotube/polypyrrole nanocomposite	Ghasemi et al. (2016)	*Bacillus* sp.	Debuy et al. (2015)
Nickel-phthalocyanine/MnOx	Tiwari et al. (2017)	*Thiobacillus ferroxidan*	Ulusoy and Dimoglo. (2018)
Cobalt oxide-nanocarbon hybrid	Song et al. (2015)	*Pseudoalteromonas* sp.	Debuy et al. (2015)
Iron-phthalocyanine/MnOx	Burkitt et al. (2016)	*Pseudomonas flourescens*	Zhang et al. (2016)
Nickel oxide/carbon nanotube composite	Huang et al. (2015)	*G. metallireducens*	Zhang et al. (2017)
Graphene oxide/MgO	Li et al. (2017)	*D. desulfuricans*	(Mohamed et al., 2017)
Silver nanoparticles	Noori et al. (2016)	*Rhodobacteraceae bacterium*	Milner et al. (2016)
Manganese dioxide Iron and aminoantipyrine (Fe-AAPyr)	(Jiang et al., 2017) (Santoro et al., 2015a,b)	*Nitrosomonas* sp.	Liao et al. (2018)
Cu/Co doped octahedral molecular sieve	(Li et al., 2011a,b,c)	*Azovibrio restrictus*	Abbas et al. (2018)
Manganese-Polypyrrole-CNT	Lu et al. (2013)	*Pseudomonas putida*	(Khater et al., 2017)
Graphene nanosheet	Wen et al. (2012)	*Sphingopyxis* sp.	Zhang et al. (2017a)
Activated carbon nanofiber	Ghasemi et al. (2011)	*Shewanella xiamenensis*	(Khater et al., 2017)
Nitrogen doped carbon nanotubes	Li et al. (2011a)	*Mycobacterium peregrinum*	Teng et al. (2016)
$CoMn_2O_4$@GE (Bare graphite electrode)	Liu et al. (2018a,b)	*Flavobacterium* sp.	Zhang et al. (2019a,b)
Polyaniline Graphene/TiO_2	(Han et al., 2018)	*Chlorobium* sp.	Qi et al. (2018)

others.

The cathodic materials can be categorized into abiotic and biotic groups. The use of a variety of cathodic material depends upon the application of MFC. Researchers have utilized an assortment of cathodic materials including; graphite, carbon paper, carbon cloth, Platinum electrode, macroporous hollow fibre cathode, air cathodes, carbon felt cathode, Pt coated carbon paper and graphite felt, among various others (Dong et al., 2012; Pasupuleti et al., 2016; Katuri et al., 2018; Chen et al., 2018; Oliot et al., 2017; Deng et al., 2009). Various researches have reported the use of biocathodes in MFCs for the oxygen reduction reactions (Watanabe, 2008; Huang et al., 2011; Rahimnejad et al., 2012a,b). Biocathodes enhance the electricity generation and power potential of the MFC thus improving the cathode efficiency. The use of biocathodes in MFCs can lower the aggregate cost of the cell thereby removing the need for using catalysts or electron mediators (Xia et al., 2013). Furthermore, the by-products produced are also eradicated by the metabolic reactions of the microbes (He and Angenent, 2006). Rahimnejad et al., categorized biocathodes into two categories based on terminal electron acceptors; aerobic and anaerobic (Rahimnejad et al., 2015). Oxygen molecules are reduced by the aerobic biocathodes generating a high power output than anaerobic biocathode. Zhang et al., demonstrated the reduction of charge transfer by using biocathodes (Zhang et al., 2012a,b).

2.1.3. Membrane/barrier

A physical membrane (barrier or separator) creates a separation between the anodic and the cathodic compartments in an MFC. Cations pass through the membrane resulting in current generation. Membranes are classified into a diverse range of groups base on their capability to filter including; selective size barriers, salt bridges and ion exchange separators (Li et al., 2011b). Furthermore, they are divided into cation exchange membranes, anion exchange membranes, ultrafiltration membranes, bipolar membrane, microfiltration membrane, glass fibres, nylon fibres, porous fabrics among various others. However, these membranes are not cost-effective. Researchers have also explored a variety of low cost substances to be utilized as separators. These comprise biodegradable shopping bags, laboratory gloves, clay ware, natural rubber, eggshells etc. (Winfield et al., 2014). In certain MFCs membranes are not necessary since these fuel cells contain ionised liquid solutions. The ions may eliminate the need to utilize membrane to separate the anode and cathode (Lee and Nirmalakhandan, 2011). In such cases, both the electrodes should be of different material resulting in electrochemical separation or placed at an appropriate distance to avoid short circuit. Utilizing a membrane-less MFC is cost-effective since it alleviates the use expensive membranes but at the same time it creates competition for anode due to the diffused oxygen from the cathode region (Wang et al., 2013). A wide variety of MFCs utilize atypical and unconventional materials that serve the dual purpose of functioning as the MFC architecture as well as ion exchange membrane. Such prototypes have been manufactured using 3D technology (Philamore et al., 2015). Complete reactors are formed from these materials that are porous and possess high durability such as nylon infused membrane, microporous filtration membrane and photocopy paper (Freguia et al., 2010; Winfield et al., 2015).

2.1.4. Microbial-entities in MFCs

As mentioned earlier, Micheal C. Potter in 1911 was the first researcher to report the utilization of microbes; *Escherichia coli* and *Saccharomyeces* sp., which disintegrate organic compounds to obtain energy. He displayed in his research findings the liberation of electric current with the change in anolyte by the microbes. Microbes utilized in MFCs can be found at numerous dwellings including activated sludge, wastewater and various sediments (Strik et al., 2011; Lu et al., 2012; Yan et al., 2012). Microbes transfer electrons to the anode through the extra cellular electron transfer mechanism after metabolising the organic substrate (Paitier et al., 2017). These exoelectrogenic microbes generate electrons to the electrode (anode) thus causing current to flow through the system towards the cathode. Majority of electrogenic microorganisms belong to the proteobacteria community (Zhang et al., 2018). However, electrogens from other microbial groups have also been reported widely (Yang et al., 2019). Up till now, no microbial community has been declared as the nonpareil. Furthermore, various researches have shown that not only electrochemically active microbes but non-electrogens have been found to facilitate the generation of electricity through a symbiotic relation of latter with previous one (Fazli et al., 2018).

2.1.5. Substrates in MFC

A decisive factor for the potency of current generation by MFC is the type of substrate used in the cell. An assortment of substrates is utilized depending upon the nature and requirements of the MFC. These range from pure compound to organic substrates, to wastewater and activated sludge. Pant et al. have discussed various types of substrates used in MFCs and their current densities in comprehensive detail in their review (Pant et al., 2010). One of the basic and simple substrate used in MFCs is acetate. Acetate has been shown to generate high current than various other substrates. It has been found to generate a current density of 0.8 mA/cm^2 at maximum power (Logan et al., 2007). Dumas et al.

used sodium fumarate as a substrate in MFC with pure culture of *G. sulfurreducens* along with stainless steel cathode and obtained a comparatively high current density of 2.05 mA/cm^2 at maximum power (Dumas et al., 2008). Some other common substrates used are starch, glucose, malt extract and lactate (Bratkova et al., 2019; Hassan et al., 2019). The type of substrate used are based on several other factors including microbes at the anode, electrode material, nature and type of MFC. Many types of wastewaters are also used as a substrate in MFC. They can vary based on the origin or their source such as synthetic wastewater, brewery wastewater obtained, which contain food-derivative organic compounds, starch-processing wastewater, which is an energy-rich resource and dye wastewater obtained as an effluent from various textile industries (Haldar et al., 2019; Nandy et al., 2019; Salar-Garcia and Ortiz-Martínez, 2019; Werkneh et al., 2019). Other wastewater sources include domestic, chocolate industry, food industry, meat processing, paper manufacturing and urban wastewaters (Corbella et al., 2019; Haavisto et al., 2019; Radeef and Ismail, 2019; Rathour et al., 2019; Subha et al., 2019). Solar radiation has also been found to be an imperative source of energy for the fuel cells thus arose the concept of "living solar cells" by Rosenbaum et al. (2005a,b). MFCs utilizing sunlight will be discussed later in this review. The MFCs not only remove pollutants from the substrate (wastewater) but also utilize them for current generation.

2.2. Bioelectrogenesis

The generation of electricity by MFCs is carried out in a series of steps (Kim et al., 2007; Patil et al., 2009). Initially the microbes metabolise the substrate present in the anodic compartment (Chae et al., 2009). Following electrogens catabolism, the electrons generated by microbes flow towards the anode. The electrons thus generated flow through the external circuit towards the cathode due to the potential gradient (Park et al., 2017). The electron acceptors present at the cathode are reduced. Protons are also formed at the anode that transfer towards the cathode through the membrane (Jana et al., 2010; Rahimnejad et al., 2011). These series of steps involved in current generation are responsible for the entire performance of MFC. The environmental factors including pH, redox potential, temperature and ionic strength influence the performance of the MFCs by affecting the above-mentioned processes (Liu and Li, 2007). An optimal pH supports the microbial growth, thus facilitating a maximal current and power output. Furthermore, it was observed by Puig et al. that a controlled pH also reduces internal resistance of an MFC (Puig et al., 2010). However, an elevated pH decreases the ORR, thus decreasing current production. Temperature fluctuations strongly effect the microbial species in MFCs and their activation energies (Oliveira et al., 2013). Power density tends to increase with the rise in temperature as it supports microbial metabolism (Larrosa-Guerrero et al., 2010). Furthermore, resistance also tends to decrease with increasing the temperature of MFC. A higher redox potential effectively regulates electron transfer along with facilitating microbial growth (Adelaja et al., 2015).

The active biocatalysts (microorganisms) are present at the anode that oxidize the carbon sources of the substrate (organic) resulting in the production of electrons and protons. The electrons that are liberated by the microbes are transferred to the anode through either DEET or IEET modes (Marsili et al., 2008; Choi and Sang, 2016). The electron transfer can be through electron mediators, cytochrome-c membrane proteins, conductive pili or bacterial nanowires (Liu et al., 2004; Prasad et al., 2007; Logan, 2009; Schaetzle et al., 2009). Oxygen is also present at the anode, which might cause hindrance in the proper functioning of the microbial cells to produce electricity. Thus, it is favourable to provide anaerobic environment at the anodic chamber. Two fundamental reactions occur at the anode and cathode that form the basis of electron flow and electricity generation.

At anode: Organic substrate + $H_2O \rightarrow CO_2 + H^+ + e^-$

At cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Microbes generate the reducing particles when they metabolise the substrate present in the fuel. These reducing particles are carried by redox components, which are later accepted by terminal electron acceptors (Srikanth and Mohan, 2012). When the liberated electrons reach the cathode after flowing through the external circuit they react with the oxygen along with the protons thus forming water (Aelterman et al., 2006). Electricity is generated which is utilized by an external resistor present between the anode and cathode in the external circuit. It is important to point out that the anode releases an equal amount of electrons and protons. The transfer of protons towards the cathodic chamber is through diffusion, which is a slow process causing internal resistance in the fuel cell. This is a limiting factor resulting in a slow reaction rate of MFC. According to Liang et al. (2007), an MFC faces several types of internal resistances based upon their source and MFC architecture. They further discussed anodic, cathodic and ohmic resistances. Fan and Li have characterised them as ohmic, charge transfer and diffusion resistances. In their review, they have explained the sources of these resistances. Ohmic resistance arises due to the electrolyte and PEM. Diffusion resistance occurs in the electrodes, thus called anodic and cathodic resistance (Fan and Li, 2016). The efficiency of proton transfer between the anode and the cathode depends upon the nature of proton exchange membrane and specific configuration of the reactor. A membrane potential called the proton motive force is formed across the membrane. This potential in turn produces a potential difference between the microbial cell membrane and the anode causing the delivery of electrons to the external circuit and protons to the cathode (Zhang et al., 2017). The negative anodic potential and the positive cathodic potential creates a potential difference called the electron motive force, which causes the electrons to move in the circuit towards the cathode (Zhao et al., 2018). Thus generating bioelectricity, which is harnessed through an external load.

2.3. Applications of MFCs

MFCs have been used for multifarious applications since their inception. A few main applications are mentioned in this review (Fig. 3). The main application of MFC is the generation of bioelectricity (Sadabad and Gholikandi, 2018). A variety of electrogenic microbes including bacteria and fungi have been utilized extensively for the

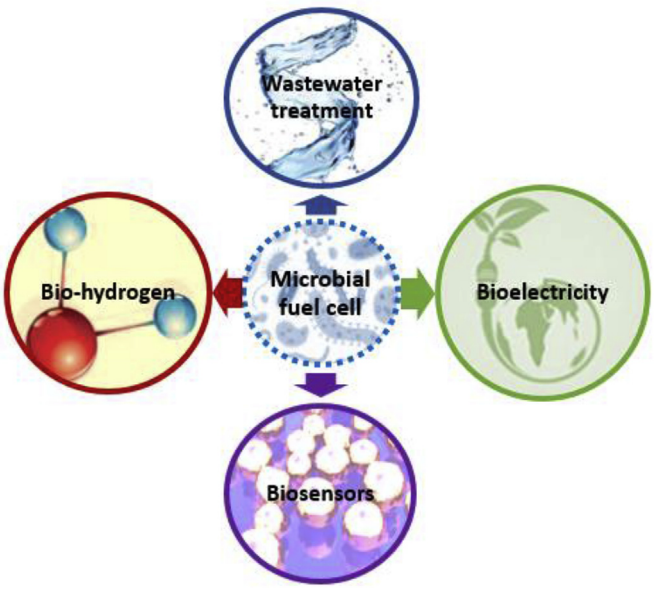

Fig. 3. Different applications of microbial fuel cells in multiple fields.

production of electricity-generating microbial fuel cells (Miran et al., 2017; Sekrecka-Belniak and Toczyłowska-Mamińska, 2018). The electricity potential depends upon a number of factors including; microbial strains, nature of substrate, electrodes material, configuration and type of fuel cell. Although extensive research has been performed on MFCs yet more studies are required to increase the efficiency and stability for adequate electricity generation. A recent and intriguing study was conducted by Ozdemir et al., who generated electricity from human urine containing tetrahydrocannabinol utilizing a microbial fuel cell with voltage generation up to 0.27 V (Ozdemir et al., 2019). It was presented by Koo et al. that the addition of supporting material at the cathode would drastically improve the electricity generation potential of the fuel cell. Koo et al. used reduced graphene oxide for elevated power density by MFC (Koo et al., 2019). Another application of MFCs usually occurring alongside bioelectricity production is the treatment of wastewater (Hiegemann et al., 2018; Yadav et al., 2018). Organic substrate i.e. wastewater from various sources is metabolized by microbes at the anode to generate electrons. The metabolism of these substrates also results in their treatment i.e. they are degraded by the microorganisms with the liberation of carbon dioxide. Liu et al. conducted the pioneer wastewater treatment study in 2004, which was followed by numerous such researches (Liu et al., 2004). Long et al. developed parallel circuit MFCs for the removal and subsequent degradation of azo dyes from water (Long et al., 2017). Instead of producing electricity, MFCs can also be utilized to produce biohydrogen (Montpart et al., 2015; Wan et al., 2015). Rathinam et al. have harnessed thermophiles to catalyse various substrates at wide operating conditions to produce biohydrogen in MFCs (Rathinam et al., 2019). Furthermore, the hydrogen produced by MFCs is renewable, which can be stored and used later. The potential at the anode is elevated for the production of hydrogen gas.

2.4. Limitations of MFCs

Power generation from MFCs has recently been considerably high and adequate to supply current to small lab-scale systems (Mohammadifar and Choi, 2019; Prasad and Tripathi, 2019). However, certain limitations and challenges are faced by such fuel cell technology. The foremost challenge is to overcome the internal resistance of the cell caused mainly by the proton exchange membrane (Shreeram et al., 2018; Wu et al., 2018). Furthermore, the high cost of the electrodes utilized in some cells such as those manufactured from gold, platinum and other expensive materials is a huge limiting factor hindering its economical usage (Kodali et al., 2017a,b; Jarosz et al., 2018; Sadeghifar and Rashid-Nadimi, 2018). The efficiency of energy extraction from wastewater is still low and requires more research to increase it. The highest electrical output achieved in 2018 by treating agricultural wastewater through MFC was 27 W/m^3 as reported by Cecconet et al. (2018). In 2019, Zhang et al. were successful in producing in-situ electricity by the degradation of organic pollutants with the electrical output reaching up to 106 W/m^3 (L. Zhang et al., 2019). However, the high power density achieved depends upon high initial concentration of the organic pollutants. The start-up time or the activation energy required by the MFC also limits its productivity. Another principal impediment to effective fuel cell working is that the energy is not enough for continuous operation of the external load attached. Low temperature is also a limit for the competent working of fuel cell since the microbial reactions are lethargic (Zhang et al., 2017). One crucial restraint is the instability of the microbial cells (Pareek et al., 2019). After their extraction and isolation from indigenous environments, the microbes may not retain enduring stability.

3. Photosynthetic MFCs

According to an estimation only 1% of energy from sunlight if converted into electricity successfully can produce energy ten times the current energy utilized by the world (Service, 2005). More focus has been devoted to non-photosynthetic MFCs for the generation of electricity. However, recently a transformation has been observed in the scientific community towards more sustainable energy production. The use of photosynthetic MFC that utilize microbial entities capable of converting sunlight into chemical energy is thus gaining popularity (Fig. 4). These microbes contain certain specialized light harvesting complexes; photosystem I and photosystem II that function as the units of photosynthesis. These light harvesting units are the same that are present in higher plant leaves that perform the function of photosynthesis. The structure and function of photosystem I and II is discussed in more detail in the next section. Their utilization in MFCs is highly sustainable in terms of bioenergy generation. However, not all photosynthetic MFCs utilize the whole living microbial cell rather subcellular components are also used for the process of photosynthesis. Various sub-cellular components used in photosynthetic MFCs include chloroplasts, thylakoid membranes and extracted photosystems (Tyszkiewicz et al., 1982; Mimeault and Carpentier, 1989; Gunther et al., 2013). The biological entities are immobilized on the photoelectrochemical fuel cells resulting in photosynthetic MFCs. Due to several limitations faced by conventional MFCs, explained previously in Section 2.4, photosynthetic MFCs technology is being explored to increase the stability of such devices.

3.1. Sub-cellullar photo MFC

Such fuel cells utilize anoxygenic photosynthetic entities attached onto the electron acceptor. Janzen and Seibert conducted the earliest known study on photosynthetic microbial fuel cell in 1980. They used photosynthetic reaction centre from *Rhodobacter sphaeroides*, a purple nonsulfur bacteria (Janzen and Seibert, 1980). The photosynthetic centres were attached on the electrodes which when irradiated produced current. Efrati et al. used extracted PS-I and PS-II from *Mastigocladus laminsus*, incorporated on the ITO anode that exhibited photoinduced redox reaction (Efrati et al., 2013). PS-I extracted from thylakoid structures of baby spinach was immobilized on Au leaf anode by Ciesielski et al. using sodium ascorbate as a feedstock and dichloroindophenol as electron transporter (Ciesielski et al., 2008). Gerter et al. saw an impressive current density by incorporating photosynthetic protein PS-I on electrode, which generated 1500 mA/m^2 under dry conditions (Gerster et al., 2012). Most photosynthetic MFCs use microbes that are devoid of PS-II reaction systems hence an exogenous electron donor and acceptor is obligate.

3.2. Whole cell photo MFC

Whole-cell autotrophic microbes are also used to generate electricity. Since sub-cellular photo MFCs utilize only a part or a sub-entity for photosynthetic function they are less potent in terms of sustainability. Whole-cell photo MFCs are capable of self-repair and generate current under light and dark conditions. Rosenbaum et al. were able to produce 182.5 mA/m^2 current density by using *Rhodobacter sphaeroides* suspension and lactate (Rosenbaum et al., 2005a,b). A mixed consortium of phototrophic microbes was incorporated on biocathode by Cao et al., which produced 750 mA/m^2 current density (Cao et al., 2009). *Shewanella oneidensis* was utilized in photosynthetic MFC by initially modifying them and deposition of biofilm on graphite (Johnson et al., 2010). Cho et al. achieved remarkable electrical output of 790 mW/m^2 using *R. sphaeroides* cells when illuminated with light (Cho et al., 2008). *Rhodopseudomonas palustris* produced a current of 5.9 mW/m^3 by metabolising *Arthrospira maxima*, a cyanobacterium (Inglesby et al., 2012). In another study, Rosenbaum et al. used green algae, *Chlamydomonas reinhardtii* in acetate to produce H_2 under aerobic conditions (Rosenbaum et al., 2005a,b). Photo MFCs are also able to produce photosynthetic biohydrogen, which displays their advantage as energy generating systems. The biohydrogen can be

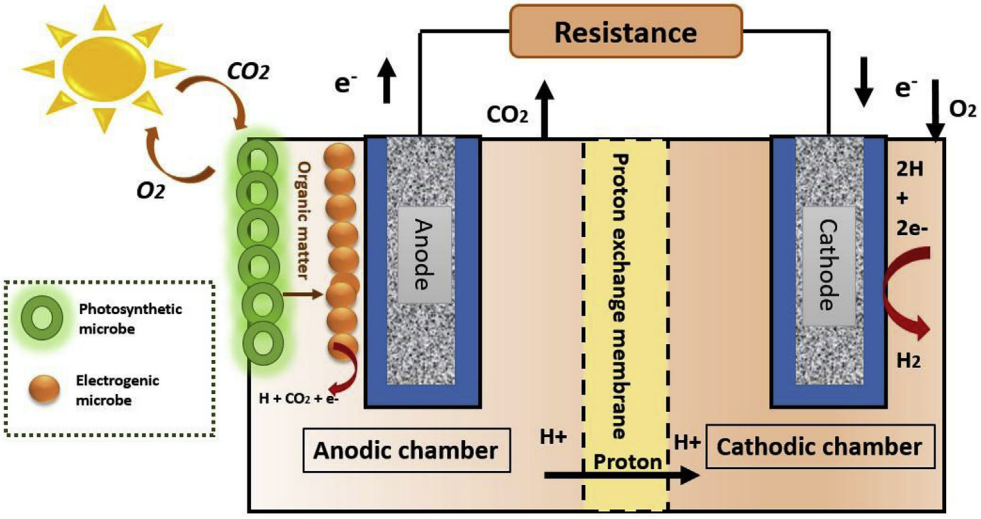

Fig. 4. Photosynthetic microbial fuel cell illustrating production of organic matter by photosynthetic microbes, which acts as a fuel and is oxidized by electrogenic microbes in the anodic chamber.

converted into bioelectricity to overcome the problem of hydrogen handling and recovery.

At times photosynthetic autotrophic microbes are mixed with heterotrophic bacteria to produce a synergistic relationship (Pillot et al., 2019; Rashid et al., 2019). In one such relationship, the photosynthetic microbes; cyanobacteria or some other bacterial group provides organic content to the heterotrophic bacteria. A better green electrical output was observed in such systems as compared to other systems with a single type of microbe. However, the current density was higher under dark conditions than light. The integration of photosynthesis with MFC technology has opened several neoteric possibilities for sustainable bioenergy generation.

4. Plant microbial fuel cells

Plant MFCs (PMFCs) are a derivative of the benthic microbial fuel cell also known as sediment microbial fuel cell. Benthic or sediment MFCs work on the principle of potential difference between sediment in the seabed and the oxygen rich water near the surface. In PMFCs, the roots exude various organic substrates, which are catalysed by the microbes present on the surface of anode generating electricity (Fig. 5). The plant root exudates serve as fuel where the anode is fixed in a matrix while the cathode is present in the fresh water upper zone. A continuous supply of organic exudates is provided by the plant roots providing advantage over conventional MFCs in terms of sustainability. Strik et al. were the pioneers to produce PMFC that used living plants and bacteria to convert solar energy into green electricity (Strik et al., 2008).

Mostly aquatic plants are preferred for PMFC including rice plant, *Anisogramma anomala*, *Glyceria maxima* and *Arundo donax* among others (Schamphelaire et al., 2008; Helder et al., 2010; Takanezawa et al., 2010; Timmers et al., 2010). Various exudates from plant roots include different secretions and gases, which comprise of carbohydrates and amino acids highly amenable to microbial degradation (Flint et al., 2012; Jin et al., 2018). Studies on PMFCs have exhibited glucose to be the most effective substrate for maximum power generation (Zhang et al., 2017c). High power densities by glucose substrate were achieved in various researches with power densities, 220 mW/m^2 and 156 mW/m^2 (Min and Logan, 2004; Chae et al., 2009). Electrons are also donated to the anode by soils instead of root exudates. Electrons are generated in the anodic zone via anaerobic respiration. Various factors effecting the conversion efficiency of PMFCs have been displayed in Fig. 6.

Electrodes materials with high surface area are favoured for PMFCs

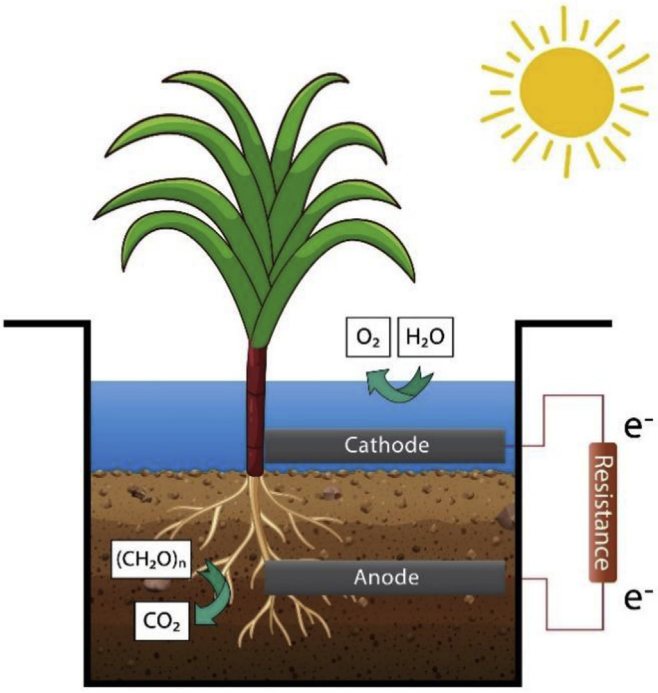

Fig. 5. Plant microbial fuel cell with microbes on anode catalysing the root exudates.

as they increase the association between the microbes and the electrode. Graphite is thus the most preferred electrode material due to its high surface area (Helder et al., 2010). Furthermore, treated electrodes (anode and cathode) efficiently increase the power generation of PMFCs (Tang et al., 2011). In such cases catalysts are utilized at the electrode which might include ferricyanide, thionine, methyl viologen etc. (Timmers et al., 2010). Furthermore, biocatalysts can also be used to enhance the working of PMFCs. Working of PMFCs require formation of biofilm on the anode of the cell. Several bacterial and fungal species have been studied that show electrogenic activity in PMFCs biofilm. Kaku et al. have explored the potential of *Natronocella acetinitrilica* on the anode of PMFCs (Kaku et al., 2008). Furthermore, alpha-proteobacteria have also been studied on the cathode of PMFCs. Various researchers have also exhibited that not all microbes functioning in

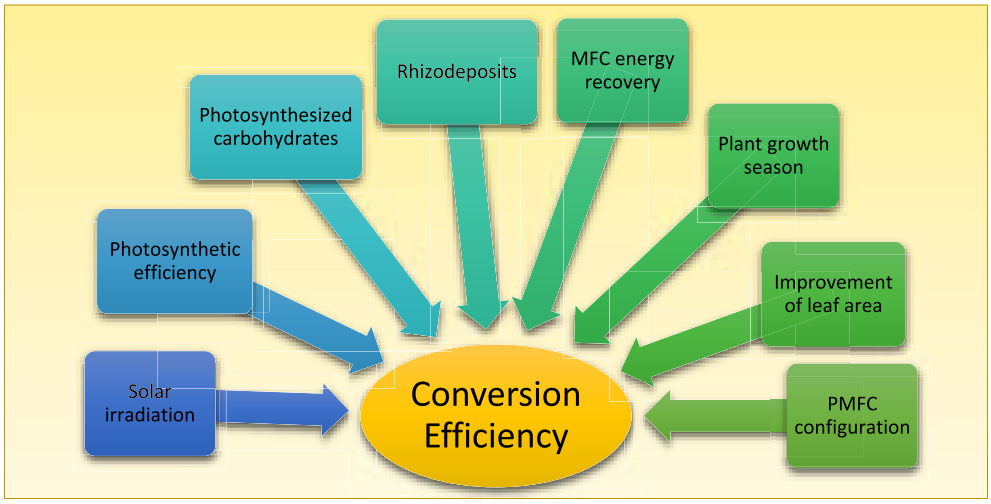

Fig. 6. Factors effecting the conversion efficiency of PMFCs.

PMFCs may necessarily be electrogenic in nature (Sorokin et al., 2007). Two types of bacteria are present on the cathode; aerobic and anaerobic. Inoculum type has a significant influence on the PMFC efficiency. In a study conducted by da Rosa, bacterial inoculum from rice field soil displayed greater potential to form biofilm and subsequently exhibit current generation activity in PMFC (Cabezas da Rosa, 2010). PMFCs have shown great potential in both current generation i.e. the production of green electricity and being an efficacious greenhouse gas removal facility simultaneously. Few studies utilizing plants in microbial fuel cells are listed in Table 2. Strik et al. have proposed an interesting and impressive concept in their review article, which states the use of PMFCs as an integration into the landscape, thus producing "green" cities (Strik et al., 2011). They suggested the use of "green roofs" which will have several beneficial implications including increase in the aesthetic value of the city, lowering of temperature and air quality recuperation, apart from production of green energy.

5. Biophotovoltaic cells

The nexus of photovoltaic and bio-electrochemical cells gives rise to bio-photovoltaic systems. In previous sections, we have discussed the use of photosynthetic entities in MFCs to produce bio-energy. In this section, the concept of bio-photovoltaic cells (BPVs) will be explained and differentiated from other light harvesting bio-electrochemical systems. The main characteristic of BPVs is the utilization of oxygenic photosynthetic bio entities only, which breakdown water when illuminated (Fig. 7). The electrons thus produced are transferred to the anode via IEET or DEET mechanism. Systems other than BPVs may or may not be able to separate charge from water. The bio entities involved in BPVs light harvesting system may be sub-cellular proteins; photosynthetic reaction centres or whole cell systems of blue green algae or photosynthetic bacteria. A chief difference between an MFC and a BPV is that, though both are bioelectrochemical systems, BPVs are specifically photo-driven systems. Furthermore, MFCs require a carbon source to operate while light energy and water as an electrolyte is enough for BPVs. MFCs contain heterotrophic microbes at the anode and BPVs have photosynthetic microorganisms.

According to McCormick et al. only 37 studies on BPV were conducted from 1964 to 2008. However, in the last decade more than 100 articles were published in various scientific journals (McCormick et al., 2015).

5.1. Photosynthetic reaction centres in BPVs

In this section, we will briefly explicate the concept and working of photosynthetic reaction centres. The process of photosynthesis is integral in various autotrophic organisms including plants. The light reactions of photosynthesis occur through the photosynthetic reaction centres; photosystem I and photosystem II (Kramer et al., 2004) (Fig. 8). The thylakoid membranes inside chloroplasts are the chief sites containing the photosynthetic reaction centres where photosynthesis occurs (Shimoni et al., 2005). Although cyanobacteria does not contain chloroplasts, they contain the photosynthetic apparatus necessary to carry out photosynthesis. Chloroplasts contain light-absorbing molecules called chlorophylls; chlorophyll a and chlorophyll b while photosynthetic bacteria contains bacteriophyll. Other than these, secondary pigments are also present including carotenoids and phycobilins. These pigments absorb light in various ranges. Photosystem I contains chlorophyll a or P700 while photosystem II contains chlorophyll b or P680 (The numbers, P700 and P680 refer to the range in which they absorb light) (Barber, 2014). Both photosynthetic reaction centres work in the form of a Z scheme of electron transport. When a photon of light falls on PS-I, the electrons become excited and thus move to a higher energy level (Yamori and Shikanai, 2016). The excited electron moves through a series of electron carriers and is accepted by NADP+. The electron carriers include phylloquinone, iron sulphur protein complex, ferrodoxin and lastly NADP+. After accepting electrons, NADP+ is converted to NADPH (Minagawa, 2016). Since the P700 is oxidized after losing electrons, it becomes unstable resulting in an electron gap. This gap is overcome by the P680 or chlorophyll b when it is hit by light. The electrons in P680 become excited and move through another chain of electron carriers eventually reaching P700 (Hartmann et al., 2018). The chain of electron carriers include; pheophytin, plastoquinone, cytochrome bf complex, plastocyanin and lastly P700 (Barber, 2016). This process also results in an unstable P680. However, the P680 can gain electrons through its oxygen evolving complex (OEC) by photolysing water to generate electrons (Shevela and Björn, 2017). The Z scheme of electron transport through P700 and P680 is illustrated in Fig. 8. The net reaction of water photolysis and conversion of NADP + to NADPH is given below.

$$2H_2O + 2NADP^+ \rightarrow 2NADPH + 2H^+ + O_2$$

BPVs utilize both PS-I and PS-II to generate energy from light. These cells use oxygenic PS-II reaction centres.

5.2. Performance of BPVs

Like other bioelectrochemical cells, BPVs are also made by using either sub-cellular components or whole cells capable of photosynthesis. In 2005, Touloupakis et al. constructed a biosensor for the

Table 2
Architecture, components and electrical outputs of some PMFCs.

Plant	Cell configuration	Anode	Cathode	Anolyte	Catholyte	Electrical Output	Reference
Acorns calamus	Plant SMFC	Carbon felt	Carbon felt	Fresh water sediment	Water	0.1902 V[a]	Liu et al. (2019)
Oryza sativa	Single chamber PVC pipe	Carbon felt anode	Air cathode	Soil	–	41.41 mW/m^2	Khudzari et al. (2019)
Typha orientalis	Constructed wetland MFC	Nano zero valent Iron	Nano zero valent Iron	Hoagland's trace elements and quartz sand	Hoagland's trace elements and quartz sand	26 mW/m^2	Wang et al. (2019)
Acorns tatarinowii	Plant sediment MFC	Graphite felt plate	Pt coated graphite felt plate	Silica sand	Water	21 mW/m^2	Liu et al. (2018a,b)
Epiprenum aureum	Plastic container	Carbon fibre brush	Carbon fibre cloth	Cow dung, garden soil, artificial microbial growth media	Artificial microbial growth media	620 mW/m^2	Sarma and Mohanty, 2018
Alisha plantago-aquatica	Plastic container	Galvanized steel plates	Graphite plates	Soil + water	Soil + water	0.072 mW/m^2	Rusyn and Hamkalo (2018)
Arundo donax	Constructed wetland MFC	Graphite felt	Graphite felt	Quartz sand matrix	Quartz sand matrix	12.82 mW/m^2	Zhou et al. (2018)
Vetiveria zizaniodes	Double chambered earthen pots	Graphite fibre	Graphite wire	Garden soil + water	–	68 mW/m^2	Regmi et al. (2018)
Chlorophytum comosum	Garden pots	Graphite	Graphite	Soil + water	Soil + water	18 mW/m^2	Azri et al., 2018
Puccinellia distans	Single chamber PVC pipe	Carbon felt anode	Air cathode	Potting mix	–	83.7 mW/m^2	Khudzari et al. (2018)
Spartina anglica	Flat porous plate	Three layers of graphite felt	Graphite felt	Nitrate-less ammonium rich plant growth medium	Aerobic wastewater	120 mA/m^2	Wetser et al. (2015)
Canna indica	Polymethyl methacrylate cylinder	Graphite disk	Annular carbon cloth	Tap water	Tap water	1015 mA/m^2	Lu et al. (2015a,b)

[a] Electrical output mentioned only in voltage.

detection of herbicides and pollutants by utilizing thylakoids from *Spinacia oleracea* and *Senecio vulgaris* on a graphite electrode (Touloupakis et al., 2005). Lam et al. was successful in generating 11 mA/m^2 current by using a suspension of thylakoid membranes on a gold anode (Lam et al., 2006). PS-II extracted from *Thermosynechococcus elongatus* on gold electrodes was studied by Badura et al. to produce bio-hydrogen. Furthermore, a current of 14 $\mu A/cm^2$ was generated upon illumination (Badura et al., 2006). Thylakoid membranes from baby spinach were fixed on polypyrrole in between two electrodes that served as a bio-chemical sensor for herbicide (Lin et al., 2006). Kato et al. fixed PS-II reaction centre from *Thermosynechococcus elongatus* on anode and generated 16 mA/m^2 current density from water photolysis (Kato et al., 2012). Calkins et al. generated 250 mA/m^2 current from Thylakoids from *Spinacia oleracea* immobilized on multi-walled carbon nanotubes (Calkins et al., 2013).

BPVs have advantage over conventional photoelectrochemical cells that they produce current in dark as well through respiratory breakdown of organic compounds produced during the light reactions (McCormick et al., 2011). Cyanobacteria, *Spirulina platensis* was attached on anode in a membrane-less fuel cell to generate 17.5 mA/m^2 (Fu et al., 2010). Thorne et al. grew a biofilm of *Chlorella vulgaris* on FTO coated glass to produce current density of 110 mA/m^2 (Thorne et al., 2011). A suspension of *Synechocystis* PCC 6714 was incorporated in a photoelectrochemical cell producing 78.75 mA/m^2 (Xie et al., 2011). In a two chambered cell, *Synechocystis* PCC6803 was utilized which produced a maximum power density of 6.7 mW/m^3 without any net CO_2 production (Madiraju et al., 2012). Raman and Lan observed the effect of various electrodes distances on power density of BPV by using Chlamydomonas reinhardtii transformation F5 (Raman and Lan, 2012). They elucidated that shorter distance between electrodes produces high power density since the internal resistance decreases. A mixed consortium of electrogenic microbes was used by Chandra et al. who demonstrated that electrons generated by light reaction were in greater number than electrons generated by dark reaction (Chandra et al., 2012). Subhash et al. utilized domestic wastewater to produce bioelectricity through mixed photosynthetic consortium. The electrogenic activity was observed to be higher during daytime than night (Subhash et al., 2013). McCormick et al. were successful in producing current density of 61.4 mA/m^2 by a suspension of *Synechocystis* PCC6803 deposited on ITO glass electrode (McCormick et al., 2013). Samsonoff et al. immobilized *Synechococcus bacillaris* (CCAP WH5701) on gold electrode explicating that denser biofilms were grown on surfaces closer to the electrode (Samsonoff et al., 2014). Microfluidic BPVs have also been fabricated by Bombelli et al. that use the soft lithography technique while the cells are settled down at the anode through gravitational force to produce impressive densities of current (Bombelli et al., 2015). Fast growing algae, Synechococcus elongates (UMACC 105) was used to generate bioelectricity from PBV on ITO and reduced graphene oxide electrodes (Ng et al., 2018). Various other electrode materials have been utilized in BPVs such as titanium oxide/reduced graphene oxide composite was used in BPV with Chlorella vulgaris cells. This combination of electrode material displayed impressive durability and generating 34.66 mW/m^2 bioelectricity (Senthilkumar et al., 2018). BPVs show great efficiencies for bioenergy generation in light as well as dark conditions. BPV technology is still in infancy stage and is open to several new options for optimisation to increase energy efficiency using various electrode materials and varying cell configuration.

5.3. BPVs in space

An interesting application of BPVs is its use in space missions. Phototrophs including green algae and cyanobacteria were examined in space and exposed to solar UV, temperature variabilities, vacuum conditions in space and cosmic radiation in the EXPOSE-E mission for 18 months by European Space Agency (Cockell et al., 2011). Two algae;

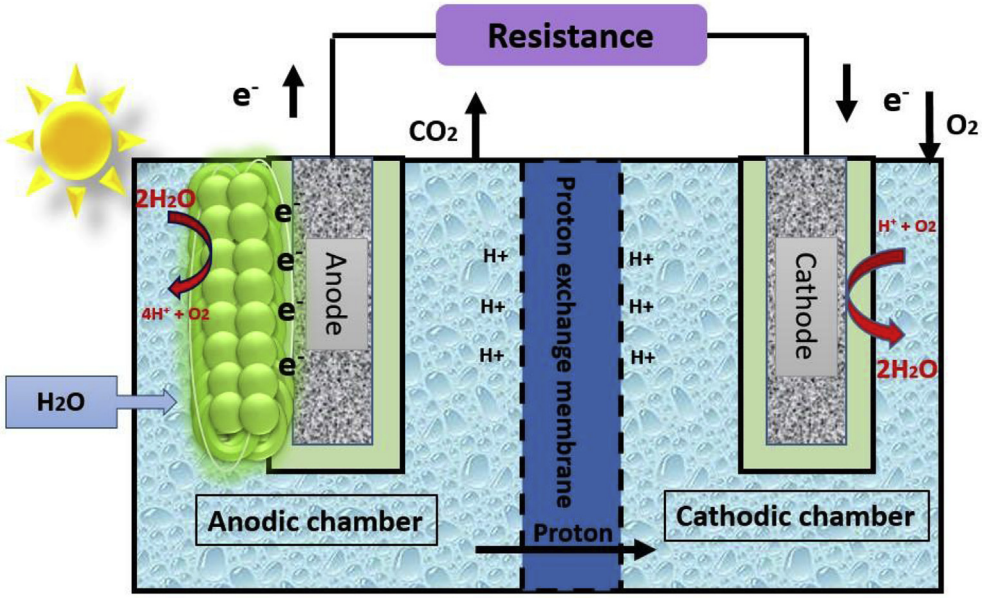

Fig. 7. Pictorial display of biophotovoltaic cell exhibiting the use of sunlight by autotrophic/photosynthetic microbes in the presence of water as substrate to produce bioenergy.

Chlorella and *Rosenvingiella* spp. and a cyanobacterium; *Gloeocapsa* sp. survived the space exposed conditions. Microbial cells were also exposed to extreme UV radiation, which might be even detrimental, yet some autotrophic communities survived. The resilient and tolerant nature of photosynthetic microbes under extreme environmental conditions aid them in their survival such as the protection of cells by surface layers. Phototrophs can thus be efficiently utilized to produce oxygen in life support systems in space missions. Other than oxygen, microalgae can also be utilized as a food production and supply to various space missions (Chacón-Lee and González-Mariño et al., 2010). Other functions of microalgae systems in space include; waste transformation, carbon dioxide reduction and regeneration of air, water and food. Such systems display extensive promise as life support systems in space missions owing to its regenerative capabilities, sustainability and stability.

5.4. Hybrid BPVs

A new hybrid BPV cell system is being researched upon, which utilizes seawater, one of the most abundant renewable resource, as an electrolyte for such cells. This technology is attributable to BPVs only. This technique, though requires more investigation, can be utilized in the future for the production of fresh water along with energy generation by desalinating seawater. Such a technology opens up a new era for entirely sustainable electricity generation from a nexus of seawater, sunlight and oxygen without the need for supplementary fuel. Mainly, BPVs can utilize any water as an electrolyte and undergo water-splitting reaction to convert it into hydrogen and oxygen at the anode. Such cells might not need any external power source to operate and rely on sunlight only to convert water into energy. Water-splitting technology of BPVs has also been utilized in 2016 for the production of hydrogen fuel. Pinhassi et al. (2016) introduced thylakoids extracted from spinach in BPV to produce a current density of 0.5 mA/cm along with the production of hydrogen fuel. Zhang et al. (2017b) constructed a BPV utilizing seawater as an electrolyte. When illuminated by solar light the cell produced 21.4 μW/cm^2 after water splitting at the TiO_2 semiconductor anode.

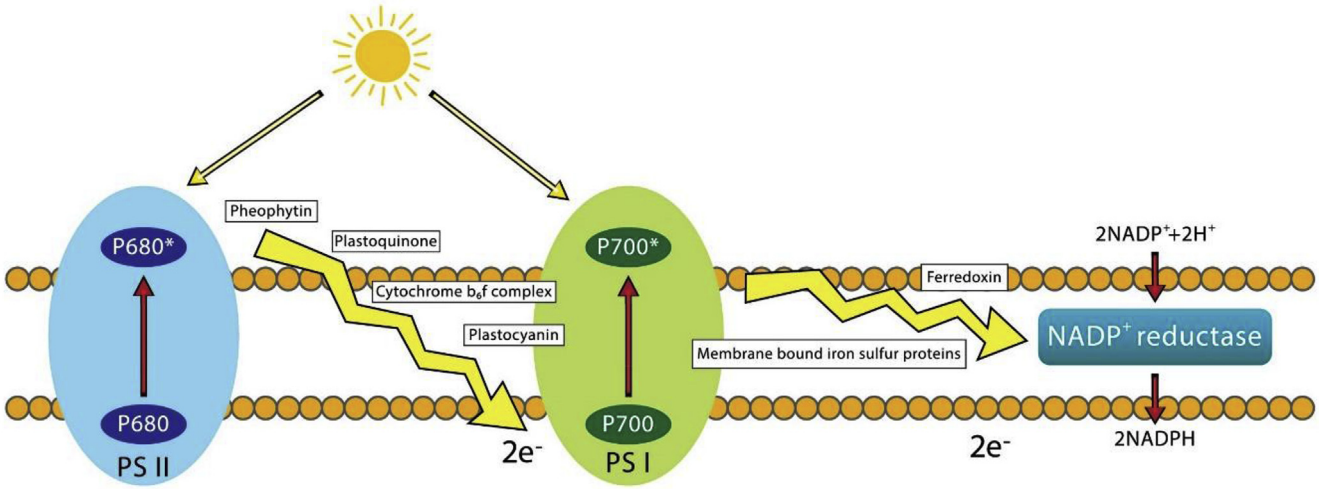

Fig. 8. Z scheme of electron transport chain through P700 and P680 photoreaction centres.

Table 3
Parameters to evaluate bioelectrochemical cell performance.

Equation	Use	Variables involved
$I = E_{cell}/(A_{mean} \times R_{ext})$	Current density	I: current density, E_{cell}: cell potential, A_{mean}: membrane area, R_{ext}: external resistance.
$P_{max} = I_{mp} \times V_{mp}$	Maximum power output	P_{max}: power output, I_{mp}: current at maximal power, V_{mp}: voltage at maximal power.
$C_E = {}^{Ms}\int_0^{ts} Idt \Big/ Fb_{es}\upsilon_{an}\Delta C$	Columbic efficiency	CE: Columbic efficiency, Ms: molecular weight of substrate, F: Faraday's constant, Van: liquid volume in the anodic part, ΔC: change in concentration of substrate over batch cycle over time period t.
$\text{Ŋ} = P_{max}/P_{in}$	Solar to electrical conversion efficiency	Ŋ: solar to electrical energy efficiency, P_{max}: maximum power output, P_{in}: incident power.
$FF = I_{mp} \times V_{mp}/I_{sc} \times V_{oc}$	Fill factor	FF: fill factor, I_{sc}: short circuit current, V_{oc}: open circuit voltage.
$EE = CE \times PE$	Energy efficiency	EE: energy efficiency, CE: columbic efficiency, PE: potential efficiency.
$E_{device} = OCV - IR$	Total energy loss	E_{device}: total energy loss, OCV: open circuit voltage, IR: internal resistance.
$Re = l/(A \times K)$	Electrolyte resistance	Re: Electrolyte resistance, l: electrode distance, A: cross sectional area through which ionic conduction occurs, K: specific conductivity of the electrolyte.
$CE = Pe \times Rp \times Ra \times Er$	Conversion efficiency of PMFC	CE: conversion efficiency, Pe: photosynthetic efficiency, Rp: photosynthesized carbohydrates, Ra: rhizodeposit availability for microorganisms, Er: microbial fuel cell energy recovery.

6. Electrical potential of biological fuel cells

Prodigious efforts have been done by researchers to increase the power density, current and stability of MFCs to make their practical application lucrative. Various parameters and equations used to calculate the efficiency and output of bioelectrochemical cells are listed in Table 3. Recently microscale MFCs have been developed which have shown to produce a very high power density of 450 A/m^2 (Ren et al., 2014). Furthermore, these MFCs behaved as supercapacitors with increased stability. A power density of 1.78 W/m^2 has been achieved by Rashid et al. by utilizing activated sludge accompanying algae biomass (Rashid et al., 2013). An impressive power density of 788 mW/m^2 was achieved by using activated sludge as a biocatalyst (Park and Zeikus, 2003). It has been found in various studies that the configuration and architecture of MFCs have a great influence on the electrical performance of fuel cells. Jadhav et al. developed a dual chambered cell with a power density of 6.5 W/m^3 (Jadhav et al., 2014). An overflow type MFC reactor was built by Li et al. which produced 18.2 W/m^3 power density (Li et al., 2009). A stacked sandwich type fuel cell by Zhang and Agelidaki has been reported to produce 0.294 W/m^2 power density (Zhang and Angelidaki, 2012). 17.85 mW/m^2 maximum power was achieved by a clay ware cell with an air cathode (Ghadge and Ghangrekar, 2015). An upflow reactor by Thung et al. utilized a tubular cylinder with carbon flake cathode producing a power density of 44.4 mW/m^2 (Thung et al., 2015). Furthermore, stacking has also been performed to increase the MFC performance. A stacked MFC system produced 22.8 mW/m^2 (An et al., 2014). Mathuriya developed an interesting wastewater treatment system with multiple anode chambers producing a continuous 359.6 mW/cm^2 power density (Mathuriya, 2017). Dong et al. developed a 90 L MFC system which operated for 6 months and produced an impressive amount of power i.e. 0.056 kW h/m^3 (Dong et al., 2015). It was observed that in a SMFC the granule size is a crucial factor determining the current density. Arends et al. used small sized carbon felt granules (0.25–0.5 mm) in a plant based SMFC and obtained 77.7 mA/m^2 current density (Arends et al., 2012). Villasenor et al. were able to achieve a high power density of 20.76 mW/m^2 (Villasenor et al., 2013). They developed a horizontal subsurface flow constructed wetland MFC (CW-MFC), which utilized wastewater as a substrate. A low organic loading in the MFC resulted in a high oxidation of wastewater organic content facilitating electric current. A higher power density of 55.05 mW/m^2 was achieved by Liu et al., from CW-MFC (Liu et al., 2014). They optimised the CW-MFC by using various cathode materials. Granular activated carbon cathode provided the highest power density due to its large surface area. Helder et al. obtained a soaring 222 mW/m^2 power density from *Spartina anglica* based PMFC (Helder et al., 2010). Chiranjeevi et al. obtained 163 mW/m^2 power density from PMFC pot reactor by using *Pennisetum sentaceum* (Chiranjeevi et al., 2012). Chiao et al. built a micro photosynthetic MFC with a power density of 0.023 mW/m^2 (Chiao et al., 2006). A maximum power density of 800 mW/m^2 was achieved by Yagishita et al. from a cellular biophotovoltaic cell (Yagishita et al., 1998) followed by 289 mW/m^2 by a *Synechoccus* sp. based BPV (Tsujimura et al., 2001). In another study, Yagishita et al. obtained 288 mW/m^2 from *Synechocystis* sp. using glucose as feedstock (Yagishita et al., 1997).

7. Conclusion and future perspectives

Microbial fuel cell technology has precedence over other renewable energy generating systems in that it not only generates green electricity but also produces a range of other fuels including bio-hydrogen and various other chemicals. Contrastingly, solar cell technology only generates electricity from solar energy conversion (Iqbal et al., 2019). MFC systems are capable of self-repairing since they utilize living cells rendering them more sustainable. These cells are environmental friendly and do not produce toxic pollutants. Bioelectrochemical fuel cells are excellent bioremediants and can remove various noxious contaminants. The photoMFCs and PMFCs also aid in improving air quality due to their ability to perform photosynthesis. Furthermore, PMFCs can also increase the aesthetic value by their incorporation into the landscape. Bioelectrochemical fuel cells can be fabricated in various configurations with utilization of several materials for electrodes. Each configuration generates varying power densities that can be further optimised by the use of high surface area electrodes. However, the electrical outputs of such systems are still not high enough to reach larger scale industrial applications although the amount of power densities of MFCs have increased considerably in the recent years. MFCs can be further optimised by using microscale cells that not only reduce internal resistance of the cell but are also portable and can scale up power efficiencies of other systems as well when used in combination. MFCs is a promising technology since it can function at extreme temperatures such as when using thermophilic microbes. The potential and resilient nature of microbes in fuel cells have also been exhibited by the study conducted in space under extreme conditions. To increase the potential and efficiencies of MFCs, various cost-effective electrode materials should be utilized and more focus should be transferred towards photosynthetic microbes that can obtain their own food and do not require much external input for functioning. However, with the current trend in green energy generation, there is an exponential increase in bioelectrochemical technology research indicating great advancements in this domain in the future.

Conflict of interest

None.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Mahwash Mahar Gul: Conceptualization, Data curation, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Khuram Shahzad Ahmad:** Conceptualization, Data curation, Investigation, Supervision, Visualization, Writing - original draft, Writing - review & editing.

References

Chacón-Lee, T.L., González-Mariño, G.E., 2010. Microalgae for "healthy" foods—possibilities and challenges. Compr. Rev. Food Sci. Food Saf. 9, 655–675.

Abbas, S.Z., Rafatullah, M., Khan, M.A., Siddiqui, M.R., 2018. Bioremediation and electricity generation by using open and closed sediment microbial fuel cells. Front. Microbiol. 9.

Adelaja, O., Keshavarz, T., Kyazze, G., 2015. The effect of salinity, redox mediators and temperature on anaerobic biodegradation of petroleum hydrocarbons in microbial fuel cells. J. Hazard Mater. 283, 211–217.

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. Environ. Sci. Technol. 40, 3388–3394.

Ahmad, K.S., Hussain, Z., Majid, S., 2018. Synthesis, characterization and PVD assisted thin film fabrication of the nano-structured bimetallic Ni3S2/MnS2 composite. Surf. Interface. 12, 190–195.

An, J., Kim, B., Jang, J.K., Lee, H.S., Chang, I.S., 2014. New architecture for modulization of membraneless and single-chambered microbial fuel cell using a bipolar plate-electrode assembly (BEA). Biosens. Bioelectron. 59, 28–34.

Appleby, A.J., 1990. From Sir William Grove to today: fuel cells and the future. J. Power Sources 29, 3–11.

Arends, J.B., Blondeel, E., Tennison, S.R., Boon, N., Verstraete, W., 2012. Suitability of granular carbon as an anode material for sediment microbial fuel cells. J. Soils Sediments 12, 1197–1206.

Aryal, N., Ammam, F., Patil, S.A., Pant, D., 2017. An overview of cathode materials for microbial electrosynthesis of chemicals from carbon dioxide. Green Chem. 19, 5748–5760.

Azri, Y.M., Tou, I., Sadi, M., Benhabyles, L., 2018. Bioelectricity generation from three ornamental plants: *Chlorophytum comosum, Chasmanthe floribunda* and *Papyrus diffusus*. Int. J. Green Energy 15, 254–263.

Badura, A., Esper, B., Ataka, K., Grunwald, C., Wöll, C., Kuhlmann, J., Heberle, J., Rögner, M., 2006. Light-driven water splitting for (bio-) hydrogen production: photosystem 2 as the central part of a bioelectrochemical device. Photochem. Photobiol. 82, 1385–1390.

Barber, J., 2014. Photosystem II: its function, structure, and implications for artificial photosynthesis. Biochemistry 79, 185–196.

Barber, J., 2016. Photosystem II: the water splitting enzyme of photosynthesis and the origin of oxygen in our atmosphere. Q. Rev. Biophys. 49.

Bhowmick, G.D., Das, S., Adhikary, K., Ghangrekar, M.M., Mitra, A., 2019. Using rhodium as a cathode catalyst for enhancing performance of microbial fuel cell. Int. J. Hydrogen Energy 44, 22218–22222.

Bombelli, P., Müller, T., Herling, T.W., Howe, C.J., Knowles, T.P., 2015. A high power-density, mediator-free, microfluidic biophotovoltaic device for cyanobacterial cells. Adv. Energy Mater. 5 (2), 1401299.

Bonanni, P.S., Schrott, G.D., Robuschi, L., Busalmen, J.P., 2012. Charge accumulation and electron transfer kinetics in *Geobacter sulfurreducens* biofilms. Energy Environ. Sci. 5, 6188–6195.

Bratkova, S., Alexieva, Z., Angelov, A., Nikolova, K., Genova, P., Ivanov, R., Gerginova, M., Peneva, N., Beschkov, V., 2019. Efficiency of microbial fuel cells based on the sulfate reduction by lactate and glucose. Int. J. Environ. Sci. Technol. 1–12.

Burkitt, R., Whiffen, T.R., Yu, E.H., 2016. Iron phthalocyanine and MnOx composite catalysts for microbial fuel cell applications. Appl. Catal. B Environ. 181, 279–288.

Cabezas da Rosa, A., 2010. Diversity and Function of the Microbial Community on Anodes of Sediment Microbial Fuel Cells Fueled by Root Exudates.

Calkins, J.O., Umasankar, Y., O'Neill, H., Ramasamy, R.P., 2013. High photo-electrochemical activity of thylakoid–carbon nanotube composites for photosynthetic energy conversion. Energy Environ. Sci. 6, 1891–1900.

Cao, X., Huang, X., Liang, P., Boon, N., Fan, M., Zhang, L., Zhang, X., 2009. A completely anoxic microbial fuel cell using a photo-biocathode for cathodic carbon dioxide reduction. Energy Environ. Sci. 2, 498–501.

Cecconet, D., Molognoni, D., Callegari, A., Capodaglio, A.G., 2018. Agro-food industry wastewater treatment with microbial fuel cells: energetic recovery issues. Int. J. Hydrogen Energy 43, 500–511.

Chae, K.J., Choi, M.J., Lee, J.W., Kim, K.Y., Kim, I.S., 2009. Effect of different substrates on the performance, bacterial diversity, and bacterial viability in microbial fuel cells. Bioresour. Technol. 100, 3518–3525.

Chandra, R., Subhash, G.V., Mohan, S.V., 2012. Mixotrophic operation of photo-bioelectrocatalytic fuel cell under anoxygenic microenvironment enhances the light dependent bioelectrogenic activity. Bioresour. Technol. 109, 46–56.

Chen, S., Patil, S.A., Schröder, U., 2018. A high-performance rotating graphite fiber brush air-cathode for microbial fuel cells. Appl. Energy 211, 1089–1094.

Cheng, S., Wu, J., 2013. Air-cathode preparation with activated carbon as catalyst, PTFE as binder and nickel foam as current collector for microbial fuel cells. Bioelectrochemistry 92, 22–26.

Chiao, M., Lam, K.B., Lin, L., 2006. Micromachined microbial and photosynthetic fuel cells. J. Micromech. Microeng. 16, 2547.

Chiranjeevi, P., Mohanakrishna, G., Mohan, S.V., 2012. Rhizosphere mediated electrogenesis with the function of anode placement for harnessing bioenergy through CO2 sequestration. Bioresour. Technol. 124, 364–370.

Cho, Y.K., Donohue, T.J., Tejedor, I., Anderson, M.A., McMahon, K.D., Noguera, D.R., 2008. Development of a solar-powered microbial fuel cell. J. Appl. Microbiol. 104, 640–650.

Choi, O., Sang, B.I., 2016. Extracellular electron transfer from cathode to microbes: application for biofuel production. Biotechnol. Biofuels 9, 11.

Ciesielski, P.N., Scott, A.M., Faulkner, C.J., Berron, B.J., Cliffel, D.E., Jennings, G.K., 2008. Functionalized nanoporous gold leaf electrode films for the immobilization of photosystem I. ACS Nano 2, 2465–2472.

Cockell, C.S., Rettberg, P., Rabbow, E., Olsson-Francis, K., 2011. Exposure of phototrophs to 548 days in low Earth orbit: microbial selection pressures in outer space and on early earth. ISME J. 5, 1671.

Corbella, C., Hartl, M., Fernandez-Gatell, M., Puigagut, J., 2019. MFC-based biosensor for domestic wastewater COD assessment in constructed wetlands. Sci. Total Environ. 660, 218–226.

Debuy, S., Pecastaings, S., Bergel, A., Erable, B., 2015. Oxygen-reducing biocathodes designed with pure cultures of microbial strains isolated from seawater biofilms. Int. Biodeterior. Biodegrad. 103, 16–22.

Deng, Q., Li, X., Zuo, J., Ling, A., Logan, B.E., 2009. Power generation using an activated carbon fiber felt cathode in an upflow microbial fuel cell. J. Power Sources 195, 1130–1135.

Dicks, A., Rand, D.A.J., 2018. Fuel Cell Systems Explained. Wiley.

Dong, H., Yu, H., Wang, X., Zhou, Q., Feng, J., 2012. A novel structure of scalable air-cathode without Nafion and Pt by rolling activated carbon and PTFE as catalyst layer in microbial fuel cells. Water Res. 46, 5777–5787.

Dong, Y., Qu, Y., He, W., Du, Y., Liu, J., Han, X., Feng, Y., 2015. A 90-liter stackable baffled microbial fuel cell for brewery wastewater treatment based on energy self sufficient mode. Bioresour. Technol. 195, 66–72.

Dumas, C., Basseguy, R., Bergel, A., 2008. Microbial electrocatalysis with Geobacter sulfurreducens biofilm on stainless steel cathodes. Electrochim. Acta 53, 2494–2500.

Efrati, A., Tel-Vered, R., Michaeli, D., Nechushtai, R., Willner, I., 2013. Cytochrome c-coupled photosystem I and photosystem II (PSI/PSII) photo-bioelectrochemical cells. Energy Environ. Sci. 6, 2950–2956.

Erbay, C., Pu, X., Choi, W., Choi, M.J., Ryu, Y., Hou, H., Lin, F., de Figueiredo, P., Yu, C., Han, A., 2015. Control of geometrical properties of carbon nanotube electrodes towards high-performance microbial fuel cells. J. Power Sources 280, 347–354.

Fan, L.P., Li, J.J., 2016. Overviews on internal resistance and its detection of microbial fuel cells. Int. J. Circ. Sys. Signal Pr. 10, 316–320.

Fazli, N., Mutamim, N.S.A., Jafri, N.M.A., Ramli, N.A.M., 2018. Microbial fuel cell (MFC) in treating spent caustic wastewater: varies in hydraulic retention time (HRT) and mixed liquor suspended solid (MLSS). J. Environ. Chem. Eng. 6, 4339–4346.

Flint, H.J., Scott, K.P., Duncan, S.H., Louis, P., Forano, E., 2012. Microbial degradation of complex carbohydrates in the gut. Gut Microb. 3, 289–306.

Freguia, S., Teh, E.H., Boon, N., Leung, K.M., Keller, J., Rabaey, K., 2010. Microbial fuel cells operating on mixed fatty acids. Bioresour. Technol. 101, 1233–1238.

Fu, C.C., Hung, T.C., Wu, W.T., Wen, T.C., Su, C.H., 2010. Current and voltage responses in instant photosynthetic microbial cells with Spirulina platensis. Biochem. Eng. J. 52, 175–180.

Furlan, C., Mortarino, C., 2017. Forecasting the impact of renewable energies in competition with non-renewable sources. Renew. Sustain. Energy Rev. 81, 1879–1886.

Gerster, D., Reichert, J., Bi, H., Barth, J.V., Kaniber, S.M., Holleitner, A.W., Visoly-Fisher, I., Sergani, S., Carmeli, I., 2012. Photocurrent of a single photosynthetic protein. Nat. Nanotechnol. 7, 673.

Ghadge, A.N., Ghangrekar, M.M., 2015. Performance of low cost scalable air–cathode microbial fuel cell made from clayware separator using multiple electrodes. Bioresour. Technol. 182, 373–377.

Ghasemi, M., Shahgaldi, S., Ismail, M., Kim, B.H., Yaakob, Z., Daud, W.R.W., 2011. Activated carbon nanofibers as an alternative cathode catalyst to platinum in a two-chamber microbial fuel cell. Int. J. Hydrogen Energy 36, 13746–13752.

Ghasemi, M., Wan, W.R., Ismail, M., Rahimnejad, A.F., Ismail, J.X., Leong, M., Miskan, K., Ben Liew, 2012. Effect of pretreatment and biofouling of proton exchange membrane on microbial fuel cell performance. Int. J. Hydrogen Energy 38, 5480–5484.

Ghasemi, M., Daud, W.R.W., Hassan, S.H., Jafary, T., Rahimnejad, M., Ahmad, A., Yazdi, M.H., 2016. Carbon nanotube/polypyrrole nanocomposite as a novel cathode catalyst and proper alternative for Pt in microbial fuel cell. Int. J. Hydrogen Energy 41, 4872–4878.

Gunther, D., LeBlanc, G., Prasai, D., Zhang, J.R., Cliffel, D.E., Bolotin, K.I., Jennings, G.K., 2013. Photosystem I on graphene as a highly transparent, photoactive electrode. Langmuir 29, 4177–4180.

Haavisto, J., Dessi, P., Chatterjee, P., Honkanen, M., Noori, M.T., Kokko, M., Lakaniemi, A.M., Lens, P.N., Puhakka, J.A., 2019. Effects of anode materials on electricity production from xylose and treatability of TMP wastewater in an up-flow microbial fuel cell. Chem. Eng. J. 372, 141–150.

Haldane, J.B.S., Toman, M.A., 2015. Analyzing Nonrenewable Resource Supply. Routledge.

Haldar, D., Manna, M.S., Sen, D., Bhowmick, T.K., Gayen, K., 2019. Microbial fuel cell for the treatment of wastewater. Microbial Fuel Cells: Mater. Appl. 46, 289–306.

Han, W., Wu, Z., Li, Y., Wang, Y., 2018. Graphene family nanomaterials (GFNs)—promising materials for antimicrobial coating and film: a review. Chem.

Eng. J 358, 1022–1037.
Harnisch, F., Schröder, U., 2010. From MFC to MXC: chemical and biological cathodes and their potential for microbial bioelectrochemical systems. Chem. Soc. Rev. 39, 4433–4448.
Hartmann, V., Ruff, A., Schuhmann, W., Rögner, M., Nowaczyk, M.M., 2018. Analysis of photosystem II electron transfer with natural PsbA-variants by redox polymer/protein biophotoelectrochemistry. Photosynthetica 56, 229–235.
Hassan, S.H., Abd el Nasser, A.Z., Kassim, R.M., 2019. Electricity generation from sugarcane molasses using microbial fuel cell technologies. Energy 178, 538–543.
He, Z., Angenent, L.T., 2006. Application of bacterial biocathodes in microbial fuel cells. Electroanalysis 18, 2009–2015.
Helder, M., Strik, D.P.B.T.B., Hamelers, H.V.M., Kuhn, A.J., Blok, C., Buisman, C.J.N., 2010. Concurrent bio-electricity and biomass production in three Plant-Microbial Fuel Cells using *Spartina anglica, Arundinella anomala* and *Arundo donax*. Bioresour. Technol. 101, 3541–3547.
Hiegemann, H., Lübken, M., Schulte, P., Schmelz, K.G., Gredigk-Hoffmann, S., Wichern, M., 2018. Inhibition of microbial fuel cell operation for municipal wastewater treatment by impact loads of free ammonia in bench-and 45L-scale. Sci. Total Environ. 624, 34–39.
Hoogers, G. (Ed.), 2002. Fuel Cell Technology Handbook. CRC press.
Huang, L., Regan, J.M., Quan, X., 2011. Electron transfer mechanisms, new applications, and performance of biocathode microbial fuel cells, Bioresource. Technol. 102, 316–323.
Huang, J., Zhu, N., Yang, T., Zhang, T., Wu, P., Dang, Z., 2015. Nickel oxide and carbon nanotube composite (NiO/CNT) as a novel cathode non-precious metal catalyst in microbial fuel cells. Biosens. Bioelectron. 72, 332–339.
Huggins, T., Wang, H., Kearns, J., Jenkins, P., Ren, Z.J., 2014. Biochar as a sustainable electrode material for electricity production in microbial fuel cells. Bioresour. Technol. 157, 114–119.
Inglesby, A.E., Beatty, D.A., Fisher, A.C., 2012. Rhodopseudomonas palustris purple bacteria fed Arthrospira maxima cyanobacteria: demonstration of application in microbial fuel cells. RSC Adv. 2, 4829–4838.
Iqbal, M., Ali, A., Ahmad, K.S., Rana, F.M., Khan, J., Khan, K., Thebo, K.H., 2019. Synthesis and characterization of transition metals doped CuO nanostructure and their application in hybrid bulk heterojunction solar cells. SN Appl. Sci. 1, 647.
Jadhav, D.A., Ghadge, A.N., Mondal, D., Ghangrekar, M.M., 2014. Comparison of oxygen and hypochlorite as cathodic electron acceptor in microbial fuel cells. Bioresour. Technol. 154, 330–335.
Jana, P.S., Behera, M., Ghangrekar, M.M., 2010. Performance comparison of up-flow microbial fuel cells fabricated using proton exchange membrane and earthen cylinder. Int. J. Hydrogen Energy 35, 5681–5686.
Janzen, A.F., Seibert, M., 1980. Photoelectrochemical conversion using reaction-centre electrodes. Nature 286, 584.
Jarosz, M., Grudzień, J., Kamiński, K., Gawlak, K., Wolski, K., Nowakowska, M., Sulka, G.D., 2018. Novel bioelectrodes based on polysaccharide modified gold surfaces and electrochemically active Lactobacillus rhamnosus GG biofilms. Electrochim. Acta 296, 999–1008.
Jiang, B., Muddemann, T., Kunz, U., Bormann, H., Niedermeiser, M., Haupt, D., Schläfer, O., Sievers, M., 2017. Evaluation of microbial fuel cells with graphite plus MnO2 and MoS2 paints as oxygen reduction cathode catalyst. J. Electrochem. Soc. 164, H3083–H3090.
Jin, H., Hiraoka, Y., Okuma, Y., Hashimoto, E.H., Kurita, M., Anas, A.R., Uemura, H., Tsuji, K., Harada, K.I., 2018. Microbial degradation of amino acid-containing compounds using the microcystin-degrading bacterial strain B-9. Mar. Drugs 16, 50.
Johnson, E.T., Baron, D.B., Naranjo, B., Bond, D.R., Schmidt-Dannert, C., Gralnick, J.A., 2010. Enhancement of survival and electricity production in an engineered bacterium by light-driven proton pumping. Appl. Environ. Microbiol. 76, 4123–4129.
Kaku, N., Yonezawa, N., Kodama, Y., Watanabe, K., 2008. Plant/microbe cooperation for electricity generation in a rice paddy field. Appl. Microbiol. Biotechnol. 79, 43–49.
Kalathil, S., Lee, J., Cho, M.H., 2011. Granular activated carbon based microbial fuel cell for simultaneous decolorization of real dye wastewater and electricity generation. N. Biotech. 29, 32–37.
Kato, M., Cardona, T., Rutherford, A.W., Reisner, E., 2012. Photoelectrochemical water oxidation with photosystem II integrated in a mesoporous indium–tin oxide electrode. J. Am. Chem. Soc. 134, 8332–8335.
Katuri, K.P., Kalathil, S., Ragab, A.A., Bian, B., Alqahtani, M.F., Pant, D., Saikaly, P.E., 2018. Dual-function electrocatalytic and macroporous hollowfiber cathode for converting waste streams to valuable resources using microbial electrochemical systems. Adv. Mater. 30, e1707072.
Khudzari, J.M., Kurian, J., Gariépy, Y., Tartakovsky, B., Raghavan, G.S.V., 2018. Effects of salinity, growing media, and photoperiod on bioelectricity production in plant microbial fuel cells with weeping alkaligrass. Biomass Bioenergy 109, 1–9.
Khudzari, J.M., Gariépy, Y., Kurian, J., Tartakovsky, B., Raghavan, G.V., 2019. Effects of biochar anodes in rice plant microbial fuel cells on the production of bioelectricity, biomass, and methane. Biochem. Eng. J. 141, 190–199.
Kim, J.R., Jung, S.H., Regan, J.M., Logan, B.E., 2007. Electricity generation and microbial community analysis of alcohol powered microbial fuel cells. Bioresour. Technol. 98, 2568–2577.
Kodali, M., Gokhale, R., Santoro, C., Serov, A., Artyushkova, K., Atanassov, P., 2017a. High performance platinum group metal-free cathode catalysts for microbial fuel cell (MFC). J. Electrochem. Soc. 164, H3041–H3046.
Kodali, M., Santoro, C., Serov, A., Kabir, S., Artyushkova, K., Matanovic, I., Atanassov, P., 2017b. Air breathing cathodes for microbial fuel cell using Mn-, Fe-, Co-and Ni-containing platinum group metal-free catalysts. Electrochim. Acta 231, 115–124.
Koo, B., Lee, S.M., Oh, S.E., Kim, E.J., Hwang, Y., Seo, D., Kim, J.Y., Kahng, Y.H., Lee, Y.W., Chung, S.Y., Kim, S.J., 2019. Addition of reduced graphene oxide to an activated-carbon cathode increases electrical power generation of a microbial fuel cell by enhancing cathodic performance. Electrochim. Acta 297, 613–622.
Kramer, D.M., Avenson, T.J., Edwards, G.E., 2004. Dynamic flexibility in the light reactions of photosynthesis governed by both electron and proton transfer reactions. Trends Plant Sci. 9, 349–357.
Lam, K.B., Johnson, E.A., Chiao, M., Lin, L., 2006. A MEMS photosynthetic electrochemical cell powered by subcellular plant photosystems. J. Microelectromech. Sys. 15, 1243–1250.
Larminie, J., Dicks, A., 2000. Fuel Cell Systems Explained. John Wiley & Sons, Chichester, pp. 308.
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, 3985–3994.
Leang, C., Malvankar, N.S., Franks, A.E., Nevin, K.P., Lovley, D.R., 2013. Engineering Geobacter sulfurreducens to produce a highly cohesive conductive matrix with enhanced capacity for current production. Energy Environ. Sci. 6, 1901–1908.
Lee, Y., Nirmalakhandan, N., 2011. Electricity production in membrane-less microbial fuel cell fed with livestock organic solid waste. Bioresour. Technol. 102, 5831–5835.
Li, Z., Zhang, X., Zeng, Y., Lei, L., 2009. Electricity production by an overflow-type wetted-wall microbial fuel cell. Bioresour. Technol. 100, 2551–2555.
Li, H., Liu, H., Jong, Z., Qu, W., Geng, D., Sun, X., Wang, H., 2011a. Nitrogen-doped carbon nanotubes with high activity for oxygen reduction in alkaline media. Int. J. Hydrogen Energy 36, 2258–2265.
Li, W.W., Sheng, G.P., Liu, X.W., Yu, H.Q., 2011b. Recent advances in the separators for microbial fuel cells, Bioresource. Technol. 102, 244–252.
Li, X., Hu, B., Suib, S., Lei, Y., Li, B., 2011c. Electricity generation in continuous flow microbial fuel cells (MFCs) with manganese dioxide (MnO2) cathodes. Biochem. Eng. J. 54, 10–15.
Li, M., Zhou, S., Xu, M., 2017. Graphene oxide supported magnesium oxide as an efficient cathode catalyst for power generation and wastewater treatment in single chamber microbial fuel cells. Chem. Eng. J. 328, 106–116.
Liang, P., Huang, X., Fan, M.Z., Cao, X.X., Wang, C., 2007. Composition and distribution of internal resistance in three types of microbial fuel cells. Appl. Microbiol. Biotechnol. 77, 551–558.
Liao, C., Wu, J., Zhou, L., Li, T., An, J., Huang, Z., Li, N., Wang, X., 2018. Repeated transfer enriches highly active electrotrophic microbial consortia on biocathodes in microbial fuel cells. Biosens. Bioelectron. 121, 118–124.
Lin, Y.H., Luo, L., Lin, L., 2006. A biosensor for simazine herbicides detection using subcellular plant photosystems. In: Nano/Micro Engineered and Molecular Systems, 2006. NEMS'06. 1st IEEE International Conference on. IEEE, pp. 1354–1357.
Liu, Z.D., Li, H.R., 2007. Effects of bio-and abio-factors on electricity production in a mediatorless microbial fuel cell. Biochem. Eng. J. 36, 209–214.
Liu, H., Ramnarayanan, R., Logan, B.E., 2004. Production of electricity during wastewater treatment using a single chamber microbial fuel cell. Environ. Sci. Technol. 38, 2281–2285.
Liu, S., Song, H., Wei, S., Yang, F., Li, X., 2014. Bio-cathode materials evaluation and configuration optimization for power output of vertical subsurface flow constructed wetland—microbial fuel cell systems. Bioresour. Technol. 166, 575–583.
Liu, B., Ji, M., Zhai, H., 2018a. Anodic potentials, electricity generation and bacterial community as affected by plant roots in sediment microbial fuel cell: effects of anode locations. Chemosphere 209, 739–747.
Liu, W., Zhou, Z., Yin, L., Zhu, Y., Zhao, J., Zhu, B., Zheng, L., Jin, Q., Wang, L., 2018b. A novel self-powered bioelectrochemical sensor based on CoMn2O4 nanoparticle modified cathode for sensitive and rapid detection of hydrogen peroxide. Sens. Actuators B Chem. 271, 247–255.
Liu, Y., Zhang, H., Lu, Z., de Lourdes Mendoza, M., Ma, J., Cai, L., Zhang, L., 2019. Decreasing sulfide in sediment and promoting plant growth by plant–sediment microbial fuel cells with emerged plants. Paddy Water Environ. 17, 13–21.
Logan, B.E., 2009. Exoelectrogenic bacteria that power microbial fuel cells. Nat. Rev. Microbiol. 7, 375.
Logan, B.E., Elimelech, M., 2012. Membrane-based processes for sustainable power generation using water. Nature 488, 313.
Logan, B.E., Hamelers, B., Rozendal, R., Schröder, U., Keller, J., Freguia, S., Aelterman, P., Verstraete, W., Rabaey, K., 2006. Microbial fuel cells: methodology and technology. Environ. Sci. Technol. 40, 5181–5192.
Logan, B., Cheng, S., Watson, V., Estadt, G., 2007. Graphite fiber brush anodes for increased power production in air-cathode microbial fuel cells. Environ. Sci. Technol. 41, 3341–3346.
Long, X., Pan, Q., Wang, C., Wang, H., Li, H., Li, X., 2017. Microbial fuel cell-photoelectrocatalytic cell combined system for the removal of azo dye wastewater. Bioresour. Technol. 244, 182–191.
Lovley, D.R., 2012. Electromicrobiology. Annual Rev. Microbiol. 66, 391–409.
Lu, L., Xing, D., Ren, N., 2012. Pyrosequencing reveals highly diverse microbial communities in microbial electrolysis cells involved in enhanced H2 production from waste activated sludge. Water Res. 46, 2425–2434.
Lu, M., Guo, L., Kharkwal, S., Ng, H.Y., Li, S.F.Y., 2013. Manganese–polypyrrole–carbon nanotube, a new oxygen reduction catalyst for air-cathode microbial fuel cells. J. Power Sources 221, 381–386.
Lu, L., Xing, D., Ren, Z.J., 2015a. Microbial community structure accompanied with electricity production in a constructed wetland plant microbial fuel cell. Bioresour. Technol. 195, 115–121.
Lu, Y., Wang, S., Sun, Y., Yan, C., 2015b. Optimal scheduling of buildings with energy generation and thermal energy storage under dynamic electricity pricing using mixed-integer nonlinear programming. Appl. Energy 147, 49–58.
Machol, B., Rizk, S., 2013. Economic value of US fossil fuel electricity health impacts. Environ. Int. 52, 75–80.
Madiraju, K.S., Lyew, D., Kok, R., Raghavan, V., 2012. Carbon neutral electricity

production by Synechocystis sp. PCC6803 in a microbial fuel cell. Bioresour. Technol. 110, 214–218.
Majid, S., Ahmad, K.S., 2018. Optical and morphological properties of environmentally benign Cu-Tin sulphide thin films grown by physical vapor deposition technique. Mater. Res. Express 6, 036406.
Majid, S., Ahmad, K.S., 2019. Analysis of dopant concentration effect on optical and morphological properties of PVD coated Cu-doped Ni3S2 thin films. Optik 187, 152–163.
Marsili, E., Baron, D.B., Shikhare, I.D., Coursolle, D., Gralnick, J.A., Bond, D.R., 2008. Shewanella secretes flavins that mediate extracellular electron transfer. Proc. Natl. Acad. Sci. 105, 3968–3973.
Mathuriya, A.S., 2017. A microbial fuel cell with interconnected anode chambers. Indian Patent 201711046878, 27 12.2017.
McCormick, A.J., Bombelli, P., Scott, A.M., Philips, A.J., Smith, A.G., Fisher, A.C., Howe, C.J., 2011. Photosynthetic biofilms in pure culture harness solar energy in a mediatorless bio-photovoltaic cell (BPV) system. Energy Environ. Sci. 4, 4699–4709.
McCormick, A.J., Bombelli, P., Lea-Smith, D.J., Bradley, R.W., Scott, A.M., Fisher, A.C., Smith, A.G., Howe, C.J., 2013. Hydrogen production through oxygenic photosynthesis using the cyanobacterium Synechocystis sp. PCC 6803 in a bio-photoelectrolysis cell (BPE) system. Energy Environ. Sci. 6, 2682–2690.
McCormick, A.J., Bombelli, P., Bradley, R.W., Thorne, R., Wenzel, T., Howe, C.J., 2015. Biophotovoltaics: oxygenic photosynthetic organisms in the world of bioelectrochemical systems. Energy Environ. Sci. 8, 1092–1109.
Meunier, C.F., Yang, X.Y., Rooke, J.C., Su, B.L., 2011. Biofuel cells based on the immobilization of photosynthetically active bioentities. ChemCatChem 3, 476–488.
Milner, E.M., Popescu, D., Curtis, T., Head, I.M., Scott, K., Eileen, H.Y., 2016. Microbial fuel cells with highly active aerobic biocathodes. J. Power Sources 324, 8–16.
Mimeault, M., Carpentier, R., 1989. Kinetics of photocurrent induction by a thylakoid containing electrochemical cell. Bioelectrochem. Bioenerg. 22, 145–158.
Min, B., Logan, B.E., 2004. Continuous electricity generation from domestic wastewater and organic substrates in a flat plate microbial fuel cell. Environ. Sci. Technol. 38, 5809–5814.
Minagawa, J., 2016. A supercomplex of cytochrome bf and photosystem I for cyclic electron flow. In: Cytochrome Complexes: Evolution, Structures, Energy Transduction, and Signaling. Springer, Dordrecht, pp. 453–462.
Miran, W., Jang, J., Nawaz, M., Shahzad, A., Jeong, S.E., Jeon, C.O., Lee, D.S., 2017. Mixed sulfate-reducing bacteria-enriched microbial fuel cells for the treatment of wastewater containing copper. Chemosphere 189, 134–142.
Mohamed, H.O., Obaid, M., Sayed, E.T., Liu, Y., Lee, J., Park, M., Barakat, N.A., Kim, H.Y., 2017. Electricity generation from real industrial wastewater using a single-chamber air cathode microbial fuel cell with an activated carbon anode. Bioproc. Biosyst. Eng. 40, 1151–1161.
Mohammadifar, M., Choi, S., 2019. A solid phase bacteria-powered biobattery for low-power, low-cost, internet of Disposable Things. J. Power Sources 429, 105–110.
Mohan, S.V., Velvizhi, G., Modestra, J.A., Srikanth, S., 2014. Microbial fuel cell: critical factors regulating bio-catalyzed electrochemical process and recent advancements. Renew. Sustain. Energy Rev. 40, 779–797.
Montpart, N., Rago, L., Baeza, J.A., Guisasola, A., 2015. Hydrogen production in single chamber microbial electrolysis cells with different complex substrates. Water Res. 68, 601–615.
Nandy, A., Jana, S., Khamrai, M., Kumar, V., Mukherjee, S., Bhattacharyya, A., Kundu, P.P., 2019. Cloning and expression of α-amylase in *E. coli*: genesis of a superior biocatalyst for substrate-specific MFC. Int. J. Green Energy 16, 309–316.
Ng, F.L., Phang, S.M., Periasamy, V., Beardall, J., Yunus, K., Fisher, A.C., 2018. Algal biophotovoltaic (BPV) device for generation of bioelectricity using *Synechococcus elongatus (Cyanophyta)*. J. Appl. Phycol. 1–8.
Noori, M.T., Jain, S.C., Ghangrekar, M.M., Mukherjee, C.K., 2016. Biofouling inhibition and enhancing performance of microbial fuel cell using silver nano-particles as fungicide and cathode catalyst. Bioresour. Technol. 220, 183–189.
O'hayre, R., Cha, S.W., Prinz, F.B., Colella, W., 2016. Fuel Cell Fundamentals. John Wiley & Sons.
Oliot, M., Etcheverry, L., Mosdale, A., Basseguy, R., Delia, M.L., Bergel, A., 2017. Separator electrode assembly (SEA) with 3-dimensional bioanode and removable air-cathode boosts microbial fuel cell performance. J. Power Sources 356, 389–399.
Oliveira, V.B., Simões, M., Melo, L.F., Pinto, A.M.F.R., 2013. Overview on the developments of microbial fuel cells. Biochem. Eng. J. 73, 53–64.
Ou, S., Kashima, H., Aaron, D.S., Regan, J.M., Mench, M.M., 2017. Full cell simulation and the evaluation of the buffer system on air-cathode microbial fuel cell. J. Power Sources 347, 159–169.
Ozdemir, M., Enisoglu-Atalay, V., Bermek, H., Ozilhan, S., Tarhan, N., Catal, T., 2019. Removal of cannabis metabolite from human urine in microbial fuel cells generating electricity. Bioresource Technol Rep 5, 121–126.
Paitier, A., Godain, A., Lyon, D., Haddour, N., Vogel, T.M., Monier, J.M., 2017. Microbial fuel cell anodic microbial population dynamics during MFC start-up. Biosens. Bioelectron. 92, 357–363.
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.
Pareek, A., Sravan, J.S., Mohan, S.V., 2019. Exploring carbon-based materials for power generation in microbial fuel cell. Mater. Sci. Energy Technol. 2, 600–606.
Park, D.H., Zeikus, J.G., 2003. Improved fuel cell and electrode designs for producing electricity from microbial degradation. Biotechnol. Bioeng. 81, 348–355.
Park, I.h., Christy, M., Kim, P., Nahma, K.S., 2014. Enhanced electrical contact of microbes using Fe3 O4/CNT nanocomposite anode in mediator-less microbial fuel cell. Biosens. Bioelectron. 58, 75–80.
Park, J.D., Roane, T.M., Ren, Z.J., Alaraj, M., 2017. Dynamic modeling of a microbial fuel cell considering anodic electron flow and electrical charge storage. Appl. Energy 193, 507–514.
Pasupuleti, S.B., Srikanth, S., Dominguez-Benetton, X., Mohan, S.V., Pant, D., 2016. Dual gas diffusion cathode design for microbial fuel cell (MFC): optimizing the suitable mode of operation in terms of bioelectrochemical and bioelectro-kinetic evaluation. J. Chem. Technol. Biotechnol. 91, 624–639.
Patil, S.A., Surakasi, V.P., Koul, S., Ijmulwar, S., Vivek, A., Shouche, Y.S., Kapadnis, B.P., 2009. Electricity generation using chocolate industry wastewater and its treatment in activated sludge based microbial fuel cell and analysis of developed microbial community in the anode chamber. Bioresour. Technol. 100, 5132–5139.
Philamore, H., Rossiter, J., Walters, P., Winfield, J., Ieropoulos, I., 2015. Cast and 3D printed ion exchange membranes for monolithic microbial fuel cell fabrication. J. Power Sources 289, 91–99.
Pillot, G., Davidson, S., Auria, R., Combet-Blanc, Y., Godfroy, A., Liebgott, P.P., 2019. Production of current by syntrophy between exoelectrogenic and fermentative hyperthermophilic microorganisms in heterotrophic biofilm from a deep-sea hydrothermal chimney. Microb. Ecol. 1–12.
Pinhassi, R.I., Kallmann, D., Saper, G., Dotan, H., Linkov, A., Kay, A., Liveanu, V., Schuster, G., Adir, N., Rothschild, A., 2016. Hybrid bio-photo-electro-chemical cells for solar water splitting. Nat. Commun. 7, 12552.
Pospischil, A., Furchi, M.M., Mueller, T., 2014. Solar-energy conversion and light emission in an atomic monolayer pn diode. Nat. Nanotechnol. 9, 257–261.
Potter, M.C., 1911. Electrical effects accompanying the decomposition of organic compounds. Proc. R. Soc. Lond. B 84, 260–276.
Prasad, J., Tripathi, R.K., 2019. Energy harvesting from sediment microbial fuel cell to supply uninterruptible regulated power for small devices. Int. J. Energy Res. 43, 2821–2831.
Prasad, D., Arun, S., Murugesan, M., Padmanaban, S., Satyanarayanan, R.S., Berchmans, S., Yegnaraman, V., 2007. Direct electron transfer with yeast cells and construction of a mediatorless microbial fuel cell. Biosens. Bioelectron. 22, 2604–2610.
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. Bioresour. Technol. 101, 9594–9599.
Qi, X., Ren, Y., Liang, P., Wang, X., 2018. New insights in photosynthetic microbial fuel cell using anoxygenic phototrophic bacteria. Bioresour. Technol. 258, 310–317.
Rabaey, K., Verstraete, W., 2005. Microbial fuel cells: novel biotechnology for energy generation. Trends Biotechnol. 23, 291–298.
Radeef, A.Y., Ismail, Z.Z., 2019. Polarization model of microbial fuel cell for treatment of actual potato chips processing wastewater associated with power generation. J. Electroanal. Chem. 836, 176–181.
Rahimnejad, M., Ghoreyshi, A.A., Najafpour, G., Jafary, T., 2011. Power generation from organic substrate in batch and continuous flow microbial fuel cell operations. Appl. Energy 88, 3999–4004.
Rahimnejad, M., Ghasemi, M., Najafpour, G.D., Ghoreyshi, A., Bakeri, G., Hassaninejad, K., Talebnia, F., 2012a. Acetone removal and bioelectricity generation in dual chamber Microbial Fuel Cell. Am. J. Biochem. Biotechnol. 8, 304–310.
Rahimnejad, M., Najafpour, G.D., Ghoreyshi, A., Talebnia, F., Premie, G., Bakeri, G.h., Kim, J., Oh, S., 2012b. Thionine increases electricity generation from microbial fuel cell using Saccharomyces cerevisiae and exoelectrogenic mixed culture. J. Microbiol. 50, 575–580.
Rahimnejad, M., Adhami, A., Darvari, S., Zirepour, A., Oh, S.E., 2015. Microbial fuel cell as new technology for bioelectricity generation: a review. Alexandria Eng. J. 54, 745–756.
Raman, K., Lan, J.C.W., 2012. Performance and kinetic study of photo microbial fuel cells (PMFCs) with different electrode distances. Appl. Energy 100, 100–105.
Rashid, N., Cui, Y.-F., Saif Ur Rehman, M., Han, J.-I., 2013. Enhanced electricity generation by using algae biomass and activated sludge in microbial fuel cell. Sci. Total Environ. 456–457, 91–94.
Rashid, N., Lee, B., Chang, Y.K., 2019. Recent trends in microalgae research for sustainable energy production and biorefinery applications. In: Microalgae Biotechnology for Development of Biofuel and Wastewater Treatment. Springer, Singapore, pp. 3–20.
Rathinam, N.K., Bibra, M., Salem, D.R., Sani, R.K., 2019. Thermophiles for biohydrogen production in microbial electrolytic cells. Bioresour. Technol. 277, 171–178.
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. Elsevier, pp. 665–692.
Ray, S.G., Ghangrekar, M.M., 2015. Enhancing organic matter removal, biopolymer recovery and electricity generation from distillery wastewater by combining fungal fermentation and microbial fuel cell. Bioresour. Technol. 176, 8–14.
Reddy, C.N., Kakarla, R., Min, B., 2019. Algal biocathodes. In: Microbial Electrochemical Technology. Elsevier, pp. 525–547.
Regmi, R., Nitisoravut, R., Charoenroongtavee, S., Yimkhaophong, W., Phanthurat, O., 2018. Earthen pot–plant microbial fuel cell powered by vetiver for bioelectricity production and wastewater treatment. Clean. - Soil, Air, Water 46, 1700193.
Rehman, S., Al-Hadhrami, L.M., Alam, M.M., 2015. Pumped hydro energy storage system: a technological review. Renew. Sustain. Energy Rev. 44, 586–598.
Ren, Z., Steinburg, L.M., Regan, J.M., 2008. Electricity production and microbial biofilm characterization in cellulose-fed microbial fuel cells. Water Sci. Technol. 58, 617–622.
Ren, H., Torres, C.I., Parameswaran, P., Rittmann, B.E., Chae, J., 2014. Improved current and power density with a micro-scale microbial fuel cell due to a small characteristic length. Biosens. Bioelectron. 61, 587–592.
Rezaei, F., Xing, D., Wagner, R., Regan, J.M., Richard, T.L., Logan, B.E., 2009. Simultaneous cellulose degradation and electricity production by *Enterobacter cloacae* in a microbial fuel cell. Appl. Environ. Microbiol. 75, 3673–3678.

Rosenbaum, M., Schröder, U., Scholz, F., 2005a. In situ electrooxidation of photobiological hydrogen in a photobioelectrochemical fuel cell based on Rhodobacter sphaeroides. Environ. Sci. Technol. 39, 6328–6333.
Rosenbaum, M., Schröder, U., Scholz, F., 2005b. Utilizing the green alga Chlamydomonas reinhardtii for microbial electricity generation: a living solar cell. Appl. Microbiol. Biotechnol. 68, 753–756.
Rusyn, I.B., Hamkalo, K.R., 2018. Bioelectricity production in an indoor plant-microbial biotechnological system with Alisma plantago-aquatica. Acta Biol. Szeged. 62, 170–179.
Sadabad, H.R., Gholikandi, G.B., 2018. Simultaneous effective sludge stabilization and direct electricity generation by merging microbial fuel cell (MFC) and Fered-Fenton reactor: an experimental study. Biomass Bioenergy 119, 75–89.
Sadeghifar, M., Rashid-Nadimi, S., 2018. Nanoporous gold electrode prepared from gold compact disk as the anode for the microbial fuel cell. J. Iran. Chem. Soc. 15, 607–612.
Salar-García, M.J., Ortiz-Martínez, V.M., 2019. Nanotechnology for wastewater treatment and bioenergy generation in microbial fuel cells. In: Advanced Research in Nanosciences for Water Technology. Springer, Cham, pp. 341–362.
Samsonoff, N., Ooms, M.D., Sinton, D., 2014. A photosynthetic-plasmonic-voltaic cell: excitation of photosynthetic bacteria and current collection through a plasmonic substrate. Appl. Phys. Lett. 104, 043704.
Santoro, C., Serov, A., Narvaez Villarrubia, C.W., Stariha, S., Babanova, S., Schuler, A.J., Artyushkova, K., Atanassov, P., 2015a. Double-chamber microbial fuel cell with a non-platinum-group metal Fe–N–C cathode catalyst. Chem. Sus. Chem. 8, 828–834.
Santoro, C., Serov, A., Villarrubia, C.W.N., Stariha, S., Babanova, S., Artyushkova, K., Schuler, A.J., Atanassov, P., 2015b. High catalytic activity and pollutants resistivity using Fe-AAPyr cathode catalyst for microbial fuel cell application. Sci. Rep. 5, 16596.
Santoro, C., Kodali, M., Herrera, S., Serov, A., Ieropoulos, I., Atanassov, P., 2018. Power generation in microbial fuel cells using platinum group metal-free cathode catalyst: effect of the catalyst loading on performance and costs. J. Power Sources 378, 169–175.
Sarma, P.J., Mohanty, K., 2018. Epipremnum aureum and Dracaena braunii as indoor plants for enhanced bio-electricity generation in a plant microbial fuel cell with electrochemically modified carbon fiber brush anode. J. Biosci. Bioeng. 126, 404–410.
Schaetzle, O., Barrière, F., Schröder, U., 2009. An improved microbial fuel cell with laccase as the oxygen reduction catalyst. Energy Environ. Sci. 2, 96–99.
Schamphelaire, L.D., Bossche, L.V.D., Dang, H.S., Höfte, M., Boon, N., Rabaey, K., Verstraete, W., 2008. Microbial fuel cells generating electricity from rhizodeposits of rice plants. Environ. Sci. Technol. 42, 3053–3058.
Sekrecka-Belniak, A., Toczyłowska-Mamińska, R., 2018. Fungi-based microbial fuel cells. Energies 11, 2827.
Senthilkumar, N., Sheet, S., Sathishkumar, Y., Lee, Y.S., Phang, S.M., Periasamy, V., 2018. Titania/reduced graphene oxide composite nanofibers for the direct extraction of photosynthetic electrons from microalgae for biophotovoltaic cell applications. Appl. Phys. A 124, 769.
Service, R.F., 2005. Solar energy. Is it time to shoot for the sun? Science 309, 548 New York, NY.
Shevela, D., Björn, L.O., 2017. Evolution of the Z-scheme of photosynthesis: a perspective. Photosynth. Res. 133, 5–15.
Shimoni, E., Rav-Hon, O., Ohad, I., Brumfeld, V., Reich, Z., 2005. Three-dimensional organization of higher-plant chloroplast thylakoid membranes revealed by electron tomography. Plant Cell 17, 2580–2586.
Shreeram, D.D., Panmanee, W., McDaniel, C.T., Daniel, S., Schaefer, D.W., Hassett, D.J., 2018. Effect of impaired twitching motility and biofilm dispersion on performance of Pseudomonas aeruginosa-powered microbial fuel cells. J. Ind. Microbiol. Biotechnol. 45, 103–109.
Song, T.S., Wang, D.B., Wang, H., Li, X., Liang, Y., Xie, J., 2015. Cobalt oxide/nanocarbon hybrid materials as alternative cathode catalyst for oxygen reduction in microbial fuel cell. Int. J. Hydrogen Energy 40, 3868–3874.
Sorokin, D.Y., Van Pelt, S., Tourova, T.P., Takaichi, S., Muyzer, G., 2007. Acetonitrile degradation under haloalkaline conditions by Natronocella acetinitrilica gen. nov., sp. nov. Microbiology 153 (4), 1157–1164.
Spiegel, C., 2007. Designing and Building Fuel Cells, vol. 87 Mcgraw-hill, New York.
Srikanth, S., Mohan, S.V., 2012. Influence of terminal electron acceptor availability to the anodic oxidation on the electrogenic activity of microbial fuel cell (MFC). Bioresour. Technol. 123, 480–487.
Strik, D.P., Hamelers, H.V.M., Snel, J.F., Buisman, C.J., 2008. Green electricity production with living plants and bacteria in a fuel cell. Int. J. Energy Res. 32, 870–876.
Strik, D.P., Timmers, R.A., Helder, M., Steinbusch, K.J., Hamelers, H.V., Buisman, C.J., 2011. Microbial solar cells: applying photosynthetic and electrochemically active organisms. Trends Biotechnol. 29, 41–49.
Subha, C., Kavitha, S., Abisheka, S., Tamilarasan, K., Arulazhagan, P., Banu, J.R., 2019. Bioelectricity generation and effect studies from organic rich chocolaterie wastewater using continuous upflow anaerobic microbial fuel cell. Fuel 251, 224–232.
Subhash, G.V., Chandra, R., Mohan, S.V., 2013. Microalgae mediated bio-electrocatalytic fuel cell facilitates bioelectricity generation through oxygenic photomixotrophic mechanism. Bioresour. Technol. 136, 644–653.
Takanezawa, K., Nishio, K., Kato, S., Hashimoto, K., Watanabe, K., 2010. Factors affecting electric output from rice-paddy microbial fuel cells. Biosci. Biotechnol. Biochem. 74, 1271–1273.
Tang, X., Guo, K., Li, H., Du, Z., Tian, J., 2011. Electrochemical treatment of graphite to enhance electron transfer from bacteria to electrodes. Bioresour. Technol. 102, 3558–3560.
Teng, W., Liu, G., Luo, H., Zhang, R., Xiang, Y., 2016. Simultaneous sulfate and zinc removal from acid wastewater using an acidophilic and autotrophic biocathode. J. Hazard Mater. 304, 159–165.
Thapa, B.S., Seetharaman, S., Chetty, R., Chandra, T.S., 2019. Xerogel based catalyst for improved cathode performance in microbial fuel cells. Enzym. Microb. Technol. 124, 1–8.
Thorne, R., Hu, H., Schneider, K., Bombelli, P., Fisher, A., Peter, L.M., Dent, A., Cameron, P.J., 2011. Porous ceramic anode materials for photo-microbial fuel cells. J. Mater. Chem. 21, 18055–18060.
Thung, W.E., Ong, S.A., Ho, L.N., Wong, Y.S., Oon, Y.L., Oon, Y.S., Lehl, H.K., 2015. Simultaneous wastewater treatment and power generation with innovative design of an upflow membrane-less microbial fuel cell. Water Air Soil Pollut. 226, 165.
Timmers, R.A., Strik, D.P., Hamelers, H.V., Buisman, C.J., 2010. Long-term performance of a plant microbial fuel cell with Spartina anglica. Appl. Microbiol. Biotechnol. 86, 973–981.
Tiwari, B.R., Noori, M.T., Ghangrekar, M.M., 2017. Carbon supported nickel-phthalocyanine/MnOx as novel cathode catalyst for microbial fuel cell application. Int. J. Hydrogen Energy 42, 23085–23094.
Touloupakis, E., Giannoudi, L., Piletsky, S.A., Guzzella, L., Pozzoni, F., Giardi, M.T., 2005. A multi-biosensor based on immobilized Photosystem II on screen-printed electrodes for the detection of herbicides in river water. Biosens. Bioelectron. 20, 1984–1992.
Tsujimura, S., Wadano, A., Kano, K., Ikeda, T., 2001. Photosynthetic bioelectrochemical cell utilizing cyanobacteria and water-generating oxidase. Enzym. Microb. Technol. 29, 225–231.
Tyszkiewicz, E., Bottin, H., Roux, E., 1982. 481—redox potential-dependent ATP synthesis in darkness in spinach chloroplasts. Bioelectrochem. Bioenerg. 9, 157–166.
Ulusoy, I., Dimoglo, A., 2018. Electricity generation in microbial fuel cell systems with Thiobacillus ferrooxidans as the cathode microorganism. Int. J. Hydrogen Energy 43, 1171–1178.
Villasenor, J., Capilla, P., Rodrigo, M.A., Canizares, P., Fernandez, F.J., 2013. Operation of a horizontal subsurface flow constructed wetland–microbial fuel cell treating wastewater under different organic loading rates. Water Res. 47, 6731–6738.
Wan, L.L., Li, X.J., Zang, G.L., Wang, X., Zhang, Y.Y., Zhou, Q.X., 2015. A solar assisted microbial electrolysis cell for hydrogen production driven by a microbial fuel cell. RSC Adv. 5, 82276–82281.
Wang, H., Jiang, S.C., Wang, Y., Xiao, B., 2013. Substrate removal and electricity generation in a membrane-less microbial fuel cell for biological treatment of wastewater. Bioresour. Technol. 138, 109–116.
Wang, J., Song, X., Li, Q., Bai, H., Zhu, C., Weng, B., Yan, D., Bai, J., 2019. Bioenergy generation and degradation pathway of phenanthrene and anthracene in a constructed wetland-microbial fuel cell with an anode amended with nZVI. Water Res. 150, 340–348.
Watanabe, K., 2008. Recent developments in microbial fuel cell technologies for sustainable bioenergy. J. Biosci. Bioeng. 106, 528–536.
Wen, Q., Wang, S., Yan, J., Cong, L., Pan, Z., Ren, Y., Fan, Z., 2012. MnO2–graphene hybrid as an alternative cathodic catalyst to platinum in microbial fuel cells. J. Power Sources 216, 187–191.
Werkneh, A.A., Beyene, H.D., Osunkunle, A.A., 2019. Recent advances in brewery wastewater treatment; approaches for water reuse and energy recovery: a review. Environ. Sustain. 1–11.
Wetser, K., Sudirjo, E., Buisman, C.J., Strik, D.P., 2015. Electricity generation by a plant microbial fuel cell with an integrated oxygen reducing biocathode. Appl. Energy 137, 151–157.
Winfield, J., Chambers, L.D., Stinchcombe, A., Rossiter, J., Ieropoulos, I., 2014. The power of glove: soft microbial fuel cell for low-power electronics. J. Power Sources 249, 327–332.
Winfield, J., Chambers, L.D., Rossiter, J., Stinchcombe, A., Walter, X.A., Greenman, J., Ieropoulos, I., 2015. Fade to green: a biodegradable stack of microbial fuel cells. Chem. Sus. Chem. 8, 2705–2712.
Wu, H., Fu, Y., Guo, C., Li, Y., Jiang, N., Yin, C., 2018. Electricity generation and removal performance of a microbial fuel cell using sulfonated poly (ether ether ketone) as proton exchange membrane to treat phenol/acetone wastewater. Bioresour. Technol. 260, 130–134.
Xia, X., Tokash, J.C., Zhang, F., Liang, P., Huang, X., Logan, B.E., 2013. Oxygen-reducing biocathodes operating with passive oxygen transfer in microbial fuel cells. Environ. Sci. Technol. 47, 2085–2091.
Xie, X.H., Li, E.L., Kang Tang, Z., 2011. Mediator toxicity and dual effect of glucose on the lifespan for current generation by Cyanobacterium Synechocystis PCC 6714 based photoelectrochemical cells. J. Chem. Technol. Biotechnol. 86, 109–114.
Xiong, Y., Shi, L., Chen, B., Mayer, M.U., Lower, B.H., Londer, Y., Bose, S., Hochella, M.F., Fredrickson, J.K., Squier, T.C., 2006. High-affinity binding and direct electron transfer to solid metals by the Shewanella oneidensis MR-1 outer membrane c-type cytochrome OmcA. J. Am. Chem. Soc. 128, 13978–13979.
Yadav, A.K., Srivastava, P., Kumar, N., Abbassi, R., Mishra, B.K., 2018. Constructed Wetland-Microbial Fuel Cell: an Emerging Integrated Technology for Potential Industrial Wastewater Treatment and Bio-Electricity Generation. Constructed Wetlands Indus. Wastewater Treat, pp. 493–510.
Yagishita, T., Sawayama, S., Tsukahara, K.I., Ogi, T., 1997. Behavior of glucose degradation in Synechocystis sp. M-203 in bioelectrochemical fuel cells. Bioelectrochem. Bioenerg. 43, 177–180.
Yagishita, T., Sawayama, S., Tsukahara, K.I., Ogi, T., 1998. Performance of photosynthetic electrochemical cells using immobilized Anabaena variabilis M-3 in discharge/culture cycles. J. Ferment. Bioeng. 85, 546–549.
Yamori, W., Shikanai, T., 2016. Physiological functions of cyclic electron transport around photosystem I in sustaining photosynthesis and plant growth. Annu. Rev. Plant Biol. 67, 81–106.
Yan, Z., Song, N., Cai, H., Tay, J.H., Jiang, H., 2012. Enhanced degradation of phenanthrene and pyrene in freshwater sediments by combined employment of sediment

microbial fuel cell and amorphous ferric hydroxide. J. Hazard Mater. 199, 217–225.
Yang, N., Zhan, G., Li, D., Wang, X., He, X., Liu, H., 2019. Complete nitrogen removal and electricity production in Thauera-dominated air-cathode single chambered microbial fuel cell. Chem. Eng. J. 356, 506–515.
Zhang, Y., Angelidaki, I., 2012. Self-stacked submersible microbial fuel cell (SSMFC) for improved remote power generation from lake sediments. Biosens. Bioelectron. 35, 265–270.
Zhang, G., Zhao, Q., Jiao, Y., Lee, D.J., Ren, N., 2012a. Efficient electricity generation from sewage sludge using biocathode microbial fuel cell. Water Res. 46, 43–52.
Zhang, Y., Sun, J., Hu, Y., Li, S., Xu, Q., 2012b. Bio-cathode materials evaluation in microbial fuel cells: a comparison of graphite felt, carbon paper and stainless steel mesh materials. Int. J. Hydrogen Energy 37, 16935–16942.
Zhang, H., Wen, Q., An, Z., Chen, Z., Nan, J., 2016. Analysis of long-term performance and microbial community structure in bio-cathode microbial desalination cells. Environ. Sci. Pollut. Res. 23, 5931–5940.
Zhang, D., Li, Z., Zhang, C., Zhou, X., Xiao, Z., Awata, T., Katayama, A., 2017. Phenol-degrading anode biofilm with high coulombic efficiency in graphite electrodes microbial fuel cell. J. Biosci. Bioeng. 123, 364–369.
Zhang, G., Feng, S., Jiao, Y., Lee, D.J., Xin, Y., Sun, H., 2017a. Cathodic reducing bacteria of dual-chambered microbial fuel cell. Int. J. Hydrogen Energy 42, 27607–27617.
Zhang, L., Álvarez-Martos, I., Vakurov, A., Ferapontova, E.E., 2017b. Seawater operating bio-photovoltaic cells coupling semiconductor photoanodes and enzymatic biocathodes. Sus. Energy Fuels 1, 842–850.
Zhang, S.H., Qiu, C.H., Fang, C.F., Ge, Q.L., Hui, Y.X., Han, B., Pang, S., 2017c. Characterization of bacterial communities in anode microbial fuel cells fed with glucose, propyl alcohol and methanol. Appl. Biochem. Microbiol. 53, 250–257.
Zhang, Y., Jiang, J., Zhao, Q., Wang, K., Yu, H., 2018. Analysis of functional genomes from metagenomes: revealing the accelerated electron transfer in microbial fuel cell with rhamnolipid addition. Bioelectrochemistry 119, 59–67.
Zhang, L., Fu, G., Zhang, Z., 2019a. Simultaneous nutrient and carbon removal and electricity generation in self-buffered biocathode microbial fuel cell for high-salinity mustard tuber wastewater treatment. Bioresour. Technol. 272, 105–113.
Zhang, M., Wang, Y., Liang, P., Zhao, X., Liang, M., Zhou, B., 2019b. Combined photo-electrocatalytic microbial fuel cell (PEC-MFC) degradation of refractory organic pollutants and in-situ electricity utilization. Chemosphere 214, 669–678.
Zhao, F., Harnisch, F., Schröder, U., Scholz, F., Bogdanoff, P., Herrmann, I., 2005. Application of pyrolysed iron (II) phthalocyanine and CoTMPP based oxygen reduction catalysts as cathode materials in microbial fuel cells. Electrochem. Commun. 7, 1405–1410.
Zhao, N., Jiang, Y., Alvarado-Morales, M., Treu, L., Angelidaki, I., Zhang, Y., 2018. Electricity generation and microbial communities in microbial fuel cell powered by macroalgal biomass. Bioelectrochemistry 123, 145–149.
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. J. Chem. Technol. Biotechnol. 88, 508–518.
Zhou, Y., Xu, D., Xiao, E., Xu, D., Xu, P., Zhang, X., Zhou, Q., He, F., Wu, Z., 2018. Relationship between electrogenic performance and physiological change of four wetland plants in constructed wetland-microbial fuel cells during non-growing seasons. J. Environ. Sci. 70, 54–62.
Zou, L., Lu, Z., Huang, Y., Long, Z.E., Qiao, Y., 2017a. Nanoporous Mo2C functionalized 3D carbon architecture anode for boosting flavins mediated interfacial bioelectrocatalysis in microbial fuel cells. J. Power Sources 359, 549–555.
Zou, L., Qiao, Y., Zhong, C., Li, C.M., 2017b. Enabling fast electron transfer through both bacterial outer-membrane redox centers and endogenous electron mediators by polyaniline hybridized large-mesoporous carbon anode for high-performance microbial fuel cells. Electrochim. Acta 229, 31–38.