Microbial fuel cells – Applications for generation of electrical power and beyond

Article *in* Critical Reviews in Microbiology · June 2014

DOI: 10.3109/1040841X.2014.905513 · Source: PubMed

2 authors:

Abhilasha Singh
Anand Engineering College
18 PUBLICATIONS **105** CITATIONS
SEE PROFILE

Jatinder Yakhmi
Bhabha Atomic Research Centre
410 PUBLICATIONS **5,239** CITATIONS
SEE PROFILE

Critical Reviews in Microbiology

http://informahealthcare.com/mby
ISSN: 1040-841X (print), 1549-7828 (electronic)

Critical Reviews in Microbiology, Early Online: 1–17
 DOI: 10.3109/1040841X.2014.905513

informa
healthcare

REVIEW ARTICLE

Microbial fuel cells – Applications for generation of electrical power and beyond

Abhilasha Singh Mathuriya[1] and J. V. Yakhmi[2]

[1]Department of Biotechnology, Anand Engineering College, Agra, Uttar Pradesh, India and [2]Atomic Energy Education Society, Western Sector, Mumbai, Maharashtra, India

Abstract

A Microbial Fuel Cell is a bioelectrochemical device that exploits metabolic activities of living microorganisms for generation of electric current. The usefulness and unique and exclusive architecture of this device has received wide attention recently of engineers and researchers of various disciplines such as microbiologists, chemical engineers, biotechnologists, environment engineers and mechanical engineers, and the subject of MFCs has thereby progressed as a well-developed technology. Sustained innovations and continuous development efforts have established the usefulness of MFCs towards many specialized and value-added applications beyond electricity generation, such as wastewater treatment and implantable body devices. This review is an attempt to provide an update on this rapidly growing technology.

Keywords

Bioelectricity, biosensors, implantable power sources, robotics, wastewater treatment

History

Received 31 January 2014
Revised 13 March 2014
Accepted 14 March 2014
Published online 4 June 2014

Introduction

Microbial fuel cells (MFCs) are bioelectrochemical systems that convert chemical energy contained in organic matter into electrical energy by using the catalytic (metabolic) activity of living microorganisms (Allen & Bennetto, 1993; Kim et al., 2002; Mathuriya & Sharma, 2009a). In an MFC, anode and cathode compartments are separated by a cation-specific membrane (Figure 1). In the anode compartment, microorganisms oxidize fuel (substrate) to generate electrons and protons. Electrons are transferred through an external circuit (which comprises the load across which a potential drop takes place, as described in Box 1) while the protons diffuse through the solution to the cathode, where electrons combine with protons and oxygen to form water (Mathuriya & Sharma, 2009a). Over the past few years, intense research and development activity by a growing community of scientists has brought MFCs to a level of maturity where we can talk of their potential for applications in a variety of areas in technology. The course of the development of MFC Technology has been documented in a series of topical review papers (Alfonta, 2010; Du et al., 2007; Duteanu et al., 2010; Logan, 2010; Logan et al., 2006; Mathuriya, 2014; Pant et al., 2010; Rozendal et al., 2008; Watanabe, 2008; Zhao et al., 2009a), and a large number of research articles based on MFC applications are being added every year, which calls for a comprehensive review article that provides an update on broader capabilities of this technology in different areas. This review is an attempt in this direction, and in it we highlight those applications which particularly lead to societal benefits. We have covered a very large number of publications available till date (as is seen from the list of References) on the subject of MFCs and their applications, as inputs in our attempt.

Address for correspondence: Abhilasha Singh Mathuriya, Department of Biotechnology, Anand Engineering College, NH-2, Keetham, Agra 282007, Uttar Pradesh, India. E-mail: imabhilasha@gmail.com

Electricity generation

Electricity generation is the main projected application of MFCs. Aided by microbes, MFCs have the potential to convert the chemical energy stored in nearly every chemical compounds to electrical energy. MFCs have been reported for the generation of bioelectricity far more than a century (Allen & Bennetto, 1993; Bond & Lovley, 2003; Kim et al., 2002; Oh & Logan, 2005; Potter, 1910; You et al., 2010). It has been demonstrated that any compound, which can be metabolized by bacteria, can be converted into electricity (Pant et al., 2010). MFCs offer several advantages over competitive electricity generation technologies, namely (a) MFCs offer high conversion efficiency due to their ability of direct conversion of substrate's chemical energy to electricity; (b) MFCs exhibit safe and quiet performance (Rabaey and Verstreates, 2005); (c) MFCs have high conversion efficiency, since MFCs can harvest up to 90% of the electrons from the bacterial electron transport system, as compared to 50% for typical fossil fuel power plants (Mathuriya, 2014); (d) MFCs operate efficiently at ambient temperature; (e) Electricity obtained from MFCs is sustainable; and (f) The fuel to electricity conversion by MFCs is not limited by the Carnot cycle because chemical energy from the oxidization of fuel molecules is converted directly into electricity instead of incurring partial heat losses and, theoretically a much higher conversion efficiency can be

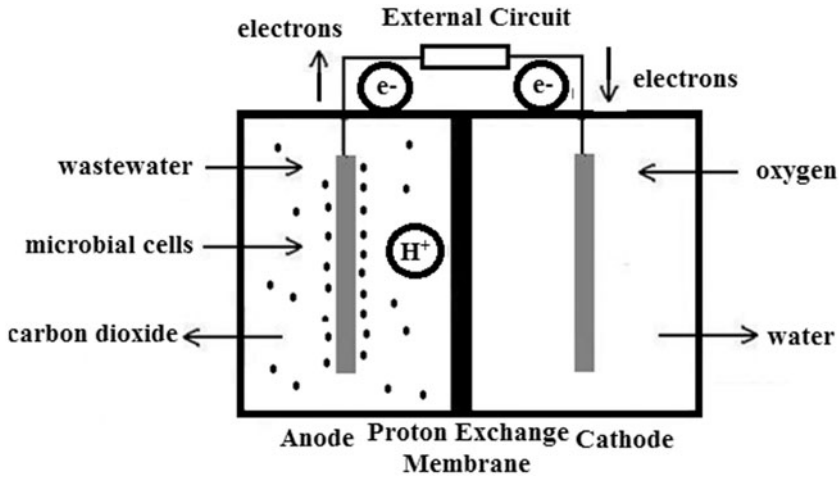

Figure 1. Schematic representation of a typical two chamber microbial fuel cell operating on wastewater.

Box 1. Working mechanism in typical microbial fuel cell.

Microbial catabolism involves anaerobic oxidation of a substrate such as carbohydrate. Electrons produced thus are collected the enzyme-active site which acts as reduced (re) intermediate (Shukla et al. 2004):

$$C_6H_{12}O_6 + 6H_2O \longrightarrow 6CO_2 + 24H^+ + 24e^- \quad (E = 0.014\ \text{Volts}) \tag{1}$$

$$(\text{Intermediate})_{ox} + e^- \longrightarrow (\text{Intermediate})_{re} \tag{2}$$

Electrons travel away from cell's metabolic pathway, across an electrode, through resistance into the oxygen-containing cathode (Balat 2010):

$$6O_2 + 24H^+ + 24e^- \longrightarrow 12H_2O \quad (E = 1.23\ \text{Volts}) \tag{3}$$

achieved (70%) just like conventional chemical fuel cells (Mathuriya, 2014). For example, a Coulombic efficiency of about 97% has been reported by Rosenbaum et al. (2006), during the oxidation of formate with the catalysis of Pt-black. Some very attractive power densities from MFCs are shown in Table 1.

Waste treatment and recovery of pure materials

Waste is unwanted byproduct of almost all human activities, which becomes even worst when mixed in water. Wastewater retains considerable amount of complex biological and chemical matter, which create serious health, sanitation and environmental problems due to their random degradation. Moreover, wastewater is a source of innumerable microbial flora, which can survive even under extreme environment. Generating electricity from degradation of wastewater by microbial flora is the driving force for the development of many modern MFCs (Mathuriya, 2014). The underlying concept is that bacteria will catalyze the biodegradation of organic matter resulting into carbon dioxide as end-product via redox reactions, and will utilize these reactions for electricity generation (Kim et al., 2001). The advantages of MFCs in wastewater treatment include: (a) MFCs do not consume much energy in comparison with activated sludge process (Watanabe, 2008) and do not require highly regulated distribution systems like the ones needed for Hydrogen-based fuel cells; (b) MFCs can treat wastewaters that are not suitable for anaerobic digestion processes, e.g. low strength wastewater and wastewater composed of many volatile fatty acids, etc. (Rittmann, 2008; Watanabe, 2008); (c) The amount of power generated by MFCs in the wastewater treatment process can potentially halve the electricity needed in a conventional treatment process that involves aerating of the activated sludge (Watanabe 2008); (d) MFCs yield 50–90% less solids to be disposed of (Du et al., 2007) and the generated sludge is more stable than the one produced by aerobic treatment process (Kim et al., 2007); (e) an MFC does not require gas treatment because the off-gases of MFCs are enriched in carbon dioxide and normally have no useful energy content (Jang et al., 2004a); and (f) MFCs do not need energy input for aeration provided the cathode is passively aerated (Mathuriya & Sharma, 2010).

Due to an intense research activity done on them over the last decade, it is considered now that MFCs are quite suitable for stationary, passive wastewater treatment applications. Sceptics have certainly not considered MFCs as serious contenders in the race for developing renewable energy technologies. Yet this is the only type of alternative system that can convert organic waste, widely distributed around the globe, directly into electricity. At the earliest stage of development, it was expected that the energy gained from wastewater treatment could at least recover the cost of wastewater treatment. This technology indeed has shown a promising perspective for this purpose. The waste therapy capabilities of MFCs may further be grouped as follows.

Table 1. Electricity generation in microbial fuel cells.

S.N	MFC Type	Microbial source	Operating time/HRT	Electrical output	References
1	TC-MFC	Activated sludge	120 h	1771 mW/m^2	Kaewkannetra et al. (2011)
2	SC-MFC	Specifically acclimated microbial consortia	60d	406 mW/m^2	Wang et al. (2009)
3	TC-MFC	*Lactobacillus helveticus* (85%), *Proteus mirabilis* (96%) and *Escherichia coli* (96%).	four cycles of 7 days	390 ± 21 W/m^2	Kassongo and Togo (2011a)
4	TC-MFC	*Lactobacillus* genus	3 m	1800 ± 120 W/m^2.	Kassongo and Togo (2011b)
5	SC-MFC	Domestic wastewater	23 h	4200 mW/m^3	Sharma and Li (2010)
6	SC-MFC	Wastewater itself	500 h	672 ± 27 mW/m^2	Huang & Logan (2008)
7	Up-flow anaerobic sludge blanket reactor-MFC-biological aerated filter	Active sludge	60 d	1410.2 mW/m^2	Zhang et al. (2009a)
8	Sequential anode-cathode TC-MFC	Anaerobic mixed sludge	HRT 14.7 h	830 mW/m^3	Wen et al. (2010a)
9	SCac-MFC	Anaerobic mixed consortia	HRT 2.13 h	669 mW/m^2	Wen et al. (2010b)
10	SCac-MFC	Domestic wastewater	–	2110 ± 68 mW/m^2	Feng et al. (2011)
11	TC-MFC	Anaerobic sludge	25 h	1600 mW/m^2	Li et al. (2008)
12	TC- MFC	–	240 h	970.2 ± 16.5 mW/m^2	Zhang (2011)
13	SCac-MFC	Bacteria from another MFC	24 h	101.2 W/m^3	Wen et al. (2011a)
14	SCac-MFC	Anaerobic activated sludge	–	6817.4 mW/m^3	You et al. (2006)
15	Three MFCs fludically connected in series and in loop	–	96 h	1822.6 W/m^2	Galvez et al. (2009)
16	MDC	Mixture of aerobic and anaerobic sludge	4 m	30.8 W/m^3	Jacobson et al. (2011)
17	SC-MFC	Mixed bacterial culture	48 and 72 h	2900 mW/m^2	Catal et al. (2009)

The removal of organic matters

The MFCs have the potential to remove organic carbon matter by treating almost every kind of organic rich wastewater ranging from Human feces wastewater (Fangzhou et al., 2011), manure sludge (Lee & Nirmalakhandan, 2011; Scott & Murano, 2007), cassava mill wastewater (Kaewkannetra et al., 2011) *Dioscorea zingiberensis C. H. Wright* wastewater (Wang et al., 2009), chocolate industry wastewater (Patil et al., 2009), confectionary wastewater (Sun et al., 2009a) composite waste vegetables (Venkata Mohan et al., 2010a), fermented vegetable waste (Mohanakrishna et al., 2010), canteen-based food waste (Venkata Mohan & Chandrasekhar, 2011), food processing wastewater (Sangeetha & Muthukumar, 2011), biodiesel waste (Feng et al., 2011; Sukkasem et al., 2011), dairy wastewater (Mathuriya & Sharma, 2009b; Velasquez-Orta et al., 2011; Venkata Mohan et al., 2010b), cheese whey (Nasirahmadi & Safekordi, 2011), landfill leachate (Habermann & Pommer, 1991; Galvez et al., 2009; Greenman et al., 2009), domestic wastewater (Ahn & Logan, 2010; Venkata Mohan et al., 2009; Zhao et al., 2010), paper industry wastewater (Huang & Logan, 2008; Mathuriya & Sharma, 2009a), molasses (Zhang et al., 2009a, 2011, 2013a) starch processing wastewater (Kim et al., 2004; Lu et al., 2009a), and brewery wastewater (Huang et al., 2011b; Mathuriya & Sharma, 2010; Wen et al., 2010a) (Table 2).

Treatment of specific pollutants

Recently many studies have discussed the treatment of various recalcitrant specific pollutants in MFCs (anodic and cathodic chambers). Applications of these procedures employing MFCs can, therefore, produce value-addition to the existing wastewater treatment protocols. The specific pollutants include: oilfield wastewater (Gong & Qin, 2012), oil sands tailings (Jiang et al., 2013), terephthalic acid (Song et al., 2009; Ye et al., 2009), refinery waste (Morris and Jin, 2008), diesel range organics (Morris et al., 2009), synthesis gas (Mehta et al., 2010; Neburchilov et al., 2011), quinoline-contaminated Water (Zhang et al., 2012a), coking wastewater (Huang et al., 2010), tannery wastewater (Mathuriya, 2012) chemical wastewater (Venkata Mohan et al., 2008) and many more (Mathuriya, 2014) (Table 3), much of which cannot be treated using established biological treatment methods. MFCs can remove nearly 100% of COD and other contaminants (Luo et al., 2011; Venkata Mohan et al., 2010b; Zhang et al., 2009b, 2010a;). Some remarkable results shown in Table 3 clearly indicate the potential candidature of MFCs as waste treatment system.

Bioremediation

Besides power sources, sediment MFCs have also been employed as an *in situ* bioremediation system (Hong et al., 2010; Morris & Jin, 2012). It has been observed that the sediment organic matter (SOM) can be oxidized by microbial community under anaerobic conditions. Compared with main sediment, the SOM became more humified, aromatic, and polydispersed around the electrodes, and even had a higher average molecular weight (Hong et al., 2010). These findings present a potential for the energy-efficient remediation. Sediment MFCs have been employed to treat various organic pollutants from subsurface environments, such as phenanthrene and pyrene, uranium-contaminated aquifers, aromatic hydrocarbon-contaminated sediments, lactate and 1,2-dichloroethane (Huang et al., 2011a; Morris & Jin, 2008,

Table 2. Efficiency of microbial fuel cells to treat wastewater of different categories.

S.N.	Wastewater type	Initial COD	Microbial source	Operating time/HRT	COD removal	References
1	Cereal wastewater	595 mg/L	Sludge	120 h	95%	Oh & Logan (2005)
2	*Dioscorea zingiberensis* wastewater	91 000 mg/L	Anaerobic sludge	72 h	93.5%	Li & Ni (2011)
3	Confectionary wastewater	22 000 mg/L	Aerobic sludge, anaerobic sludge, and wetland sediment	–	92%	Sun et al. (2009a)
4	Rice mill wastewater	1100–1125 mg/L	Anaerobic sludge	288 h	96.5% COD; 84% lignin; 81% phenol	Behera et al. (2010)
5	Dairy wastewater	4.44 kgCOD/m^3	Anaerobic mixed consortia as anodic biocatalyst	–	95.49% COD, 78.07% protein, 91.98% carbohydrates and 99.02% turbidity.	Venkata Mohan et al. (2010b)
6	Effluent from hydrogen producing biofermentor	6.3 g/L	Domestic wastewater	23 h	97%	Sharma & Li (2010)
7	Paper wastewater	0.48 g/L	Wastewater itself	500 h	76±4% TCOD; 96±1% Cellulose removed	Huang & Logan (2008)
8	Starch processing wastewater	4852 mg/L	Wastewater itself	four cycles of 140 days	98% COD; 90.6% ammonia-nitrogen removal	Lu et al. (2009b)
9	Brewery wastewater	1710 mg/L	Wastewater itself	15 d	93.8%	Mathuriya & Sharma (2010)
10	Biodiesel waste	1400 mg/L	Domestic wastewater	–	90%	Feng et al. (2011)

Table 3. Efficiency of microbial fuel cells to treat refractory pollutants.

S.N.	Pollutant type	Initial COD	Microbial source	Operating time/HRT	Pollutant removal	References
1	Quinoline	500 mg/L	–	6 h	Complete removal	Zhang et al. (2010a)
2	Refractory contaminants (Furfural)	300 mg/L	Anaerobic and aerobic sludge	60 h	96% COD; 100% furfural	Luo et al. (2011)
3	Indole wastewater	250 mg/L indole:1000 mg/L glucose	Anaerobic and aerobic sludge	10 h	89.5% COD; complete removal of indole	Luo et al. (2010)
4	N-heterocyclic compounds – Pyridine – Quinoline – Indole	120 mg/L of each	Anaerobic sludge	Indole: 122 h Quinoline: 102 h Pyridine: 63 h	88% COD; Indole: 95%; Quinoline: 93%; Pyridine: 86%	Hu et al. (2011)
5	Pyridine	500 mg/L	Mixed aerobic and anaerobic activated sludge	12 h	Complete removal	Zhang et al. (2009b)
6	4-chlorophenol	60 mg/L	Anaerobic sludge	45 h	Complete dechlorination	Gu et al. (2007)
7	Pentachlorophenol glucose and acetate as co substrate	PCP: 15 mg/L Glucose: 780 mg/L	Domestic wastewater	96 h	Removal rate 0.12 mg/L h	Huang et al. (2011b)
8	Synthetic penicillin wastewater	50 mg/L penicillin: 1000 mg/L glucose mix	Bacteria from another MFC	24 h	98%	Wen et al. (2011a)
9	Ceftriaxone sodium (Cs)	50 mg/L (Cs): 1000 mg/L glucose	Bacteria from another glucose-fed MFC	24 h	96%	Wen et al. (2011b)
10	Selenite wastewater	50 and 200 mg/L	Mixed bacterial culture	48 and 72 h	99%	Catal et al. (2009)
11	Phenol	phenol (400 mg/L) glucose mixture	Mixed aerobic and anaerobic activated sludge	60 h	95%	Luo et al. (2009)
12	Palm oil effluent	10000 mg/L	3.5 g/L	HRT 48 h	100% phenol; 96.5% COD; 93.6% ammonia-nitrogen	Cheng et al. (2010)
13	*p*-Nitrophenol wastewater	NIF	Anaerobic sludge	12 h	Complete degradation	Zhu & Ni (2009)

2012; Pham et al., 2009; Tront et al., 2008a; Williams et al., 2010a, 2010b; Yan et al., 2010; Yuan et al., 2010). Very recently, in an interesting study, an MFC was exploited as a pretreatment step to remove dissolved organic matter (DOM) from polluted lake water, and simultaneously generate electricity. After MFC treatment, the total organic carbon concentration in the raw lake water was reduced by 50%, the physicochemical nature of DOMs got substantially altered and the genotoxic agents in the polluted lake water were almost completely removed (He et al., 2013).

Heavy metal recovery

The term ''heavy metal'' is often used for a diverse range of elements. There are hundreds of sources of heavy metal pollution, including the coal, natural gas, paper, acid mine drainage (AMD), chlor-alkali industries and many more (Mathuriya, 2012). Such pollutants have received worldwide attention due to their harmful environmental effects. Conventionally, heavy metal waste waters can be treated and recovered via Chemical precipitation, Hydroxide precipitation, Sulfide precipitation, Heavy metal chelating precipitation, Ion exchange, Adsorption, Ultrafiltration, Reverse osmosis, Coagulation and flocculation, Electrodialysis, and Flotation processes (Fu and Wang 2011). Every process has its own inherent advantages and limitations. Heavy metal treatment is possible in both anode and cathode chamber of MFCs, as discussed below (Figure 2).

In general, MFCs have been applied as functional half-cell, i.e. only the anode chamber is used to degrade pollutants/organics through biocatalytic oxidation (Mathuriya, 2013). The cathode chamber of an MFC mainly serves the role for MFC circuit closure (as the destination for electrons and protons). Theoretically, any compound with adequately high redox potentials can serve as the cathodic electron acceptor in an MFC. When contaminants serve as electron acceptors in the MFC cathode chamber, the environmental benefits of MFCs could be greatly enhanced. MFC methods involve the plating-out of metal ions on a cathode surface and can recover metals in the elemental metal state. Based on this hypothesis, recently a few studies investigated cathodic reduction as a mechanism for recovering metallic contaminants (Choi & Hu 2013; Liu et al., 2011a). Various heavy metals have been treated and recovered in anodic and cathodic chambers of MFCs. These include chromium (Li et al., 2009a; Tandukar et al., 2009; Yeon et al., 2011; Zhao et al., 2009b), vanadium (Li et al., 2009b; Zhang, 2011; Zhang et al., 2010b), copper (Heijne et al., 2010; Liang et al., 2011; Zhang et al., 2012b), arsenic (Xue et al., 2013), gold (Choi & Hu, 2013), silver (Choi & Cui, 2012; Wang et al., 2013), cobalt (Huang et al., 2013) and even uranium (Gregory et al., 2004). Metallic solutions can be treated to recover up to 100% of heavy metals in certain cases (Table 4). In addition, in many studies, metals are recovered and precipitated in pure form (Li et al., 2008; Zhang, 2011). Recovering metals during electricity generation certainly eliminates the energy need for treatment process. In addition, MFCs can remove and recover metals even in very low concentrations, which is not possible using any other process.

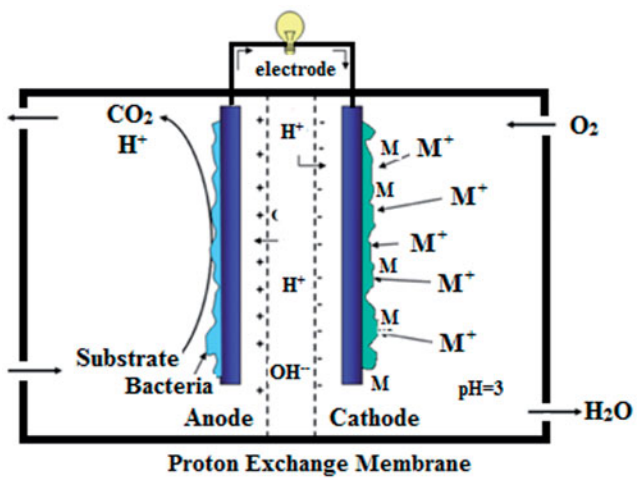

Figure 2. Concept of heavy metal recovery in a microbial fuel cell. ''M'' represents heavy metal.

Nitrification and denitrification

Nitrogen is present in domestic and industrial wastewater mainly in the form of ammonium ($NH4^+$) and nitrate ($NO3^-$) (Tchobanoglous et al., 2003). Technologies for efficient nitrogen removal in small wastewater treatment systems are very limited because of the sophisticated operational requirements. Besides, there is a requirement to have simultaneous removal of organic and nitrogen from wastewater. Recently, there have been reports of simultaneous removal of organic matter and nitrate, along with electricity generation using two-chamber MFCs where denitrification was accomplished by microorganisms at the cathode (Clauwaert et al., 2007; Lefebvre et al., 2008; Puig et al., 2011; Virdis et al., 2010; Wang, et al., 2011a; Zhang et al., 2013b). Specifically, efficiencies of removal of up to 95% of nitrogen (Virdis et al., 2010), more than 99% COD (Yu et al., 2011), 100% ammonium (Feng et al., 2013a) have been observed, and power generation of up to $900\pm25 mW/m^2$ (Yan et al., 2012) and $16.6 W/m^3$ (Virdis et al., 2010) have been reported. Very recently Zhang et al. (2013b) reported removal of 90.2% of total ammonium nitrogen in just 98 h.

Dye decolorization

Dyes are substances that possess high degree of coloration and are, in general, employed in the textile, pharmaceutical, cosmetics, plastics, photographic, paper and food industries (Zollinger, 1991). Many dyes are difficult to fade due to their complex structure and synthetic origin. The color and toxicity of dyes influence the quality of life by causing health problems besides influencing the efficiency of some water treatment techniques (Carneiro et al., 2007). Therefore, establishing removal technologies for dyes is a challenging problem which also calls for urgent attention. Recently, many studies have been done to decolorize dyes using MFCs (Cao et al., 2010; Sun et al., 2009b, 2013). Several dyes namely Azo dyes (Fu et al., 2010b; Fang et al., 2013), Amaranth Dye (Fu et al., 2010b), Active brilliant red X-3B (Sun et al., 2009b, 2011), Congo Red (Cao et al., 2010; Hou et al., 2011; Sun et al., 2013), methyl orange (Ding et al., 2010), C.I.

Table 4. Heavy metal recovery using microbial fuel cells.

S.N.	Metal type	MFC Type	Initial concentration	Microbial source	Operating time/HRT	% removal	References
1	Electroplating wastewater	TC-MFC	Cr(VI) 204 ppm	Anaerobic sludge	25 h	99.5% Cr (VI); 66.2% total Cr	Li et al. (2008)
2	Cr(VI)	TC-MFC	100 mg/L	Domestic wastewater	150 h	Complete removal	Wang et al. (2008)
3	Cr(VI)	TC-MFC with rutile-coated cathode	26 mg/L	Anaerobic sludge	26 h	97%	Li et al. (2009a)
4	Cr(VI)	TC-MFC	177 mg/L	–	10 h	92.8%	Zhao et al. (2009b)
5	Cr(VI)	air bubbling cathode (carbon felt) TC- MFC	10 mg/L	*Shewanella decolorationis S12, Klebsiella pneumoniae L17* and mixed culture	4 h	Complete reduction	Liu et al. (2011a)
6	Cr(VI)	TC-MFC	5 mg/L and 25 mg/L	*β-Proteobacteria, Actinobacteria, Acinetobacter*	6 d	93% and 61%	Yeon et al. (2011)
7	Sulfide and vanadium	TC-MFC	Sulphide (anode): 50–200 mg/L; V(V) (cathode): 250–1,000 mg/L	Anaerobic granular sludge	72 h	82.2% sulfide; 26.1% Vanadium	Zhang et al. (2010b)
8	Cu^{2+} containing wastewater	TC-MFC	1000 mg/L	Excess sludge as anolyte and, $CuSO_4$ solution as the catholyte	288 h	97.8%	Liang et al. (2011)

reactive blue 160 (Chen et al., 2010b), C.I. Acid Orange 7 (Zhang & Zhu, 2011), reactive blue 221 (Bakhshian et al., 2011) have been investigated, in this context. Some research groups have investigated the degradation of real dye wastewater, too (Chen et al., 2010b; Kalathil et al., 2011, 2012). Many bacterial strains were identified as dye decolorizers and used in various studies, these include *Proteus hauseri ZMd44* (Chen et al., 2010a), *Acinetobacter johnsonii NIUx72, Enterobacter cancerogenus BYm30, Klebsiella pneumoniae ZMd31* (Chen et al., 2010b), *Geobacter sulfurreducens*, *Beta Proteobacteria and plant sps. Ipomoea aquatic* (Fang et al., 2013). Under some studies attempts were made to either modify or combine MFCs with other processes like MFC with rutile-coated graphite cathode (Ding et al., 2010), granular activated carbon based MFC (Kalathil et al., 2011), or MFC-Fenton system (Fu et al., 2010b) to ensure process efficiency. Salient achievements in this context are: complete decolorization (Sun et al., 2009b; Cao et al., 2010), handsome COD removal (Bakhshian et al., 2011; Kalathil et al. 2011) alongwith attractive power generation in just 1 h (Sun et al., 2009b, 2011) (Fu et al., 2010b) (Table 5). However, additions of C.I. reactive blue 160 apparently repressed bacterial activity of *Acinetobacter johnsonii* NIUx72, *Enterobacter cancerogenus* BYm30 for power generation in MFC (Chen et al. 2010b).

Phosphorus recovery

Some recent studies have shown phosphorus recovery in MFCs (Hirooka et al., 2013; Ichihashi et al., 2012; Zang et al., 2012). Ichihashi et al. (2012) studied phosphorus recovery from swine wastewater. During operation, 70–82% of the phosphorus was removed from the influent, and 4.6–27% equivalent precipitations were observed on the surface of the cathodes. Zang et al. (2012) studied the recovery of a slow-release fertilizer and electricity from urine. In a two-step process, both nitrogen and phosphorus were recovered, and organic matters in the urine are converted into electricity.

Water softening

Salt and hardness removal is an important process to ensure process and drinking water quality, including during seawater recycling. Most of the salt removing technologies viz., reverse osmosis, electrodialysis, and distillation are both energy and capital intensive (Shannon et al., 2008). Based on the MFC technology, a new technique has been developed recently to reduce the salinity of brackish water during electricity generation, and is called microbial desalination cell (MDC) technology (Cao et al., 2009b; Chen et al., 2012; Mehanna et al., 2010a, 2010b). Venkata Mohan & Srikanth (2011) studied salt removal in both the anode and cathode chambers in dual chambered MFC under varying biocathode microenvironment and achieved handsome Total Dissolved Solids (TDS) (cathode, 90.2±1%; anode, 39.7±0.5%) and substrate (cathode, 98.07±0.06%; anode, 96.2±0.3%) removal in MFC with aerobic biocathode. Jacobson et al. (2011) developed a continuously operated upflow MDC for salt removal. During its 4-month operation, a Power Density (PD) of 30.8 W/m^3 was generated along with over 99% of NaCl

Table 5. Dye decolorization in microbial fuel cells.

S.N.	Dye	MFC architecture	Initial concentration	Inoculum source	Operating Time/HRT	Decolorization (%)	Source of information
1	Active brilliant red X-3B	SC-MFC	300 mg/L	Aerobic sludge :anaerobic sludge (1:1, v:v)	48 h	Complete	Sun et al. (2009b)
2	Congo Red (Glucose as co-substrate)	TC-MFC	300 mg/L	Aerobic sludge: anaerobic sludge, (1:1, v:v)	36 h	98%	Cao et al. (2010)
3	Amaranth Dye	MFC-Fenton system	75 mg/L	–	1 h	82.59%	Fu et al. (2010a)
4	Dye wastewater	SC-MFC	450 mg/L	*Proteus hauseri ZMd44*	20d	98%	Chen et al. (2010b)
5	C.I. Acid Orange 7	SC-MFC	NIF	NIF	168 h	97% decolorization and degradation	Zhang & Zhu (2011)
6	Real dye wastewater	TC-MFC without Nafion	2080 mg/l and color 488 Pt–Co units	Only wastewater in anode and aerobic sludge in cathode	48 h	COD: 71% (anode); 73% (cathode), Color: 73% (anode); 77% (cathode)	Kalathil et al. (2011)
7	Reactive blue 221 laccase in the cathode chamber; Molasses in the anode chamber	TC-MFC	Molasses: 1000 mg/l); Reactive Blue221: 41.5 mg/L	Molasses	30 h	87%decolorization efficiency; 84% COD from molasses	Bakhshian et al. (2011)
8	Congo red	TC-MFC	300 mg/L	–	–	90%	Hou et al. (2011)

removal from the salt solution (initial salt concentration of 30 g/l). In addition, the TDS removal rate was 7.50 g/l d (salt solution volume) or 5.25 g/l d (wastewater volume), and the desalinated water met the drinking water standard in terms of TDS concentration. Brastad & He (2013) developed an MDC consisting of three compartments – the anode, the cathode, and a salt compartment between the anode and the cathode. This MDC was used to soften the hard water and achieved more than 90% removal of hardness from several hard water samples along with four heavy metals (arsenic – 89%; copper – 97%; mercury – 99%, and 95% of the nickel) from a synthetic water sample.

Bioproduction and related aspects

The production of biofuels and related chemicals from renewable resources has emerged as one of the great engineering challenges of the twent-first century. There is a great deal of interest in the development of technologies that simultaneously improve energy capture and transfer to biosynthetic pathways optimized for production of useful compounds (Khunjar et al., 2012). MFCs can meet these challenges by producing various fuels and chemicals in both anodic and cathodic chambers. The microbial assisted chemicals production, called microbial electrosynthesis, offers a highly attractive, novel route for producing valuable products from wastewater along with electricity generation (Rabaey & Rozendal, 2010).

Biomethane

Methane is a potent greenhouse gas, which can be produced from chemical and biochemical routes and is claimed to be more environmentally friendly than other fossil fuels such as gasoline/petrol and diesel (Huzel, 1992). It is the major component of Liquefied natural gas or LNG (Duren et al., 2004) and liquid methane rocket fuel (Huzel, 1992; Todd, 2012). Methane production is another attractive application of MFCs. Studies have demonstrated electricity and methane production from alkaline pre-treated sludge (Xiao et al., 2013), glucose or acetate (Martin et al., 2010), paddy (Rizzo et al., 2013). It was observed that anodic methane producing methanogens did not affect the electricity production but in fact co-existed with electricity-producing bacteria, mostly on the surface as well as inside the anode (Xiao et al., 2013). In another interesting study, Inglesby & Fisher (2012) integrated a semi-continuously fed continuous stirred tank reactor, advanced flow-through anaerobic reactor and advanced flow-through anaerobic digester with an integrated recirculation loop MFC for the production of methane using *Arthrospira maxima* as the sole feedstock and demonstrated that the inclusion of a recirculation loop MFC increased the methane yields and energy efficiency of anaerobic digestion of *Arthrospira maxima* biomass.

Biohydrogen

Hydrogen gas is a potential environmental friendly fuel for vehicles, bulk percentage of which is produced from nonrenewable sources using natural gas (50%), petroleum-derived napthenes and distillates (30%), coal (18%), or by

using electricity produced from a variety of Fuels (2%) (Cheng & Logan, 2011; Manish & Banerjee, 2008). Production of hydrogen with the aid of an MFC is referred to as biocatalyzed electrolysis (Booth, 2005; Rozendal et al., 2006, 2007) or a bio-electrochemically assisted microbial reactor (BEAMR) process (Liu et al., 2005) or electro-hydrogenesis (Cheng & Logan, 2007). Among the first attempts to produce hydrogen from MFCs was by Kreysa and co-workers in 1994 who proposed the utilization of a combination of an MFC with water electrolysis. More recently, Logan's group (Call & Logan, 2008; Cheng & Logan, 2007, 2011; Oh & Logan, 2005) made successful attempt of hydrogen production in MFCs. Microbial electro-hydrogenesis provides a new approach for hydrogen generation from biomass, and wastewater during current generation in a microbial electrolysis cell (MEC-a native of MFC) accomplishing waste treatment at the same time (Cheng & Logan, 2011; Ditzig et al., 2007; Logan et al., 2008; Rozendal et al., 2006, 2007; Wagner et al., 2009). This process also has multiple advantages over the fermentative hydrogen production, such as higher hydrogen recovery, high conversion efficiency and more diverse substrates. More than 90% of hydrogen can be harvested using microbial electrohydrogenesis vis-à-vis 33% by employing fermentation (Chaudhari & Lovely, 2003; Du et al., 2007). In MFCs, hydrogen yield from acetate have reached 2.9 moles of hydrogen per mole of acetate (versus a theoretical maximum of 4mol/mol) for an energy input equivalent to 0.5moles of hydrogen (Logan & Regan, 2006). Earlier tests with two-chamber MECs had yielded low hydrogen production rates (0.01–0.1m^3/m^3d) (Liu et al., 2005; Rozendal et al., 2006). By increasing anode surface area and by using an anionic exchange membrane, hydrogen production increased to $1.1 m^3/m^3d$ (Cheng & Logan, 2007). The production rate increased to $3.12 m^3/m^3d$ by using a single-chamber MEC (Call and Logan, 2008). Highest hydrogen yield of $4.8\pm0.7/2.5\pm0.4$ mol-H_2/mol-propionate was obtained at 10Ω by using a MEC–MFC-coupled system (Sun et al., 2010). Many other studies also produced interesting results (Hu et al., 2008; Stamatelatou et al., 2011; Tartakovsky et al., 2008). Wang et al. (2011) integrated fermentation, MFC and MEC systems to produce hydrogen gas from cellulose. The overall hydrogen production for the integrated system was increased by 41% compared with fermentation alone to 14.3 mmol H_2/g cellulose, with a total hydrogen production rate of 0.24 m^3 $H_2/m^3/d$ and an overall energy recovery efficiency of 23% (based on cellulose removed) without the need for any external electrical energy input. Very recently, by adding a gold precursor at its cathode, Kalathil et al. (2013), demonstrated to form gold nanoparticles in an MFC that can be used to simultaneously produce bioelectricity and hydrogen. Gold nanoparticles have also been demonstrated to mediate hydrogen production without requiring any external power supply, while the MFC produces a stable power density.

Hydrogen peroxide

Hydrogen peroxide (H_2O_2) is a common green and environmental friendly reagent often used as a bleaching or cleaning agent. It is commercially produced by toxic and expensive anthraquinone process. MFCs may provide a cost-effective way for H_2O_2 production at cathode. As reported earlier (Fu et al., 2010a, 2010b), a two-electron oxygen reduction could be controlled for H_2O_2 production by using a corrosion-resistant spectrographically pure graphite (SPG) electrode with a relatively low energy consumption (Fu et al., 2010a).

Biomass

Biomass production is another application of MFCs. Inexhaustible availability of CO_2 could provide a promising technology for biomass production with simultaneous energy recovery, under this methodology. Powell et al. (2008a) were the first to use an algae *Chlorella vulgaris*, as the biological electron acceptor at the cathode while reducing CO_2 to biomass using a mediator resulting in the generation of bioelectricity. Since than many efforts have been put in this direction (Cao et al., 2009a; Powell et al., 2008a, 2008b, 2009; Rashid et al. 2013). These studies demonstrated that MFCs could be used to fix carbon dioxide for biomass production as well as to produce electricity, to some extent. Helder et al. (2010) checked concurrent biomass and bio-electricity production in a plant-MFC. *Spartina anglica* and *Arundinella anomala* concurrently produced biomass and bio-electricity for six months, consecutively.

Acetic acid

The co-production of acetic acid and electricity by applying MFC technology was successfully demonstrated by Tanino et al. (2013) through a series of repeated batch fermentations. Although the production rate of acetic acid by this route was rather small, it increased with the number of repeated batch fermentations. Further nearly identical (73.1%) or larger (89.9%) acetic acid yielded than that typically achieved by aerated fermentation (75.8%).

Robotics

Autonomous robots having the capacity to work efficiently in remote, terrestrial or underwater locations are being increasingly employed in industry and their use is contemplated for many diverse applications in future. However, designing them poses many challenges for engineers, including the need to incorporate energy-packs in them for sustained operation. Generally, small mobile robots run on electrical energy supplied by standard battery-packs (electrochemical energy source) or in a few instances, by photovoltaic panels (the *Sojourner* Mars rover for example) (Begley, 1997; Kluger, 1997), which may often require human intervention. At times, big robots used in industry require bulky electrical cables as power-feeds (Wilkinson, 2000a). As power sources to run the robots, the MFCs can provide viable options in situations where energy entrapped in the form of complex waste water/pure compounds can be converted into useful electricity (Ieropoulos et al., 2012; Melhuish et al., 2006). This environmentally benign and compact energy solution is a pre-requisite for a host of terrestrial outdoor robot applications, especially those assigned ''start and forget'' missions (Wilkinson & Campbell, 1996). There are various generations

of robots, which have been shown to employ MFCs as their power source (Ieropoulos et al., 2005; Kelly et al., 1999; Melhuish et al., 2006; Wilkinson 1999, 2000a).

Gastrobots (Gast = Gastrum, Robot = machine), a class of intelligent bioelecrochemical machines, derives its operational power by trapping the energy of food digestion via microbial catalytic activities (Kelly et al., 1999; Wilkinson, 1999, 2000a). World's first robot using bacteria was Wilkinson's Gastronome (Chew-chew) in 2000, which employed chemical Fuel Cells to charge Ni-Cd batteries (Wilkinson, 2000b). It worked on the electrical power generated by *E. coli* consuming sugar, via synthetic mediator (HNQ).

EcoBot (Ecological robot) is another autonomous robot that employs MFCs, as the onboard energy supply (Ieropoulos et al., 2005; Melhuish et al., 2006). Till date, EcoBot-I, EcoBot-II and EcoBot-III have been developed with same operational principle. MFCs can generate electrical energy to power the complimentary artificial muscle technologies of dielectric elastomer actuators and ionic-polymer metal composites. In EcoBot I, the MFC forms a soft stomach and gut and the artificial muscles form a soft pliable body (Ieropoulos et al., 2008). EcoBot II (Figure 3), powered by eight MFCs (Ieropoulos et al., 2003a, 2003b, 2004) performs environmental monitoring. It is integrated with a wireless transmitter connected to a temperature sensor. The sensed and transmitted data does not limit to temperature only but it may include toxic levels, humidity or an indication of its internal state, such as pH, fluid substrate level etc. EcoBot-III, a robot with an artificial digestion system, is the first model, which exhibits symbiosis (Symbot) for digestion and autonomous operation as an exemplar of artificial life. It is also powered by MFCs and designed to collect food and water from the environment, to digest the collected food and can be operated for seven days when fed with anaerobic or pasteurized sludge (Ieropoulos et al., 2010).

Melhuish et al. (2006) reported the first-stage underwater MFCs which can operate by utilizing dissolved oxygen within the cathodic half-cell, likened to an artificial gill (Melhuish & Kubo, 2004). ''Slugbot'' is a robot that utilizes the electrical power produced from biomass. It ferments slug mass and converts it into electrical energy, and uses it to catch the slugs in the field (Kelly et al., 1999).

Biosensor applications

Biosensors are molecular sensors that combine a biological recognition mechanism with a physical transduction technique to generate a signal proportional to the analyte concentration (Cornell et al., 1997). This signal can result from a change in protons concentration, release or uptake of gases, light emission, absorption etc., brought about by the metabolism of the target compound by the biological recognition element. The transducer converts this biological signal into a measurable response such as current, potential or absorption of light, electrochemically or optically, which can be amplified, processed and stored for further analysis (Mulchandani & Rogers, 1998). Schematic representation of the microbial lactate sensor is shown in Figure 4. MFCs may be applied as biosensors (Kim et al., 2009) in many ways:

BOD monitoring

Biochemical Oxygen Demand (BOD) refers to the amount of oxygen that would be consumed if all the organics in one liter of water were oxidized by bacteria (Young et al., 1981). Since the electrical charge generated from a mediator-less MFC is proportional to the concentration of fuel used, MFCs can be used as a BOD sensors (Kim et al., 2003a). MFC-based BOD sensors offer various advantages over other BOD sensors like excellent operational stability, accuracy, good reproducibility, ability to work in remote or dangerous areas, potential to self power and substantially longer life-span (Kim et al., 2009). An MFC-type BOD sensor can operate for over 5 years without extra maintenance (Kim et al., 2003a), far longer than other types of BOD sensors. As early as in 1977, Karube et al. reported a BOD sensor based on MFC using the hydrogen produced by *Clostridium butyricum*

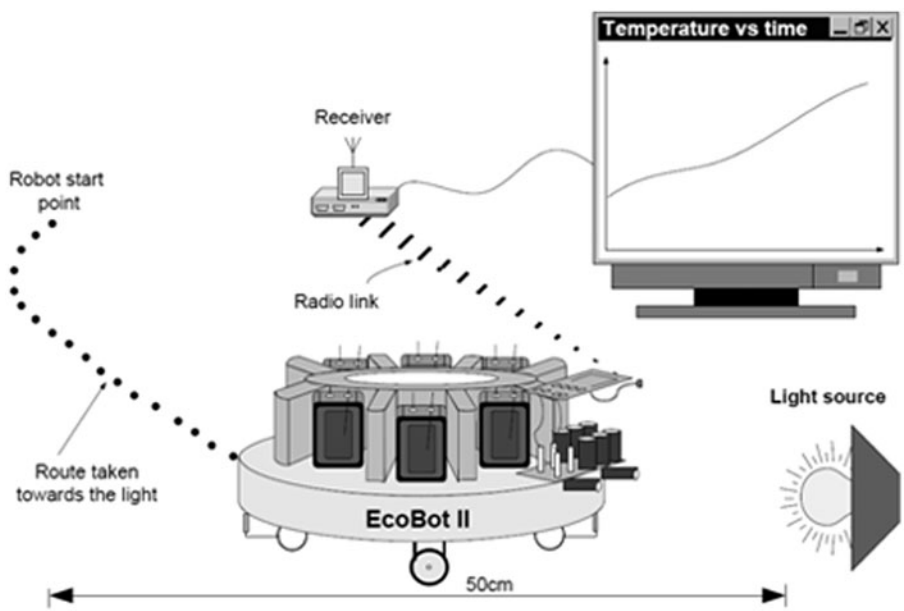

Figure 3. Experimental setup for the EcoBot-II (Included and adapted after permission from Ieropoulos et al. (2005), copyright 2005 InTech – open Access Company).

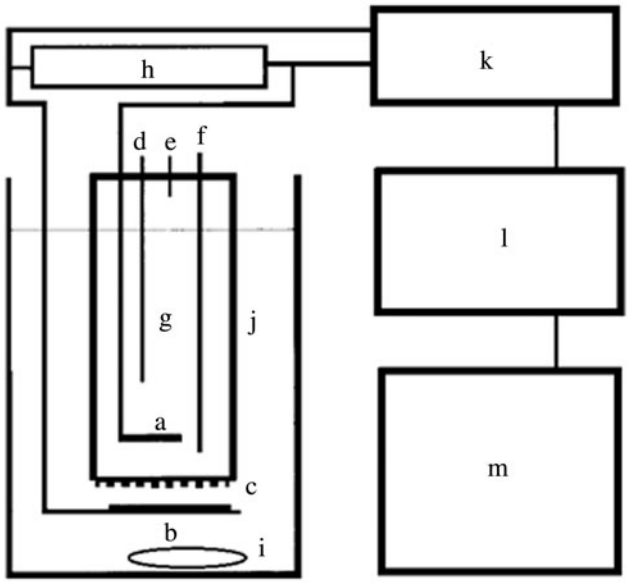

Figure 4. Schematic diagram of the microbial lactate sensor: (a) working electrode (anode) (b) counter electrode (cathode) (c) ion exchange membrane (d) sample injection port (e) N_2 outlet (f) N_2 Inlet (g) anode compartment (h) resistor (i) magnetic stirrer bar (j) cathode compartment (k) voltmeter (l) Scanner (m) data acquisition system. (Included and adapted after permission from Kim et al. (1999), copyright 1999 Korean Society for Microbiology and Biotechnology).

immobilized on the electrode. Since then, several types of MFC-based biosensors have been developed for monitoring of BOD in surface water, secondary effluents or wastewater samples and showed good stability, accuracy and wide detection range when compared with other types of biosensors (Di Lorenzo et al., 2009a, 2009b; Jang et al. 2004b; Kang et al., 2003; ; Kumlanghan et al., 2007; Moon et al., 2004; Pasco et al., 2004; Shantaram et al., 2005).

An accurate method to determine the BOD value of a liquid stream is to calculate its Coulombic yield. Many researchers (Kim et al., 2003a, 2003b; Chang et al., 2004) showed a linear relationship between the Coulombic yield and wastewater strength in a wide BOD concentration range, e.g. BOD in sewage has been promisingly quantified using systems based on the microorganism *Shewanella* (Moon et al., 2004; Chang et al., 2005) because of the correlation between the Coulombic yield of MFCs and wastewater concentration within a large range. Later, it was realized that electric current is more suitable as an indicator than Coulombic yield for BOD monitoring, as Coulombic yield is calculated only after the BOD has been consumed and thus a high BOD level requires a long response time (Du et al., 2007). Efforts have been made to improve the dynamic responses of MFC-based BOD sensors. Moon et al. (2004) investigated the dynamic behavior of a continuous mediator-less MFC as BOD sensor, which had the shortest response time of 36 min. Various types of MFC reactors including two-chamber and single-chamber systems have been used as BOD sensor, and BOD levels from 2 to 350 mg/L have been detected in wastewater (Di Lorenzo et al., 2009b; Moon et al., 2004). To develop a MFC-type BOD sensor having enhanced performance and providing high sensitivity and accuracy, membrane-electrode assembly has been employed (Kim et al., 2009).

Monitoring of chemical toxicants

Chemical toxicants can inhibit the metabolic activity of anodic microbial population, influence the transfer rate of electrons to the electrode and thus decrease the electricity production. Therefore, MFCs can be proposed as a toxicity sensor for monitoring the presence of chemical toxicants in various environments (Stein et al., 2012) like in rivers, at the entrance of wastewater treatment plants, to detect pollution or illegal dumping, or to perform research on polluted sites (Chang et al., 2004; Meyer et al., 2002). The compact design of these devices made them suitable for their incorporation into measurement equipments either as an individual device or as an array of sensors for high throughput processing. Various toxicants including formaldehyde (Davila et al., 2011), anaerobic digestion fluid (Liu et al., 2011b), Cr, Hg, Pb and phenol in the test water (Kim et al., 2003b), toxic components in drinking water (Stein et al., 2012) have been monitored by MFC sensors. Kaur et al. (2013) demonstrated volatile fatty acid concentration by MFC-biosensor and this biosensor array was capable of measuring individual acetate, propionate and butyrate concentrations with sensitivity down to 5 mg/l and up to 40 mg/l. A portable wall-jet MFC biosensor developed by Liu et al. (2011b) showed on-line measurements (i.e. pH, gas flow rate) and off-line analysis (i.e. COD) over 6-month operation. Recently MFC technology is integrated with other technologies like with artificial neural networks (Feng et al., 2013b); and time series analysis (Feng et al., 2013c) for enhanced waster quality monitoring. Very recently, MFC was also developed as a Cu(II) toxicity biomonitoring system (Shen et al., 2013).

Microbial activity assessment and screening of bacteria

Microbial activity monitoring has also been proposed as another application of an MFC-based sensor (Patchett et al., 1988; Tront et al., 2008a,b; Williams et al., 2010b). The idea is based on the response of current generation to different substrate (BOD) concentrations based on the activity of the biofilm colonized on the anode. Williams et al. (2010a) developed an electrode-based approach by placing anode electrode in anoxic subsurface environments for monitoring of microbial activity. *Geobacter* species in the subsurface environments readily colonized the graphite electrode and produced current which correlated to the availability of acetate added to promote U(VI) reduction. Abrevaya et al. (2010) reported a cylindrical reactor without anode chamber for extraterrestrial microbial life detection. Hou et al. (2012) described an MFC array device that incorporated microfluidic technology used in screening microbial consortia collected from geographically diverse environments for enhanced MFC performance. Mukherjee et al. (2013) developed an array of six MEMS (micro-electro-mechanical systems) and MFCs, for rapid screening of electrochemically active bacteria (*S. oneidensis* and *P. aeruginosa*). A membrane-less microfluidic μMFC for rapid detection of microorganism's electroactivity was demonstrated by Wang & Su (2013) by measuring open circuit voltage.

In situ power supply

In situ power source for remote locations is another application of MFCs that has attracted attention towards the recovery of electricity from sediments. MFCs can provide *in situ* power source for electronic devices (e.g. environmental sensors) in remote areas, such as the ocean and the bottom of deep-water, where routine access is restricted to replace traditional batteries (Logan & Regan, 2006; Lovley, 2006). A popular sediment-MFC is benthic unattached generator (BUG), in which the anode is buried in anoxic or anaerobic marine sediments connected to a cathode suspended in the overlying aerobic water. Organic matter in the sediments is used to produce electricity in BUG (Kim et al., 2008). Recently, Donovan et al. (2013) develop a power management system (PMS) based on sediment MFC to power a submersible ultrasonic receiver (SUR). The integrated PMS was tested and operated the SUR continuously for six weeks.

Implantable power sources

Various implanted biomedical devices require power which is generally supplied by batteries with a finite life, necessitating another surgery to replace the power source. A method for continuously generating electricity within the body would revolutionize biomedical devices and enhance patient care (Clayton, 2006). An unusual application for MFC technology is to power implanted medical devices using glucose and oxygen from blood. An implanted MFC could provide power indefinitely and negate the need for surgery to replace batteries (Franks & Nevin, 2010). Clayton (2006) examined the feasibility of MFC technology to the areas of glucose sensing and cardiac pacing and discusses the problems that are likely be encountered. Recently MFCs have been investigated as implantable medical devices (IMDs), proposed to be placed in human large intestine and could utilize intestinal contents and microorganisms to generate electricity (Dong et al., 2013; Han et al., 2010). Considering human anatomy and inner environmental conditions of large intestine, transverse colon was chosen to be the appropriate location for the implantation of MFC. Moreover, the changes of environmental conditions in the chambers of MFC did not have a significant impact on human body, as demonstrated by the analysis of pH and DO values (Han et al., 2010).

Miscellaneous

In addition to the above-mentioned applications, the MFCs many more studies are being made by researchers currently which prove MFCs as versatile devices.

Lagooning is a well-known process of ponds, in which sunlight, bacterial action and oxygen cause self-purification of water (Kruzic & Kreissi, 2009). Very recently, Lobato et al. (2013) described a lagooning-MFC, consisting of a photosynthetic system at the cathode coupled to a microbial anodic system. Again, Fraiwan et al. (2013) developed a paper-based MFC, which has the advantages of ease of use, low production cost, and high portability for powering on-chip functions.

During treatment of Acid Mine Drainage, Cheng et al. (2011) generated spherical nanoparticles of iron oxide (120 to 700 nm), that upon drying, transformed to goethite (α-FeOOH). Particle diameters could be controlled by varying the conditions in the MFC, especially current density (0.04e0.12 mA/cm^2), pH (4–7.5), and initial Fe(II) concentration (50–1000 mg/L). By adding a gold precursor at the cathode, Kalathil et al. (2013) demonstrated the formation of gold nanoparticles in MFCs.

Perspectives

Over the last decade, MFC technology has developed remarkably. This is attributed to sustained efforts made in altering their designs, such as optimization of the MFC configurations, their physical and chemical operating conditions, and the choice of biocatalyst. The MFC technology holds promise towards sustainable power generation along with applications in several areas discussed in this article.

Although MFC technology is rapidly spreading its aura in every dimension, still the applicability of MFC is in nascent phase. Major responsible reason is its limitation up to small laboratory scale and much time is required for its pilot scale sustainability. Other major factors include: its inferior performance in comparison to its competitors like methanogenic anaerobic digesters; less efficiency at process scale up (Clauwaert et al., 2007); high cost of Proton Exchange Membrane (PEM) (Duteanu et al., 2010). Addition of mediator may lead inactivity of pure culture microbes. MFCs have another limitation of long start up and Hydraulic retention time compared to other processes (Duteanu et al., 2010). In addition, degradation of recalcitrant wastes is possible up to a certain concentration, after that it leads to inhibition in biological treatment process and can kill microbial flora (Abbas et al., 2009; Mayen-Mondragon et al., 2008), for example excess amounts of total ammonia nitrogen, which is produced by the hydrolysis of proteinous organic materials, is one limiting factor in microbial metabolism and has been found to severely inhibit the function of electrochemically active microorganisms (Nam et al., 2010). Sometimes, final products of recalcitrant waste degradation might be more toxic than their parent substances (Huang et al., 2011c). MFCs used in robotics also displaying lower efficiency (Ieropoulos et al., 2005; 2012).

However, if MFC technology is to achieve wide acceptance for practical implementation, several important challenges need to be met. More studies are required to tackle the following aspects: improved power generation, controlled microbial performance occurring in the system, development of new full-scale MFC designs to minimize potential losses for optimized performance. Most of all, the capital costs of MFCs have to be reduced for their practical applications. The extent to which these challenges can be circumvented will eventually determine the success of MFC technology to meet the demands for applications in future.

References

Abbas AA, Guo J, Liu Z, Pan YY, Al-Rekabi WS. (2009). Review on landfill leachate treatments. Am J Appl Sci 6:672–84.

Abrevaya XC, Mauas PJ, Corton E. (2010). Microbial fuel cells applied to the metabolically based detection of extraterrestrial life. Astrobiol 10:965–71.

Ahn Y, Logan BE. (2010). Effectiveness of domestic wastewater treatment using microbial fuel cells at ambient and mesophilic temperatures. Bioresource Technol 101:469–75.

Alfonta L. (2010). Genetically engineered microbial fuel cells. Electroanalysis 22:822–31.

Allen RM, Bennetto HP. (1993). Microbial fuel-cells: electricity production from carbohydrates. Appl Biochem Biotechnol 39:27–40.

Bakhshian S, Kariminia HR, Roshandel R. (2011). Bioelectricity generation enhancement in a dual chamber microbial fuel cell under cathodic enzyme catalyzed dye decolorization. Biores Technol 102: 6761–5.

Balat M. (2010). Microbial fuel cells as an alternative energy option. Energ Sour, A 32:26–35.

Begley S. (1997). Greetings from Mars. Newsweek 14 July, 22–9.

Behera M, Jana PS, More TT, Ghangrekar MM. (2010). Rice mill wastewater treatment in microbial fuel cells fabricated using proton exchange membrane and earthen pot at different pH. Bioelectrochem 79:228–33.

Bond DR, Lovley DR. (2003). Electricity production by *Geobacter sulfurreducens* attached to electrodes. Appl Env Microbiol 69: 1548–55.

Booth B. (2005). Hydrogen from a microbial fuel cell. Environ Sci Technol 39:235A.

Brastad KS, He Z. (2013). Water softening using microbial desalination cell technology. Desalination 309:32–7.

Call D, Logan BE. (2008). Hydrogen production in a single chamber microbial electrolysis cell (MEC) lacking a membrane. Environ Sci Technol 42:3401–06.

Cao XX, Huang X, Liang P, et al. (2009a). A completely anoxic microbial fuel cell using a photo-biocathode for cathodic carbon dioxide reduction. Energy Env Sci 2:498–501.

Cao X, Huang X, Liang P, et al. (2009b). A new method for water desalination using microbial desalination cells. Environ Sci Technol 43:7148–52.

Cao Y, Hu Y, Sun J, Hou B. (2010). Explore various co-substrates for simultaneous electricity generation and Congo red degradation in air-cathode single-chamber microbial fuel cell. Bioelectrochem 79:71–6.

Carneiro PA, Nogueira RFP, Zanoni MVB. (2007). Homogeneous photodegradation of C.I. Reactive Blue 4 using a photo-Fenton process under artificial and solar irradiation. Dyes Pigment 7:127–32.

Catal T, Bermek H, Liu H. (2009). Removal of selenite from wastewater using microbial fuel cells. Biotechnol Lett 31:1211–16.

Chang IS, Jang JK, Gil GC, et al. (2004). Continuous determination of biochemical oxygen demand using microbial fuel cell type biosensor. Biosen Bioelectron 19:607–13.

Chang IS, Moon H, Jang JK, Kim BH. (2005). Improvement of a microbial fuel cell performance as BOD sensor using respiratory inhibitors. Biosen Bioelectron 20:1856–9.

Chaudhari SK, Lovely DR. (2003). Electricity generation by direct oxidation of glucose in microbial fuel cells. Nature Biotechnol 111–14.

Chen BY, Zhang MM, Chang CT, et al. (2010a). Assessment upon azo dye decolorization and bioelectricity generation by *Proteus hauseri*. Biores Technol 101:4737–41.

Chen BY, Zhang MM, Ding Y, Chang CT. (2010b). Feasibility study of simultaneous bioelectricity generation and dye decolorization using naturally occurring decolorizers. J Taiwan Inst Chem Eng 41:682–8.

Chen S, Liu G, Zhang R, Qin B, Luo Y. (2012). Development of the microbial electrolysis desalination and chemical-production cell for desalination as well as acid and alkali productions. Environ Sci Technol 46:2467–72.

Cheng S, Jang JH, Dempsey BA, Logan BE. (2011). Efficient recovery of nano-sized iron oxide particles from synthetic acid-mine drainage (AMD) water using fuel cell technologies. Water Res 45:303–7.

Cheng J, Zhu X, Ni J, Borthwick A. (2010). Palm oil mill effluent treatment using a two stage microbial fuel cells system integrated with immobilized biological aerated filters. Biores Technol 101:2729–34.

Cheng S, Logan BE. (2011). High hydrogen production rate of microbial electrolysis cell (MEC) with reduced electrode spacing Biores Technol 102:3571–4.

Cheng S, Logan BE. (2007). Sustainable and efficient biohydrogen production via electrohydrogenesis. PNAS 104:18871–3.

Choi C, Cui Y. (2012). Recovery of silver from wastewater coupled with power generation using a microbial fuel cell. Biores Technol 107: 522–5.

Choi C, Hu N. (2013). The modeling of gold recovery from tetrachloroaurate wastewater using a microbial fuel cell. Biores Technol 133:589–98. doi: 10.1016/j.biortech.2013.01.143.

Clauwaert P, Rabaey K, Aelterman P, et al. (2007). Biological denitrification in microbial fuel cells. Env Sci Technol 41:3354–60.

Clayton B. (2006). Applicability and Feasibility of Incorporating Microbial Fuel Cell Technology into Implantable Biomedical Devices [Thesis]. College of Engineering: Ohio State University; Spring. http://hdl.handle.net/1811/6443 [last accessed 18 April 2013].

Cornell BA, Braach-Maksvytis VL, King LG, et al. (1997). A biosensor that uses ion-channel switches. Nature 387:580–3.

Davila D, Esquivel JP, Sabate N, Mas J. (2011). Silicon-based microfabricated microbial fuel cell toxicity sensor. Biosen Bioelectron 26:2426–30.

Di Lorenzo M, Curtis TP, Head IM, Scott K. (2009a). A single-chamber microbial fuel cell as a biosensor for wastewaters. Water Res 43: 3145–54.

Di Lorenzo M, Curtis TP, Head IM, et al. (2009b). A single chamber packed bed microbial fuel cell biosensor for measuring organic content of wastewater. Water Sci Technol 60:2879–87.

Ding H, Li Y, Lu A, Jin S, et al. (2010). Photocatalytically improved azo dye reduction in a microbial fuel cell with rutile-cathode. Biores Technol 101:3500–5.

Ditzig J, Liu H, Logan BE. (2007). Production of hydrogen from domestic wastewater using a bioelectrochemically assisted microbial reactor (BEAMR). Int J Hydrogen Energy 32:2296–04.

Dong K, Jia B, Yu C, et al. (2013). Microbial fuel cell as power supply for implantable medical devices: a novel configuration design for simulating colonic environment. Biosens Bioelectron 41: 916–9.

Donovan C, Dewan A, Heo D, et al. (2013). Sediment microbial fuel cell powering a submersible ultrasonic receiver: new approach to remote monitoring. J Power Sou 233:79–85.

Du Z, Li H, Gu T. (2007). A state of the art review on microbial fuel cells: a promising technology for wastewater treatment and bioenergy. Biotechnol Adv 25:464–82.

Duren T, Sarkisov L, Yaghi OM, Snurr RQ. (2004). Design of New Materials for Methane Storage. Langmuir 20:2683–9.

Duteanu NM, Ghangrekar MM, Erable B, Scott K. (2010). Microbial fuel cells – an option for wastewater treatment. Env Eng Manage J 9: 1069–87.

Fang Z, Song HL, Cang N, Li XN. (2013). Performance of microbial fuel cell coupled constructed wetland system for decolorization of azo dye and bioelectricity generation. Biores Technol 144: 165–71.

Fangzhou D, Zhenglong L, Shaoqiang Y, et al. (2011). Electricity generation directly using human feces wastewater for life support system. Acta Astronautica 68:1537–47.

Feng C, Hu A, Chen S, Yu CP. (2013a). A decentralized wastewater treatment system using microbial fuel cell techniques and its response to a copper shock load. Biores Technol 143:76–82.

Feng Y, Barr W, Harper Jr WF. (2013b). Neural network processing of microbial fuel cell signals for the identification of chemicals present in water. J Environ Manage 120:84–92.

Feng Y, Kayode O, Harper Jr WF. (2013c). Using microbial fuel cell output metrics and nonlinear modeling techniques for smart biosensing. Sci Total Environ 449:223–8.

Feng Y, Yang Q, Wang X, et al. (2011). Treatment of biodiesel production wastes with simultaneous electricity generation using a single-chamber microbial fuel cell. Biores Technol 102:411–15.

Fraiwan A, Mukherjee S, Sundermier S, et al. (2013). A paper-based microbial fuel cell: instant battery for disposable diagnostic devices. Biosens Bioelectron 49:410–14.

Franks AE, Nevin KP. (2010). Microbial fuel cells, a current review. Energies 3:899–919.

Fu F, Wang Q. (2011). Removal of heavy metal ions from wastewaters: a review. J Environ Manag 92:407–18.

Fu L, You SJ, Yang FL, et al. (2010a). Synthesis of hydrogen peroxide in microbial fuel cell. J Chem Technol Biotechnol 85:715–19.

Fu L, You SJ, Zhang GQ, et al. (2010b). Degradation of azo dyes using in-situ Fenton reaction incorporated into H_2O_2-producing microbial fuel cell. Chem Eng J 160:164–9.

Galvez A, Greenman J, Ieropoulos I. (2009). Landfill leachate treatment with microbial fuel cells; scale-up through plurality. Biores Technol 100:5085–91.

Gong D, Qin G. (2012). Treatment of oilfield wastewater using a microbial fuel cell integrated with an up-flow anaerobic sludge blanket reactor. Desalination Water Treatm 49:272–80.
Greenman J, Gálvez A, Giust L, Ieropoulos I. (2009). Electricity from landfill leachate using microbial fuel cells: Comparison with a biological aerated filter. Enz Microb Technol 44:112–19.
Gregory KB, Bond DR, Lovley DR. (2004). Graphite electrodes as electron donors for anaerobic respiration. Environ Microbiol 6: 596–604.
Gu HY, Zhang XW, Li ZJ, Lei LC. (2007). Studies on treatment of chlorophenol-containing wastewater by microbial fuel cell. Chin Sci Bull 52:3448–51.
Habermann W, Pommer EH. (1991). Biological fuel cells with sulphide storage capacity. Appl Microbiol Biotechnol 35:128–33.
Han Y, Yu C, Liu H. (2010). A microbial fuel cell as power supply for implantable medical devices. Biosens Bioelectron 25:2156–60.
He YR, Xiao X, Li WW, et al. (2013). Electricity generation from dissolved organic matter in polluted lake water using a microbial fuel cell (MFC). Biochem Eng J 71:57–61.
Heijne AT, Liu F, Weijden RVD, et al. (2010). Copper recovery combined with electricity production in a microbial fuel cell. Env Sci Technol 44:4376–81.
Helder M, Strik DP, Hamelers HV, et al. (2010). Concurrent bio-electricity and biomass production in three plant-microbial fuel cells using *Spartina anglica, Arundinella anomala* and *Arundo donax*. Biores Technol 101:3541–7.
Hirooka K, Ichihashi O. (2013). Phosphorus recovery from artificial wastewater by microbial fuel cell and its effect on power generation. Biores Technol 137:368–75.
Hong SW, Kim HS, Chung TH. (2010). Alteration of sediment organic matter in sediment microbial fuel cells. Env Pollut 158:185–91.
Hou B, Sun J, Hu Y. (2011). Effect of enrichment procedures on performance and microbial diversity of microbial fuel cell for Congo red decolorization and electricity generation. Appl Microbiol Biotechnol 90:1563–72.
Hou H, Li L, Ceylan CU, et al. (2012). Microfluidic microbial fuel cell array that supports long-term multiplexed analyses of electricigens. Lab Chip 12:4151–9.
Hu H, Fan Y, Liu H. (2008). Hydrogen production using single-chamber membrane-free microbial electrolysis cells. Water Res 42:4172–8.
Hu J, Niu CG, Wang Y, et al. (2011). Nitrogenous heterocyclic compounds degradation in the microbial fuel cells. Process Safety Env Protection 89:133–40.
Huang DY, Zhou SG, Chen Q, et al. (2011a). Enhanced anaerobic degradation of organic pollutants in a soil microbial fuel cell. Che Eng J 172:647–53.
Huang J, Yang P, Guo Y, Zhang K. (2011b). Electricity generation during wastewater treatment: an approach using an AFB-MFC for alcohol distillery wastewater. Desalination 276:373–8.
Huang L, Cheng S, Chen G. (2011c). Bioelectrochemical systems for efficient recalcitrant wastes treatment. J Chem Technol Biotechnol 86: 481–91.
Huang L, Gan L, Zhao Q, et al. (2011d). Degradation of pentachlorophenol with the presence of fermentable and non-fermentable co-substrates in a microbial fuel cell. Biores Technol 102:8762–8.
Huang L, Li T, Liu C, et al. (2013). Synergetic interactions improve cobalt leaching from lithium cobalt oxide in microbial fuel cells. Biores Technol 128:539–46.
Huang L, Logan BE. (2008). Electricity generation and treatment of paper recycling wastewater using a microbial fuel cell. Appl Microb Biotechnol 80:349–55.
Huang L, Yang X, Quan X, et al. (2010). A microbial fuel cell–electro-oxidation system for coking wastewater treatment and bioelectricity generation. J Chem Technol Biotechnol 85:621–7.
Huzel DK. (1992). Modern engineering for design of liquid-propellant rocket engines. Washington, DC: American Institute of Aeronautics and Astronautics.
Ichihashi O, Hirooka K. (2012). Removal and recovery of phosphorus as struvite from swine wastewater using microbial fuel cell. Biores Technol 114:303–7.
Ieropoulos IA, Melhuish C, Greenman J. (2004). Energetically autonomous robots. Proceedings of the 8th intelligent autonomous systems conference (IAS-8), Amsterdam, The Netherlands, March, 128–35.
Ieropoulos IA, Greenman J, Melhuish C, eds. (2003a). Imitating metabolism: energy autonomy in biologically inspired robotics. Proceedings of the AISB '03:2nd International Symposium on imitation in animals and artifacts, Aberystwyth, Wales, April, 191–4.
Ieropoulos IA, Greenman J, Melhuish C, Horseld I. (2010). EcoBot-III: a robot with guts. In: Fellermann H, Dorr M, Hanczyc M, et al., eds. Artificial life X: Proceedings of the 12th International Conference on the Synthesis and Simulation of Living Systems. Massachusetts, USA: Massachusetts Institute of Technology Press, 733–40.
Ieropoulos IA, Greenman J, Melhuish C, Horsfield I. (2012). Microbial fuel cells for robotics: energy autonomy through artificial symbiosis. ChemsumChem 5:1020–6.
Ieropoulos IA, Greenman J, Melhuish C. (2008). Microbial fuel cells based on carbon veil electrodes: stack configuration and scalability. Int J Energy Res 32:1228–40.
Ieropoulos IA, Melhuish C, Greenman J, Horsfield I. (2005). EcoBot-II: an artificial agent with a natural metabolism. J Adv Robotic Syst 2: 295–300.
Ieropoulos IA, Melhuish C, Greenman J. (2003b). Artificial metabolism: towards true energetic autonomy in artificial life. Proceedings of the 7th European Conference in Artificial Life (ECAL 2003); Sept, 792–9.
Inglesby AE, Fisher AC. (2012). Enhanced methane yields from anaerobic digestion of *Arthrospira maxima* biomass in an advanced flow-through reactor with an integrated recirculation loop microbial fuel cell. Energy Environ Sci 5:7996–8006.
Jacobson KS, Drew DM, He Z. (2011). Efficient salt removal in a continuously operated upflow microbial desalination cell with an air cathode. Biores Technol 102:376–80.
Jang JD, Barford JP, Lindawati R. (2004b). Application of biochemical oxygen demand (BOD) biosensor for optimization of biological carbon and nitrogen removal from synthetic wastewater in a sequencing batch reactor system. Biosen Bioelectron 19:805–12.
Jang JK, Pham TH, Chang IS, et al. (2004a). Construction and operation of a novel mediator and membrane-less microbial fuel cell. Process Biochem 39:1007–12.
Jiang Y, Ulrich AC, Liu Y. (2013). Coupling bioelectricity generation and oil sands tailings treatment using microbial fuel cells. Biores Technol 139:349–54.
Kaewkannetra P, Chiwes W, Chiu TY. (2011). Treatment of cassava mill wastewater and production of electricity through microbial fuel cell technology. Fuel 90:2746–50.
Kalathil S, Lee J, Cho MH. (2012). Efficient decolorization of real dye wastewater and bioelectricity generation using a novel single chamber biocathode-microbial fuel cell. Biores Technol 119:22–7.
Kalathil S, Lee J, Cho MH. (2013). Gold nanoparticles produced in situ mediate bioelectricity and hydrogen production in a microbial fuel cell by quantized capacitance charging. ChemsusChem 6: 246–50.
Kalathil S, Lee J, Cho MH. (2011). Granular activated carbon based microbial fuel cell for simultaneous decolorization of real dye wastewater and electricity generation. New Biotechnol 29:32–7.
Kang KH, Jang JK, Pham TH, et al. (2003). A microbial fuel cell with improved cathode reaction as a low biochemical oxygen demand. Biotechnol Lett 25:1357–61.
Karube I, Matsunga T, Mitsuda S, Suzuki S. (1977). Microbial electrode BOD sensors. Biotechnol Bioeng 19:1530–47.
Kassongo J, Togo CA. (2011b). Performance improvement of whey-driven microbial fuel cells by acclimation of indigenous anodophilic microbes. African J Biotechnol 10:7846–52.
Kassongo J, Togo CA. (2011a). The impact of electrode reuse on the biofilm community and performance of whey-fuelled H-type microbial fuel cell. African J Microbiol Res 5:1090–6.
Kaur A, Kim JR, Michie I, et al. (2013). Microbial fuel cell type biosensor for specific volatile fatty acids using acclimated bacterial communities. Biosens Bioelectron 47:50–5.
Kelly ID, Holland O, Scull M, McFarland D. (1999). Artificial autonomy in the natural world: building a robot predator. Proceedings of the 5th European Conference on Artificial Life. Swiss Federal Institute of Technology, Lausanne (EPFL). Switzerland: Springer-Verlag, 289–93.
Khunjar WO, Sahin A, West AC, Chandran K, Banta S. (2012). Biomass production from electricity using ammonia as an electron carrier in a reverse microbial fuel cell. PLoS One 7:e44846.

Kim B, Chang I, Hyun M, Kim H, Park H. (2001). A biofuel cell using wastewater and active sludge for wastewater treatment. International patent WO0104061, Jan 18.

Kim BH, Chang IS, Gadd GM. (2007). Challenges in microbial fuel cell development and operation. Appl Microb Biotechnol 76:485–94.

Kim BH, Chang IS, Gil GC, Park HS, Kim HJ. (2003a). Novel BOD sensor using mediator-less microbial fuel cell. Biotechnol Lett 25: 541–5.

Kim BH, Park HS, Kim HJ, et al. (2004). Enrichment of microbial community generating electricity using a fuel-cell-type electrochemical cell. Appl Microbiol Biotechnol 63:672–81.

Kim HJ, Hyun MS, Chang IS, Kim BH. (1999). A microbial fuel cell type lactate biosensor using a metal-reducing bacterium, *Shewanella putrefaciens*, J Microbiol Biotechnol 9:365–7.

Kim HJ, Park HS, Hyun MS, et al. (2002). A mediator-less microbial fuel cell using a metal reducing bacterium, *Shewanella putrefacians*. Enz Microb Technol 30:45–52.

Kim IS, Chae KJ, Choi MJ, Verstraete W. (2008). Microbial fuel cells: recent advances, bacterial communities and application beyond electricity generation. Environ Eng Res 13:51–65.

Kim M, Hyun MS, Gadd GM, et al. (2009). Membrane-electrode assembly enhances performance of a microbial fuel cell type biological oxygen demand sensor. Env Technol 30:329–36.

Kim M, Youn SM, Shin SH, et al. (2003b). Practical field application of a novel BOD monitoring system. J Environ Monit 5: 640–3.

Kluger J. (1997). Uncovering the secrets of Mars. Time 14 July, 26–36.

Kreysa G, Juttner K, Lapique F, et al. (1994). Electrochemical engineering and energy. New York: Plenum.

Kruzic AP, Kreissi JF. (2009). Natural treatment and onsite systems. Water Environ Res 81:1346–60.

Kumlanghan A, Liu J, Thavarungkul P, et al. (2007). Microbial fuel cell-based biosensor for fast analysis of biodegradable organic matter. Biosens Bioelectron 22:2939–44.

Lee Y, Nirmalakhandan N. (2011). Electricity production in membraneless microbial fuel cell fed with livestock organic solid waste. Biores Technol 102:5831–5.

Lefebvre O, Mamun AA, Ooi WK, et al. (2008). An insight into cathode options for microbial fuel cells. Water Sci Technol 57: 2031–7.

Li H, Feng Y, Zou X, Luo X. (2009b). Study on microbial reduction of vanadium matallurgical waste water. Hydrometallurgy 99:13–7.

Li H, Ni J. (2011). Treatment of wastewater from *Dioscorea zingiberensis* tubers used for producing steroid hormones in a microbial fuel cell. Biores Technol 102:2731–5.

Li Y, Lu A, Ding H, Jin S, et al. (2009a). Cr(VI) reduction at rutile-catalyzed cathode in microbial fuel cells. Electrochem Comm 11: 1496–9.

Li Z, Zhang X, Lei L. (2008). Electricity production during the treatment of real electroplating wastewater containing Cr^{6+} using microbial fuel cell. Processes Biochem 43:1352–8.

Liang M, Tao HC, Li SF, et al. (2011). Treatment of Cu^{2+}-containing wastewater by microbial fuel cell with excess sludge as anodic substrate. Env Sci Technol 32:179–85.

Liu H, Grot S, Logan BE. (2005). Electrochemically assisted microbial production of hydrogen from acetate. Environ Sci Technol 39: 4317–20.

Liu L, Yuan Y, Li F, Feng C. (2011a). In-situ Cr(VI) reduction with electro-generated hydrogen peroxide driven by iron-reducing bacteria. Biores Technol 102:2468–73.

Liu Z, Liu J, Zhang S, et al. (2011b). Microbial fuel cell based biosensor for in situ monitoring of anaerobic digestion process. Biores Technol 102:10221–9.

Lobato J, Campo AGC, Fernández FJ, et al. (2013). Lagooning microbial fuel cells: a first approach by coupling electricity-producing microorganisms and algae. Appl Energ 110:220–6.

Logan BE, Call D, Cheng S, et al. 2008. Microbial electrolysis cells for high yield hydrogen gas production from organic matter. Environ Sci Technol 42:8630–40.

Logan BE, Hamelers B, Rozendal R, et al. (2006). Microbial fuel cells: Methodology and technology. Env Sci Technol 40:5181–92.

Logan BE, Regan JM. (2006). Microbial fuel cells -challenges and applications. Environ Sci Technol 40:5172–80.

Logan BE. (2010). Scaling up microbial fuel cells and other bioelectrochemical systems. Appl Microb Biotechnol 85:1665–71.

Lovley DR. (2006). Microbial fuel cells: novel microbial physiologies and engineering approaches. Curr Opin Biotechnol 17:327–32.

Lu N, Zhou B, Deng L, et al. (2009a). Starch processing wastewater treatment using a continuous microbial fuel cell with MnO_2 cathodic catalyst. J Basic Sci Eng 17:65–73.

Lu N, Zhou SG, Zhuang L, et al. (2009b). Electricity generation from starch processing wastewater using microbial fuel cell technology. Biochem Eng J 43:246–51.

Luo H, Liu G, Zhang R, Jin S. (2009). Phenol degradation in microbial fuel cells. Chem Eng J 147:259–64.

Luo Y, Zhang R, Liu G, Li J, et al. (2011). Simultaneous degradation of refractory contaminants in both the anode and cathode chambers of the microbial fuel cell. Biores Technol 102:3827–32.

Luo Y, Zhang RD, Li J, et al. (2010). Electricity generation from indole degradation using the microbial fuel cell. China Env Sci 30:770–4.

Manish S, Banerjee R. (2008). Comparison of biohydrogen production processes. Int J Hyd Energy 33:279–86.

Martin E, Savadogo O, Guiot SR, Tartakovsky B. (2010). The influence of operational conditions on the performance of a microbial fuel cell seeded with mesophilic anaerobic sludge. Biochem Eng J 51:132–9.

Mathuriya AS, Sharma VN. (2009a). Bioelectricity production from paper industry waste using a microbial fuel cell by *Clostridium species*. J Biochem Technol 1:49–52.

Mathuriya AS, Sharma VN. (2009b). Bioelectricity production from various wastewaters through microbial fuel cell technology. J Biochem Technol 2:133–7.

Mathuriya AS, Sharma VN. (2010). Treatment of Brewery Wastewater and Production of Electricity through Microbial Fuel Cell Technology. Int J Biotechnol Biochem 6:71–80.

Mathuriya AS. (2014). Eco-affectionate face of microbial fuel cells. Critical Rev Env Sci Technol 44:97–153.

Mathuriya AS. (2012). Enhanced Tannery wastewater treatment and simultaneous electricity generation in Microbial Fuel cell by bacterial strains isolated from tannery waste. Env Eng Manage J. (Accepted Manuscript). http://omicron.ch.tuiasi.ro/EEMJ/pdfs/accepted/133_605_Mathuriya_11.pdf

Mathuriya AS. (2013). Inoculum selection to enhance performance of a microbial fuel cell for electricity generation during wastewater treatment. Env Technol: Sustain Technol Bioener Biofuel Biowaste Biomass 34:1957–64.

Mayen-Mondragon R, Ibanez JG, Vasquez-Medrano R. (2008). Simultaneous electrochemical oxidation and reduction of representative organic pollutants. Fresenius Environ Bull 17:1294–9.

Mehanna M, Kiely PD, Call DF, Logan BE. (2010a). Microbial electrodialysis cell for simultaneous water desalination and hydrogen gas production. Environ Sci Technol 44:9578–83.

Mehanna M, Saito T, Yan J, et al. (2010b). Using microbial desalination cells to reduce water salinity prior to reverse osmosis. Energy Environ Sci 3:1114–20.

Mehta P, Hussain A, Tartakovsky B, et al. (2010). Electricity generation from carbon monoxide in a single chamber microbial fuel cell. Enz Microb Technol 46:450–5.

Melhuish C, Ieropoulos I, Greenman, J, Horsfield I. (2006). Energetically autonomous robots: food for thought. Autonomous Robots 21:187–98.

Melhuish C, Kubo M. (2004). Collective energy distribution: maintaining the energy balance in distributed autonomous robots. In the proceedings of 7th International Symposium on Distributed Autonomous Robotic Systems, Toulouse, France, p 261–270.

Meyer RL, Larsen LH, Revsbech NP. (2002). Microscale biosensor for measurement of volatile fatty acids in anoxic environments. Appl Env Microbiol 68:1204–10.

Mohanakrishna G, Venkata Mohan S, Sarma PN. (2010). Utilizing acid-rich effluents of fermentative hydrogen production process as substrate for harnessing bioelectricity: an integrative approach. Int J Hyd Ener 35:3440–9.

Moon H, Chang IS, Kang KH, et al. (2004). Improving the dynamic response of a mediator-less microbial fuel cell as a biochemical oxygen demand (BOD) sensor. Biotechnol Lett 26:1717–21.

Morris JM, Jin S, Crimi B, Pruden A. (2009). Microbial fuel cell in enhancing anaerobic biodegradation of diesel. Chem Eng J 146: 161–7.

Morris JM, Jin S. (2012). Enhanced biodegradation of hydrocarbon-contaminated sediments using microbial fuel cells. J hazard mater 213-214:474–7.

Morris JM, Jin S. (2008), Feasibility of using microbial fuel cell technology for bioremediation of hydrocarbons in groundwater. J Env Sci Health A Tox Hazard Subst Env Eng 43:18–23.

Mukherjee S, Su S, Panmanee W, et al. (2013). A microliter-scale microbial fuel cell array for bacterial electrogenic screening. Sen Actuat A Phy 201:532–7.

Mulchandani Rogers KR. (Eds.) (1998). Enzyme and micriobial biosensors: techniques and protocols. Totowa, NJ: Humana Press.

Nam JY, Kim HW, Shin HS. (2010). Ammonia inhibition of electricity generation in single-chambered microbial fuel cells. J Power Sources 195:6428–33.

Nasirahmadi S, Safekordi AA. (2011). Whey as a substrate for generation of bioelectricity in microbial fuel cell using *E. coli*. Int J Env Sci Technol 8:823–30.

Neburchilov V, Mehta P, Hussain A, et al. (2011). Microbial fuel cell operation on carbon monoxide: cathode catalyst selection. Int J Hyd Ener 36:11929–35.

Oh SE, Logan BE. (2005). Hydrogen and electricity production from a food processing wastewater using fermentation and microbial fuel cell technologies. Water Res 39:4673–82.

Pant D, Bogaert GV, Diels L, Vanbroekhoven K. (2010). A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production. Biores Technol 101:1533–43.

Pasco N, Baronian K, Jeffries C, Webber J, Hay J. (2004). MICREDOX(R) – development of a ferricyanide-mediated rapid biochemical oxygen demand method using an immobilised *Proteus vulgaris* biocomponent. Biosen Bioelectron 20:524–32.

Patchett RA, Kelly AF, Kroll RG. (1988). Use of a microbial fuel cell for the rapid enumeration of bacteria. Applied Microbiol Biotechnol 28: 26–31.

Patil SA, Surakasi VP, Koul S, et al. (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. Biores Technol 100: 5132–9.

Pham H, Boon N, Marzorati M, Verstraete W. (2009). Enhanced removal of 1,2-dichloroethane by anodophilic microbial consortia. Water Res 43:2936–46.

Potter MC. (1910). On the difference of potential due to the vital activity of microorganisms. In: Proceedings of University Durham Philosophical Society 3:245–9.

Powell EE, Bolster JC, Hill GA, Evitts RW. (2008a). Complete microbiological fuel cell: A photosynthetic cathode coupled to a fermentative anode. Boca Raton, FL:CRC Press.

Powell EE, Evitts RW, Hill GA, Bolster JC. (208b). A microbial fuel cell with a photosynthetic microalgae cathodic half cell coupled to a yeast anodic half cell. Ener Sources A – Recovery Utilization Env Effects 33:440–8.

Powell EE, Mapiour ML, Evitts RW, Hill GA. (2009). Growth kinetics of *Chlorella vulgaris* and its use as a cathodic half cell. Biores Technol 100:269–74.

Puig S, Serra M, Coma M, et al. (2011). Simultaneous domestic wastewater treatment and renewable energy production using microbial fuel cells (MFCs). Water Sci Technol 64:904–9.

Rabaey K, Rozendal RA. (2010). Microbial electrosynthesis-revisiting the electrical route for microbial production. Nat Rev Microbiol 8: 706–16.

Rabaey K, Verstraete W. (2005). Microbial fuel cells: novel biotechnology for energy generation. Trends Biotechnol 23:291–8.

Rashid N, Cui YF, Saif Ur Rehman, Han JI. (2013). Enhanced electricity generation by using algae biomass and activated sludge in microbial fuel cell. Sci Total Environ 456-457:91–4.

Rittmann BE. (2008). Opportunities for renewable bioenergy using microorganisms. Biotechnol Bioeng 100:203–12.

Rizzo A, Boano F, Revelli R, Ridolfi L. (2013). Can microbial fuel cells be an effective mitigation strategy for methane emissions from paddy fields? Ecolog Eng 60:161–71.

Rosenbaum M, Zhao F, Schröder U, Scholz F. (2006). Interfacing electrocatalysis and biocatalysis with tungsten carbide: a high performance noble-metal-free microbial fuel cell. Angew Chem (Int Ed) 45:6658–61.

Rozendal R, Hamelers HVM, Molenkamp RJ, Buisman CJN. (2007). Performance of single chamber biocatalyzed electrolysis with different types of ion exchange membranes. Water Res 41:1984–94.

Rozendal RA, Hamelers HV, Rabaey K, et al. (2008). Towards practical implementation of bioelectrochemical wastewater treatment. Trend Biotechnol 26:450–9.

Rozendal RA, Hamelers HVM, Euverink GJW, et al. (2006). Principle and perspectives of hydrogen production through biocatalyzed electrolysis. Int J Hydrogen Energ 31:1632–40.

Sangeetha T, Muthukumar M. (2011). Catholyte performance as an influencing factor on electricity production in a dual-chambered microbial fuel cell employing food processing wastewater. Ener Source A Recov Utilization Envl Effect 33:1514–22.

Scott K, Murano C. (2007). A study of a microbial fuel cell battery using manure sludge waste. J Chem Technol Biotechnol 82:809–17.

Shannon MA, Bohn PW, Elimelech M, et al. (2008). Science and technology for water purification in the coming decades. Nature 452: 301–10.

Shantaram A, Beyenal H, Raajan R, et al. (2005). Wireless Sensors Powered by Microbial Fuel Cells. Environ Sci Technol 39: 5037–42.

Sharma Y, Li B. (2010). Optimizing energy harvest in wastewater treatment by combining anaerobic hydrogen producing biofermentor (HPB) and microbial fuel cell (MFC). Int J Hydrogen Energ 35: 3789–97.

Shen Y, Wang M, Chang IS, Ng HY. (2013). Effect of shear rate on the response of microbial fuel cell toxicity sensor to Cu(II). Biores Technol 136:707–10.

Shukla AK, Suresh P, Berchmans S, Rajendran A. (2004). Biological fuel cells and their applications. Curr Sci 87:455–68.

Song T, Xu Y, Ye Y, et al. (2009). Electricity generation from terephthalic acid using a microbial fuel cell. J Chem Technol Biotechnol 84:356–60.

Stamatelatou K, Antonopoulou G, Tremouli A, Lyberatos G. (2011). Production of gaseous biofuels and electricity from cheese whey. Ind Eng Chem Res 50:639–44.

Stein NK, Hamelers HMV, Straten GV, Keesman KJ. (2012). On-line detection of toxic components using a microbial fuel cell-based biosensor. J Process Control 22:1755–61.

Sukkasem C, Laehlah S, Hniman A, et al. (2011). Upflow bio-filter circuit (UBFC): Biocatalyst microbial fuel cell (MFC) configuration and application to biodiesel wastewater treatment. Biores Technol 102:10363–70.

Sun J, Bi Z, Hou B, Cao YQ, Hu YY. (2011). Further treatment of decolorization liquid of azo dye coupled with increased power production using microbial fuel cell equipped with an aerobic biocathode. Water Res 45:283–91.

Sun J, Hu Y, Bi Z, Cao Y. (2009a). Improved performance of air-cathode single-chamber microbial fuel cell for wastewater treatment using microfiltration membranes and multiple sludge inoculation. J Power Sources 87:471–9.

Sun J, Hua YY, Bi Z, Cao YQ. (2009b). Simultaneous decolorization of azo dye and bioelectricity generation using a microfiltration membrane air-cathode single-chamber microbial fuel cell. Biores Technol 100:3185–92.

Sun J, Li W, Li Y, et al. (2013). Redox mediator enhanced simultaneous decolorization of azo dye and bioelectricity generation in air-cathode microbial fuel cell. Biores Technol 142:407–14.

Sun M, Mu ZX, Sheng GP, et al. (2010). Hydrogen production from propionate in a biocatalyzed system with *in-situ* utilization of the electricity generated from a microbial fuel cell. Int J Biodeterioration Biodegrad 64:378–82.

Tandukar M, Huber SJ, Onodera T, Pavlostathis SG. (2009). Biological Chromium(VI) Reduction in the Cathode of a Microbial Fuel Cell. Env Sci Technol 43:8159–65.

Tanino T, Nara Y, Tsujiguchi T, Ohshima T. (2013). Coproduction of acetic acid and electricity by application of microbial fuel cell technology to vinegar fermentation. J Biosci Bioeng 116:219–23.

Tartakovsky B, Manuel MF, Neburchilov V, et al. (2008). Biocatalyzed hydrogen production in a continuous flow microbial fuel cell with a gas phase cathode. J Power Sources 182:291–7.

Tchobanoglous G, Burton FL, Stensel HD. (2003). Wastewater engineering, treatment and reuse. New York: McGraw-Hill.

Todd D. Musk goes for methane-burning resusable rockets as step to colonise Mars. Flight Global Hyperbola. 2012-11-20. http://www.flightglobal.com/blogs/hyperbola/2012/11/musk_goes_for_methane-burning/ [last accessed 16 August 2013].

Tront JM, Fortner JD, Plotze M, et al. (2008a). Microbial fuel cell technology for measurement of microbial respiration of lactate as an example of bioremediation amendment. Biotechnol Lett 30:1385–90.
Tront JM, Fortner JD, Plotze M, et al. (2008b). Microbial fuel cell biosensor for in situ assessment of microbial activity. Biosens Bioelectron 24:586–90.
Velasquez-Orta SB, Head IM, Curtis TP, Scott K. (2011). Factors affecting current production in microbial fuel cells using different industrial wastewaters. Biores Technol 102:5105–12.
Venkata Mohan S, Chandrasekhar K. (2011). Solid phase microbial fuel cell (SMFC) for harnessing bioelectricity from composite food waste fermentation: Influence of electrode assembly and buffering capacity. Biores Technol 102:7077–85.
Venkata Mohan S, Mohanakrishna G, Sarma PN. (2010a). Composite vegetable waste as renewable resource for bioelectricity generation through non-catalyzed open-air cathode microbial fuel cell. Biores Technol 101:970–6.
Venkata Mohan S, Mohanakrishna G, Srikanth S, Sarma PN. (2008). Harnessing of bioelectricity in microbial fuel cell (MFC) employing aerated cathode through anaerobic treatment of chemical wastewater using selectively enriched hydrogen producing mixed consortia. Fuel 87:2667–76.
Venkata Mohan S, Mohanakrishna G, Velvizhi G, et al. (2010b). Bio catalyzed electrochemical treatment of real field dairy wastewater with simultaneous power generation. Biochem Eng J 51:32–9.
Venkata Mohan S, Srikanth S, Sarma PN. (2009). Non-catalyzed microbial fuel cell (MFC) with open air cathode for bioelectricity generation during acidogenic wastewater treatment. Bioelectrochem 75:130–5.
Venkata Mohan S, Srikanth S. (2011). Enhanced wastewater treatment efficiency through microbially catalyzed oxidation and reduction: Synergistic effect of biocathode microenvironment. Biores Technol 102:10210–20.
Virdis B, Rabaey K, Rozendal RA, Yuan Z, Kelle J. (2010). Simultaneous nitrification, denitrification and carbon removal in microbial fuel cells. Water Res 44:2970–80.
Wagner RC, Regan JM, Oh SE, et al. (2009). Hydrogen and methane production from swine wastewater using microbial electrolysis cells. Water Res 43:1480–8.
Wang A, Sun D, Cao G, et al. (2011). Integrated hydrogen production process from cellulose by combining dark fermentation, microbial fuel cells, and a microbial electrolysis cell. Biores Technol 102: 4137–43.
Wang C, Xue A, Zhao HZ, et al. (2009). Performance of a single chamber microbial fuel cell utilizing *Dioscorea zingiberensis C. H. Wright* wastewater. Huan Jing Ke Xue 30:3093–8.
Wang G, Huang L, Zhang Y. (2008). Cathodic reduction of hexavalent chromium [Cr(VI)] coupled with electricity generation in microbial fuel cells. Biotechnol Lett 30:1959–66.
Wang HY, Su JY. (2013). Membraneless microfluidic microbial fuel cell for rapid detection of electrochemical activity of microorganism. Biores Technol 145:271–4.
Wang J, Xia X, Chen S, et al. (2011a). Removing nitrate from wastewater in single and double-chamber microbial fuel cells. Acta Scientiae Circumstantiae 31:254–9.
Wang YH, Wang BS, Pan B, et al. (2013). Electricity production from a bio-electrochemical cell for silver recovery in alkaline media. Appl Energy 112:1337–41.
Watanabe K. (2008). Recent developments in microbial fuel cell technologies for sustainable bioenergy. J Biosci Bioeng 106:528–36.
Wen Q, Kong F, Zheng H, et al. (2011a). Electricity generation from synthetic penicillin wastewater in an air-cathode single chamber microbial fuel cell. Chem Eng J 168:572–6.
Wen Q, Kong F, Zheng H, et al. (2011b). Simultaneous processes of electricity generation and ceftriaxone sodium degradation in an air-cathode single chamber microbial fuel cell. J Power Sources 196: 2567–72.
Wen Q, Wu Y, Zhao L, et al. (2010a). Electricity generation and brewery wastewater treatment from sequential anode-cathode microbial fuel cell. J Zhejiang Univ Sci B 11:87–93.
Wen Q, Wu Y, Zhao L, Sun Q. (2010b). Production of electricity from the treatment of continuous brewery wastewater using a microbial fuel cell. Fuel 89:1381–5.
Wilkinson S, Campbell CS. (1996). Green bug robots — renewable environmental power for miniature robots. Proceedings of 4th IASTED International Conference on Robotics and Manufacturing. Aug 19–22, Honolulu, Hawaii, 275–8.
Wilkinson S. (2000a). ''Gastrobots''—benefits and challenges of microbial fuel cells in food powered robot applications. Autonomous Robots 9:99–111.
Wilkinson S. (2000b). ''Gastronome'' – a pioneering food powered mobile robot. Proceedings of the IASTED International Conference on Robotics and Applications. Aug 14-16, Honolulu, Hawaii 176–181.
Wilkinson S. (1999). Accrued but novel carrot powered 'Gastrobot' for middle or high school demonstrations. Proceedings of 7th IASTED International Conference on Robotics and Applications. Santa Barbara, CaliforniaOct 28–30:347–51.
Williams KH, Nevin KP, Franks A, et al. (2010b). Electrode-based approach for monitoring in situ microbial activity during subsurface bioremediation. Environ Sci Technol 44:47–54.
Williams KH, N'Guessan AL, Druhan J, et al. (2010a). Electrodic voltages accompanying stimulated bioremediation of a uranium-contaminated aquifer. J Geophys Res Biogeosci 115:1–10.
Xiao B, Yang F, Liu J. (2013). Evaluation of electricity production from alkaline pretreated sludge using two-chamber microbial fuel cell. J Hazard Mater 254-255:57–63.
Xue A, Shen ZZ, Zhao B, Zhao HZ. (2013). Arsenite removal from aqueous solution by a microbial fuel cell–zerovalent iron hybrid process. J Hazard Mat 261:621–7.
Yan H, Saito T, Regan JM. (2012). Nitrogen removal in a single-chamber microbial fuel cell with nitrifying biofilm enriched at the air cathode. Water Res 46:2215–24.
Yan Z, Song N, Cai H, et al. (2010). Enhanced degradation of phenanthrene and pyrene in freshwater sediments by combined employment of sediment microbial fuel cell and amorphous ferric hydroxide. J Hazard Mater 199:217–25.
Ye YJ, Song TS, Xu Y, et al. (2009). Electricity generation using high concentration terephthalic acid solution by microbial fuel cell. Huan Jing Ke Xue 30:1221–6.
Yeon RE, Kim M, Lee SJ. (2011). Characterization of microbial fuel cells enriched using Cr(VI)-containing sludge. J Microbiol Biotechnol 21:187–91.
You SJ, Zhang JN, Yuan YX, et al. (2010). Development of microbial fuel cell with anoxic/oxic design for treatment of saline seafood wastewater and biological electricity generation. J Chem Technol Biotechnol 85:1077–83.
You SJ, Zhao QL, Jiang JQ, et al. (2006). Sustainable approach for leachate treatment: electricity generation in microbial fuel cell. J Env Sci Health A: Toxic/Hazard Subs Env Eng 41: 2721–34.
Young JC, Mcdermott GN, Jenkins D. (1981). Alterations in the BOD procedure for the 15th edition of standard methods for the examination of water and wastewater. J Water Pollut Control Fed 53: 1253–9.
Yu CP, Liang Z, Das A, Hu Z. (2011). Nitrogen removal from wastewater using membrane aerated microbial fuel cell techniques. Water Res 45:1157–64.
Yuan Y, Zhou S, Zhuang L. (2010). A new approach to in situ sediment remediation based on air-cathode microbial fuel cells. J Soil Sediment 10:1427–33.
Zang GL, Sheng GP, Li WW, et al. (2012). Nutrient removal and energy production in a urine treatment process using magnesium ammonium phosphate precipitation and a microbial fuel cell technique. Phys Chem Chem Phys 14:1978–84.
Zhang B, Zhao H, Zhou S, et al. (2009a). A novel UASB-MFC-BAF integrated system for high strength molasses wastewater treatment and bioelectricity generation. Biores Technol 100: 5687–93.
Zhang B, Zhu Y. (2011). Simultaneous decolorization and degradation of azo dye with electricity generation in microbial fuel cells. Mechanic Automation and Control Engineering (MACE), Second International Conference. Hohhot; July 15-17:2570–3.
Zhang B. (2011). Microbial fuel cells operated with two respective electron acceptors for energy and metal recovery during treatment of vanadium containing wastewater. ACS National Meeting Book of Abstracts March 30:1–3.
Zhang BG, Zhou SG, Zhao HZ, et al. (2010b). Factors affecting the performance of microbial fuel cells for sulfide and vanadium (V) treatment. Bioproc Biosys Eng 33:187–94.

Zhang C, Li M, Liu G, et al. (2009b). Pyridine degradation in the microbial fuel cells. J Hazard Mat 172:465–71.
Zhang C, Liu G, Zhang R, Luo H. (2010a). Electricity production from and biodegradation of quinoline in the microbial fuel cell. J Env Sci Health A 45:250–6.
Zhang CP, Chen SS, Liu GL, et al. (2012a). Characterization of strain *Pseudomonas* sp. Q1 in microbial fuel cell for treatment of quinoline-contaminated water. Pedosphere 22:528–35.
Zhang LJ, Tao HC, Wei XY, et al. (2012b). Bioelectrochemical recovery of ammonia–copper(II) complexes from wastewater using a dual chamber microbial fuel cell. Chemosphere 89:1177–82.
Zhang X, Zhu F, Chen L, et al. (2013b). Removal of ammonia nitrogen from wastewater using an aerobic cathode microbial fuel cell. Biores Technol 146:161–8.
Zhang YJ, Sun CY, Liu XY, et al. (2013a). Electricity production from molasses wastewater in two-chamber microbial fuel cell. Water Sci Technol 68:494–8.
Zhao F, Slade RCT, Varcoe JR. (2009a). Techniques for the study and development of microbial fuel cells: an electrochemical perspective. Chem Soc Rev 38:1926–39.
Zhao LX, Kong FY, Wang X, et al. (2009b). Cr(VI)-containing wastewater treatment coupled with electricity generation using microbial fuel cell. Modern Chem Ind 29:37–9.
Zhao QL, Jiang JQ, Wang K, Zhang LW. (2010). Simultaneous treatment of sludge and generation of electricity with a microbial fuel cell. J Harbin Eng Univ 31:780–5.
Zhong C, Zhang B, Kong L, et al. (2011). Electricity generation from molasses wastewater by an anaerobic baffled stacking microbial fuel cell. J Chem Technol Biotechnol 86:406–13.
Zhu X, Ni J. (2009). Simultaneous processes of electricity generation and p-nitrophenol degradation in a microbial fuel cell. Electrochem Comm 11:274–7.
Zollinger H. (1991). Color chemistry-synthesis, properties and applications of organic dyes and pigments. New York: VCH Publisher.