

Microbial Fuel Cells: Recent Advances, Bacterial Communities and Application Beyond Electricity Generation

In S. Kim[†], Kyu-Jung Chae, Mi-Jin Choi, and Willy Verstraete¹

Department of Environmental Science and Engineering, Gwangju Institute of Science and Technology (GIST), 261 Cheomdan-gwagiro, Buk-gu,
Gwangju 500-712, South Korea

¹Laboratory of Microbial Ecology and Technology (LabMET), Faculty of Bioscience Engineering, Ghent University,
Coupure Links 653, B-9000 Ghent, Belgium

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Abstract

The increasing demand for energy in the near future has created strong motivation for environmentally clean alternative energy resources. Microbial fuel cells (MFCs) have opened up new ways of utilizing renewable energy sources. MFCs are devices that convert the chemical energy in the organic compounds to electrical energy through microbial catalysis at the anode under anaerobic conditions, and the reduction of a terminal electron acceptor, most preferentially oxygen, at the cathode. Due to the rapid advances in MFC-based technology over the last decade, the currently achievable MFC power production has increased by several orders of magnitude, and niche applications have been extended into a variety of areas. Newly emerging concepts with alternative materials for electrodes and catalysts as well as innovative designs have made MFCs promising technologies. Aerobic bacteria can also be used as cathode catalysts. This is an encouraging finding because not only biofouling on the cathode is unavoidable in the prolonged-run MFCs but also noble catalysts can be substituted with aerobic bacteria. This article discusses some of the recent advances in MFCs with an emphasis on the performance, materials, microbial community structures and applications beyond electricity generation.

Keywords: Bacterial community, Energy, Electricity, Electrochemically active bacteria, Microbial fuel cells

1. Introduction

An increasing need for new energy sources due to the concerns of the limited availability of fossil fuels has motivated the development of microbial fuel cells-based technology. After pioneering studies by groups led by Kim, Zeikus, Lovley and others, microbial fuel cells (MFCs) have attracted considerable attention over the last decade as a sustainable technology for simultaneous electricity generation and wastewater treatment.

Currently, electricity can be generated from any biodegradable compounds, such as pure chemicals and even wastewater.¹⁾ The primary mechanisms for electrochemically active microorganisms, which are the key biocatalysts involved in electricity generation in MFCs, to transfer electrons to the electrodes, metabolic or physiological characteristics, and the fundamentals of the anodic or cathodic reactions are well understood.²⁾ As a way of increasing the performance of MFCs, there has

been considerable work on MFC configurations, their physical and chemical operating conditions, the choice of microorganisms, and optimization of the microbial metabolism to increase electron donation to the electrodes.³⁻⁹⁾ As a result, currently achievable MFC power production has increased by several orders of magnitude (approximately 10^6) in less than a decade.¹⁾ However, many limitations and bottlenecks still need to be overcome in order to achieve full scale applications. This might be accomplished with a better understanding of the bacterial community and dominant anodic species. Community analysis of anodic biofilms enriched in electrochemically active organisms has been carried out by several researchers. These studies showed that electrochemically active bacteria are widespread in nature and belong to most phyla of bacteria. The bacterial consortia and predominant species vary with the operational conditions, such as inoculum and substrate type.^{1,10-15)} The considerable diversity of bacterial consortia in the anode biofilm suggests the potential existence of other unknown species, beyond the well-known iron reducing bacteria, such as *Geobacter* and *Shewanella* species.

In recent years, as a result of the rapid advances in MFC re-

[†] Corresponding author
E-mail: iskim@gist.ac.kr
Tel: +82-62-970-2436, Fax: +82-62-970-2434

search, there are several valuable reviews on MFCs reported. These include the following: the microbial metabolism and parameters defining the performance of MFC,¹⁶⁾ MFC methodology and characterizations,⁶⁾ electricity-producing bacterial communities,¹⁾ the characteristics of electrochemically active bacteria in a mediator-less system,¹⁷⁾ microbial physiology and engineering approaches regarding Benthic Unattended Generators (BUGs) for powering remote sensors,¹⁸⁾ the primary mechanism for electron transfer of electricigens to electrodes,¹⁹⁾ the advantages and disadvantages of MFCs compared to the conventional anaerobic digestion technology,²⁰⁾ the inherent constraints of MFCs and suggestion for MFC performance improvement,²¹⁾ the recent advances in MFC configurations and performances,²²⁾ and the anodic electron transfer mechanisms in electrochemically active bacteria.²⁾ Therefore, this article presents a critical review on the advances in MFC with an emphasis on the performances of MFC, materials, operational factors, microbial community structures, and applications beyond electricity generation.

2. MFC Configurations and Designs

In order to increase the power output of MFCs, many studies have focused on altering their designs to overcome the barriers to electron and proton transport and to enhance the surface area and reactivity of the electrodes. The essential physical components of MFCs are the anode, cathode and proton exchange membrane (PEM, or more precisely a cation exchange membrane (CEM)), as shown in Fig. 1. Electrochemically active bacteria in the anode chamber oxidize the substrate, and separate the electrons from protons. These electrons and protons travel to the cathode, the former through an external circuit, and the latter diffusing through the electrolyte and a PEM. The protons and electrons subsequently combine at the cathode with oxygen, aided by a catalyst such as platinum, to form water.

A number of configurations for MFCs have been developed. These are run in batch, fed-bath, or continuous mode, and have a variety of shapes. A two-chambered configuration is a typical MFC, which consists of an anode and a cathode chamber separated by a CEM such as Nafion^{23,24)} or Ultrex,^{25,26)} or even by a salt bridge.²⁷⁾ Recently, there has been considerable attention on a single-chambered MFC, which does not require a cathode compartment because the cathode is exposed directly to air.^{7,28)} Single-chambered MFCs are quite attractive for increasing the power output because they can be run without artificial aeration in an open air cathode systems and can reduce the internal ohmic resistance by avoiding the use of a catholyte as a result of combining two chambers. The membrane-less configuration is the most significant advantage of single-chambered MFCs. However, many single-chambered MFCs still use Nafion (or PEM) as a physical separator, where Nafion is either hot-pressed directly onto the cathode or works as a membrane electrode assembly.^{8,12)} In this case, the use of a catholyte can be avoided but a Nafion membrane rather is still used. The undesirable back diffusion of oxygen from the cathode to the anode and microbial contamination of the cathode are the two major concerns with single-chambered MFCs. A substantial increase in oxygen transfer into the

anode chamber in the absence of a PEM was reported.⁸⁾ On the other hand, even with a relatively low power output, two-chambered MFCs can have a wide variety of applications. Cathodic denitrification (nitrate removal as an opportunity for cathodes) or external power assisted biohydrogen production is good example (explained in detail in a later section). Although membrane-less single chambered MFCs could probably be the future of MFCs due to their elimination of membrane associated problems, there is still considerable room for a two chambered system. Jang et al. (2004) suggested a continuous upflow membrane-less MFC, in which the anode is at the bottom and the cathode at the top, with a physical separation by glass wool and glass beads instead of membranes.³⁾ In this system the fuel is supplied continuously to the bottom of the anode and the effluent passes through the cathode compartment. This configuration is attractive for wastewater treatment due to its easy scale-up and lack of CEM associated limitations, such as proton transfer problems.^{3,29)} However, oxygen back diffusion is a critical drawback, which is more severe than in membrane-used MFCs. Recently, Clauwaert et al. (2007) demonstrated successful generation of electricity using an open air biocathode system with microorganisms that act as biocatalysts for oxygen reduction instead of chemical catalysts. This is an encouraging finding because noble catalysts can be substituted with aerobic bacteria.³⁰⁾

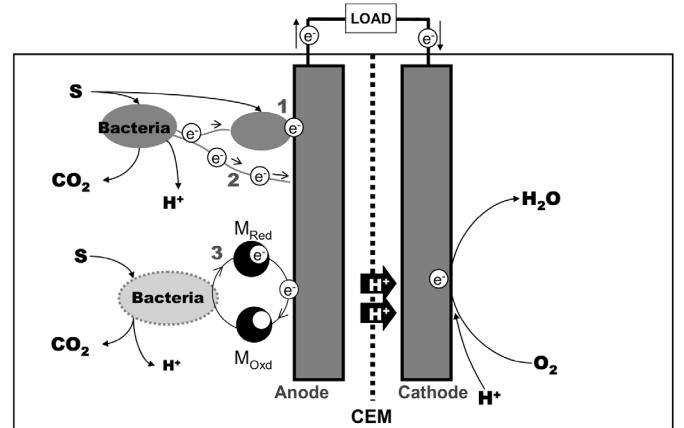


Fig. 1. Conceptual diagram of a microbial fuel cell. This configuration is a typical two-chambered type with an oxygen cathode. The air-breeding single chambered system does not require a cathodic chamber. The electrons produced from anodic organic oxidation flow through an external circuit, whereas the protons are transported through the CEM. The electrons and protons combine with oxygen at the cathode to form water. The final electron acceptors are as diverse as oxygen, ferricyanide, hydrogen peroxide, and nitrate. The electrons retrieved from the microbial oxidation of the substrate are transferred to the anode by diverse ways such as direct electron transfer from the attached bacteria (1), highly conductive nanowires produced by specific bacteria as a long distance transfer (2), and an exogenous mediator or bacterial-origin mediator (3). The use of a CEM is optional. S: substrate, CEM: cation exchange membrane, M_{Red}: reduced mediator, M_{Oxid}: oxidized mediator.

3. Electrode Materials and Catalysts

Currently, finding or choosing the proper materials, such as the anode, cathode electrodes, and a CEM is one of the critical

challenges for practical applications of MFC. The specific materials for each compartment used in MFCs can affect the power density (PD) and coulombic efficiency (CE). The coulombic efficiency is defined as the ratio of total electrons recovered as current, to maximum possible electrons if all substrate removal produced current. Table 1 gives a summary of the basic components and materials of MFCs. The materials for the anode electrode must be noncorrosive, conducting, biocompatible, and chemically stable in an electrolyte.^{6,31)} Carbon felt is a common electrode material because it is inexpensive, has a high surface area, and is highly conducting but quite fragile. Many studies have attempted to increase the anode performance by adapting chemical and physical modification of electrode materials. It was reported that the electrical energy produced by MFC was increased 1000-fold by adapting a Mn⁴⁺-graphite anode and a Fe³⁺-graphite cathode (788 mW/m²) compared with a woven graphite anode (0.17 mW/m²).³²⁾ A polytetrafluoroaniline or poly(2-fluoroaniline) modified electrode showed a higher level of current generation capacity than the unmodified platinum electrode (530 µA/cm² for polytetrafluoroaniline, 455 µA/cm² for poly(2-fluoroaniline), 11 µA/cm² for unmodified platinum electrode).^{33,34)} Other modified anodes with anthraquinone-1, 6-disulfonic acid (AQDS) or a graphite-ceramic composite containing Mn²⁺ and Ni²⁺ showed 1.7- 2.2 times greater kinetic acti-

vity and 5 times greater power density than plain graphite.³⁵⁾ Anode materials modified with inorganic or organic charge transfer mediators have shown improved kinetics, more rapid transfer of electrons. Moreover, the addition of a mediator may directly reduce the extracytoplasmic electron carriers.

In the cathode compartment, expensive catalysts, such as platinum, are generally used to reduce the high overpotential for oxygen reduction.²⁸⁾ A plain carbon cathode recorded only a maximum power of 0.02 mW, whereas 0.097 mW was obtained with a Pt-coated (0.5 mg/cm²) carbon electrode.⁹⁾ Recently, noble metal-free catalysts, such as pyrolyzed iron phthalocyanine (FePc) or cobalt tetramethoxyphenylporphyrin (CoTMPP), and even non-catalysts showing comparable performance to a catalyzed cathode³⁶⁾ have been applied with successful current generation, as summarized in Table 2. Interestingly, aerobic bacteria can also be used as cathode catalysts, so-called biocathodes. However, there are contradictory reports regarding their efficiency.^{3,37,38)} Aerobic bacteria respire oxygen at the maximum capacity in a dissolved oxygen (DO) concentration as low as 0.1 mg/L because the terminal oxidases of the aerobic respiratory electron transport systems have substantially strong affinity for oxygen.²¹⁾ He and Angenent (2006) showed an increase in the performance of MFC with the development of a biofilm on the cathode.³⁸⁾ This is quite encouraging because not only biofou-

Table 1. Basic components and materials for MFCs

Components	Materials	Remarks	References
Anode	Stainless steel mesh, graphite plates, rods, granules, carbon felt, carbon paper, carbon cloth, carbon foam, glassy carbon, Pt, Pt black, reticulated vitreous carbon	- Necessary - Must be noncorrosive, conductive, biocompatible, chemically stable, and non-toxic	5, 24, 26, 31, 50, 96-99)
Cathode	Graphite, carbon felt, carbon paper, carbon cloth, carbon form, glassy carbon, Pt, Pt black, reticulated vitreous carbon	- Necessary	
Ion exchange membrane ^a	CEM (Nafion, Ultrex), salt bridge, anion exchange membrane	- Optional - Permeable to O ₂ , ferricyanide, ions, organic matters (drawbacks)	25, 49, 84)
Electrode catalyst ^b	Pt, Pt black, MnO ₂ , polyaniline, electron mediator immobilized on anode	- Optional - To overcome high overpotential for O ₂ reduction	28, 36, 52, 75, 99, 100)

^a Single-chambered systems, such as the air cathode and membrane-less upflow MFC, do not require an ion exchange membrane.

^b Biocathode system without noble catalyst functions efficiently.

Table 2. Comparison of the power density and Coulombic efficiency obtained from MFCs with different cathodic catalysts

Cathode material	Catalyst	Electron acceptor	Electrode surface area (cm ²)	CE (%) ^a	PD (W/m ³) ^b	References
Carbon paper	None	Air	11.3	NM	0.064	9)
Carbon paper	Pt (0.5 mg/cm ²)	Air	11.3	63-78	0.312	9)
Carbon cloth	CoTMPP (2 mg/cm ²)	Air	30	NM	13.88 ^c	100)
Graphite foil	FePc (2 mg/cm ²)	Air	30	NM	14.32 ^c	100)
Graphite foil	Pyr-FePc (1 mg/cm ²) ^d	Air	60	NM	9.20	51)
Carbon cloth	None	Air	7	10-20	0.093 W/m ²	28)e
Carbon cloth	Pt (0.5 mg/cm ²) + CoTMPP (0.6 mg/cm ²)	Air	7	7.9-16.3	0.369 W/m ²	28)e
Carbon cloth	CoTMPP (0.5 mg/cm ²)	Air	7	19.7	0.483 W/m ²	90)e
Carbon cloth	FePc-KJB (0.5 mg/cm ²) ^f	Air	7	28.29	0.53 W/m ²	90)e
Carbon cloth	Pt (1 mg/cm ²)	Air	7	19.6	0.474 W/m ²	90)e
Graphite granule	None	Air	1260	65	21	36)

^a NM: not mentioned.

^c Acidified catholyte (pH 3.3) was used.

^e Single-chambered MFC.

^b Watt per anode volume.

^d Pyrolyzed FePc.

^f FePc on Ketjenblack (KJB) carbon.

ling (or bacterial contamination) on the cathode is unavoidable in prolonged-run MFCs but also a noble catalyst can be substituted with aerobic bacteria if they produce a successful performance. In contrast, a significant decrease in performance was observed in a membrane-less MFC probably due to oxygen deficiencies on the cathode as a result of the competitive oxygen consumption by heterotrophic bacteria in the cathode biofilm.³⁷⁾

In addition, typical MFC designs require a CEM to separate the anode and the cathode compartment. Nafion (DuPont, USA) is the most commonly used CEM but it is expensive. Ultrex CMI-7000 (Membrane International Inc., Glen Rock, NJ) is as an alternative because it is cheap and shows comparable (in some cases much better) performance to Nafion. Recently, instead of CEM, an anion exchange membrane has been applied to MFC or the modified MFC for biohydrogen production.^{39,40)} Although Nafion was called a PEM due to the expectation of selective proton transport in the early research stage, it should be named a CEM based on the active transport of other cations (Na^+ , K^+ , NH_4^+ , Ca^{2+} , and Mg^{2+}) rather than protons,^{41,42)} which inhibit proton transport through Nafion and eventually reduce the performance of MFCs.

4. MFC Operational Factors

The performance of MFCs is affected by a variety of operational factors such as pH, DO concentration, temperature, and electrolyte strength. The power output cannot reach the theoretical value due to the overpotential related to ohmic, activation and concentration losses. These losses can be reduced by optimizing the reactor configuration, such as minimizing the electrode spacing, applying a high protons-selective membrane, increasing the electrode surface area and improving catalyst activity etc.^{43,44)} Fig. 2 summarizes the potential losses that occur during electron transfer in a MFC.

In order to achieve a better performance of MFCs, the anode material should have a larger surface area with relatively fewer activation losses.³¹⁾ The level of current generation is proportional to the electrode surface areas: a threefold higher current was generated with graphite felt (200 cm^2 as geometric surface area) than with graphite rods (65 cm^2).³¹⁾ The closer electrode spacing between the anode and cathode indicates a lower internal resistance, which facilitates the proton transport through the CEM.^{3,43)} As electrode spacing was decreased from 4 to 2 cm, the power density was increased by 168%.⁴⁵⁾ However, when the distance between both electrodes was decreased from 2 cm to 1 cm the power output from the single chambered MFC was reduced from 811 to 423 mW/m² with a similar decrease in the CEs from 28 to 18%. This contrary decrease is probably due to the more severe damage to the anodic bacteria by oxygen that diffuses more readily through a cathode exposed to air when the distance is decreased further.⁴⁶⁾

The level of DO affects the performance of MFCs. Oxygen is not only essential due to its role as an electron acceptor in the cathode but also plays an inhibitory role on anaerobic anodic bacteria. DO is a major limiting factor when oxygen is unsaturated.^{3,5,47)} The power output caused by the DO concentration

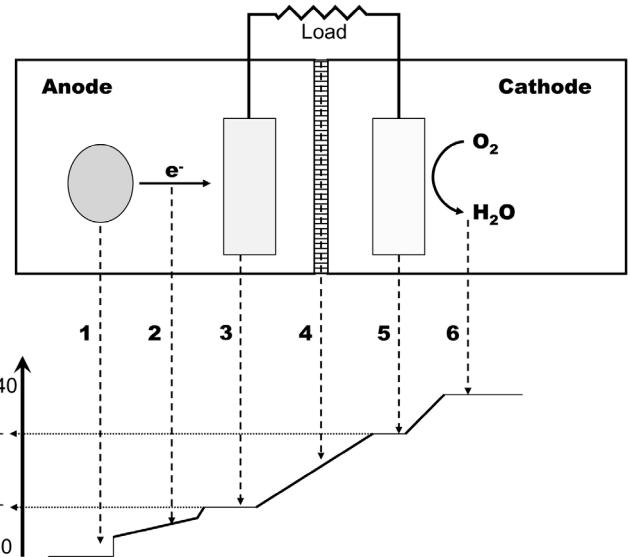


Fig. 2. Various potential losses during electron transfer in a MFC. 1) Losses due to bacterial electron transfer. 2) Losses due to electrolyte resistance. 3) Losses at the anode. 4) Losses at the MFC resistance (useful potential difference) and membrane resistance losses. 5) Losses at the cathode. 6) Losses due to electron acceptor reduction. The maximal open circuit potentials observed in a MFC are approximately 750–800 mV, but the practically achievable MFC potentials under a closed electrical circuit are typically 300–450 mV due to overpotential (drawn with modification after Rabaey and Verstraete, 2005).¹⁶⁾

followed the Monod relationship with a half saturation constant, K_{DO} , of 1.74 mg O₂/L in a two-chambered MFC,⁹⁾ and there was no further increase in PD above a DO concentration of 6.6 mg/L.⁴⁷⁾ It should be noted that excess DO can adversely decrease the CE due to the undesirable growth of heterotrophic bacteria that compete with the anodic electricigens as a result of oxygen back diffusion to the anode. Oxygen is the most favorable final electron acceptor on account of its abundance and non-toxicity. However, ferricyanide ($\text{K}_3[\text{Fe}(\text{CN})_6]$) is also popular due to its low overpotential.³²⁾ A comparison of the CEs and PDs between oxygen and ferricyanide-used MFC showed no significant differences if one data point of an extremely noticeable PD obtained using ferricyanide is ignored (Fig. 3). Some researchers reported remarkable power outputs with ferricyanide of 7200 mW/m²⁴⁸⁾ 3600 mW/m²²⁵⁾ and 4310 mW/m²⁴⁹⁾ compared with those obtained with oxygen (e.g., 788 mW/m²,^{2,32)} 496 mV/m²⁸⁾). However, ferricyanide requires regular replacement due to the insufficient reoxidation of hexacyanoferrate(II),^{47,50)} and diffuses to the anode through the CEM⁶⁾ and inhibits anodic bacteria. Kim et al. (2006) reported that the cathodic reaction is a serious limiting factor in a MFC, and proton mass transfer is the main constraint in a MFC, increasing the internal resistance. This suggests that the choice of the proper cathodic catalyst or electron acceptor is critical for achieving a better performance of MFCs.¹⁰⁾

The PD and current generation increase with increasing ionic strength (i.e., conductivity) of electrolytes: a maximum PD of 720 and 1330 mW/m² for an electrolyte with an ionic strength of 100 and 400 mM, respectively.^{5,45,51)} This was attributed to

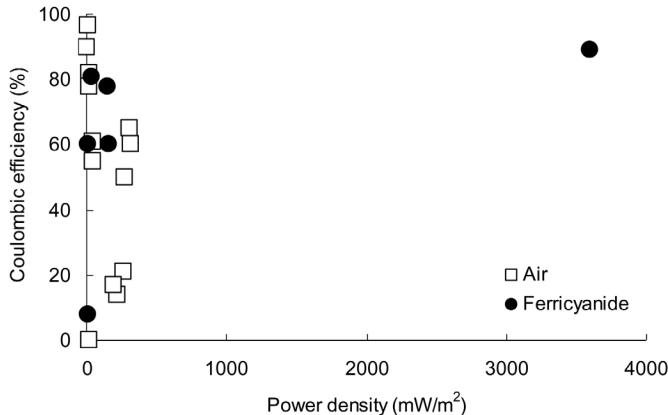


Fig. 3. Comparison of the efficiency (CEs and PDs) of different electron acceptors in the cathode of two-chambered MFCs based on published results providing both CEs and PDs. Single-chambered systems are not included in this comparison.^{9,12,23,25,31,53,55,70,82-86}

the decreased internal resistance (R_{int}) as a result of the increasing electrolyte strength (R_{int} : 161 Ω for 100 mM, 91 Ω for 200 mM, and 79 Ω for 400 mM). However, the strength of electrolytes should be changed within the proper limits for bacterial growth because an excessively strong electrolyte alters the osmotic pressure of the bacterial cell membrane.

The size of the CEM is also important because it governs the internal resistance of a MFC as a consequence of mass transport (e.g., protons and ions) through the CEM. Oh and Logan (2006)⁵³ reported that the power density increases with increasing CEM size (45 mW/m² at 3.5 cm², 68 mW/m² at 6.2 cm², and 190 mW/m² at 30.6 cm²).

External resistance is another important factor that affects the performance of a MFC. The maximum power output can be achieved when the internal resistance is equal to the external resistance.⁶ The polarization curve is an efficient way of determining the optimum external resistance. In a polarization curve, the internal resistance can be calculated from Ohm's law using the specific voltage and current obtained at the point of maximum power density.

A decrease in pH in the anode chamber due to proton accumulation during substrate degradation and a corresponding increase in pH in the cathode chamber of prolonged-run MFCs is a common CEM-associated problem as reported previously.^{41,42} Recently, the lower activation energy for oxygen reduction and the enhanced power output was suggested at a relatively lower pH of the catholyte.^{36,51}

Interestingly, the operating temperature of MFCs does not show any noticeable difference in CE or PD.^{45,52} The PD was decreased by 9% and the CE was almost same when temperature was changed from 32°C (CE: 25-46%) to 20°C (CE: 17-45%).⁴⁵

5. MFC Performances

The performance of a MFC is affected by a variety of factors, such as reactor configuration, type of seed culture or substrate, and various operational parameters, such as pH, DO, and electrolyte strength. Table 3 summarizes the performance obtained

from various studies. In many cases, it is difficult to compare the results reported in the literature because the key experimental parameters were sometimes not provided or the critical comparative measurements of electrical output were not reported. Several studies showed an at least one order of magnitude difference in the PD, even in cases of MFCs using a similar seed culture and substrate.

The power outputs of MFCs have improved rapidly over the last decade. Fig. 4 compares the trends of power improvement in single- or two-chambered MFCs using air as the terminal electron acceptor at the cathode. However, the low CE and low power output of MFCs are a major limitation to their wider application. The highest power outputs are still less than several watts per square meter of the anode surface, even when a readily biodegradable pure substrate, e.g. glucose, is used. This power is not sufficient to power a mechanical device (e.g., pump or blower), which is essential in full scale wastewater treatment plants. However, the currently achievable MFC power production has been improved by several orders of magnitude (approximately 10⁶) within a short period.¹ This improvement was obtained by altering their experimental designs such as optimization of the MFC configurations, their physical and chemical operating conditions, and their choice of microorganisms.^{3-6,9} For example, by using a larger CEM (30.6 cm²), the power was increased by 184% compared with that obtained with a smaller CEM (3.5 cm²).⁵³ In addition, enhanced voltage and current generation can be achieved using a stacked MFC with a hexacyanoferrate cathode by connecting several MFCs either in series or in parallel.⁵⁴ The connection of the 6 MFC units produced an increase in voltages (2.02 V at 228 W/m³) and current (255 mA at 248 W/m³), while retaining high power output.

Fig. 5 shows the performance of single-chambered and two-chambered systems, in which the electron acceptor is identical as oxygen. Single-chambered MFCs generally show much greater PDs but much less CEs than those obtained with the two-chambered systems (Figs. 4 & 5). The much greater PDs in single-chambered MFCs are most likely due to the low internal resistance, which implies their more preferentiality for the practical application. However, the much lower CEs in the single-chambered systems are caused by the growth of undesirable aerobic microorganisms as a result of the more severe oxygen

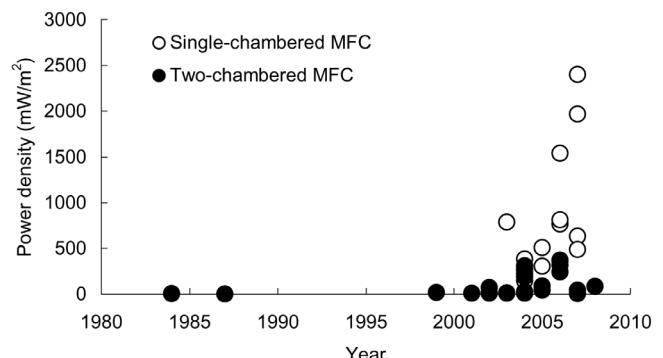


Fig. 4. Trends of power output in MFCs using oxygen (air) as the electron acceptor over time based on published results. Ferricyanide-driven MFCs are not included in this figure.^{5,7-9,12,13,23,28,32,46,51-53,55,70,75,82,84-95}

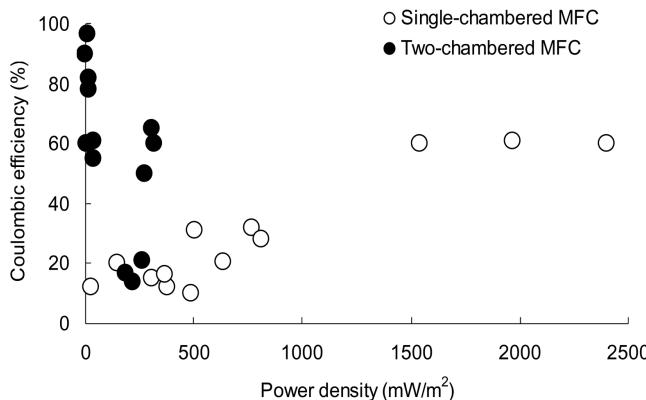


Fig. 5. CEs and PDs obtained from different configurations (single-chambered vs. two-chambered system) of MFCs using oxygen (air) as the electron acceptor. The data is based on published results providing both CEs and PDs. Ferricyanide driven-systems are not included in this comparison.^{7-9,12,23,28,46,53,55,70,75,82,84,86-90}

diffusion from the cathode to the anode with no membrane separation.³⁹ As ferricyanide was used as the electron acceptor at the cathode, considerably greater PDs were achieved even in the two-chambered MFCs: 3600 mW/m²²⁵ and 4300 mW/m²⁴⁹. A comparison of the effectiveness of different electron donors on the performance of air-supplied cathode MFCs showed that wastewater produces less power and a lower CE than pure chemicals, such as acetate and glucose (Fig. 6). This is probably due to the nature of the fuel. In other words, wastewater containing complex compounds requires the assistance of fermentation bacteria for the utilization by electricigens, which use lower-carbon compounds such as acetate, in the metabolism for electricity generation. The participation of these fermentation

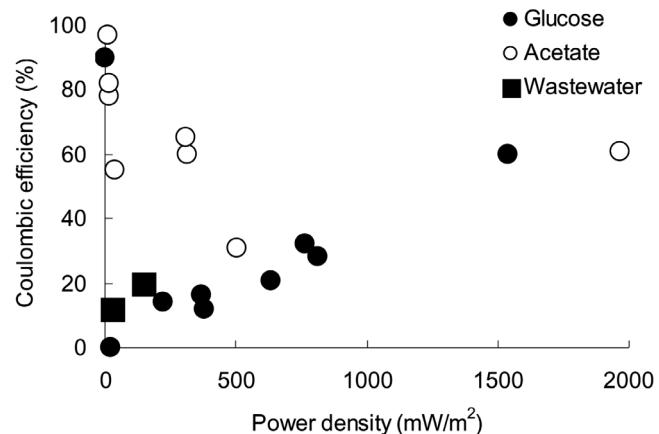


Fig. 6. Effects of different electron donors on the CEs and PDs for MFCs using oxygen (air) as the electron acceptor. The data is based on published results providing both CEs and PDs irrespective of single- or two-chambered MFCs. Ferricyanide driven-systems are not included in this comparison.^{7-9,12,23,28,32,46,53,55,70,75,84-86,88-90,95}

bacteria results in a lower CE due to their competition with electricigens for the substrate. Glucose results a relatively higher PD but acetate results in a relatively higher CE.

6. Bacterial Community and Viability

6.1. Biocatalyst and Bacterial Community Structure

The electrochemically active bacteria on the anode in MFCs are widely referred to as electricigens,¹⁹ anodophilic bacteria⁶ and exoelectrogens,¹ based on their ability to exocellular transfer electrons to the electrodes without of the need for exogenous

Table 3. Performances obtained from the various MFCs

MFC configuration ^a	Feeding mode	Electron donor (g COD/L) ^b	Electron acceptor	CEM	CE (%)	PD (mW/m ²)	References
TC	Fed-batch	Acetate (0.056)	Air	Nafion 117	82	14	23)
TC	Fed-batch	Glucose (1.92)	Ferricyanide	Nafion 117	81	31	31)
TC	Continuous	Glucose (1.0)	Air	Nafion 117	14	220	70) c
TC	Continuous	Glucose (1.0 g/L·d)	Ferricyanide	Ultrex	20	37 W/m ³	98) d
TC	Continuous	Acetate (1.61 g/L·d)	Ferricyanide	Ultrex	65	21 W/m ³	36) d
TC	Fed-batch	Ethanol (0.093)	Air	Nafion 117	61	40	12)
TC	Continuous	Wastewater (4.316)	Ferricyanide	Nafion 117	NM ^e	119.3	101)
TC	Continuous	Wastewater (4.316)	Air	Nafion 117	NM ^e	82.3	101)
SC	Fed-batch	Glucose (NM ^e)	Air	Nafion 117	28	262	8)
SC	Fed-batch	Glucose (NM ^e)	Air	None	20	494	8)
SC	Continuous	Wastewater (0.2)	Air	Nafion 117	12	26	75)
SC	Fed-batch	Acetate (0.76)	Air	None	31	506	7)
SC	Fed-batch	Glucose (0.54)	Air	None	32	766	88)
SC	Fed-batch	Acetate (0.95)	Air	None	61	1970	89)
SC	Fed-batch	Ethanol (0.47)	Air	None	10	488	12)
SC	Fed-batch	Acetate (0.95)	Air	None	60	2400	87) f
UMFC	Continuous	Sucrose (0.57 g/L·d)	Hexacyanoferrocene	Ultrex	51	29 W/m ³	38) d

^a TC: two-chambered; SC: single-chambered; UMFC: upflow microbial fuel cell.

^b Flat plate microbial fuel cell.

^c Not mentioned.

^b Calculated as chemical oxygen demand (COD) equivalent.

^d Granular graphite as the anode material.

^e Graphite fiber brush anode electrode was installed to obtain much higher surface area.

mediators. They can completely oxidize organic compounds to carbon dioxide with the electrode serving as the sole electron acceptor. Electron transfer can occur either through membrane-associated components,⁴⁹⁾ soluble electron shuttles generated by specific bacteria,⁵⁵⁾ or highly conductive nanowires.⁵⁶⁻⁵⁸⁾ The mechanisms for electron transfer to the electrodes were reviewed by Lovley (2006) and Schroder (2007). The properties of well-known electrochemically active bacteria, such as *Shewanella putrefaciens*, *Geobacteraceae sulfurreducens* and *Geobacter metallireducens*, are not covered in this paper.^{2,18)}

In general, when a MFC is inoculated with a mixed culture, only electrochemically active bacteria and others symbiotically related to these bacteria are expected to proliferate. However, according to bacterial community analysis of enriched-anode biofilms from a variety of MFCs, the substantial phylogenetic diversity in the anode community with no single dominant bacterial species have been reported. This considerable diversity suggests the existence of other candidates beyond the well-known *Geobacter* and *Shewanella* species that contribute to electricity generation through various ways. Based on 16S rDNA sequencing analysis, the bacterial consortia and predominant species vary with the operational conditions, such as the inoculum and electron donors, as shown in Table 4.^{1,10-15,59)} The predominance of β -Proteobacteria clones in the phylogenetically

diverse anode community was reported by Kim et al. (2004)¹³⁾ using a two-chamber MFC inoculated with anaerobic sludge and fed starch processing wastewater, by Phung et al. (2004)¹⁴⁾ using a river water fed-MFC with a river sediment inoculum and by Kim et al. (2007)¹²⁾ using ethanol enriched-MFC inoculated with anaerobic sludge. However, δ -Proteobacteria dominated in the MFCs inoculated with aquatic sediments⁶⁰⁾ and Logan et al. (2005)¹⁵⁾ reported the substantial abundance of γ -Proteobacteria in a cysteine-enriched MFC inoculated with sediments. Interestingly, ε -Proteobacteria, which were absent or rare in other studies, were dominant in a unique seawater and marine plankton - filled MFC.⁵⁹⁾ The functional significance of these dominant community members is still unclear, and more in-depth study is needed. The former bacterial communities-related studies were generally carried out with a single substrate or each study used different inoculum, which caused difficulty in making a general comparison because the bacterial communities are influenced not only by substrate but by the inoculum. Chae et al. (submitted) compared the influences of the substrate type (e.g., acetate, propionate, butyrate, and glucose) on the bacterial community using MFCs inoculated with an identical anaerobic sludge in order to normalize for the effect of the inoculum. According to their study, there was a relative abundance of β -Proteobacteria but an absence of γ -Proteobacteria

Table 4. Bacterial communities from a variety of MFCs operated with different inoculums and substrates

Substrate	Inoculums a	MFC types b	Most dominant species	Proteobacteria (%)				Firmicutes (%)	Others (%)	Reference
				α -	β -	γ -	δ -			
Glucose/glutamate	RS	TC	-	64.4	21.1	3.3	0	0	11.1	14)
Glucose/glutamate	Activated sludge	TC	-	1.4	6.8	36.5	14.9	27.0	13.4	63)
Starch processing wastewater	AD	TC	-	27.2	40.9	0	0	4.5	27.1	13)
River water	RS	TC	-	10.8	46.2	12.9	12.9	0	17.2	14)
Acetate	Thermophilic AD	Thermophilic TC	<i>Uncultured clone, clone E4</i> 0 (57.8%)	0	0	0	0	24.1	75.9	61)
Freshwater sediment	FWS	SFC	<i>Geobacter</i>	0	7.0	9.7	53.5	3.0	26.8	60)
Salt marsh sediment	SMS	SFC	<i>Desulfuromonas</i>	7.05	0	8.75	65.2	3.0	15.9	60)
Marine sediment	MS	SFC	<i>Desulfuromonas</i>	7.5	0	2.35	70.0	11.6	14.8	60)
Ethanol	AD	TC	<i>Proteobacterium Core-1</i> (33%)	0	82.6	0	17.4	0	0	12)
Seawater/marine plankton	MP	TC	-	0	0	1	25	0	20 ^c	59)
Seawater/marine plankton	MP	TC	-	0	0	9	33	0	52 ^d	59)
Acetate	AD	TC ^e	<i>Pelobacter propionicus</i> DSM 2379	0	20	0	72	0	8	f
Acetate	AD	TC	<i>Thauera aromatica</i> LG356	2.4	48.8	0.0	31.7	0.0	17.1	f
Propionate	AD	TC	<i>Bacillus sp.</i> NAF001	3.7	18.5	14.8	1.9	59.3	1.9	f
Butyrate	AD	TC	<i>Dechloromonas sp.</i> PCI	18.2	59.1	0.0	13.6	4.5	4.5	f
Glucose	AD	TC	<i>Azonexus caeni</i>	10.0	34.0	0.0	18.0	2.0	36.0	f

^a RS, river sediment; AD, anaerobic digester sludge; MS, marine sediment; FWS, freshwater sediment; SMS, salt marsh sediment; MP, marine plankton.

^b TC, two-chambered MFC; SFC, sediment fuel cell.

^c + ε -Proteobacteria 54%.

^d + ε -Proteobacteria 6%.

^e A modified MFC for hydrogen production with the assistance of external power.

^f Chae et al. (submitted).

observed in all MFCs with the exception of the propionate-fed system. However, a propionate-fed MFC was dominated by *Firmicutes* (59.3% of clones), followed by γ -*Proteobacteria* (18.5%). Similarly, *Firmicutes* have been reported to be integral members of the MFC bacterial community; they can transfer the electrons retrieved from the metabolism of organic matter to the anode.^{49,61-63)} The glucose fed-MFC showed the most diverse community with a relatively broad distribution of α -, β -, and δ -subclasses of *Proteobacteria*, and *Firmicutes*. This was most likely due to the inherent fermentable characteristics of glucose, which results in the diversity of bacteria that can metabolize the soluble fermentation end products of glucose (e.g., acetate, propionate and butyrate).

The electrochemically active bacteria in MFCs are considered to be iron-reducing bacteria, such as *Shewanella* and *Geobacter* species,^{19,23,64)} as a result of their wide observation in many types of MFCs using aquatic sediments.^{15,60)} With the exception of propionate-enriched MFC, *Geobacter*-like species, the most representative being *Geobacter sulfurreducens*, were found to be an integral member of the bacterial community in MFCs fed with acetate (31.7%), butyrate (13.6%), and glucose (14%) (Chae et al., submitted). However, another model strain, *Shewanella*-like sequences, was not detected. Jung and Regan (2007)¹¹⁾ similarly reported the dominance of various *Geobacter*-like strains in their various substrate-fed MFCs but no *Shewanella* sp., even with lactate, which is one of the favorable substrate for *Shewanella* species. Lovley (2006)¹⁹⁾ reported that *Geobacter* species, which directly transfer electrons to electrodes, are more advantageous when competing for space on the anode than *Shewanella* species because of the substrates they utilize. This is probably because *Shewanella* species utilize lactate, which is not a key extracellular intermediate in the anaerobic degradation of organic compounds, and only incompletely oxidize lactate to acetate, leading to inefficient electricity generation. Iron-reducing bacteria in the family *Geobacteraceae* can transfer electrons directly onto an electrode.⁵⁵⁾ However, the range of electron donors that these bacteria can utilize is limited primarily to simple organic acids, such as acetate. Hence, they rely on fermentative bacteria to produce their required electron donors from complex organic compounds, such as glucose. This explains the more diverse composition of the bacterial community in glucose fed-anode biofilms than with other simple substrate-fed MFCs. Based on many reports, *Geobacter* species play a key role in the exocellular electron transfer to the electrodes in MFCs. However, these bacteria require syntrophic or symbiotic bacteria due to their limited substrate versatility, which results in a variety of bacterial community structures, as determined by 16S-rDNA sequencing.

It appears that cooperative consortia and pathways are required to effectively convert organic matter to electricity. Likewise, for the practical application of MFCs, mixed cultures appear more favorable than pure cultures based on both their much wider substrate specificity and power output, due to the synergistic interactions within the more complex cooperative anode communities, including currently unknown species or mechanisms.²¹⁾

6.2. Bacterial Viability on the Anode Biofilms

The quantity of a biocatalyst is one of the most critical factors for the performance of a MFC. Bacterial viability data has important implications for the design of MFCs because an improvement in the performance of MFC can be achieved not only by increasing the surface area of the anode, which simply increases the total bacterial quantity, but also by increasing the number of metabolically viable cells contributing to electron transfer on a given surface. In a MFC with highly structured, multilayer biofilms by *Geobacter sulfurreducens* on the anode surface, bacteria at a distance from the anode remained viable, and there is no decrease in the efficiency of current production as the thickness of the biofilm increased.⁵⁸⁾ Highly conductive nanowires produced by bacteria or conducting pili probably provide an electronic network that permeates the biofilm that can promote long-range electrical transfer in an energy-efficient manner. Therefore, the cells not in direct contact with the anode appear to contribute to current production because they remain viable, and the per-cell efficiency of current production does not decrease as the biofilm develops. Logan and Regan (2006)¹¹⁾ suggested a mound of live bacteria are capable of transferring electrons to the electrode, even when they are distant from the electrode surface, and may be the integral members of the community. According to a study investigating the influence of electron donors on the bacterial viability (Chae et al., submitted), the overall cell viability was similar regardless of the electron donors, such as acetate, butyrate, propionate and glucose. The significant presence of dead bacteria was also observed because of their natural metabolic life cycle or that many bacteria in the inoculum might have adhered to the electrode surface but could not use it as an electron acceptor.¹¹⁾

7. Applications Beyond Electricity Generation

7.1. Biohydrogen Production via Bioelectrolysis

A MFC can also harness energy in the form of hydrogen. The MFC can be modified to produce hydrogen instead of electricity (Fig. 7). This modified system, which was recently suggested and referred to as biocatalyzed electrolysis^{40,65)} or a bio-electrochemically assisted microbial reactor (BEAMR) process,⁶⁶⁾ or electrohydrogenesis,⁶⁷⁾ has been considered an interesting new technology for the production of biohydrogen from organics. However, hydrogen generation from the protons and electrons produced by the anaerobic degradation of a substrate by electrochemically active bacteria in a modified MFC is thermodynamically unfavorable.^{65,66)} This thermodynamic barrier can be overcome by applying an external potential. In this system, the protons and electrons produced by the anodic reaction migrate and combined at the cathode to form hydrogen under anaerobic conditions. The potential for the oxidation of acetate (1M) at the anode and the reduction of protons to hydrogen at the cathode are -0.28 and -0.42 V (NHE), respectively. Therefore, hydrogen can theoretically be produced at the cathode by applying a voltage > 0.14 V (i.e., -0.42 - (-0.28) V), as previously reported by Rozendal

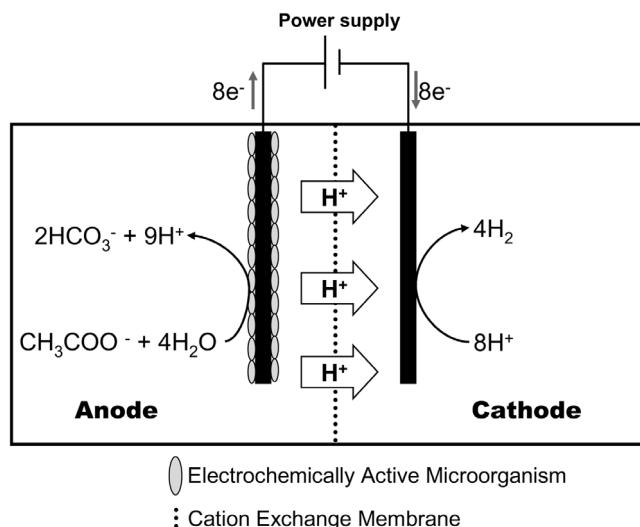


Fig. 7. Schematic diagram of hydrogen production through the biocatalyzed electrolysis of acetate using a modified-MFC assisted by the addition of a small amount of external power (drawn with modification after Rozendal et al., 2006).⁶⁵⁾

et al. (2006).⁶⁵⁾ The required voltage (0.14 V) is substantially lower than that needed to produce hydrogen from the direct electrolysis of water (1.23 V at pH 7), because some of the energy comes from the substrate oxidation process in the anode chamber.

The modified MFCs have many advantages over the technologies currently used to generate hydrogen from organic matter. First, the direct conversion of the substrate to hydrogen enables high conversion efficiency, as shown in Table 5. A notable high yield of 8-9 mol H₂/mol glucose was reported compared to the typical 4 mol H₂/mol glucose achieved by conventional hydrogen producing-dark fermentation.⁶⁶⁾ In biohydrogen production using MFCs, electron loss due to oxygen diffusion in the cathode can be eliminated because oxygen is no longer required in the cathode chamber. In addition, the high purity of hydrogen produced is another advantage over other methods for producing biohydro-

gen from organic materials containing a diverse mixture of biogases or other impurities (e.g. CH₄, CO₂, H₂S, NH₃, etc.), which require expensive gas purification.⁶⁸⁾ Another advantage over an electricity generating-MFC is that hydrogen can be stored for future use e.g. for electricity generation and for transportation fuel, and easily transported to areas of hydrogen demand.⁶⁹⁾

When acetate was used as the sole substrate, Liu et al. (2005)⁶⁶⁾ reported an overall yield of 2.9 mol H₂/mol acetate (72.5% hydrogen recovery) in the BEAMR by supplying 0.85 V. Rozendal et al. (2006)⁶⁵⁾ obtained an overall hydrogen production efficiency of 53% in their biocatalyzed electrolysis system with an applied voltage of 0.5 V. More recently, Rozendal et al. (2007)⁶⁷⁾ suggested a single chamber biocatalyzed electrolysis system by implementing a gas diffusion electrode in two configurations: with both CEM and AEM. The performance of both configurations was comparable but with much lower overall hydrogen production efficiencies of around 23% at 1.0 V than their previous achievement. Recently, the modified MFCs have been operated successfully on a variety of complex substrates.⁶⁷⁾ This substrate versatility provides another opportunity for much wider applications.

Biocatalyzed electrolysis also uses the same biocatalysts, such as electrochemically active microorganisms.^{6,19)} Therefore, electrons and protons are retrieved at the anode in the same manner as with the MFC, except that an external voltage is supplied continuously to reduce the protons to hydrogen at the cathode. This exogenous voltage augmentation probably affects the consortia or viability of the electrochemically active bacteria. However, there are few reports on this subject. Much of the information required is still unclear. Furthermore, unlike single-chambered MFCs, in hydrogen-producing MFCs, the installation of a membrane is essential to separate the hydrogen produced at the cathode from the biogas mixture in the anode chamber. This suggests that in depth consideration is required on the CEM-associated problems.

7.2. Wastewater Treatment and Cathodic Denitrification

Table 5. Biohydrogen production using the bioelectrolysis of a modified hydrogen-producing MFC fed with varying substrates

Substrate	H ₂ yield (mol of H ₂ /mol of substrate)	Overall H ₂ efficiency (%)	MFC type ^a	Applied voltage (V)	References
Acetic acid	2.12	53	TC	0.5	⁶⁵⁾
Acetic acid	0.92	23	SC/AEM	1.0	⁴⁰⁾ b
Acetic acid	2.9	72.5	TC	0.85	⁶⁶⁾
Acetic acid	2.1	52.5	TC	0.8	d
Glucose	8.55	71	TC	0.6	⁶⁷⁾
Cellulose ^c	8.20	68	TC	0.6	⁶⁷⁾
Acetic acid	3.65	91	TC	0.6	⁶⁷⁾
Butyric acid	8.01	80	TC	0.6	⁶⁷⁾
Lactic acid	5.45	91	TC	0.6	⁶⁷⁾
Propionic acid	6.25	89	TC	0.6	⁶⁷⁾
Valeric acid	8.77	67	TC	0.6	⁶⁷⁾

^a TC, two chambered MFC; SC, single chambered MFC.

^b Single chamber bioelectrolysis system in two configurations with an anion exchange membrane or cation exchange membrane.

^c Calculated per mole of hexose equivalent.

^d Chae et al. (submitted).

A MFC can act as a sustainable technology for the simultaneous wastewater treatment for BOD, sulfide even nutrients and electricity production. Electricity generation using a variety of biodegradable materials including not only pure chemicals, such as acetate, glucose, cysteine and ethanol, but also wastewater, such as swine wastewater, food processing wastewater, domestic wastewater, and corn stover, has been reported.^{7,12,15,31,70-75)} With the great energy demand for wastewater treatment, an MFC-based wastewater treatment system can have wide applications because wastewater must be treated and the substrate is free. Furthermore, MFCs yield 50-90% less excess sludge, which eventually reduces the sludge disposal cost.⁶⁹⁾ Despite the rapid advances in MFCs, this technology is still facing considerable challenges before its full scale application, which are mainly related to materials, such as electrodes and CEM. The single-chambered MFC with a continuous flow is considered an alternative system because CEM associated proton transfer problems no longer apply. In particular, continuous upflow membrane-less MFC is attractive for wastewater treatment due to its easy scale-up and free of CEM associated limitations.^{3,29)}

For nutrient removal, MFC cathodes can be driven effectively by biological nitrate reduction to nitrite⁷⁶⁾ or to nitrogen gas.⁷⁷⁾ This type of cathode is referred to as a biocathode when bacteria are used as catalysts to assist in cathodic reduction. Gregory et al. (2004)⁷⁶⁾ reported that a bacterial culture enriched in *Geobacter* species could reduce nitrate to nitrite using the cathode as the sole electron donor. Recently, Clauwaert et al. (2007)³⁰⁾ demonstrated that full biological denitrification is possible at a biocathode in the acetate-fed MFC. They showed an effective application, such as biocathode-based MFC for simultaneous organic removal, power production, and complete denitrification without relying on H₂-formation or external added power.

7.3. Bioremediation

A MFC can be modified in an attractive way for bioremediation because bacteria, such as *Geobacter* species, can not only donate electrons to the anode but can also accept electrons from the cathode if the cathode is poised at a negative potential.^{18,19,76)}

For successful bioremediation of contaminated environments, the addition of an electron acceptor or donor to promote the desired biodegradation is the most common methodology. Electrodes can potentially serve as electron donors or acceptors for the bioremediation of contaminants such as organics or metals in contaminated groundwater. For example, a typical strategy of removing chlorinated solvents from contaminated groundwater is to add organic electron donors to stimulate biological reductive dechlorination. Supplying the electron donors to the target site in the correct amount is difficult. However, supplying the correct amount of electron donor amendment might be possible with electrodes. Gregory et al. (2004)⁷⁶⁾ reported microbial reduction of the oxidized form of soluble uranium U⁶⁺ to insoluble U⁴⁺ and the precipitation of U⁴⁺ onto a cathode when the electrode serves as an electron donor by poising the electrodes with a negative potential (-500 mV). This poised-electrode sys-

tem can act as a potential (or more preferable) strategy for the bioremediation of uranium-contaminated groundwater by simply placing electrodes in wells drilled into contaminated subsurface environments^{19,76,78)} compared to the addition of organic electron donors. Nitrate can also be converted to nitrite when electrodes are used as electron donors.⁷⁶⁾ On the other hand, electrodes can also act as a more convenient electron acceptor for the bioremediation of hydrocarbons compared with diverse electron acceptors such as oxygen, Fe³⁺ and sulfate. *Geobacter metallireducens* oxidizes aromatic hydrocarbon contaminants with an electrode serving as the sole electron acceptor.

Considering that the optimum delivery of electron acceptors or donors to promote the desired biodegradation is the main difficulty in the bioremediation of contaminated subsurface areas with organic pollutants or metals, the electrodes in the modified MFC can be used as an effective alternative for an electron source or sink.

7.4. Biosensors

MFCs have been examined for use in a variety of applications. One of the most common is the use of MFCs as biosensors for pollutant analysis and in situ process monitoring due to the instant and reliable current response during the degradation of electron donors. A MFC using *Shewanella* as a biocatalyst was demonstrated to be an effective sensor for quantifying the biological oxygen demand (BOD) because of the correlation between the Coulombic yield of MFCs and the strength of the wastewater within quite a large range.^{71,79,80)} MFC-based BOD sensors have many advantages, such as an excellent operational stability, reproducibility, and substantially longer life span over 5 years without the need for serious maintenance, compared with other types of BOD sensors. Furthermore, an easy and effective expansion of MFC based sensors to detect other candidates that can act as electron donors for electricity generation is expected.

7.5. In-situ Power Source for Remote Areas

Another application of MFCs that has attracted increasing interests is the recovery of electricity from sediments. MFCs can provide an *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 it is difficult to routinely access to replace traditional batteries.^{18,81)} A good example is sediment MFC with the most well known being the 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 was used to produce electricity in BUG. A mud battery can serve not only as a power source for the sensors in remote locations but also as a bioremediation method. However, even with this conceptual advantage, sediment MFC has a technical challenge, such as low power density due to both the low organic matter concentration and its high intrinsic internal resistance.⁸¹⁾

8. Technological Challenges

In MFC-like systems, the installation of a membrane, such as the CEM (most commonly Nafion 117), is essential to separate the anode from the cathode but allow the transfer of electrons and protons produced in the anode chamber. There are still a number of problems associated with Nafion membranes, including oxygen back diffusion, substrate loss, cation transport and accumulation rather than protons, and biofouling.^{16,41,42} Of these, changes in pH, such as decreases at the anode but increases at the cathode chambers, can inhibit the growth of electrochemically active bacteria. Nafion is easily biofouled, which reduces the level of proton migration. Furthermore, the following problems need to be solved in order to achieve viable MFCs for full scale applications: the increasing biomass density at both the anode and cathode (if a biocathode is used); the suppression of competitive metabolisms, such as methanogenesis and sulfate reducing; and the reduction of capital costs. For successful commercial uses, much concern should be paid for finding not only alternative membranes to the expensive Nafion membrane, but sufficiently sturdy materials instead of conventional anodes, such as carbon felt and carbon paper.

9. Conclusion

The achievable power output from MFCs has increased remarkably over the last decade, which was obtained by altering their designs, such as optimization of the MFC configurations, their physical and chemical operating conditions, and their choice of biocatalyst. The membrane-less single chambered configurations are more preferable for practical applications due to their elimination of CEM-associated problems and easy scale-up, but they are adversely affected by accelerated oxygen diffusion. Even with a relatively low PD compared with single chambered-MFCs, there is considerable room for two-chambered systems based on their new applications, such as an external power assisted biohydrogen production and cathodic denitrification. Bacterial community analysis of enriched-anode biofilms from a variety of MFCs showed no prevailing species of electricigens. This suggests that current generation in MFCs is due to special characteristics of bacteria but not to a special bacterium. The great diversity of bacterial consortia in an anode biofilm suggests the potential existence of other candidates contributing to electricity generation through a variety of ways such as identified or currently unidentified, beyond *Geobacter* and *Shewanella* species.

MFCs have not been commonly considered as the energy supplying ways for the future despite their outstanding advantages because MFC-based technology is not sufficiently advanced enough to produce substantial quantities of energy in a cost-effective manner. The highest power outputs are still less than several watts per square meter of anode surface, even with a readily biodegradable pure substrate such as glucose. However, the recent advances might shorten the time required for their actual full scale application for both energy harvesting and wastewater treatment systems. In particular, for successful

commercial uses, it is important to identify not only sufficiently sturdy materials with a large surface area instead of conventional electrodes but also alternative membranes or their elimination to remove the problems currently facing CEM. In addition, more study will be needed to expand the applications of MFC based-technology beyond electricity generation.

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