

## Effects of applied voltages and dissolved oxygen on sustained power generation by microbial fuel cells

S. E. Oh, J. R. Kim, J.-H. Joo and B. E. Logan

### ABSTRACT

Oxygen intrusion into the anode chamber through proton exchange membrane can result in positive redox conditions in fed-batch, two chamber MFCs at the end of a cycle when the substrate is depleted. A slight increase in dissolved oxygen to 0.3 mg/L during MFC operation was not found to adversely affect power generation over subsequent cycles if sufficient substrate (acetate) was provided. Purging the anode chamber with air or pure oxygen for up to 10 days and 10 hrs also did not affect power generation, as power rapidly returned to previous levels when the chamber was sparged with nitrogen gas. When MFCs are connected in series, voltage reversal can occur resulting in a positive voltage applied to the anode biofilm. To investigate if this adversely affected the bacteria, voltages of 1, 2, 3, 4, and 9 V, were applied for 1 hr to the MFC before reconnecting it back to a fixed external load (1,000  $\Omega$ ). A voltage of <2 V did not affect power generation. However, applying 3 V resulted in a 15 h lag phase before recovery, and 9 V produced a 60 h lag phase suggesting substantial damage to the bacteria that required re-growth of bacteria in the biofilm. These results indicate that charge reversal will be a more serious problem than oxygen intrusion into the anode chamber for sustained performance of MFCs.

**Key words** | anode, applied voltage, dissolved oxygen, microbial fuel cell stack, voltage reversal

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### INTRODUCTION

A microbial fuel cell (MFC) is a bio-electrochemical system that produces current from oxidation of biodegradable organic compounds using microorganisms, called exoelectrogens, that are capable of transferring electrons outside their cell. In order for bacteria to produce current, the cells must use the anode as an electron acceptor, and not other electron acceptors such as oxygen. Microorganisms that grow in an MFC are therefore bacteria that typically grow under completely anoxic conditions. Fermentative bacteria, facultative, and obligate anaerobes have been shown to be capable of exoelectrogenic growth in MFCs, including: *Clostridium butyricum* (Park *et al.* 2001), *Geobacter sulfurreducens* (Bond & Lovley 2003; Richter *et al.* 2008), *Rhodoferrax ferrireducens* (Chaudhuri & Lovley 2003), *Aeromonas hydrophila* (Pham *et al.* 2003), *Pseudomonas*

*aeruginosa*, (Rabaey *et al.* 2004) *Geopsychronacter electrodiphilus* (Holmes *et al.* 2004a,b), *Desulfobulbus propionicus* (Holmes *et al.* 2004a,b), *Rhodopseudomonas palustris* DX-1 (Xing *et al.* 2008) and *Shewanella oneidensis* (Ringeisen *et al.* 2007). Oxygen diffusion through the cathode (Kim *et al.* 2007) and into the anode chamber could adversely affect the microbial community and therefore power generation, particularly by obligate anaerobes. The effect of oxygen on anode biofilms, however, has not been well studied. The genus *Clostridium* are obligately anaerobic bacteria. *Geobacter* were previously considered to be strict anaerobes, but it has been shown that *Geobacter sulfurreducens* can grow with oxygen as a terminal electron acceptor (Lin *et al.* 2004). Another prominent exoelectrogen, *Shewanella putrefaciens*, is a facultative anaerobe and

thus can grow with oxygen. However, the effect of exposure to oxygen, particularly at the end of a batch cycle of operation when substrate is depleted, on subsequent power generation is unknown. Some exoelectrogenic bacteria in the anode chamber could be adversely affected by oxygen contamination. Facultative bacteria could use oxygen in the anode chamber as electron acceptor, and not transfer electrons to the anode, resulting in lowered current generation. As far as the authors know, oxygen effects in the anode on MFC power generation have not been previously investigated.

A typical MFC produces an open circuit voltage (OCV) of less than 0.8 V, with a working voltage in the range of ~0.5 V that is lower than the OCV due to energy utilization by bacteria, electrode overpotential, and internal resistance. In order to increase voltage, MFCs can be stacked together in series. Stacked MFCs have been investigated in only a few studies (Aelterman *et al.* 2006; Shin *et al.* 2006; Oh & Logan 2007). However, various conditions can bring about voltage reversal in fuel cells, resulting in the application of a positive voltage to the anode of a cell. Voltage reversal occurs when one of cells is weak compared to other cells, resulting in the stronger cell charging the weaker cell (Oh & Logan 2007). If the anode potential rises to the potential for water electrolysis in the weaker cell, then oxygen could be produced in the anode of the cell. It was found that starvation of bacteria in one cell hooked in series to another cell could produce voltage reversal (Oh & Logan 2007). Other reasons include insufficient oxygen at the cathode, impedance differences, and a lack of catalyst. Voltage reversal can adversely affect the bacteria and other fuel cell components. It is well known that applying a voltage to bacteria can affect the cell membrane potential and disrupt the cell integrity (Luther *et al.* 1983; Gross *et al.* 1986). Applied voltages have been used in wastewater treatment as a method of disinfection (Matsunaga *et al.* 1994; Diao *et al.* 2004). The effect of an applied voltage on exoelectrogenic bacteria and the subsequent performance of the MFC have not been previously examined extensively. While applied voltages at low set potentials have been used to examine the effect of anode potential on performance (Torres *et al.* 2007; Aelterman *et al.* 2008; Cheng *et al.* 2008), these voltages were not set high enough to adversely affect the

bacteria. In this study, we therefore examined the effects of voltage reversal and dissolved oxygen on the performance of an MFC.

## MATERIALS AND METHODS

### Culture and medium

Dewatered anaerobic sludge (85% water), collected from the Pennsylvania State University Wastewater Treatment plant in State College, PA, was used as the original inoculum. Thereafter, the solids produced in the anode compartment were used to inoculate additional MFCs.

Acetate (2 mM) was used as the electron donor in the anode chamber in a nutrient solution (pH = 7.0) containing (per litre of deionized water): NaHCO<sub>3</sub> (3.13 g/L), NH<sub>4</sub>Cl (0.31 g/L), NaH<sub>2</sub>PO<sub>4</sub>·H<sub>2</sub>O (0.75 g/L), KCl (0.13 g/L), NaH<sub>2</sub>PO<sub>4</sub> (4.22 g/L), Na<sub>2</sub>HPO<sub>4</sub> (2.75 g/L); and metal (12.5 mL) and vitamin (12.5 mL) solutions (Oh *et al.* 2004). In some experiments, oxygen was removed from the medium by sparging with nitrogen gas. All MFCs were operated at 30°C in a constant temperature room.

### MFC construction and operation

MFCs were constructed by joining two media bottles (310 mL capacity, Corning Inc. NY) with a glass tube clamped between the flattened ends of the glass tubes (inner diameter of 1.3 cm) fitted with two rubber gaskets (3.5 cm<sup>2</sup> cross section) between which a cation exchange membrane (CEM) was placed (Nafion<sup>®</sup> 117, Dupont Co., Delaware). The CEM was pretreated by boiling in H<sub>2</sub>O<sub>2</sub> (30%) and deionized water, followed by 0.5 M H<sub>2</sub>SO<sub>4</sub> and deionized water, each for 1 hr, and then stored in deionized water prior to being used. The electrodes were both made of carbon paper (2.5 × 4.5 cm). The cathode was coated with a Pt-catalyst (0.5 mg/cm<sup>2</sup>; 10% Pt) on one side (De Nora North America, Inc.). Electrodes were soaked in DI water for 1 day before tests. Copper wire inserted inside fluorinated ethylene propylene tubing (Chemfluor<sup>®</sup> FEP Tubing; inner diameter: 0.8 mm) was used to connect the electrodes and all exposed metal surfaces were sealed with a nonconductive epoxy (Dexter Corp. NJ, USA).

The anode compartment was filled with nutrient solution (250 mL) containing acetate (2 mM) and the cathode compartment contained only nutrient solution (250 mL). The anode chamber was inoculated and sparged with nitrogen gas for 3 minutes and sealed with a rubber stopper and cap. The anode and cathode were connected with a resistor (1 k $\Omega$  except as stated otherwise) and the current produced was calculated by measuring the voltage across a resistor every 30 minutes using a multimeter. Both chambers were mixed using a magnetic stirrer. In some tests, an Ag/AgCl reference electrode (0.195 V corrected to a normal hydrogen electrode; NHE) was placed into the cathode compartments to determine individual electrode potentials.

### Effect of dissolved oxygen (DO) concentration

In a two-chambered MFC, oxygen diffuses through the CEM from the cathode to the anode compartment. If this oxygen is not immediately used, the DO concentration in the anode can increase. In order to determine the effect of oxygen on MFC performance, the DO and voltage output were monitored during the MFC operation, including during the time of fuel starvation.

In order to directly observe the effect of oxygen on the anode performance, the anode chamber was aerated. Once the MFC demonstrated a repeatable cycle of power generation, the anode chamber was opened and continuously sparged with air or pure oxygen for specified time (gas flow rate of 50 mL/min).

### Effect of applied voltages

Once the MFC operation was stable, producing a voltage of  $\sim 300$  mV (1 k $\Omega$  external resistance), a power supply was connected to the MFC (plus terminal to the anode) for 1 hr to study the effect of an applied voltage. The cathode chamber was sparged with air throughout the experiment and a reference electrode was inserted into the cathode chamber to monitor individual potentials. The applied voltages were 1, 2, 3, 4, and 9 V. After applying one of these voltages for an hour, the MFC was reconnected to an electrical circuit containing the resistor and the voltage was again monitored in 30 minute intervals.

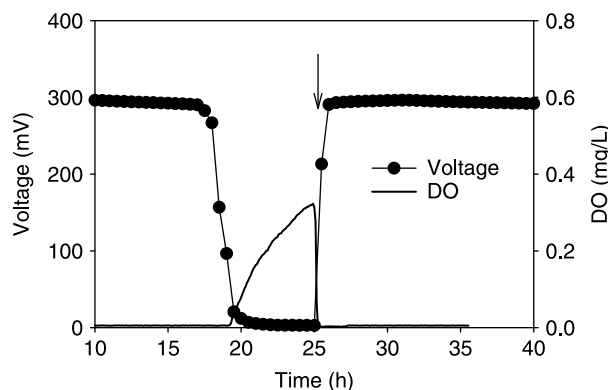
### Analysis

Voltages were monitored using a precision multimeter and a data acquisition system (Model 2700, Keithly Instruments, Inc., OH, USA). Power ( $P$ ) was calculated according to  $P = IV$ , where  $I$  (C/s) is the current and  $V$  (V) the voltage. Dissolved oxygen was measured using a non-consumptive fiber optic oxygen probe (FOXY-18G SF2000, Ocean Optics Inc., Dunedin, FL) and the manufacturer's software (OOIFOXY oxygen sensor software, v. 1.67.15F). Prior to measuring samples, the probe was calibrated with oxygen-saturated medium (using air) in the same type of bottle (250 mL), and medium in which the DO was scavenged using sodium hydrosulfite.

## RESULTS AND DISCUSSION

### Oxygen concentrations during MFC operation

The DO in the anode chamber was monitored during substrate-rich and fuel starvation conditions (Figure 1). When power was produced by the reactor (until  $\sim 17$  hr), the DO was very low ( $< 0.03$  mg/L). However, when the voltage began to drop after 17 hr to less than 10 mV, the DO concentration increased to 0.3 mg/L within 6 hrs. This result shows that while there is power generation, any oxygen that might leak into the anode chamber is effectively depleted. When additional substrate was added to the anode chamber at 25 h, the DO concentration

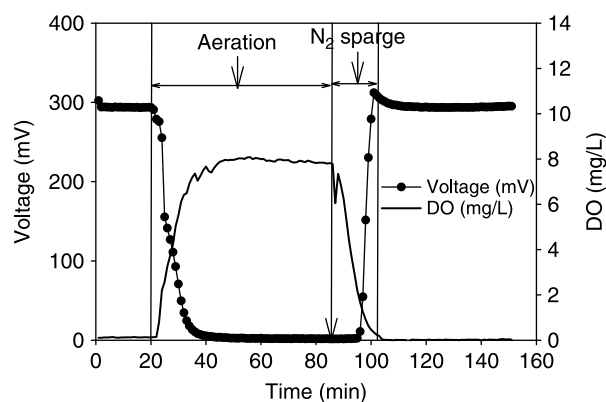


**Figure 1** | Oxygen diffusion from the cathode to the anode compartment and voltage output in a two-chambered MFC. The anode chamber was continuously sparged with air throughout the experiment (The arrow indicates addition of 1 mL of 1 M acetate).

rapidly decreased to  $<0.03$  mg/L, and the voltage returned to the previous level (approximately 300 mV). Bacterial growth was visually observed on both sides of the CEM, suggesting both substrate and oxygen crossover. CEMs such as Nafion have previously been shown to be permeable to both oxygen and acetate (Kim *et al.* 2007). Because voltage returned to the original level after the cycle, this suggested that temporary exposure of the biofilm to oxygen did not inhibit subsequent power generation. The main impact of the oxygen transfer into the anode chamber therefore appears to be to lower Coulombic efficiency as a result of aerobic degradation of substrate (Liu & Logan 2004; Kim *et al.* 2007).

### Effect of imposed oxygen concentrations on power generation

To further explore the effect of oxygen on MFC performance, the DO in the anode chamber containing substrate (10 mM acetate) was increased by air sparging (Figure 2). During aeration, there was a decrease in voltage while the DO increased to saturation levels ( $\sim 8$  mg/L). When nitrogen gas was sparged to remove DO after 85 minutes, an increase in voltage generation was not observed until the DO decreased to approximately 1 mg/L. After this time, the voltage began to increase back to the previous level ( $\sim 300$  mV). This result suggests that there may be a critical oxygen threshold that allows current generation even in the presence of small concentrations of dissolved oxygen. However, since we did not measure DO within the porous



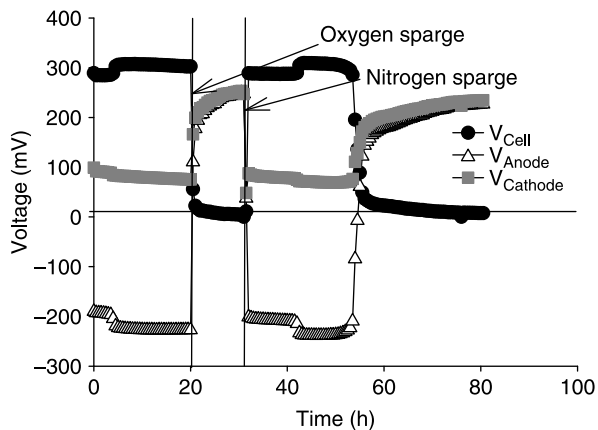
**Figure 2** | Voltage and DO concentration over time during aeration and nitrogen gas sparging of the anode chamber while substrate is still present.

electrode, it may be that oxygen was effectively reduced within the electrode or in biofilms on the electrode. The observation that voltage was again recovered after exposure to high DO conditions further indicates that DO conditions do not affect power production once the oxygen is removed or depleted in the reactor.

To determine whether exoelectrogenic bacteria survived exposure to higher DO concentrations, pure oxygen was introduced to the anode chamber (Figure 3). With 10 hr of pure oxygen sparging, both anode and cathode cell potentials increased to +250 mV resulting in  $V_{\text{Cell}} = 0$ . However, following nitrogen sparging both electrode potentials returned and were stable at their previous levels of  $V_{\text{Cathode}} = 90$ –100 mV, and  $V_{\text{Anode}} = -230$  mV.

In order to examine long-term exposure to oxygen the anode chamber was sparged with air for  $\sim 10$  days, and then sparged with nitrogen gas (with substrate addition). After this long period of oxygen exposure, it took only 4 hrs to reach the previous voltage level of  $\sim 300$  mV (data not shown). This result shows that even after prolonged oxygen exposure, the bacterial community was not substantially impacted in terms of its exoelectrogenic capabilities in this type of MFC.

It has been reported that *Shewanella* or even *Geobacter* can use oxygen as an electron acceptor. Therefore, oxygen may not be so critical damage especially to mixed culture MFC biofilm. We may not exclude that it could change biofilm structure or metabolic pathway when the MFC exposed to oxygen for a very long period of time. Although



**Figure 3** | Effect of sparging the anode chamber with pure oxygen on voltage output.

there is no information on biofilm and community shift in this period, oxygen would be used as alternative electron acceptor by bacteria rather than by anode since oxygen is the most favorable electron acceptor. If oxygen inhibited the biofilm, there should be a lag phase. However, when oxygen in the medium is removed, voltage is sharply increased, meaning aerobic or facultative bacteria used oxygen as an electron acceptor. Furthermore, oxygen could be effectively removed by mixed microbial community accompanied by consuming substrate and decreasing Coulombic efficiency. It was reported that the diffused oxygen from the cathode chamber was used aerobically resulting in substrate consumption and lower Coulombic efficiency in a previous report (Kim *et al.* 2007). However, longer time exposure to high DO might alter biofilm structure and affect MFC performance eventually.

### Effect of an applied voltage

Two two-chambered MFCs were linked in series by a wire (cathode of the first MFC was connected to the anode of the second MFC) where the first MFC was an active MFC with substrate in the anode chamber and the second one was without substrate (external load = 1 k $\Omega$ ). Under this condition, voltage reversal occurred by fuel starvation. The voltage of the first MFC was 0.7 V and the second MFC was -0.63 V. The individual electrode potentials of the second reactor were  $V_{\text{Anode}} = 0.74$  V and  $V_{\text{Cathode}} = 0.11$  V. Thereafter, the second MFC was disconnected from the first MFC and voltage was applied to the second MFC (+ pole of a power supply connected to anode) to mimic that which was occurring under normal operation conditions. When 0.7 V (which was the voltage of the first MFC) was supplied to the second MFC, the electrode potentials were  $V_{\text{Anode}} = 0.78$  V and  $V_{\text{Cathode}} = 0.1$  V. Individual potentials of the weak cell under voltage reversal was the same as the potentials of the weak cell when using the power supply.

The power supply was used to see the effect of different applied voltages on performance of the MFC. When an applied voltage was less than 2 V (for 1 hr), there was no affect on subsequent voltage generation (Figure 4). When the voltage was increased to >3 V, the MFC performance was adversely affected as indicated by a lag phase when the reactor was switched back to MFC

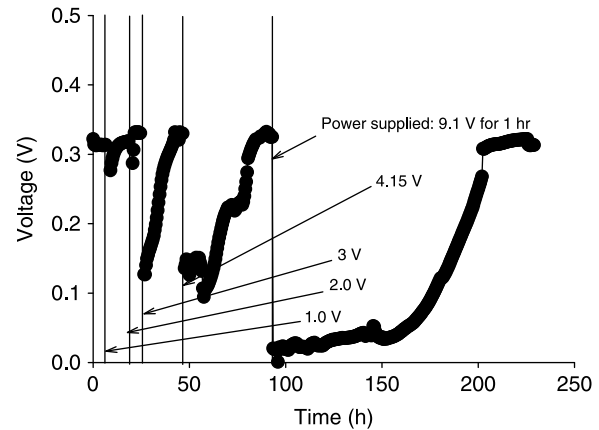


Figure 4 | Effect of applied voltages on subsequent voltage output.

mode. At an applied voltage of 9.1 V, there was a lag phase of 60 hr before voltage production, with a total of 110 hr for the MFC to recover to previous levels of voltage production. The mechanisms by which bacteria are damaged by these applied voltage include both a result of high potential and the production of free radicals (Diao *et al.* 2004). The 60 hr of lag phase at 9.1 V of power supply is similar to the original acclimation time when the substrate and inoculum were first added to the same two-chambered MFC. The lag phase of 50–60 hr has also been reported with swine wastewater as inoculum (Min *et al.* 2005) or anaerobic sludge (Oh *et al.* 2004; Oh & Logan 2005) when using the same type of two-chambered MFC.

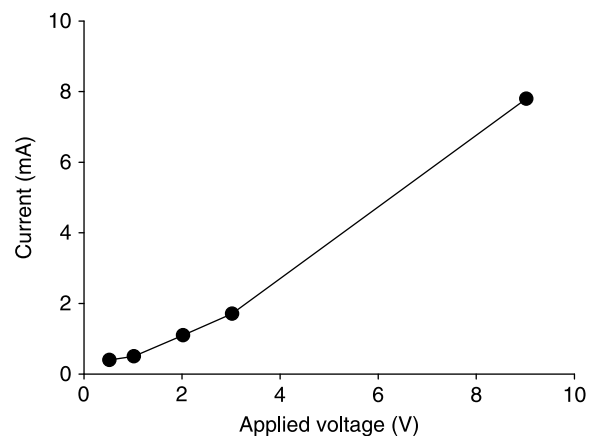
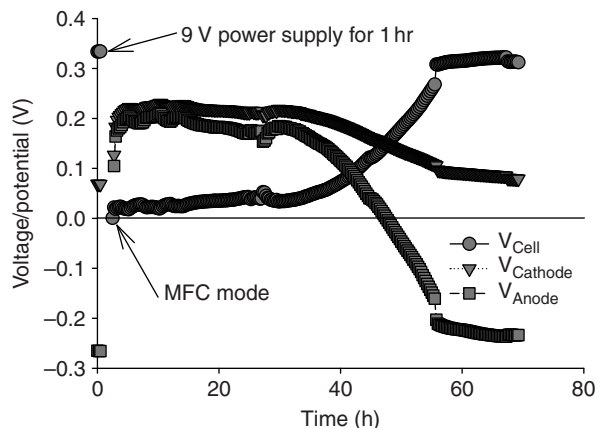


Figure 5 | Current flow from the anode to the cathode when the voltage was applied using the power supply. (An external resistor of 5  $\Omega$  was used for this test).



**Figure 6** | Electrode potential and whole cell voltages in the MFC mode after applying 9 V for 1 hr.

Current flow from the anode to the cathode increased by increasing applied voltages in the range of 0 to 9 V (Figure 5). Bacterial activity on the anode was especially inhibited at 9 V for 1 h (Figure 5 and Figure 6), which produced a current flow as high as 8 mA. Under the condition lots of bubbles from the anode were noticed and identified as oxygen meaning water electrolysis. Also, some carbon oxidation of the electrode might take place. It was reported that water electrolysis appears kinetically preferred and thus proceeds at a greater rate than that of carbon oxidation (Knights *et al.* 2003). In an MFC mode at operating at maximum power (1 k $\Omega$  external load), 0.3 mA (266 mA/m<sup>2</sup>) of current is typically produced. At a very low external load (100  $\Omega$ ), 0.6 mA (533 mA/m<sup>2</sup>) of current was produced here.

When 9.1 V was applied for 1 hr, the patterns of  $V_{\text{Anode}}$ ,  $V_{\text{Cathode}}$  and  $V_{\text{Cell}}$  over time were very similar to that obtained when the anode of a MFC was acclimated to exoelectrogenic bacteria (Figure 6). This suggests that undamaged suspended bacteria needed time to re-colonize the anode. Also, it should be noted that once the applied voltage is above 1.2 V, it is possible that oxygen (or electrochemically generated oxidants) are produced in the anode chamber (Diao *et al.* 2004; Polcaro *et al.* 2007). Based on the above experiments, however, it appears that oxygen contamination would be less of a problem than oxidant production. Therefore, when voltage reversal occurs, a weak cell would be damaged mainly due to high voltage and not due to oxygen production in the anode.

## CONCLUSIONS

Based on the experiments, the following conclusions can be drawn.

1. Increasing the DO concentration in the anode chamber by sparging with air or oxygen decreased power generation of a two chambered MFC while oxygen was present. When the DO concentration in the anode chamber was decreased by nitrogen sparging or bacterial consumption, voltage recovered to the previous level indicating no lasting damage to the anodic bacteria.
2. When a voltage lower than 2 V was applied to a two chamber MFC using the power supply, there was no adverse effect on MFC performance. Above 3 V, the MFC operation was adversely affected resulting in long lag times before power production could be restored.
3. If voltage reversal occurs in stacked MFCs, a weak cell would be damaged mainly due to high voltage and not oxygen production in the anode chamber.

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## REFERENCES

- Aelterman, P., Freguia, S., Keller, J., Verstraete, W. & Rabaey, K. 2008 The anode potential regulates bacterial activity in microbial fuel cells. *Appl. Microbiol. Biotechnol.* **78**(3), 409–418.
- Aelterman, P., Rabaey, K., Pham, H. T., Boon, N. & Verstraete, W. 2006 Continuous electricity generation at high voltages and currents using stacked microbial fuel cells. *Environ. Sci. Technol.* **40**(10), 3388–3394.
- Bond, D. R. & Lovley, D. R. 2003 Electricity production by *Geobacter sulfurreducens* attached to electrodes. *Appl. Environ. Microbiol.* **69**(3), 1548–1555.
- Chaudhuri, S. K. & Lovley, D. R. 2003 Electricity generation by direct oxidation of glucose in mediatorless microbial fuel cells. *Nat. Biotechnol.* **21**(10), 1229–1232.

- Cheng, K. Y., Ho, G. & Cord-Ruwisch, R. 2008 Affinity of microbial fuel cell biofilm for the anodic potential. *Environ. Sci. Technol.* **42**(10), 3828–3834.
- Diao, H. F., Li, X. Y., Gu, J. D., Shi, H. C. & Xie, Z. M. 2004 Electron microscopic investigation of the bactericidal action of electrochemical disinfection in comparison with chlorination, ozonation and Fenton reaction. *Process Biochem.* **39**(11), 1421–1426.
- Gross, D., Loew, L. M. & Webb, W. W. 1986 Optical imaging of cell membrane potential changes induced by applied electric fields. *Biophys. J.* **50**(2), 339–348.
- Holmes, D. E., Bond, D. R. & Lovley, D. R. 2004a Electron transfer by *Desulfobulbus propionicus* to Fe(III) and graphite electrodes. *Appl. Environ. Microbiol.* **70**(2), 1234–1237.
- Holmes, D. E., Nicoll, J. S., Bond, D. R. & Lovley, D. R. 2004b Potential role of a novel psychrotolerant member of the family *Geobacteraceae*, *Geopsychrobacter electrodiphilus* gen. nov., sp. nov., in electricity production by a marine sediment fuel cell. *Appl. Environ. Microbiol.* **70**(10), 6023–6030.
- Kim, J. R., Cheng, S., Oh, S. E. & Logan, B. E. 2007 Power generation using different cation, anion and ultrafiltration membranes in microbial fuel cells. *Environ. Sci. Technol.* **41**(3), 1004–1009.
- Knights, S. D., Taylor, J. L., Wilkinson, D. P. & Wainwright, D. S. 2003 Fuel cell anode structures for voltage reversal tolerance. United States Patents.
- Lin, W. C., Coppi, M. V. & Lovley, D. R. 2004 *Geobacter sulfurreducens* can grow with oxygen as a terminal electron acceptor. *Appl. Environ. Microbiol.* **70**(4), 2525–2528.
- Liu, H. & Logan, B. E. 2004 Electricity generation using an air-cathode single chamber microbial fuel cell in the presence and absence of a proton exchange membrane. *Environ. Sci. Technol.* **38**(14), 4040–4046.
- Luther, P. W., Peng, H. B. & Lin, J. J.-C. 1983 Changes in cell shape and actin distribution induced by constant electric fields. *Nature* **303**(5912), 61–64.
- Matsunaga, T., Nakasono, S., Kitajima, Y. & Horiguchi, K. 1994 Electrochemical disinfection of bacteria in drinking water using activated carbon fibers. *Biotechnol. Bioeng.* **43**(5), 429–433.
- Min, B., Kim, J. R., Oh, S., Regan, J. M. & Logan, B. E. 2005 Electricity generation from swine wastewater using microbial fuel cells. *Water Res.* **39**(20), 4961–4968.
- Oh, S. & Logan, B. E. 2005 Hydrogen and electricity production from a food processing wastewater using fermentation and microbial fuel cell technologies. *Water Res.* **39**(19), 4673–4682.
- Oh, S., Min, B. & Logan, B. E. 2004 Cathode performance as a factor in electricity generation in microbial fuel cells. *Environ. Sci. Technol.* **38**(18), 4900–4904.
- Oh, S. E. & Logan, B. E. 2007 Voltage reversal during microbial fuel cell stack operation. *J. Power Sources* **167**(1), 11–17.
- Park, H. S., Kim, B. H., Kim, H. S., Kim, H. J., Kim, G. T., Kim, M. A., Chang, I. S., Park, Y. K. & Chang, H. I. 2001 A novel electrochemically active and Fe(III)-reducing bacterium phylogenetically related to *Clostridium butyricum* isolated from an microbial fuel cell. *Anaerobe* **7**, 297–306.
- Pham, C. A., Jung, S. J., Phung, N. T., Lee, J., Chang, I. S., Kim, B. H., Yi, H. & Chun, J. 2003 A novel electrochemically active and Fe(III)-reducing bacterium phylogenetically related to *Aeromonas hydrophila*, isolated from a microbial fuel cell. *FEMS Microbiol. Lett.* **223**(1), 129–134.
- Polcaro, A. M., Vacca, A., Mascia, M., Palmas, S., Pompei, R. & Laconi, S. 2007 Characterization of a stirred tank electrochemical cell for water disinfection processes. *Electrochim. Acta* **52**(7), 2595–2602.
- Rabaey, K., Boon, N., Siciliano, S. D., Verhaege, M. & Verstraete, W. 2004 Biofuel cells select for microbial consortia that self-mediate electron transfer. *Appl. Environ. Microbiol.* **70**(9), 5373–5382.
- Richter, H., McCarthy, K., Nevin, K. P., Johnson, J. P., Rotello, V. M. & Lovley, D. R. 2008 Electricity generation by *Geobacter sulfurreducens* attached to gold electrodes. *Langmuir* **24**(8), 4376–4379.
- Ringeisen, B. R., Ray, R. & Little, B. 2007 A miniature microbial fuel cell operating with an aerobic anode chamber. *J. Power Sources* **165**(2), 591–597.
- Shin, S.-H., Choi, Y., Na, S.-H., Jung, S. & Kim, S. 2006 Development of bipolar plate stack type microbial fuel cells. *Bull. Korean Chem. Soc.* **27**(2), 281–285.
- Torres, C., Kato Marcus, A. & Rittmann, B. 2007 Kinetics of consumption of fermentation products by anode-respiring bacteria. *Appl. Microbiol. Biotechnol.* **77**(3), 689–697.
- Xing, D., Zuo, Y., Cheng, S., Regan, J. M. & Logan, B. E. 2008 Electricity generation by *Rhodospseudomonas palustris* DX-1. *Environ. Sci. Technol.* **42**(11), 4146–4151.