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A microbial fuel cell as power supply for implantable medical devices

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ABSTRACT

This study seeks a new way to provide lasting and secure power for implantable medical devices (IMDs) using a microbial fuel cell (MFC) which was proposed to be placed in human large intestine and could utilize intestinal contents and microorganisms to generate electricity. Based on the anatomic structure and inner environmental conditions of large intestine, transverse colon was chosen to be the appropriate location for the implantation of MFC. The performance of the MFC which simulated the environmental features of transverse colon by controlling dissolved oxygen (DO) and pH and was inoculated with simulated intestinal fluid (SIF) was investigated. Stable power generation of MFC was obtained after two months operation with open circuit voltage (OCV) of 552.2 mV, maximum power density of 73.3 mW/m^2, and average voltage output of 308 mV (with external resistance of 500 Ω). Moreover, the changes of environmental conditions in the chambers of MFC did not have a significant impact on human body based on the analysis of pH and DO values. Further studies on internal resistance and power density showed that the MFC could generate power of 7–10 mW according to the size of intestinal surface area, which was enough for IMDs. These results suggested that MFCs located in large intestine could be a promising power source for IMDs.

1. Introduction

With rapid development of biomedical engineering technology, tremendous progresses have been made in implantable medical devices (IMDs). Appropriate working of an active IMD heavily relies on the continuous supply of electricity. Because of the characteristics of working time and environment, IMDs' power supply should possess such properties as long running life, low self-discharging rate, high reliability and biocompatibility with human body. Although the requirement of each IMD is different, the necessary power they need generally falls in the level of μW–mW (Szczesny et al., 2006).

At present, the most popular power supply of IMDs is lithium battery which has been widely adopted for its relatively high energy density and safe performance. Although its longevity is up to 10 years (Mallela et al., 2004), its actual service life is far from enough to meet the needs of patients. For example, more than 60% of the implanted cardiac pacemakers need to be replaced for the reason of battery within 5–8 years (Orhan, 2002). Thus, when batteries of IMDs run out, the patients require surgeries to replace the whole IMD, suffering great pains and enormous financial burdens.

Although the nuclear battery's life can reach more than 15 years, the potential radioactive danger as well as the expensive cost makes it still unacceptable (Drews et al., 2001). In recent years, many newly emerging technologies in the fields of magnetics, thermotics, acoustics and electricity are gradually being introduced as power supplies for the IMDs and some progress have been made (Suzuki et al., 2002; Weiner and Cooper, 2005; Wang et al., 2007; Liu et al., 2006). However, they still have obvious bottlenecks respectively and have not been applicable yet. How to provide energy for IMDs via a highly safe, efficient and continuous way is, therefore, extremely important in biomedical engineering and related research fields.

Microbial fuel cell (MFC) technology has been developed to produce electricity from organic matters using microorganisms as the biocatalyst since 1970s (Logan et al., 2006; Li et al., 2008). In the recent 10 years, plenty of studies on MFC have been carried out (Bond et al., 2002; Liu and Logan, 2004; Yang et al., 2009). Taking into account the close symbiotic relationship between human and microorganisms, MFC could be a continuous, long-life and safe power source for IMDs. Siu and Mu (2008) once managed to develop a micro-MFC using glucose in blood as organic matters, however the location of MFC was proposed in blood vessels which might lead to thrombosis and rejection reaction of patient.

Considering locations of microorganisms and organic matters in human body, we think the best implantation site of MFC is the large intestine. Our group has carried on studies of MFC inoculated by extracted solution of feces and found that MFC could produce a maximum power of 240 mW/m^2 (Du et al., 2010). This indicates that the microorganisms in large intestine can produce

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Table 1
Environmental conditions in different parts of colon.

Measurement site	pH[a]	Length (cm)[b]	Diameter (cm)[b]	ptO_2 (mmHg ± SD)[c]
Ascending colon	4.9–5.8	15.6 ± 5.8	6.3 ± 0.5	33.7 ± 7.5
Transverse colon	5.7–6.2	40.3 ± 8.5	5.0 ± 0.7	40.7 ± 8.2
Descending colon	5.8–6.3	23.2 ± 7.2	3.5 ± 0.6	31.8 ± 7.4
Sigmoid colon	6.0–6.7	34.3 ± 10.0	3.0 ± 0.3	41.2 ± 8.7

[a] Average pH values of the contents inside the colon (Michelle et al., 2003).
[b] Peng et al. (2000).
[c] Partial pressure of oxygen here is measured from the surface of the tissues and is not equal to the partial pressure of oxygen inside the colon but can reflect the oxygen amount in it. SD means standard deviation (William et al., 1987).

electricity and the power output can meet the standard requirements of IMDs. Large intestine is divided into caecum, colon consisting of ascending colon, transverse colon, descending colon and sigmoid colon, and rectum. Caecum is very short and keeps inner acidic condition. Rectum presents unstable inner environmental parameters because it is the place for temporary storage of feces. Thus, neither of them but colon is suitable for the implantation of MFC. Environmental conditions in the different parts of colon are shown in Table 1. Based on the comprehensive analysis of environmental conditions, such as pH, length, diameter and partial pressure of oxygen in various parts of colon, we suggest that transverse colon is a reasonable implantation site for MFC because of its nearly neutral pH and relatively large length and diameter.

How to construct an MFC which generally consists of anaerobic anode and aerobic cathode compartments in transverse colon is further considered. In the colon, there are a large number of anaerobic microorganisms tightly adhering to the intestinal mucosa, while in the lumen there are many aerobic microorganisms flowing with the contents (Macfarlane et al., 1992). Accordingly, the anode of MFC can be made tubular in the transverse colon adhering to the mucosa while the cathode can be located at the center of the lumen.

According to the above conception, an MFC which simulated the environmental features of transverse colon was constructed and its power output and changes of environmental conditions were studied to identify its feasibility. In addition, further studies on resistance and power density were carried out to improve the power output.

2. Materials and methods

2.1. MFC configuration

The experiment MFC consisted of two chambers made of plastic materials (Plexiglas) (shown in Fig. 1). Each chamber was of rectangular parallelepiped (10 cm long by 2.5 cm wide by 10 cm high) with net volume of 125 mL. The anode electrode was made up of activated carbon fiber cloth in size of 6 cm × 6 cm without catalyst. The cathode was a carbon paper electrode (thickness of 0.29 mm, area of 12 cm^2) containing 0.5 mg/cm^2 of Pt catalyst on only one side. The anode chamber was sealed to maintain anaerobic condition and the cathode chamber was connected to the air via a hole at the top of cathode chamber. There was a carbon paper with thickness of 0.29 mm between the two chambers to reduce the oxygen diffusion from cathode chamber which would affect the growth and electricity generation reactions of anaerobic microorganisms in anode chamber. The circuit was closed via titanium line with diameter of 0.5 mm and a resistor of 500 Ω.

2.2. Simulated intestinal fluid

The composition of electrode solution was determined according to the contents of large intestine. With reference to experiments of colon-specific drug absorption (Tozaki et al., 1997), the simulated intestinal fluid (SIF) was made, which contained 110 mM $NaHCO_3$, 20 mM $Na_2HPO_4{\cdot}12H_2O$, 8 mM NaCl, 6 mM KCl, 0.5 mM $CaCl_2{\cdot}2H_2O$, and 0.4 mM $MgCl_2{\cdot}6H_2O$. Fresh fecal samples were added into the above solution with the mass fraction of 30% (w/v). Subsequently the mixture was filtrated with 4 layers of gauze and sparged with N_2 before being added into the reactor to maintain anaerobic conditions and prevent aerobic oxidation of the organic matters. The obtained SIF was preserved at 4 °C.

2.3. Working conditions in anode and cathode chambers

Working conditions of MFC were mainly based on the conception mentioned above that the anode of MFC could be made tubular in the transverse colon adhering to the mucosa while the cathode could be located in the center of the subsequent lumen. So the pH in anode chamber was determined to be about 7.8 according to the combined effect of mucus and the average pH value of contents in transverse colon (Table 1). To exclude the interference of microorganisms, the cathode chamber was filled with SIF without fecal samples (pH 8.3). Moreover, according to the physiology researches and the oxygen-resistant extent of microorganisms in intestinal contents, the partial pressure of oxygen close to the intestinal wall is about 10 mmHg with that in the lumen of 20–30 mmHg. Therefore the concentration of dissolved oxygen (DO) in anode chamber is maintained at about 0.14 mg/L, with that in cathode chamber of 0.27–0.45 mg/L in the experiment to be consistent with those in colon of wall and lumen, respectively. In addition, the MFC was

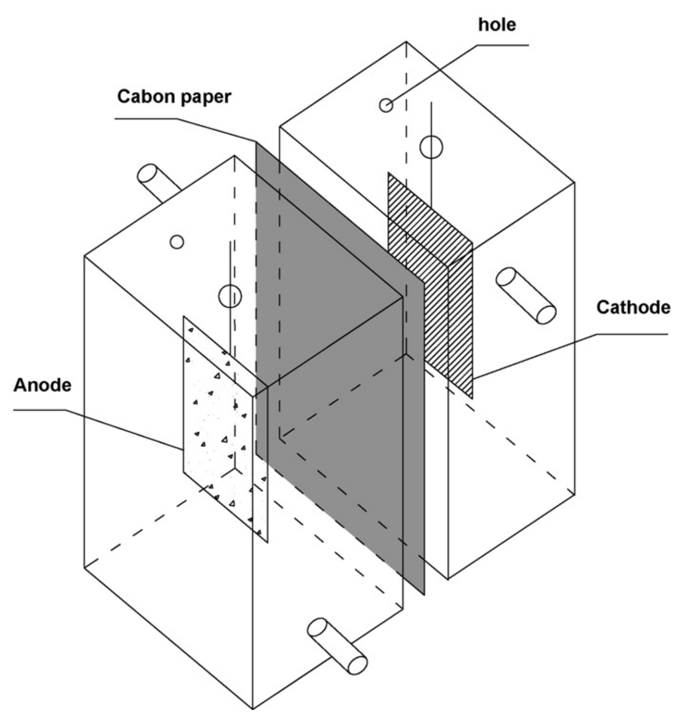

Fig. 1. Schematic prototype of MFC.

operated at 37 ± 1 °C in accordance with that of large intestine during the experiment.

2.4. MFC operation

The MFC was operated in fed-batch mode at 36–38 °C in a temperature-controlled water-bath. The anode chamber was filled with SIF (pH 7.8) which contained the inoculum from fresh fecal samples, while the cathode chamber was filled with SIF without fecal samples (pH 8.3) to exclude the interference of microorganisms. The voltage outputs of MFC were monitored on-line. The polarization curves and electrode potential curves were obtained when a consistent and repeatable cycle of power generation was gained. At the end of a cycle, the values of pH and DO in the anode and cathode compartments were quickly measured respectively.

2.5. Analytical measurements and calculations

Values of pH and DO were measured using pH meter (PHS-3C, Shanghai, China) and DO meter (Model 95, YSI Incorporated, USA), respectively. Voltage across the given external resistance was recorded every minute by using a data acquisition system (PMD-1608FS, MCC Corporation, USA) and converted to power density.

Power density, P (W/m^2), was calculated as $P = IV/A$, where I (A) is the current, V (V) is the voltage, and A (m^2) is the surface area of anode. The current density was calculated as $i = V/(R_{ex}A)$, where R_{ex} (Ω) is the external resistance.

The polarization curves were obtained according to the method used in Menicucci et al. (2006). Two saturated calomel reference electrodes (SCE, 0.241 V against standard hydrogen electrode, SHE) were put into the two chambers to obtain the electrode potentials. Apparent resistance which includes the ohmic resistance, activation overpotentials and diffusion resistance was obtained by calculating the slope of the linear ohmic polarization part of the polarization curves. The interrupted current technique was used in the experiment to determine the ohmic resistance (Aelterman et al., 2006).

3. Results and discussion

3.1. Electricity generation of MFC

The voltage generation of MFC with external resistance of 500 Ω during initial several cycles was shown in Fig. 2A). The negative voltage outputs at first may resulted from potential difference between the two electrodes. Then, the values gradually increased, and stable power generation was obtained after five sequential replacements of SIF. The voltage stabilized at 308 ± 3 mV at about 250 h. This MFC simulated the environmental features of transverse colon and was inoculated with simulated intestinal fluid possessing nearly the same compositions as those in colon. Therefore it could be speculated that reactions in the experimental MFC similar with those in colon took place. The residues in feces such as cellulose, hemicellulose and protein were degraded by anaerobic fermentation to generate acetic acid, propionic acid, butyric acid and other short-chain fatty acids (SCFA) (Daniel and Néstor, 2008). These SCFA were further degraded by the electroactive microorganisms to produce electrons and protons which were transferred to the electrodes to complete the fuel cell reactions. In this way, the microorganisms which could generate electricity were domesticated and acclimatized to the environment in anode chamber as the anaerobic fermentation took place. The filaments of microorganisms attached to the activated carbon fiber cloth electrode. As more and more microorganisms enriched on the electrode with several replacements of SIF, the biofilms formed gradually and the voltage increased and then stabilized according to the suspected principle of electricity generation (Logan et al., 2006).

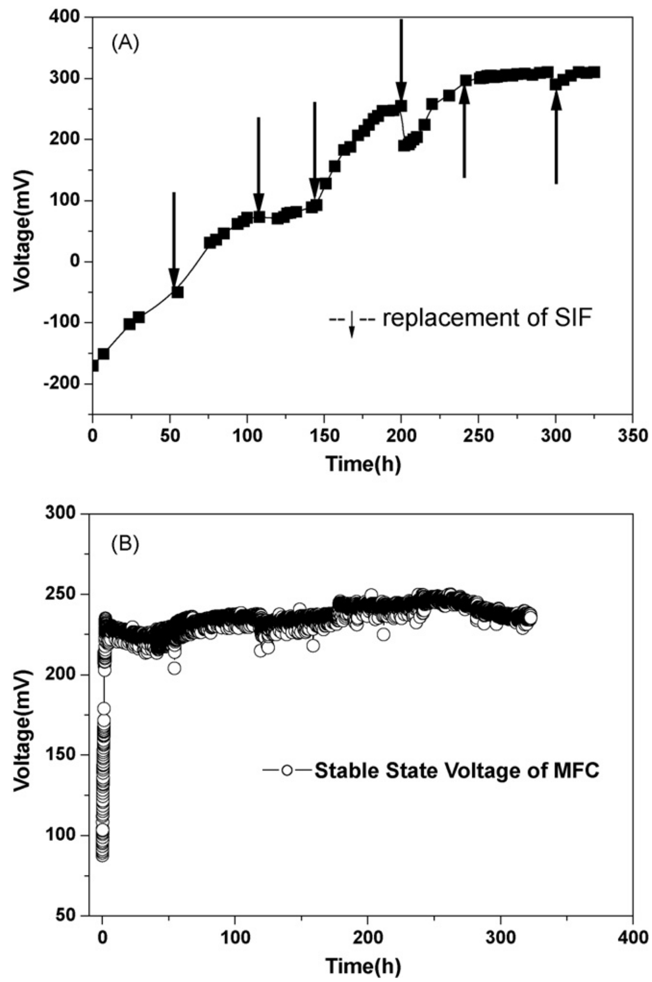

Fig. 2. (A) Voltage outputs of MFC with external resistance of 500 Ω during initial several cycles. (Arrows showed the replacement of SIF at the end of each cycle.) (B) Voltage generation of MFC in a typical cycle at stable state (external resistance of 300 Ω).

After two months operation, a more stable power generation was obtained and the external resistance was changed to 300 Ω according to the internal resistance. As seen in Fig. 2B), after SIF was replaced, the voltage of MFC reached to about 220 mV within 2 h, then slowly increased to the highest voltage around 250 mV at 240 h, and subsequently dropped slightly. The result indicated that the biofilms on the anode surface were formed. The stable voltage output of 240 ± 5 mV was maintained for at least 200 h (from 50 h to 250 h), which is very important for continuous power supply of IMDs.

3.2. Environmental conditions during MFC operation

The applicability of MFC implanted in large intestine is not only determined by the stability of power output operation but also the slight changes of internal environmental conditions. Lots of researches about the changes of pH in MFCs have been carried out; however, the conclusions were various. During a cycle, the pH in anode chamber could increase and became stable (Li et al., 2008); or it could decrease first, then increase and kept steady (Zhi et al., 2008). On the whole, the pH in MFCs did not change greatly in these studies.

Table 2
Changes of environmental conditions in MFC.

Operation time (d)[a]	Anode pH[b]	Cathode pH[b]	Anode DO (mg/L)[c]	Cathode DO (mg/L)[c]
25	7.73	8.73	0.07	0.19
30	7.51	8.73	0.09	0.19
34	7.59	8.87	0.09	0.19
39	7.54	8.92	0.08	0.18
45	7.58	8.91	0.08	0.19
52	7.43	8.94	0.09	0.21
60	7.42	8.92	0.09	0.20

[a] All the data were measured at the end of each cycle.
[b] The initial values of pH in anode and cathode chambers are 7.8 and 8.3, respectively.
[c] The initial values of DO in anode and cathode chambers are 0.30 ± 0.09 and 1.12 ± 0.12, respectively.

Environmental conditions in MFC during the experiment were given in Table 2. According to the initial and final pH value in certain cycles, we can see that during the experiment the pH values of the anode solution decreased slightly while in cathode the values increased but the changes were not significant to affect the overall pH value in human gut contents (within the initial pH $\pm$ 0.5). It is consistent with the result from Rozendal et al. (2006), i.e., a decreasing anode pH and an increasing cathode pH. This can be explained with the theory of cation transport, which sustains the electroneutrality in an operating MFC (Rozendal et al., 2006). The protons generated in anode chamber might be accumulated because of the slow transporting rate through the carbon paper, while the increased pH in cathode chamber was due to the consumption of protons. The DO in anode and cathode chambers was utilized by the reactions and kept at a low level, within the extent of that in colon. Therefore we suggest that the MFC system does not have significant impact on the environment of large intestine.

3.3. Approaches to power output improvement

Based on the above results, the experimental MFC could generate stable electricity using SIF and the changes of inner conditions were not significant. Studies on power density and internal resistance were further carried out to obtain approaches to improvement.

The polarization curves and power density curves after the performance of MFC stabilized were shown as Fig. 3A. The open circuit voltage (OCV) of MFC reached 552.2 mV with maximum power density of 73.3 mW/m^2 normalized by anode area (586.4 W/m^3 according to the empty bed volume of anode chamber) at current density of 225.6 mA/m^2. The internal resistance was about 300 Ω. Fig. 3B shows that the anodic potential slightly increased with the increase in current density, while the cathodic potential decreased drastically. This demonstrates that the cathode was the current-limiting electrode, which may be caused by relatively small cathode surface area and the little oxygen concentration in cathode chamber.

The power density produced by MFCs is typically limited by high internal resistance and electrode-based losses (Logan et al., 2006). Three kinds of resistances could affect the electricity generation of MFC, i.e., ohmic resistance, activation resistance and diffusion resistance. Ohmic resistance comes from the transfer of protons in electrolyte and electrons close to electrode surface, including resistance of electrode and other contact resistances. Activation resistance occurs when organic matters are decomposed by microorganisms on the surface of electrodes, while diffusion resistance is the resistance of protons transferring through the carbon paper and electrolyte (SIF in this experiment). Both of them are regarded as non-ohmic resistances (Liang et al., 2007). In this work, the large internal resistance of MFC is about 300 Ω. To find ways of reducing the internal resistance to further enhance maximum power density, the distribution of internal resistance was analyzed.

The ohmic resistance of MFC was about 172 Ω, accounting for 57.3% of the apparent resistance, which meant the activation and diffusion resistances also accounted for a great proportion. The ohmic resistance can be reduced by shortening the distance between anode and cathode electrodes, while the proton transfer resistance can be cut down if the carbon paper between two chambers is removed. The activation resistance can be reduced by modifying the electrode surface, such as immobilizing carbon nanotubes to improve the property of anode which will increase the amount of catalytic microorganisms attaching to the electrodes and thus enhance the efficiency of electron transfer (Liang et al., 2007).

The maximum power density and OCV increased with the operating time of MFC (shown in Fig. 4). This indicates that the internal resistance decreased with the formation of biofilm and it is still possible to improve the power density. According to the colon surface area (0.3 m^2) and the above experimental data, MFC implanted in human large intestine could produce electricity of around 7–10 mW

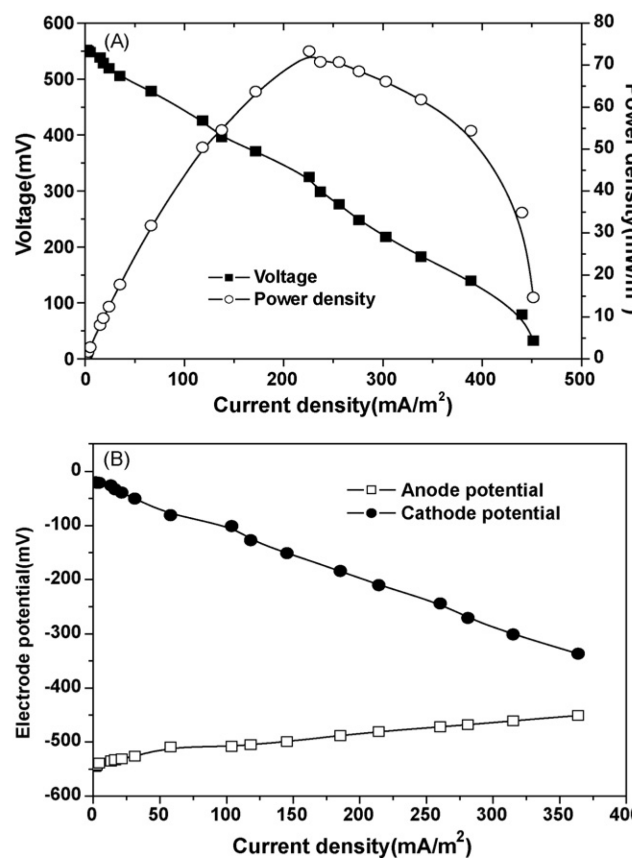

Fig. 3. (A) Polarization curves and power density–current curves after MFC stabilized; (B) electrode potentials (vs SCE, 0.241 V against SHE) as a function of current density obtained by varying the external resistance (10,000–10 Ω).

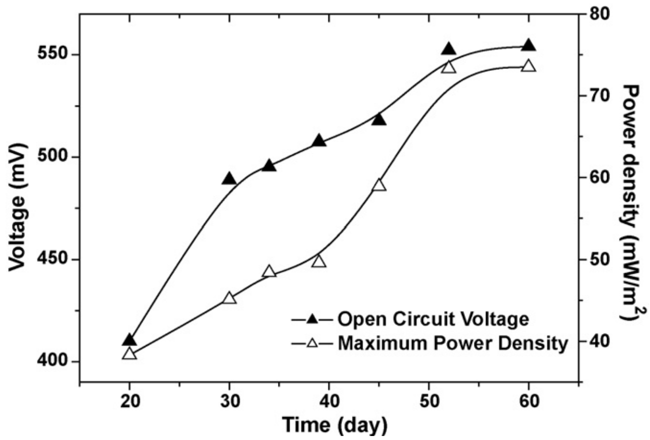

Fig. 4. Power performance of MFC changed with the operating time. Open circuit voltage (filled symbols), maximum power density (open symbols, normalized by the projected anode surface area).

with the methods described above, which is enough for the power supply of IMDs, such as pacemaker (30–100 μW), cardiac defibrillator (30–100 μW), drug pump (100 μW to 2 mW) and cochlear implants (10 mW) (Szczesny et al., 2006).

4. Conclusion

There are advantages as follows if MFC was placed in the large intestine: (1) the microorganisms could be directly used to achieve electron transfer, (2) undigested cellulose contained in the paste contents could be used as fuel source of MFC and help clear the electrode surface as well, (3) low partial pressure of oxygen inside the large intestine does not disturb the electricity generation reactions of microorganisms, and (4) semi-continuous flow system of the large intestine could realize continuous working condition of MFC.

In this paper, transverse colon was chosen to be a reasonable position for MFC implantation. According to the environmental features of transverse colon, an experimental MFC was developed to investigate its performance and changes of environmental conditions. The MFC could generate electricity stably for at least 200 h after two months operation. The maximum power density was 73.3 mW/m^2 with OCV of 552.2 mV. In addition, the changes in the chambers did not have a significant impact on the environmental conditions based on the analysis of the values of pH and DO. Further studies on resistance and power density showed that the MFC could generate around 7–10 mW of power according to the size of intestinal surface area, which was enough for the power supply of IMDs. Further works will focus on examining the influence of removing the carbon paper between two chambers, the addition of microorganisms into cathode chamber, as well as the effect on the microorganism communities.

Acknowledgments

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