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Factors Affecting the Performance of Single-Chamber Soil Microbial Fuel Cells for Power Generation*[1]

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ABSTRACT

There is limited information about the factors that affect the power generation of single-chamber microbial fuel cells (MFCs) using soil organic matter as a fuel source. We examined the effect of soil and water depths, and temperature on the performance of soil MFCs with anode being embedded in the flooded soil and cathode in the overlaying water. Results showed that the MFC with 5 cm deep soil and 3 cm overlaying water exhibited the highest open circuit voltage of 562 mV and a power density of 0.72 mW m^{-2}. The ohmic resistance increased with more soil and water. The polarization resistance of cathode increased with more soil while that of anode increased with more water. During the 30 d operation, the cell voltage positively correlated with temperature and reached a maximum of 162 mV with a 500 Ω external load. After the operation, the bacterial 16S rRNA gene from the soil and anode was sequenced. The bacteria in the soil were more diverse than those adhere to the anode where the bacteria were mainly affiliated to *Escherichia coli* and *Deltaproteobacteria*. In summary, the two bacterial groups may generate electricity and the electrical properties were affected by temperature and the depth of soil and water.

Key Words: electrogenic bacteria, impedance, soil depth, soil organic matter, voltage

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INTRODUCTION

Microbial fuel cells (MFCs) are devices that convert chemical energy directly into electricity. In an MFC, electrogenic bacteria degrade organic compounds under anaerobic condition and transfer electrons to anode. The electrons then flow through a conducting wire to cathode where the electron acceptors are reduced. The electrical current can be generated during the process. Materials with a large population of microorganisms and high content of organic matter have been used to generate power in MFCs, including marine sediment (Bond *et al.*, 2002; Scott *et al.*, 2008), sewage sludge (Zhang *et al.*, 2012), garden compost (Parot *et al.*, 2008), industrial/domestic wastewater (Rabaey and Verstraete, 2005) and animal waste (Yokoyama *et al.*, 2006). Soil generally has a bacterial population of approximately 10^9 cells g^{-1} (Whitman *et al.*, 1998) and organic matter content of within 100 mg g^{-1} (Bot and Benites, 2005), in spite of the variation between different soil types, *e.g.*, in organic soil, the abundance of bacteria and organic matter can be much higher (Troeh and Thompson, 2005). The presence of bacteria and organic matter endows soil with the potential to be a vast resource of electrical energy.

Studies on soil MFCs exhibited various directions. Ishii *et al.* (2008a) found that methane emission from soil, which was filled in the anode chamber, was suppressed after running an MFC. The reason could be that the soil organic carbon was reduced to generate electrical power rather than methane. Another study showed that by running two chambered MFCs for 10 d with phenol contaminated soil in the anode chamber, 90% of phenol was removed from soil, compared with 13% in non-MFC control (Huang *et al.*, 2011). Power generation was studied by inoculating rice paddy field

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soil with cellulose as the energy resource in a two-chamber MFC (Ishii *et al.*, 2008b). However, soil MFC without the carbon addition may generate power by using its own organic matter as a fuel. Moreover, the cost of a single-chamber MFC is much lower than that of a two-chamber one. To keep O_2 away from anode, single-chamber MFCs such as sediment-MFCs need a thick layer of soil or sediment, leading to a high internal resistance (Deng *et al.*, 2012), thus the performance of single-chamber soil MFCs deserves studies. In addition, several factors were reported to have a major impact on the performance of MFCs. Internal resistance of MFCs increased with distance between electrodes (Jang *et al.*, 2004); dissolved oxygen impaired the anaerobic conditions at anode and decreased power output (Kim *et al.*, 2007); temperature was a major factor that seriously affected microbial activity and thus the electrogenic activity (Min *et al.*, 2008). As a result, a study on the performance and the influencing factors of soil MFCs may help improve the efficiency of power output and soil remediation.

Electrogenic bacteria enrich on anode during the generation of current. Their composition differs between inoculums, although *Geobacter* and many other *Deltaproteobacteria* are well-known electrogenic bacteria and are often detected in anode biofilms (Franks *et al.*, 2010; Logan, 2009). The sequencing method based on 16S rRNA gene was intensively used to understand the presence of electrogenic bacteria. Liu *et al.* (2011) found that *Betaproteobacteria*, *Acetoanaerobium noterae* and *Chlorobium* sp. dominated the anode biofilm when MFCs were fed with domestic wastewater. Ishii *et al.* (2008b) found that *Clostridiales*, *Chloroflexi*, *Rhizobiales* and *Methanobacterium* dominated the anode biofilm in MFCs inoculated with rice field soil and fed cellulose as fuels. Kaku *et al.* (2008) operated plant-MFCs in which soil organic carbon and root exudates served as energy resources, and found that *Natronocella acetinitrilica*, *Beijerinckiaceae bacterium* and *Rhizobiales bacterium* were dominant on anode. However, the fed cellulose or rhizosphere effects (Moorhead and Reddy, 1988) are selective for specific bacteria in soil. For MFCs using soil organic carbon as an energy resource, understanding the dominant bacteria in anode biofilm could help improve the performance of this kind of MFCs by optimizing the living conditions for these bacteria.

In this study, we hypothesized that the performance including cell voltage, power output and internal resistance were affected by electrode distance and temperature. To testify the hypothesis, MFCs were set up with a series of soil and water depths, and correlations between temperature and cell voltage were studied. Bacteria from soil and from anode were cloned and sequenced based on 16S rRNA gene. The aims of this study were to understand i) the effect of soil and water depths, and temperature on the performance of soil MFCs; and ii) the electrogenic bacteria from soil.

MATERIALS AND METHODS

Soil sampling

Soil was collected in Jimei District, Xiamen City, China (118°02′ N, 24°37′ E). The climate is subtropical and wet with a mean annual precipitation of 1 200 mm and mean annual temperature of 21 °C. Soil sampling was carried out in October 2011. Soil was collected from an arid farmland at a depth of 0–20 cm. After sampling, soil was gently separated by hand and passed through a 2 mm mesh.

Soil chemical analysis

After thorough mixing, a part of the soil was air-dried for physiochemical analysis. Soil texture was determined using the pipette method (Gee and Bauder, 1986). Soil organic matter was measured using the $K_2Cr_2O_7$ method (Sims and Haby, 1971). NO_3^- and NH_4^+ were measured using ion chromatography (Mou *et al.*, 1993). Soil pH was measured at a soil-water ratio of 1:2.5 (w:v). The soil physiochemical properties were as follows: texture, clay loam; organic matter, 27 mg kg^{-1}; NO_3^-, 50.2 mg kg^{-1}; NH_4^+, 2.9 mg kg^{-1}; and pH, 6.5.

MFC set-up

Six MFC reactors were constructed in Oroglas each with a dimension of 50 cm × 30 cm × 30 cm (length × width × height) (Fig. 1). In each reactor, the anode and cathode were carbon felt with an area of 0.150 m^2 (50 cm × 30 cm) and 0.045 m^2 (30 cm × 15 cm), respectively. The thickness of the carbon felt was 0.5 cm. The anode was positioned close to the bottom of the reactor and embedded with soil while the cathode was fixed at the overlaying water surface. The water was added gently to the soil and the MFCs were operated after the overlaying water was clear. The anode and cathode was connected with a 1 000 Ω external load using titanium wire. To study the relationship between electrical properties and depths of soil and overlaying water, five reactors were assigned to the following treatments: i) 3 cm soil with 3 cm water (3S+3W); ii) 5 cm soil with 3 cm water (5S+3W); iii) 7 cm soil with 3 cm water (7S+3W); iv) 5 cm soil with 6 cm water (5S+6W) and v) 5 cm soil with 9 cm water (5S+9W). Here the soil