Research article

Methods for Improving the Performance of Paddy Soil-Used Sediment Microbial Fuel Cells

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Abstract Sediment microbial fuel cells (SMFCs) have received considerable attention for remediating sediment and wastewater while providing electricity. This technology offers many benefits for rural regions, particularly for those in developing counties. SMFCs can treat agricultural wastewater, household sewage, and organic waste while providing electricity to households. However, the performance of SMFCs remains low and must be improved. It has reported that mixing steelmaking slag (SS) with littoral sediment improves SMFC performance. The present study examines the use of SS to potentially improve the performance of a SMFC that uses paddy soil as its fuel (PS-SMFC). Moreover, we examine changes in the performance of a SS-SMFC (the PS-SMFC that the anode chamber is filled with SS) that uses lactic acid bacteria (LAB) and BN strain of Bacillus subtilis (BNB) solution-mixed paddy soil as its fuel. In laboratory experiments, paddy soil was poured into the SS layer (the anode chamber) of a SS-SMFC. LAB or BNB were added to the SS-SMFC anode by mixing a bacteria solution with the paddy soil. The SMFC performance was evaluated by measuring the polarization (current–voltage relation) and power density. The power density of the SS-SMFC was observed to be 152 mW.m^{-2}, which is approximately twice than that observed without using SS (80 mW.m^{-2}, as reported in previous studies). This shows that the performance of a paddy soil-used SMFC increases after mixing SS with the paddy soil. Furthermore, the SS-SMFC power density increased from 66 to 191 mW.m^{-2} after adding BNB and to 247 mW.m^{-2} after adding LAB. Thus, adding LAB or BNB to paddy soil is shown to improve SMFC performance. In comparison with BNB, LAB has greater potential for increasing SMFC performance.

Keywords sediment microbial fuel cell, performance, paddy soil, steelmaking slag, lactic acid bacteria, BN strain *B. subtilis*

INTRODUCTION

Recently, sediment microbial fuel cells (SMFCs) have received considerable attention for improving sediment and water quality. Numerous studies have reported that when using SMFCs, the amount and variations in the state of the organic matter present in sediment-applied SMFCs decrease and the redox potential of the sediment increases (Sacco et al., 2012; Sajana et al., 2013; Touch et al., 2014). Furthermore, SMFCs have been proven to be effective in preventing the deterioration of water quality due to ion diffusion from sediment (Touch et al., 2017a) and improving the benthic habitat environment in highly reduced sediment (Touch et al., 2018a). Moreover, Touch et al. (2017b) showed that using SMFCs is effective for removing hydrogen sulfide from sediment and fixing phosphate in them; they showed that the oxidation of reduced substances at the SMFC anode plays an important role in improving the sediment quality and the benthic habitat environment. As such, SMFCs were employed into the sediment deposited near a sewage outlet (Touch et al., 2018b) and an oyster farm (Touch et al., 2018c) to improve the quality of the sediment and water.

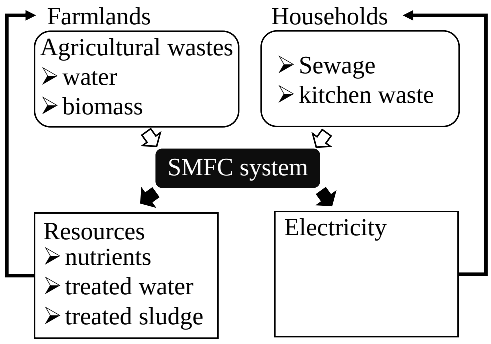

Fig. 1 Benefits of using SMFCs in rural regions

The achievements reported in previous studies suggested that SMFCs offer many benefits for rural regions, particularly those in developing counties. For example, SMFCs can treat agricultural wastewater, household sewage, and organic waste while providing electricity to households and recycled resources to farmlands (Fig. 1). However, the performance of SMFCs remains low and must be improved. Kouzuma et al. (2014) reported the maximum power and short-circuit current densities of SMFCs in rice paddy fields are only 80 $mW.m^{-2}$ and 550 $mA.m^{-2}$, respectively (based on the projected anode area). Many methods have been proposed for improving the SMFC performance, such as adding mediators to the sediment (Lovley et al., 2004) and the activation of organisms on electrode (Wang et al., 2009). It has been showed that adding steelmaking slag (SS) to littoral sediment could improve the SMFC performance (Nishimura et al., 2018). In the present study, we focus on using SS to improve the performance of a SMFC that uses paddy soil as its fuel (PS-SMFC); further, we examine the applicability of lactic acid bacteria (LAB) and the BN strain of *Bacillus subtilis* (BNB) to improve the performance of a SS-SMFC (the PS-SMFC that the anode chamber is filled with SS).

OBJECTIVE

The first objective of this study was to examine the changes in the performance (current and power) of a PS-SMFC after adding SS to the anode chamber, i.e., the performance of SS-SMFC. The second objective of this study was to examine the applicability of LAB and BNB to improve the performance of SS-SMFC.

METHODOLOGY

Experimental Device and Materials

The experimental device comprised a cylindrical bottle with an inner diameter and height of 120 mm and 150 mm, respectively. The bottle was filled with SS (diameter range of 5–40 mm) to a depth of 20 mm, and the anode electrode was placed on the SS layer. Then, 20 mm of the SS layer was placed on the anode electrode. The wet paddy soil was mixed with deionized water in a soil-to-water weight ratio of 1:2; subsequently, the mixture was slowly poured into the bottle until it reached a height of 50 mm from the bottom of the bottle. Finally, tap water was poured over the soil layer, and the cathode electrode was submerged near the surface of the water (Fig. 2a).

The paddy soil was collected from a rice filed (Ebina, Kanagawa, Japan) during the agricultural off-season. Approximately 150 mm of the surface soil was collected and transported to the laboratory. The paddy soil was mixed with deionized water to facilitate its easy pouring into the SS layer. Solutions of LAB or BNB were used instead of the aforementioned deionized water to examine their effects. Either 50-g Natto or 75-g yogurt (commercial products) was mixed with 3-L tap water and fermented for 7 days at ambient temperature. Then, the supernatant was extracted and mixed with the paddy soil.

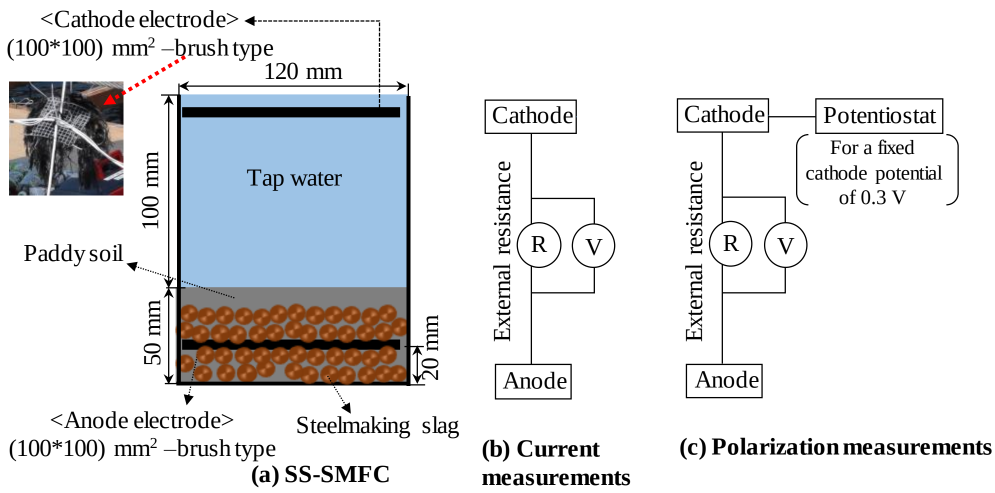

Fig. 2 Experimental device and measurement methods

The electrode material used was carbon cloth (News Company, PL200-E), which was heated at 500 °C for 1 h to improve its performance before being used as the electrode material according to Nagatsu et al. (2014). The heated carbon cloth, with a surface area of 10000 mm^2 (100-mm width and 100-mm long), was separated into carbon fibers to make the brush-type anode or cathode (Fig. 2a). Plastic-coated copper wire was used for all the connections in the SS-SMFC and operating circuits.

Operations and Measurements

The experiments were conducted by following the operations and measurements as shown in Fig. 3. All SS-SMFCs were put into an open circuit (without electrical current flow) mode until their voltages stabilized (~7 days), after which the polarization was measured using the circuit shown in Fig. 2b. An external resistance was loaded between the anode and cathode and varied over 2.2 Ω–10 kΩ. The cell voltage was recorded 1 min after each external resistance was loaded. The recorded voltage was used to calculate the current according to the Ohm's law, namely, $I = U/R_{ex}$, where U [V] is the voltage, I [A] is the current, and R_{ex} [Ω] is the external resistance; further, the power P was calculated according to $P = IU$. The current and power densities were obtained by dividing these values by the surface area of the electrode, i.e., 0.01 m^2. To understand the long-term performance of SS-SMFCs, an external resistance of 20 Ω was loaded between the anode and the cathode electrodes (Fig. 2b), after the polarization measurement.

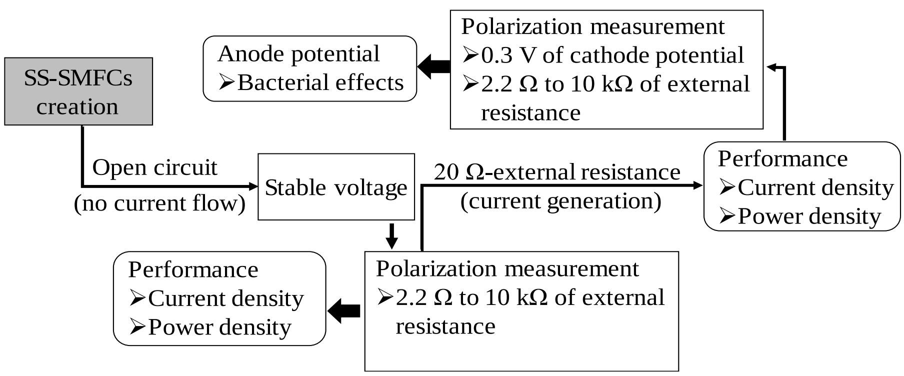

Fig. 3 Operation conditions and measurements during experiments

To calculate the circuit current, the voltage across the external resistance was measured every 30 min using a voltmeter (Graphtec, midi LOGGER GL840-M). After long-term current generation, the SS-SMFCs were put into an open circuit mode again until their voltages stabilized. To evaluate the effects of LAB or BNB in the SS-SMFCs, the polarization was measured by fixing the cathode potential at 0.3 V versus Ag/AgCl using a potentiostat (Hokuto, HB-151B) (Fig. 2c). This value was sourced from the study conducted by Nagama et al. (2018), who noted that the potential of sea water is approximately 0.3 V. After fixing the cathode potential, an external resistance was loaded between the anode and cathode and varied over 2.2 Ω–10 kΩ. The cell voltage was recorded 1 min after loading each external resistance.

RESULTS AND DISCUSSION

Improved Performance of Paddy Soil-Used SMFCs by Steelmaking Slag

Fig. 4 shows the polarization curves of the SS-SMFCs before they generate electrical current. As shown in Fig. 4a, the maximum power and current densities of the SS-SMFCs were approximately 150 $mW.m^{-2}$ and 1600 $mA.m^{-2}$, respectively. Kouzuma et al. (2014) reported the maximum power and short-circuit current densities of SMFCs in rice paddy fields were only 80 $mW.m^{-2}$ and 550 $mA.m^{-2}$, respectively. Comparison with the two latter shows that the performance of a PS-SMFC increases when SS is used in the anode chamber of the PS-SMFC.

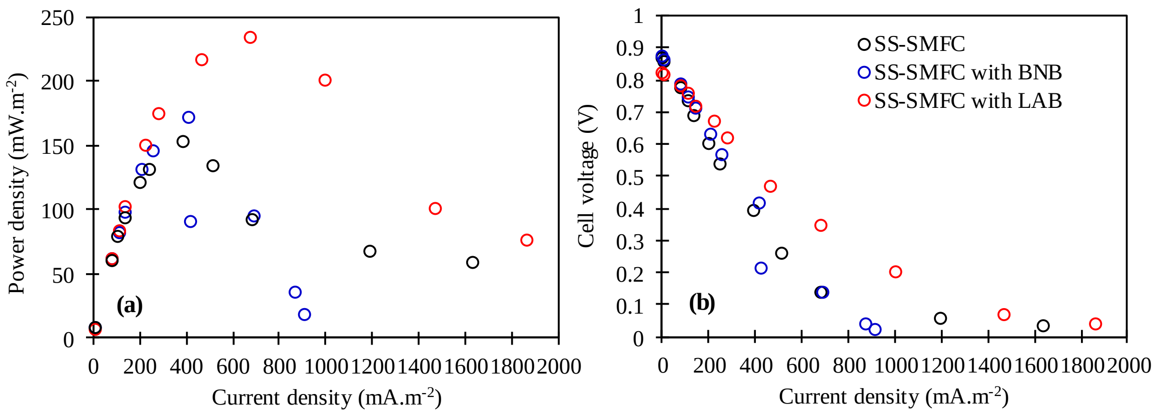

Fig. 4 Polarization curves of SS-SMFCs before generating electrical current

The results of the present study agree well with those of Nishimura et al. (2018), who suggested that mixing SS with littoral sediment increases SMFC performance. They argued that the reduction of iron compounds in the SS and its dissolution could make sediment into a higher reduced condition. Furthermore, the SS might play an important role in supporting electron transfer in the sediment. Our results suggest that mixing SS with either littoral sediment or paddy soil can improve SMFC performance.

Effects of Lactic Acid Bacteria (LAB) and BN stain of *Bacillus subtilis* (BNB) in SS-SMFCs

Fig. 4 (the polarization without fixing the cathode potential) shows that the differences in the power and current densities of a SS-SMFC with and without BNB were unclear; this occurs because the SMFC performance depends on the performance of the cathode and anode electrodes. Thus, we must fix the cathode electrode at the same potential to obtain a better understanding the anode electrode performance, i.e., the effects of either LAB or BNB in the SS-SMFC anode.

Fig. 5 depicts the polarization curves for a fixed cathode potential of 0.3 V. The maximum power density was 66 $mW.m^{-2}$ in the case of using paddy soil alone; it increased to 190 $mW.m^{-2}$ (a threefold increase) after adding BNB to the paddy soil and to 247 $mW.m^{-2}$ (an increase of 3.74 times) after adding LAB (Fig. 5a). This suggests that adding either BNB or LAB improves SS-SMFC performance, with LAB improving the performance more. A Similar conclusion is reached by comparing the current density of each SS-SMFC (Fig. 5).

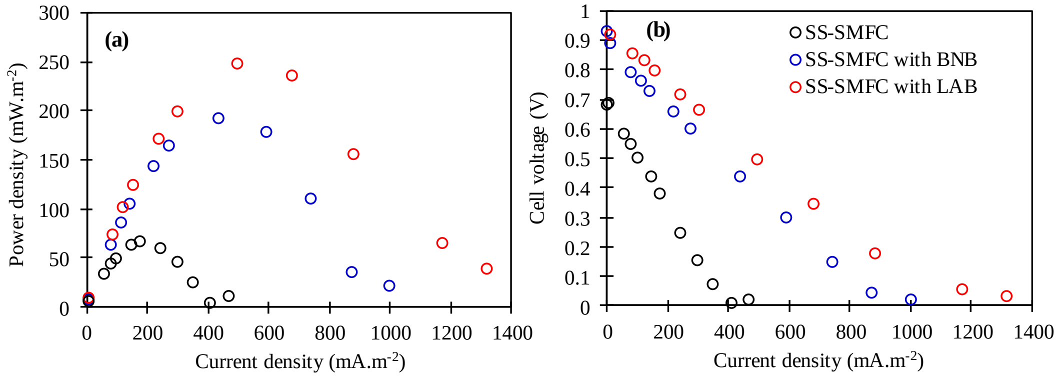

Fig. 5 Polarization curves for a fixed cathode potential of 0.3 V

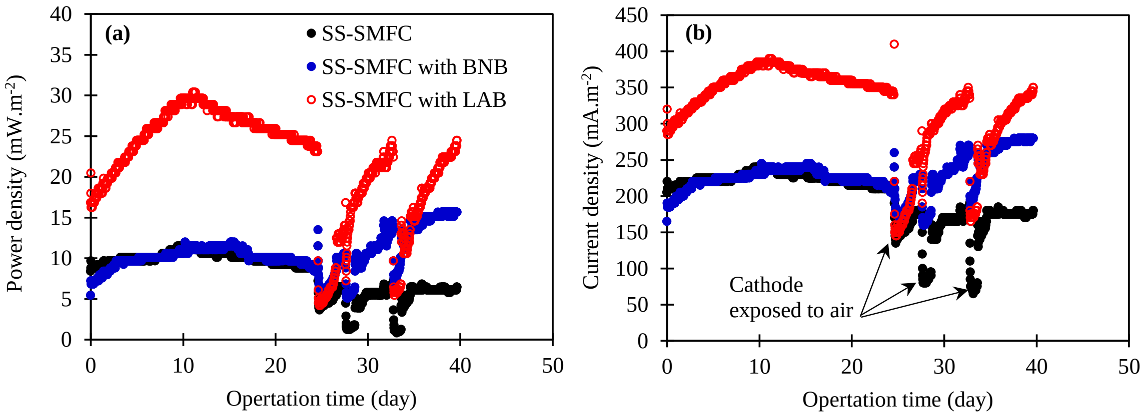

Fig. 6 Long-term variations of power and current densities of SS-SMFCs

A SMFC experiences various potential losses that decrease the cell voltage during electricity generation (Touch et al., 2019). In other words, the cell voltage of a SMFC with higher performance is less reduced for a given generated current. For a current density of 400 mA.m^{-2}, Fig. 5b shows that the cell voltage decreased by approximately 0.70, 0.45, and 0.35 V for the basic SS-SMFC, SS-SMFC with BNB, and SS-SMFC with LAB, respectively. From this, it can be said that adding either BNB or LAB can improve the SS-SMFC performance. The improvement may be partly due to the enhanced electron transfer to the anode and the accelerated decomposition of organic matter by the bacteria; unfortunately, those reasons could not be examined in the present study.

In addition, having continuously generated electrical current for 40 days, the power densities were 7, 16, and 25 mW.m^{-2} for the basic SS-SMFC, SS-SMFC with BNB, and SS-SMFC with LAB, respectively (Fig. 6a), and the current densities were 180, 280, and 350 mA.m^{-2}, respectively (Fig. 6b). These results suggest that the bacteria will continue to affect the SS-SMFCs during long-term operations.

CONCLUSION

In this study, laboratory experiments were conducted to examine changes in the performance of the PS-SMFC when using SS in the anode chamber and the applicability of LAB and BNB for improving SS-SMFC performance. A twofold increase in the power density was observed, suggesting that the utilization of SS in the anode chamber improves the PS-SMFC performance. Furthermore, the power density increased by 2.9 times after adding BNB and 3.7 times after adding LAB to paddy soil, thereby indicating that adding either LAB or BNB improves the SS-SMFC performance; further, adding LAB was shown to increase the SS-SMFC performance more. It was considered that these bacteria enhance the electron transfer to the anode and accelerate the decomposition of organic matter.

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