Research article

Benefits of Applying Microbial Fuel Cell Technology in Organic Farming for Sustainable Agriculture

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Abstract Increasing the productivity of organic farming is a strategy to achieve sustainable agriculture. However, it is necessary to maintain soil redox potential (ORP) in continuously oxidized conditions and to promote bacterial metabolisms in soils to increase productivity. Previously, applying microbial fuel cell technology (MFCT) into sediment improved ORP and benthos survival in the sediment. It is thought that these positive effects of MFCT can also provide many benefits for soil cultivation in organic farming. This study aims to examine the changes in the biochemical properties of soil following MFCT application. In laboratory experiments, MFCT was applied to cow manure compost-mixed andosol. An anode (oxidation reaction) and a cathode (reduction reaction) were installed in the soil, and a 1.5-V solar cell was used to produce an electric current between the two electrodes. Three months after MFCT application, the chemical properties and adenosine triphosphate (ATP) of the soil were measured. Our results showed an electric potential distribution in the soil, and the soil located within 20 cm of the electrode was strongly affected by the electrode reaction. This suggests that applying MFCT to soil can change the soil's redox conditions. The ATP and ammonium concentrations increased, suggesting bacterial activation and enhanced organic matter decomposition in the soil. It is recommended that farmers should apply MFCT into soils for enhancing bacterial metabolism and increasing organic matter decomposition in soils.

Keywords microbial fuel cell, organic farming, soil reduction, soil oxidation, nitrogen release, bacterial activation

INTRODUCTION

According to the Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF), organic farming is a strategy to achieve sustainable agriculture. However, the ratio of total organic farmland to all cultivated land remains low. In 2018, the ratio was 0.2% in Japan and 1.5% worldwide. On the basis of the questionnaire survey conducted by MAFF (2018), technologies to enhance productivity and implementation systems are required to facilitate organic farming. This study focuses on technology to enhance the productivity of organic farming.

Understanding of the soil chemical environment (SCE) is useful to ensure healthy soil that can sustain crop production (Yan and Hou, 2018). Because a decline in soil fertility results in a decrease in productivity (Buresh et al., 1997), soil fertility and health management play an important role in realizing sustainable agriculture (Prasad and Power, 1997). In organic farming, as nutrients are supplied by the decomposition of organic matter, facilitating this decomposition plays an important role in providing higher productivity. However, the SCE varies with the decomposition of organic matter (soil reduction). This variation affects biological soil properties, resulting in a decrease in the decomposition rate of organic matter. Therefore, technology that can reduce changes in the SCE and continuously activating bacterial metabolism is required to provide higher productivity in organic farming.

Numerous studies have reported that applying microbial fuel cell technology (MFCT) to sediment facilitates the decomposition of organic matter and increases the redox potential of the sediment (Sacco et al., 2012; Sajana et al., 2013; Touch et al., 2014). Furthermore, MFCT has been proven to effectively improve the benthic habitat environment in highly reduced sediment (Touch et al., 2018a). It is thought that these benefits of MFCT would be also useful for organic farming.

OBJECTIVE

This study aims to examine the benefits of applying MFCT for organic farming. Specifically, we examined changes in the soil redox potential, biological properties, and nutrient release following MFCT application. This was conducted by applying MFCT into cow manure compost-mixed andosol with a generated electric current for 3 months.

METHODOLOGY

Experimental Procedures and Operations

Commercial products, i.e., cow manure compost and andosol, were used in laboratory experiments. First, cow manure compost was mixed with andosol at a volume ratio of 47% (generally, 40% to 60% is used). The mixture was then used in the experiments which were conducted under three conditions, i.e., without treatment (Case 1), treated with a solar cell (Case 2), and treated with a sediment microbial fuel cell (Case 3). Case 2 was conducted in duplicate. In Case 1, no electrode was installed in the mixture (Fig. 1a).

In Case 2, two electrodes were installed in the soil layer (Fig. 1b). For generating an electrical current, one of the both electrodes were connected to the positive, and another was connected to the negative terminals of a 1.5-V solar cell (Tamiya, 1.5 V) using the circuit shown in Fig. 1b. A 2.2-Ω external resistance was loaded between the anode and solar cell. In Case 3, an electrode was placed in the soil layer (anode), and another was placed near the water surface (cathode), as shown in Fig. 1c. For generating an electrical current, a 2.2-Ω external resistance was loaded between the anode and cathode. This system is generally called a sediment microbial fuel cell (SMFC). Note that both systems used in Cases 2&3 are different types of MFCT in which the system of Case 2 used a solar cell as an external power supply. Here the solar cell was used following the study by Touch et al. (2020), who suggested that using a solar cell increased the electric current of the SMFC and improved the decomposition of organic matter present in paddy soils. The electrode material was carbon cloth (News Company, PL200-E), which was heated at 500°C for 1 h prior to use to improve its performance, as was suggested by Nagatsu et al. (2014). The heated carbon cloth with a width of 20 cm and height of 10 cm was separated into fibers to form a brush-type electrode (Fig. 1d). The electrode was placed in a plastic net (1-mm mesh) and installed in the soil layer.

After the installation of both electrodes, the container was filled with tap water. As a result, a 2-cm water layer was formed on the soil surface, which can prevent the soil from drying due to evaporation. The experiments were conducted from June to November in 2020.The voltage at both terminals of the external resistance was measured every 15 min using a voltage logger (T&D Corp., MCR-4V) to calculate the circuit current according to the Ohm's law. The current density was obtained by dividing the current by the surface area of the electrode, i.e., 0.02 m^2. To measure the anode potential of each case, the anode and a reference electrode (Toyo Corp., W-RE-7A) placed in the overlying water were connected to the voltage logger.

Analyses

Three months after the experiments started, soil sampling was conducted. First, 1 cm of surface soil was removed, and then, pH and redox potential (ORP) were measured using a pH/ORP meter (Horiba, D-50) at intervals of 5 cm from the anode. Soil samples were collected (Fig. 1e) after the pH and ORP measurements. Only half-length of the soil layer should be collected for examining the effects of solar cell or SMFC on the soil properties. However, in Case 2 (SC), the soils between the electrodes were collected to determine the effective range of electrode reaction. Next, each soil sample was centrifuged at 6000 rpm for 5 min (As one, CN-2060) to extract the porewater. Finally, the nutrient concentration (phosphate, PO_4^{3-}; ammonium, NH_4^+), and adenosine triphosphate (ATP) were measured. PO_4^{3-} and NH_4^+ concentrations were measured using PACKTEST (Kyoritsu Corp., WAK). ATP concentration was measured using a lumitester (Kikkoman, Lumitester-Smart), and the result represents the sum concentration of adenosine triphosphate, adenosine diphosphate, and adenosine monophosphate.

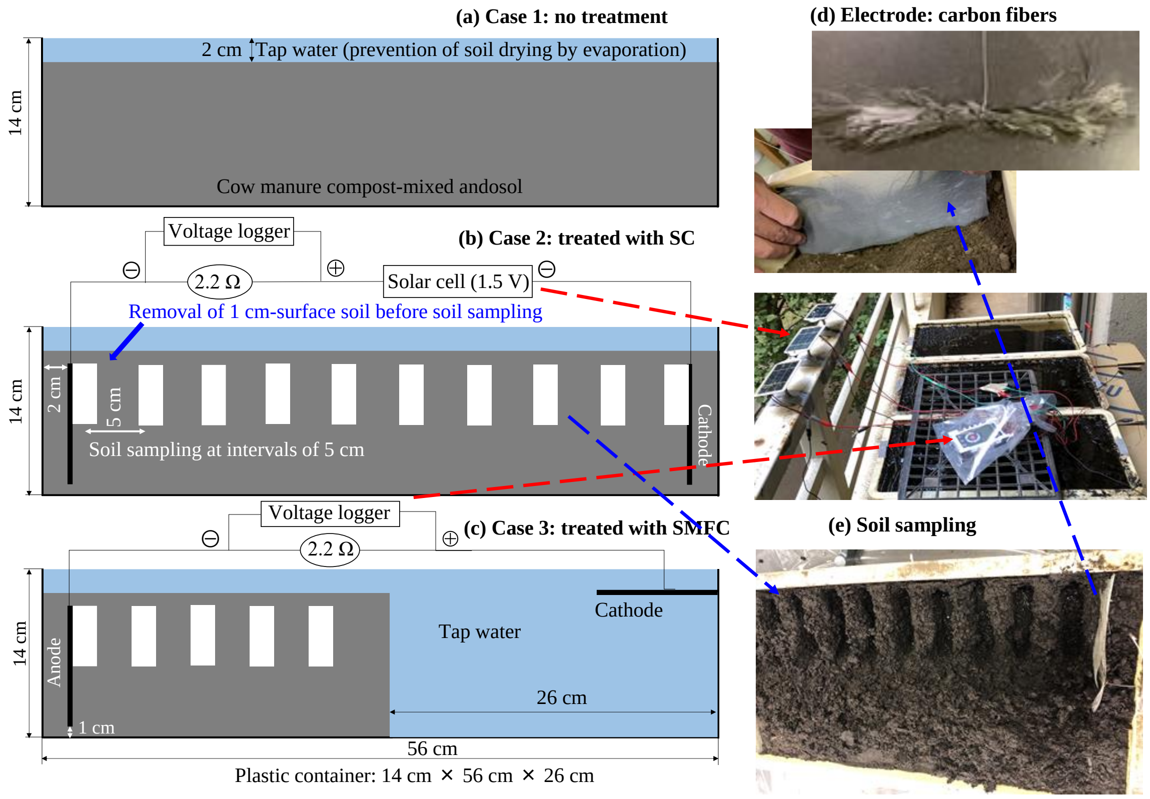


Fig. 1 Experimental devices and operations

RESULTS AND DISCUSSION

Comparison of Current Density Generated Using SMFC and a Solar Cell

Figure 2 depicts the temporal changes in the current densities generated using the SMFC and solar cell during the first 30 days of the experiments.

As can be seen from the figure, the maximum current density generated by the SMFC was approximately 60 mA/m^2, which increased to 200 mA/m^2 when using the solar cell. During the first month of the experiments, the total electric charge was 50,415 C/m^2/month when the SMFC was used whereas the total was 59,220 C/m^2/month when the solar cell was used. Although, more than three times the current density was observed, only a 1.17-fold change in the total electric charge was found between both cases. This is because no electrical current was generated at night when the solar cell was used.

Changes in Redox Conditions at the End of the Experiment

Figure 3 shows the changes in pH and ORP due to current generation at the end of the experiment. In the figure, 0 and 45 cm refer to the soil samples at the anode and cathode, respectively (Case 2). In Fig. 3a, the pH at the anode was 6.97 for Case 1 (without current generation), which decreased to 6.44 when using the SMFC (Case 3) and to 6.39 when using the solar cell (Case 2). In Case 3, the large increases in pH at distances greater than 10 cm were due to the effects of cathode water (Fig. 1c).

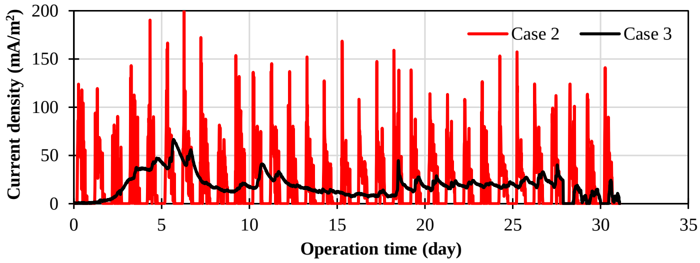
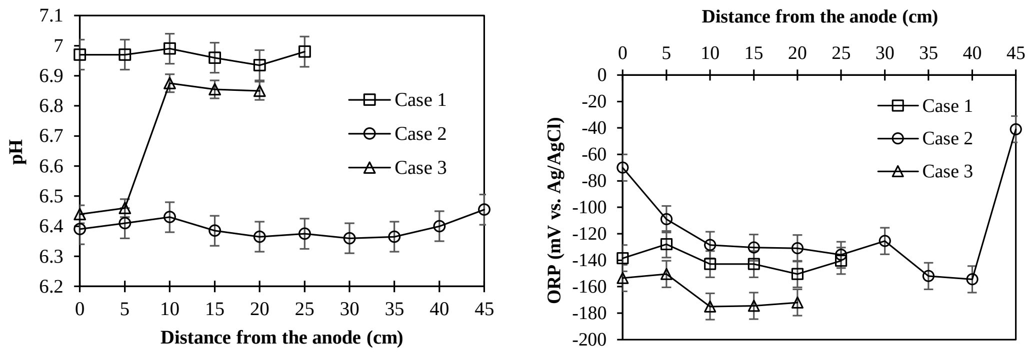


Fig. 2 Comparison of current densities generated using the SMFC and solar cell

In contrast to the literature, our results showed no increase in ORP following SMFC application. However, increases in ORP were observed when the solar cell was used. The increases in ORP were caused by large variations in the electrode potential due to the use of the solar cell (Fig. 4). In Fig. 4, the anode potential was in the ranges from 0.2 to 0.4 V and −0.2 to 0.8 V vs. Ag/AgCl when using the SMFC (Case 3) and the solar cell (Case 2), respectively. The oxidation reactions at the anode following current generation caused the decrease in pH and increase in ORP. These results suggest that the solar cell can be used to effectively control the soil redox conditions, i.e., pH and ORP. From the ORP distribution, it is thought that the soil located within 20 cm of the electrode was affected by current generation using the solar cell. It is expected that nutrient release and microbial activation differ in response to these changes in pH and ORP.



(a) pH distribution (b) ORP distribution

Fig. 3 Changes in pH and ORP due to current generation at the end of the experiment

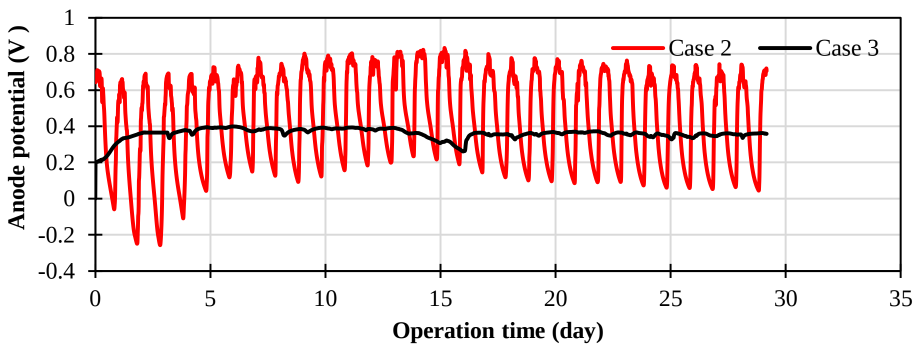
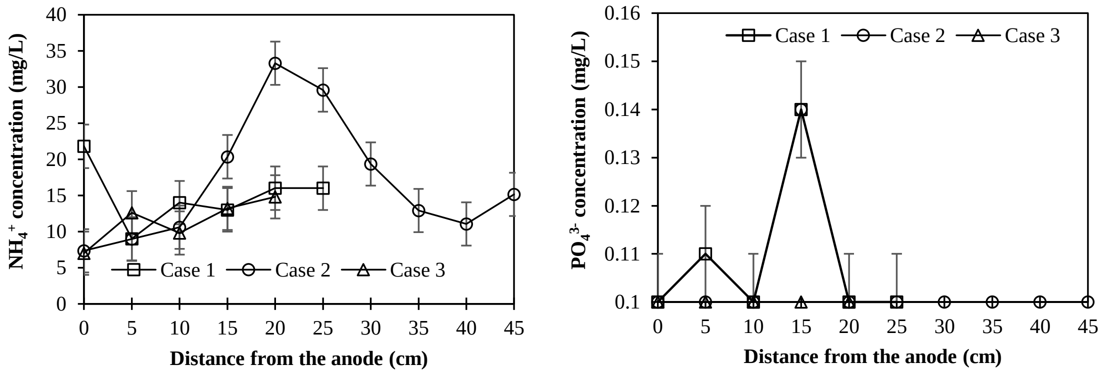


Fig. 4 Temporal changes of the anode potential during the first month of the experiment

Nutrient Release due to Current Generation

Figure 5 shows the distributions of ammonium (NH_4^+) and phosphate (PO_4^{3-}). No differences were observed between Case 1 and Case 3 (differences were within the error range), suggesting that the SMFC had little effect on the decomposition of organic matter. Interestingly, a large increase in NH_4^+ concentration was observed between Cases 1 and 2, at distances from 15 to 30 cm from the anode. A 2-fold increase in NH_4^+ concentration was observed 20 cm from the anode. However, the PO_4^{3-} concentrations in all cases were on the same order of magnitude (Fig. 5b).

The released NH_4^+ is believed to arise from the decomposition of organic matter. Even though the generated electric charges were on the same order of magnitude (Case 2: 59,220 C/m^2/month; Case 3: 50,415 C/m^2/month), the decomposition behavior of organic matter differed. This may be due to the differences in electrode potential between Cases 2 and 3 (Fig. 4). The decomposition of organic matter was facilitated when the solar cell was used, which is in good agreement with the results obtained by Touch et al. (2020). According to Touch et al. (2018b), the lower NH_4^+ concentration near both electrodes (Fig. 5a) may be due to the oxidation of NH_4^+ at the electrodes due to the high electrode potential when the solar cell is used (Fig. 4).



(a) Ammonium concentration (b) Phosphate concentration

Fig. 5 Comparison of nutrient concentration distributions of each case

Changes in ATP due to Current Generation

Figure 6 illustrates the ATP distribution of each case. Similar to the distribution of NH_4^+, almost no difference in ATP was found between Cases 1 and 3. However, two to threefold increases in ATP were observed when the solar cell was used (Case 2). These results suggest that using the solar cell can provide a better biological environment, resulting in a higher decomposition rate of organic matter. This may be the cause of the higher NH_4^+ concentration observed when the solar cell was used (Fig. 5a, Case 2).

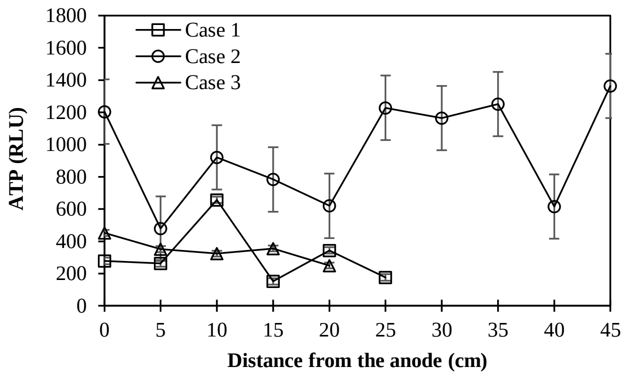


Fig. 6 Changes in ATP due to current generation

CONCLUSIONS

Laboratory experiments were conducted to examine the benefits of applying MFCT in organic farming. Specifically, changes in the soil redox potential, biological properties, and nutrient release following the application of MFCT to cow manure compost-mixed andosol were investigated. Similar to previous results when applying MFCT into littoral sediments, an increase in ORP near an electrode was observed. Following current generation using a solar cell, an ORP distribution was formed in the soil, and the soil located within 20 cm from the electrode was affected by the electrode reaction. This suggests that applying MFCT to soil can change the soil's redox conditions. The ATP and ammonium concentrations increased because of the current generated by the solar cell, suggesting bacterial activation and enhanced organic matter decomposition in the soil. It can be concluded that applying MFCT can control soil biochemical conditions and can enhance bacterial metabolism and organic matter decomposition in soils, which are the most important factors in organic farming.

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