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Evaluation of the Dependence of Microbial Fuel Cells on Soil Composition and Water Content

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In recent years, microbial fuel cells (MFCs), which utilize microorganisms in the soil, have been attracting attention as a new environmental power generation technology. Fuel cells (FCs), which have already been put to practical use in power generators and automobiles, use hydrogen as fuel and generate electric current using hydrogen's electrons. On the other hand, MFCs have the same principle as fuel cells but use organic materials as fuel. Microorganisms break down the organic materials to extract electrons. Various organic materials can be used as fuel, including sugars, carbohydrates, alcohols, agricultural wastewater, and sewage sludge. To expand the application of this technology, it is essential to study the use of freshwater with low conductivity and the optimal conditions of the soil environment. In this study, we focused on the moisture content of the soil to improve the efficiency of microbial fuel cells in freshwater. Soils with different moisture contents were prepared and used in microbial fuel cells to quantitatively evaluate the effect of moisture content on microbial power generation. Under conditions of MFC moisture content up to 82 %, the open-circuit voltage tended to increase with increasing moisture content; when MFC was kept stationary for five days, the highest power generation was observed at 86 % moisture content in the high moisture content region, and power generation tended to decrease as moisture content increased to 91 %. When MFCs with similar moisture content were mixed once a day, the amount of electricity generated grew higher when the moisture content was 91 % than when the moisture content was 86 %.

1. Introduction

The market size of energy harvesting technologies (Mateu and Moll, 2005) is growing. More research is being conducted on the effective use of novel light energy materials and dilute energy (Wang et al., 2018). Various methods have been developed for autonomous power supply technologies that support the IoT society, including technologies that use small temperature changes near room temperature, pressure, and microorganisms. Materials and systems that can flexibly adapt to the location of use are under construction. Among these, sunlight is moving toward higher efficiency, and next-generation solar panels (Hashemi et al., 2020) and piezoelectric elements have become widely used (Liu et al., 2018). Research on unused thermal energy has been developing (Petsagkourakis et al., 2018), such as the use of changes in magnetic moments (Kansha and Ishizuka, 2019). Microbial fuel cells (MFCs) (Logan et al., 2006), which utilize microorganisms in the soil (Rabaey and Verstraete, 2005) as well as energy harvesting technologies (Rabaey and Verstraete, 2005), have recently gained attention as a promising technology that can simultaneously purify soil and water quality. MFCs are based on the same principle as fuel cells (FCs). FCs are fueled by hydrogen and use electrons in the hydrogen to generate electric current, whereas MFCs are driven by organic matter and powered by microorganisms (Ferriday and Middleton, 2021). Electricity is generated using electrons released outside the cells as the microorganisms break down the organic matter (Logan et al., 2006). A schematic diagram of the interior of an MFC is shown in Figure 1. Electrons generated by the metabolism of electricity-generating microorganisms and reaching the anode electrode are consumed by reduction reactions at the cathode electrode via an external resistance. Organic materials such as sugars, carbohydrates, alcohols, agricultural wastewater, and domestic wastewater can be used as fuel in various states. MFCs are relatively inexpensive to produce and maintain because they use power-generating microorganisms such as Schwanella bacteria in soil,

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which are ubiquitous. It can also be used in severely contaminated sites and is being studied as a technology used in various areas (Jatoi et al., 2021). In particular, its practical application in water treatment is increasing. Research is also underway to simultaneously generate electricity and treat wastewater using organic matter contained in wastewater and sludge and recover resources in wastewater (Ichihashi et al., 2012).

Various styles of MFCs have been fabricated and studied, including one- and two-layer MFCs for the liquid phase, sediment microbial fuel cells (SMFCs) that use soil, and plant microbial fuel cells (PMFCs) that simultaneously grow plants. Among these, SMFCs can use not only sewage sludge but also a wide range of soils, such as those near rice paddies, estuaries, and lakeshores, and are being considered an effective method of generation technology, such as independent environmental power sources in non-electrified area (Srivastava et al., 2021). To increase power generation, it is desirable to have high nutrient and anaerobic conditions to make the power-generating microorganisms highly active. Sludge and sewage, highly nutritious for power-generating microorganisms, are effective when used in cells (Xu et al., 2019).

However, supposing the application of SMFCs is to be expanded as a power source in un-electrified areas. It is necessary to build SMFCs systems with high power generation capacity, even in freshwater with low conductivity and little organic matter. Adding organic matter and salts to improve conductivity for activating microorganisms, not for environmental cleaning, is an ecological burden (Abbas and Rafatullah, 2021). It has been confirmed that microorganisms can be activated if only the anode side is highly anaerobic, even when no organic matter is provided (Logan et al., 2021). On the other hand, the cathode side must be in a shape that facilitates oxygen supply. In SMFCs, if the moisture content of the soil is low, the anaerobic condition on the anode side is insufficient, and the electrical conductivity is low (Abbas and Rafatullah, 2021), resulting in lower mobility of hydrogen ions and lower power generation. If the moisture content is too high, the percentage of the electrolyte decreases. Depending on the cell conditions, the distance between the electrodes opens up, reducing the mobility of hydrogen ions and making it challenging to obtain electricity (Abbas and Rafatullah, 2021). Due to the complexity of the system, the relationship between soil water content and electricity production in SMFCs has only been discussed qualitatively.

In this study, SMFCs with different soil moisture contents were fabricated using the same organic soil with uniform nutrient conditions, focusing on the effect of moisture content on the high nature of SMFCs. We quantitatively evaluated the impact of soil moisture content on power generation and provided a basis for constructing promising SMFCs even under freshwater and relatively low organic matter conditions.

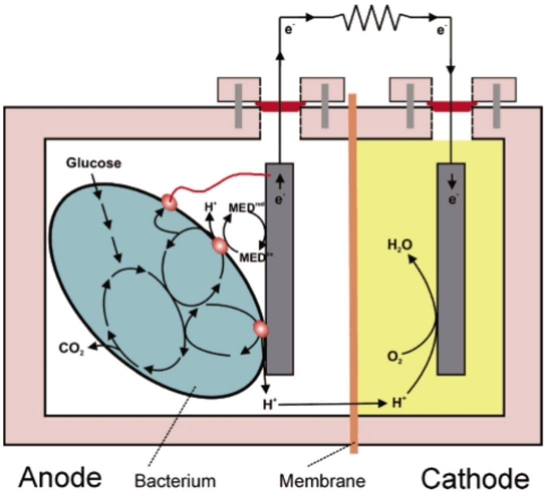


Figure 1: Schematic diagram of an MFC. Bacteria metabolize glucose in the anode chamber, and the electrons produced move from the anode to the cathode chamber, where they reduce oxygen. (Logan et al., 2006)

2. Experimental Methods

2.1 Preparation of SMFCs

Wood chip-based organic soil was used for the preparation of SMFCs. First, to check the amount of water in the untreated soil, three 200 mL beakers were filled with 50 g of soil at a high fill rate. These beakers were placed in a thermostatic bath at 120 °C and recorded every 10 min until the change in mass was small (about 300 min) (Figure 2). A 35 % decrease in mass was observed in all beakers after 300 min compared to untreated soil. When the soil was left in the thermostatic chamber, therefore an extended period, the soil mass gradually decreased. Imitating the conditions of the SMFCs to be made, we prepared 30 g of soil in a 200 mL beaker without compressing the soil and heat treated it at a lower fill rate, which resulted in an average mass loss of 47

%. It is believed that heat treatment at a lower fill rate sufficiently reduced the amount of water in the soil. In all studies, the dry reference moisture content of the untreated soil was assumed to be 47 %, and SMFCs were prepared with distilled water added for conditioning soils of different moisture contents. The soil weight used for all cells was adjusted to be the same for comparison for each study. Figure 3(a) shows a schematic of the SMFCs used in the experiment. A beaker (100-200 mL) was used with a 5 mm thick carbon felt electrode on the anode side and a 12 mm thick carbon felt electrode on the cathode side. The cell was prepared with 5 g of untreated soil (47 % moisture content) below the anode and 20 g between the anode and cathode, with anaerobic conditions on the anode side and aerobic conditions on the cathode side.

2.2 Study to optimize the water content of the microbial fuel cell

Four cells were prepared for each of the three types of SMFCs with different water content:

- Group A was a cell with no distilled water added (47 % water content).
- Group B was a cell with 25 g distilled water added (73 % water content).
- Group C was a cell with 50 g distilled water added (82 % water content).

Distilled water for moisture content adjustment was added evenly to the soil above and below the anodes to ensure that the water was evenly distributed throughout the cell (Figure 3a). The SMFCs were stored in desiccators under high humidity conditions, and the open-circuit voltage was measured as one of the methods to evaluate the performance of MFCs (Winfield et al., 2013). This method is predominantly used to check the power generation state until a specific voltage is reached due to increased microorganisms (Sanchez et al., 2022). To evaluate the performance of each SMFCs, their stable open−circuit voltage values within 5 s were recorded once a day for 16 consecutive days with a digital multimeter (Linkman LDM81B). The results were used to investigate the relationship between the moisture content and the open-circuit voltage of the SMFC.

2.3 The relationship between the water content of the microbial fuel cell and the amount of electricity generated

SMFCs with water content was adjusted to 86 %, and 91 % were prepared. When the SMFCs were left for an extended period with a moisture content of 86 % or higher, the heavier soil was divided near the anode and the lighter soil near the cathode. A layer with shallow soil content and almost exclusively water was formed in the middle, as shown in Figure 3b. The effect of soil content on power production was investigated in two cells. The soil was left separated on the anode and cathode sides at each moisture content, and on the other, the soil was mixed once daily so that it would not be separated. Samples that were left separated were labeled "separated" and samples mixed daily to prevent separation were labeled "mixed.

Current potential measurements were performed on these SMFCs using an Automatic Polarization System (Hokuto Denko Corp., HSV-110), with the anode side as the working pole and the cathode side as the pole counter electrode (Wang and Jiang, 2019). The voltage was swept from open-circuit voltage to 0 V at 10 mV/s. The Linear Sweep Voltammetry (LSV) results were used to determine the maximum value of power for each SMFC using equation (1) from the voltage and current values (Table 1).

$$P = I * V = I^2 * R = \frac{V^2}{R} \quad (1)$$

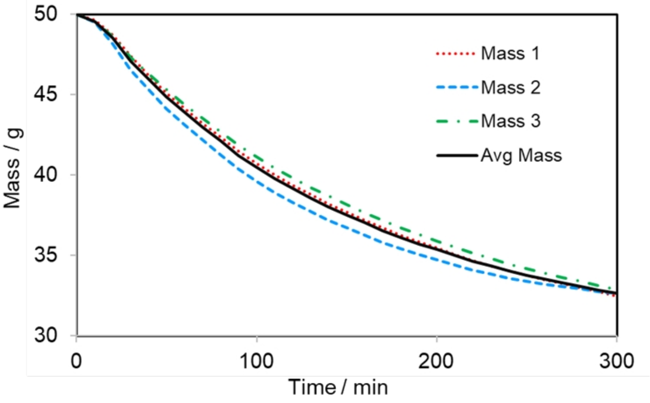
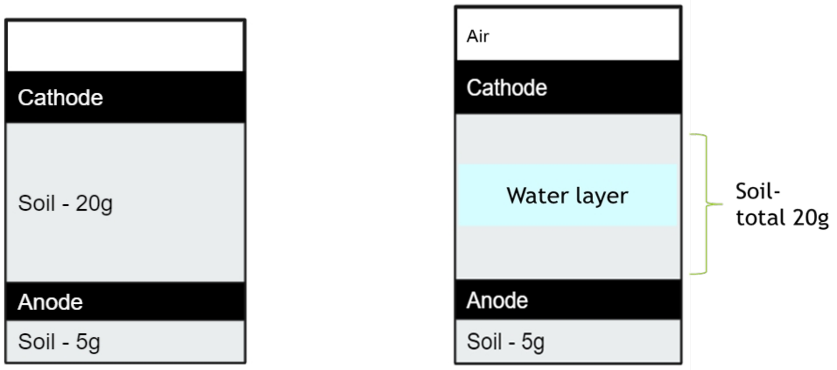


Figure 2: Water lost by mass overtime during the first heat drying test



(a) (b)

Figure 3: Schematic of the SMFCs layout used for the voltage test. Soil volume refers to dry base soil only. Water was distributed evenly throughout the cells.

3. Results and discussion

3.1 Change over time of open-circuit voltage of MFC

Figure 4 shows the change over time in the open-circuit voltage. The dashed line shows the measurement results for each cell, and the solid line shows the average of the results for each moisture content. The cells were stored in desiccators, but the cathode side was opened at the top to become aerobic, so the water in the soil tended to decrease slowly. Therefore, on days 7 and 14, evaporated water was added up to the specified amount. When compared in terms of average voltage, group C, with 82 % water content, had the highes showed little change in voltage to which no distilled water was added little change in voltage. Group B showed little change in voltage but only slightly higher than Group A. Group B, with 73 % moisture content, showed the highest average voltage. In contrast, Group C, with 82 % moisture content, showed the lowest average voltage. Group B, with 73 % moisture content, showed almost no increase in open-circuit voltage values after 16 days of measurements, confirming that 73 % moisture content is insufficient for SMFCs. It is considered that a higher moisture content facilitates the movement of electrons produced by microorganisms to the anode side and, at the same time, facilitates the diffusion of hydrogen ions produced, which reach the cathode side at a higher rate, resulting in a particular potential difference (Rossi et al., 2019). On the other hand, if the soil moisture content is low, the anode side does not become sufficiently anaerobic, making it difficult for microbial activity to increase. In addition, the measurement of electrical conductivity (EC) of soil is greatly affected by moisture, so it is necessary to make sure that all the objects being measured have the same specific moisture content (Abbas and Rafatullah, 2021). The lack of moisture content makes it difficult for the generated electrons to move to the anode side and, at the same time, prevents the migration of the generated hydrogen ions. Therefore, it is thought to be why a potential difference could not be observed. In this study, the voltage value tended to increase as the water content in the soil increased. However, if the water content increased significantly, the concentration of hydrogen ions generated by the power-generating microorganisms would decrease, and the arrival rate at the cathode side would also decrease. For Group C, with 82 % water content, a significant increase in open-circuit voltage was observed immediately after the start. Since the water was spread over the entire soil, the generated hydrogen reached the cathode side, and the reduction reaction on the cathode side was considered to have progressed. However, the open-circuit voltage reversed for two of the four cells and temporarily observed an inversion of the open-circuit voltage. Voltage output has been reported to be stabilized by providing external resistance or by increasing the concentration of organic matter in the cell (Oh and Logan, 2007). Also, if the anode side is not sufficiently anaerobic or otherwise inactive for the bacteria, the amount of electricity generated will be insufficient, and voltage reversal will occur (Winfield et al., 2013). In the present case, the concentration of easily degradable organic matter was low, and the measurements were taken at open voltage. In addition, the anode side was not deep enough, so bacterial activity was not stable, and a voltage reversal was observed. The anode side must be more anaerobic to suppress a voltage reversal phenomenon. Therefore, power generation was examined using conditions where soil moisture content exceeded 82 %.

3.2 MFC power generation in high moisture content region

Table 1 shows the amount of electricity generated by each cell of SMFCs prepared with 86 % and 91 % moisture content five days after the start of the experiment. As the moisture content increases, the soil tends to separate

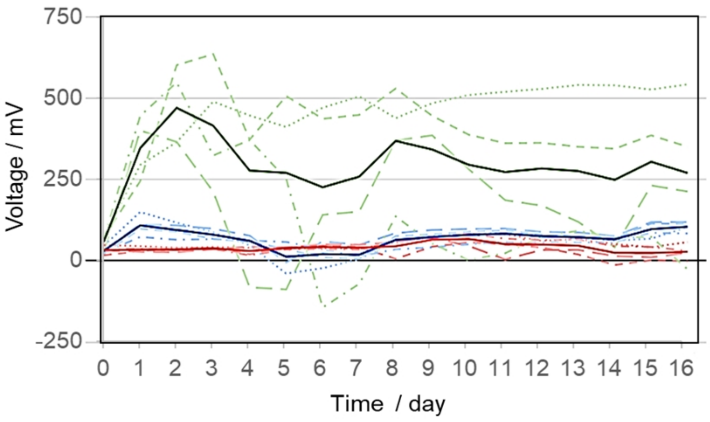


Figure 4: Initial daily voltage readings over 16 days. Samples from group A (blue) had a 47 % moisture content, group B (red) had a 73 % moisture content, and group C (green) had an 82 % moisture content.

on the anode side and the cathode side after a long period of standing. Therefore, we prepared four types of cells, one in which the soil was left separated at each moisture content (separated) and one in which the soil was mixed once a day (mixed). This study showed that the 91 % water content separation generated the least power, 22.5 µW, and the mixed generated the most power, 30.5 µW. When comparing the power generation of the 86 % separation and 91 % separation left for 5 days, the 86 % separation showed a tendency to generate about 12 % more power. However, for the 86 % mixing and 91 % mixing, which were mixed once each day, the 91 % mixing generated about 7 % more power. Comparing separation and mixing, the mixed mixture generated more power for the 86 % and 91 % moisture content cases, with a 13 % increase for the 86 % moisture content case and a 36 % increase for the 91 % moisture content case. Since all SMFCs were fabricated in the same vessel, the separation with 91 % water content has the anode located further away from the water surface. It is more anaerobic, and microorganisms are activated, resulting in higher power generation than the separation with 86 % water content (Rossi et al., 2019). It has also been reported that the addition of silica colloids to low-conductivity paddy soil forms a network of silica colloids in the cells, which reduces soil resistance, resulting in increased ion mobility and a 10-fold increase in power generation (Garay et al., 2013). Mixing the separated solids and liquid may have contributed to the increase in power generation as the fine soil acted as a silica colloid. Therefore, in the 91 % mixed, microbial power generation increased due to increased anaerobic activity on the anode side. In the case of separation, on the other hand, the mobility of hydrogen ions is considered to be lower as the distance between the electrodes increases because there is less fine soil between the electrodes.

Table 1 Relationship between fuel cell condition and power generation at 86 % and 91 % moisture content

	86 % separated	86 % mixed	91 % separated	91 % mixed
Power / µW	25.3	28.6	22.5	30.5

Furthermore, forming an almost water layer in the middle of the SMFCs increases the resistance (Garay et al., 2013). It reduces the probability of the generated hydrogen ions reaching the cathode side, which may have resulted in the 91 % water content separation producing less electricity than the 86 % water content. Although microorganisms are more active in regions of high water content and anaerobic activity, the relationship is thought to be reduced mobility due to increased solid-liquid separation. Therefore, it is believed that more power can be obtained by mixing solid-liquid when the percentage of the liquid phase is high.

4. Conclusions

In SMFCs, the open-circuit voltage and the amount of electricity generated tended to increase as the moisture content increased for conditions up to 82 %. The electricity generated was higher when the SMFCs were left to stand at 86 % moisture content than at 91 % moisture content. However, when the SMFCs were mixed, the amount of electricity generated was higher at 91 % moisture content, indicating that in systems with high moisture content and solid-liquid separation, the amount of electricity generated tends to increase when the SMFCs are mixed. The results suggest that highly nutrient-rich soils, such as those contaminated with organic matter, and soils with relatively low organic matter, can quickly improve power generation by adjusting water content and mixing. For SMFCs with high water content and solid-liquid separation, various external vibrations from walking or vehicle driving can be amplified and incorporated into the solid-liquid mixing system in the battery, resulting in a location-independent, high-performance SMFC. So, the proposed system is a highly promising.

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