Research article

Design of a Two-Chamber Microbial Fuel Cell Without a Proton Exchange Membrane for Electricity Generation from Food Waste

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Abstract A conventional biomass-fired power plant requires substantial construction costs, making its implementation difficult in rural areas of developing countries. In contrast, microbial fuel cell (MFC) technology offers numerous benefits over conventional plants; however, its performance is currently inadequate and requires improvement before it can be deployed. This study proposed a new design for the anode chamber of a two-chamber MFC without a proton exchange membrane when food waste is used as a substrate. Different configurations of the anode chamber, including those with and without a soil layer and different anode positions, were investigated. The effects of each structure on MFC performance were investigated by measuring temporal changes in the cathode potential and examining the electrical conductivity (EC), oxidation–reduction potential (ORP) of the cathode water, and electrical current of MFC. The analysis of EC and ORP variations revealed that the introduction of a soil layer in the anode chamber resulted in lower EC values and higher cathode potentials, indicating that the soil layer acted as a filter to reduce the diffusion of ions from the anode chamber to the cathode chamber. However, this adsorption process increased the ohmic losses in the MFC system and decreased the current density. In the designs without a soil layer, when the anode was installed in the steelmaking slag (SS) layer, a higher cathode potential was observed compared with the design in which the anode was placed on the SS layer. Consequently, this higher potential induced a higher current density. However, without the exchange of cathode water, the current density decreased temporally, and no significant difference in the current density was observed between these designs during the first 7 days after generating electrical current. Therefore, placing the anode on the SS layer is a suitable design for recovering electricity from food waste.

Keywords electricity, food waste, diffusion, anode chamber, cathode water quality

INTRODUCTION

Electricity generation, particularly through coal-fired power plants, is a significant contributor to carbon dioxide (CO_2) emissions, exacerbating global warming concerns. Over the past few decades, efforts have been made to replace coal-fired power generation with renewable energy sources. Among these, biomass-based electricity generation plays a crucial role in reducing CO_2 emissions. Biomass-fired power plants are a conventional approach widely employed to convert biomass into electricity. However, this process involves converting chemical energy to thermal energy and then to electricity. As a result, substantial construction costs are required to construct a biomass-fired power plant. This cost barrier poses a challenge for achieving Sustainable Development Goal 7, particularly in the rural areas of developing countries.

The use of microbial fuel cells (MFCs) is an alternative approach for converting biomass into electricity, offering numerous benefits over conventional biomass-fired power plants, such as direct biomass-to-electricity conversion and a simplified structure. Previous studies have focused on converting organic waste, such as food or fruit waste, into electricity using MFCs (Li et al., 2016; Kumar et al., 2022; Zafar et al., 2023). However, the performance of MFCs remains low and must be improved before deployment. Furthermore, the cost-effectiveness of MFCs is affected using expensive proton exchange membranes (PEMs).

Following Touch et al. (2020), who demonstrated improved performance of sediment MFC through the addition of steelmaking slag (SS) with paddy soil, Shigetomi et al. (2022) succeeded in enhancing the performance of food waste by incorporating SS. Importantly, their MFC structure eliminated the need for PEMs, resulting in a new cost-effective approach for generating electricity from food waste. However, without the use of PEMs, the organic particles from food waste floated to the cathode chamber (Fig. 1) and decomposed, leading to a decrease in MFC performance. Shigetomi et al. (2023) proposed a new structure for the anode chamber of a single-chamber MFC; however, decreases in MFC performance still occurred. Therefore, the development of a new two-chamber MFC structure is required to mitigate the decrease in MFC performance.

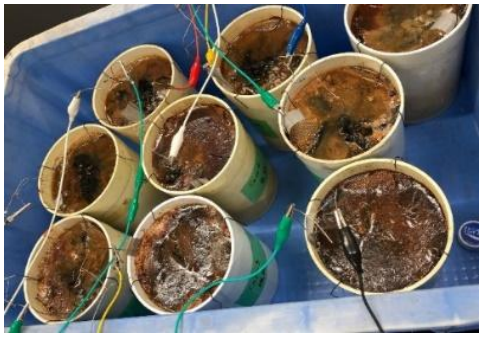

Fig. 1 Floating food waste particles into the cathode chamber

OBJECTIVE

This study proposes a new design for the anode chamber of a two-chamber MFC that can mitigate the decrease in MFC performance when food waste is used as a substrate. Different structures of the anode chamber, including those with and without soil layers and different anode positions, were examined. The effects of each structure on MFC performance were examined by measuring temporal changes in the cathode potential and assessing the electrical conductivity (EC), oxidation-reduction potential (ORP) of the cathode water, and electrical current of MFC.

METHODOLOGY

Experimental Materials and Procedures

The experimental setup comprised two connected cylindrical bottles (inner diameter = 12 cm and height = 14 cm). One bottle (the anode chamber) was filled with SS (diameter range of 5–40 mm) and food waste, and the other (the cathode chamber) was filled with tap water (Fig. 2). Three different designs of the anode chamber were made: (a) an 8-cm layer of SS was prepared, and the anode was then placed on the SS layer. A 3 cm layer of food waste was placed on the anode (Fig. 2a, DS1). (b) A 4-cm layer of SS was prepared, and the anode was then placed on the SS layer. Another 4 cm layer of SS was placed on the anode, followed by loading a 3 cm layer of food waste on the SS layer (Fig. 2b, DS2). (c) A 4-cm layer of dried upper land soils was prepared, and a 4-cm layer of SS was placed on the soil layer. Then, the anode was placed on the SS layer, and a 3-cm layer of food waste was loaded on the anode (Fig. 2c, DS3). DS1 and DS2 were designed to examine the potential of the

anode, and DS3 was designed to examine the potential of the soil layer as a filter. The cathode chamber design was the same as that for DS1–DS3. This involved submerging a plastic net near the water surface on which the cathode was placed.

Carbon cloth (News Company, PL200-E) was used as the electrode material. Before use, the carbon cloth was heated at 500°C for 1 h to improve its performance, following the method described by Nagatsu et al. (2014). The heated carbon cloth, with a surface area of 0.1 m^2 (10 cm width and 10 cm long), was separated into carbon fibers to create a brush-type anode or cathode (Fig.1d). The food waste used was a commercially available product made by refining vegetable waste, mixing it with rice husk, and fermenting for 1 month (Fig. 2e).

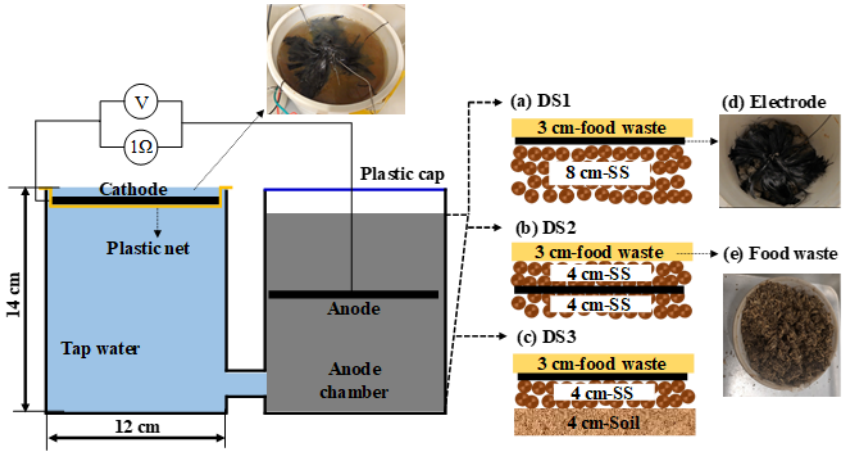

Fig. 2 Experimental procedures

Operations and Measurements

All MFCs were placed in an open-circuit (without electrical current flow) mode for 3 days. To generate electrical current, an external resistance of 1 Ω was connected between the anode and the cathode. The cell voltage was measured after 1 min of applying each external resistance and was used to calculate the current using Ohm's law: $I = U/R_{ex}$, where U [V] is the voltage, I [A] is the current, and R_{ex} [Ω] is the external resistance. The current density was determined by dividing the current by the electrode surface area, which was 0.01 m^2.

During the experiments, the ORP and EC of the cathode water were measured using an ORP/EC meter (Horiba, D-74). Furthermore, the cathode potential was measured by connecting the cathode and an Ag/AgCl reference electrode to the positive and negative terminals of the voltage meter.

RESULTS AND DISCUSSION

Temporal Changes in Electrical Conductivity of Cathode Water

Figure 3 shows a comparison of the EC of cathode water. EC increases when ions diffuse from the anode chamber to the cathode chamber. Thus, it enables us to understand the diffusion characteristics based on the variation trend of EC. Throughout the 35-day experimental period, the cathode water was exchanged twice, particularly on Days 14 and 22 (Fig. 3), where a significant decrease in EC was observed.

There was a slight difference in EC between DS1 and DS3, averaging less than 5 mS/m. Comparing DS3 with other designs was difficult because of the use of soil particles. However, by comparing DS1 with DS2, the EC of DS1 was higher than that of DS2, indicating that DS1 enables more ions to diffuse into the cathode chamber. From Days 0 to 14, the EC of DS3 was higher than that of DS2, which can be attributed to the diffusion of ions present in the soil layer. However, from Days 14 to 35, the EC in DS 3 was lower than that in DS1 and DS2, indicating the adsorption of ions

from the food waste layer to the cathode chamber by the soil layer. In other words, the function of the soil layer as a filter was confirmed.

Based on the EC variations, it can be concluded that DS3, which incorporates a soil layer, is more effective in reducing ion diffusion into the cathode water. Without using a soil layer, the anode should be installed in the SS layer to minimize ion diffusion into the cathode water.

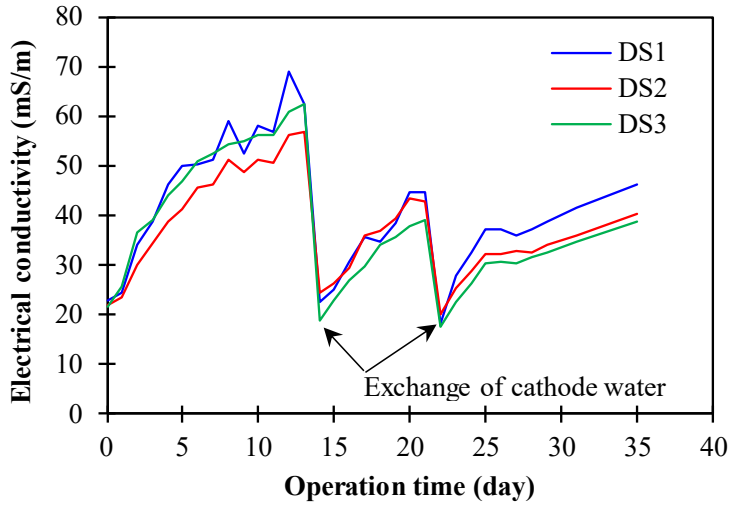

Fig. 3 Temporal variations in electrical conductivity of the cathode water

Temporal Changes in the Redox Potential of Cathode Water

The variation trend of the ORP of the cathode water can also provide insight into the diffusion of ions from the anode chamber to the cathode chamber. When ions diffuse into a water body, they consume oxygen and react with oxidants in the water body via oxidation-reduction reactions. Consequently, this decreases the ORP of the water.

Figure 4 depicts the decreases in the cathode water ORP. From Days 0 to 14, the decrease in ORP from DS1 to DS3 was of the same order of magnitude. However, from Days 14 to 25, decreases in the ORP of DS3 become lower, indicating a higher ORP than those of DS1 and DS2. This finding agrees well with the observations in Figure 2, indicating that the soil layer reduces diffusion.

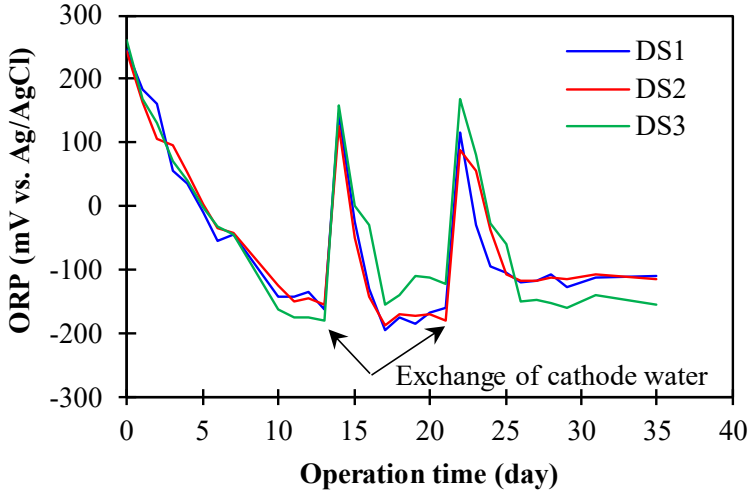

Fig. 4 Temporal changes in the cathode water ORP

Temporal Changes in Cathode Potential

Because cathode performance directly affects MFC performance, it is crucial to have a design that minimizes the decrease in cathode potential. The variation in the cathode potential during the experimental period is shown in Fig. 5.

As discussed earlier, DS2 outperforms DS1 in terms of reducing diffusion into the cathode chamber, resulting in a higher cathode potential for DS2. However, the decreasing trend in the first 2 days after the water exchange was the same for both designs. Figure 4 also shows that DS3 is more effective in reducing diffusion into the cathode water because a higher cathode potential was obtained. Furthermore, a different trend with a lower decrease in the cathode potential was observed compared with the other designs.

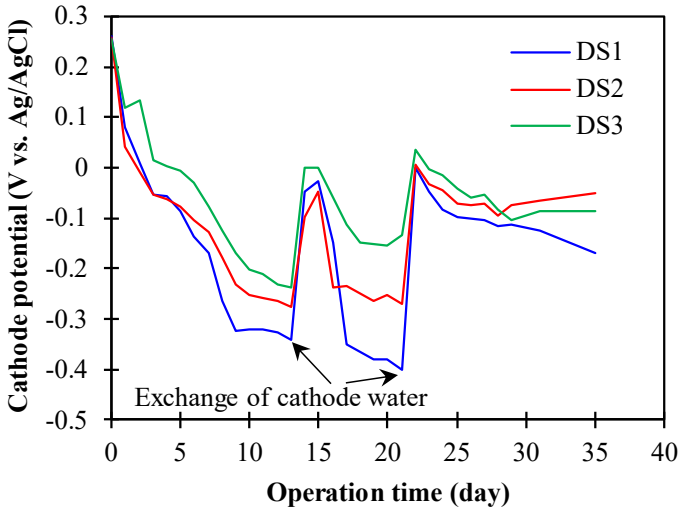

Fig. 5 Temporal changes in the cathode potential

Temporal Changes in Current Density

Although DS3 had a higher cathode potential than DS1 and DS2 (Fig. 5), its current density was lower than that of the other designs (Fig. 6). During the first 14 days, the average current density of DS3 was approximately 30 mA/m^2, which was half that of DS1 and DS1 (averaging 60 mA/m^2). The use of a soil layer as a filter reduces the current density. In other words, the adsorption of ions by the soil layer decreases the performance of the MFC. This decrease is attributed to the increase in ohmic losses in the MFC system because of the limitations of ion flow through the soil layer from the anode chamber to the cathode chamber.

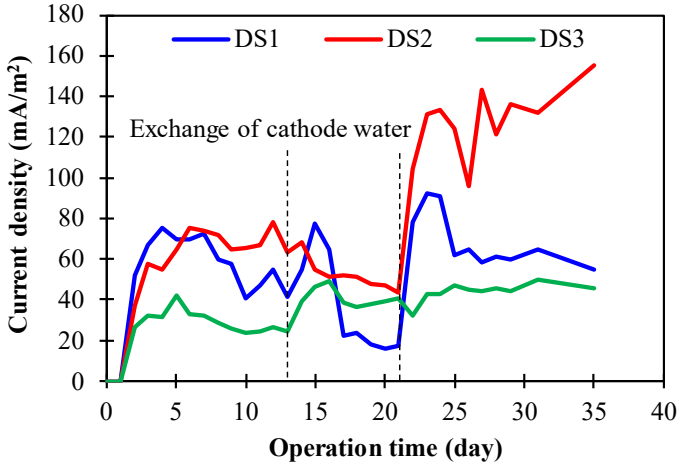

Fig. 6 Temporal changes in current density

By comparing the designs without a soil layer (DS1 and DS2), the current density of DS2 was found to be higher than that of DS2. The higher cathode potential of DS2 (Fig. 5) contributed to this increase in current density. Note that the current density decreased gradually without the exchange of cathode water. The decrease in current density began approximately 7 days after the current generation. During the first 7 days of the current generation, there was no significant difference in current density between DS1 and DS2. However, from a practical viewpoint, DS1 is better than DS2 because it allows the separation of food waste and SS by the anode, making it easier to replace the food waste after the experiment ends.

CONCLUSIONS

In this study, a new design was examined for the anode chamber of a two-chamber MFC for recovering electricity from food waste. Different anode chamber structures were proposed, and their effects were examined in terms of variation in cathode water quality and MFC performance. Analysis of the EC and ORP variations revealed that the use of a soil layer as a filter in the anode chamber (DS3) effectively reduced the diffusion of ions from the anode chamber to the cathode chamber. The adsorption of ions in the soil layer contributed to this reduction. However, this increased the ohmic losses in the MFC system and decreased the MFC performance. By comparing the placement of the anode on the SS layer (DS1) with the installation of the anode in the SS layer (DS2), it was observed that the DS2 maintained a higher cathode potential when the cathode water was exchanged, resulting in a higher current density. Unfortunately, without the exchange of cathode water, the current density decreased temporally, and no significant difference in the current density was observed between DS1 and DS2 during the first 7 days of electrical current generation. Therefore, DS1 should be a suitable design for the recovery of electricity from food waste because it facilitates the easy replacement of food waste at the end of the experiment. Even though DS1 could improve the SS-SMFC performance, the current density started to decrease after 7 days. Hence, the design of the cathode chamber needs to be considered for long-term electricity generation.

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