Article

Effect of Composting Parameters on the Power Performance of Solid Microbial Fuel Cells

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Abstract: Nowadays, solid organic waste is of major environmental concern and is reaching critical levels worldwide. Currently, a form of natural decomposition, known as composting technology, is widely used to deal with organic waste. This method is applied to enhance the performance of solid microbial fuel cells (SMFCs) in this study. Operational composting parameters (carbon/nitrogen ratio, moisture content and pH value) are investigated to explore the optimal power performance of solid microbial fuel cells (SMFCs). Results indicate that the carbon/nitrogen ratio and the moisture content displayed the most significant impact on SMFCs. When the carbon/nitrogen ratio is 31.4 and moisture content is 60%, along with a pH value of 6–8, a better SMFC power performance would be obtained. These findings would provide positive information regarding the application of compost in SMFCs.

1. Introduction

Solid organic waste is a major source of environmental pollution. The large accumulation of agricultural waste, animal husbandry excrement and urban garbage has become a serious environmental issue [1], with various methods being used to help solve it [2,3]. Currently, the composting method is

widely utilized in the treatment of solid organic waste [4]. This method uses natural microorganisms to decompose and convert the organic waste into mature compost, which would then be applied to microbial fuel cells (MFCs) to enhance power performance[5,6]. MFCs use bacterial reactions to generate electricity and handle the organic matter in all kinds of waste, such as domestic sewage, agricultural waste, sewage sludge in sewage treatment plants, livestock waste water, food waste water and lingo cellulosic biomass [7]. Combined bioremediation [8] and microbial treatment in SMFCs can actually reduce the concentration of pollutants. In this study, composting-related operational technology would be applied to the SMFCs due to its similar biochemical reaction process.
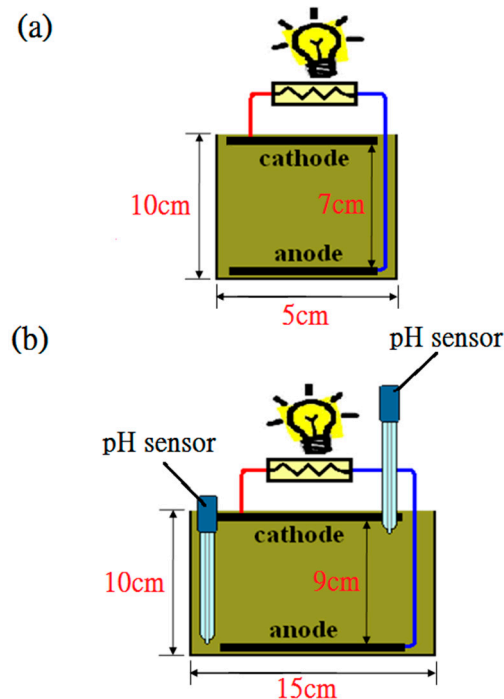
In applying composting technology to SMFCs, the relevant operating parameters in compost are found to have an important impact on their electrical performance and are therefore worth further exploration. Important influencing factors in composting include C/N ratio, moisture content and pH value, of which the C/N ratio heavily affects the microorganism growth in compost. If the C/N ratio is lower than 20, microorganism activity is limited. On the other hand, when the C/N ratio is higher than 40, the compost is deemed harmful to the environment. General compost needs an optimal C/N ratio of about 25 to 35 to enable the quickest composting procedure [9].The moisture content in the compost affects the conduction of the substrate and microbial metabolism [10]. Excessive moisture (above 80%) will hinder oxygen supply and carbon dioxide efflux, resulting in the accumulation of harmful substances in the compost [11]. But when the moisture content is less than 40%, microbial activity will be reduced. The best effects of composting are found when the moisture content is between 50% and 70% [10]. In addition, the pH value will affect the growth environment of microbes, with a pH value of between 6 and 9 obtaining an optimal composting rate [12]. Nonetheless, few studies discuss the effect of composting parameters specifically on SMFCs. In this study we will focus on investigating the effects of composting factors on the performance of SMFCs to explore the most significant factors that would enable better power generation.

2. Design and Methods of Experiments

2.1. Model of Experiments

A batch-type of single-chamber solid microbial fuel cell (SMFC), shown in Figure 1, was adopted as the system structure for the experiment. The chamber material was made from an acrylic sheet, and carbon felt was selected as the electrode material. As carbon felt has a high porosity and large surface area, and is conducive to microbial growth [13], adhesion, and reduction of activation impedance [14], it was considered the best choice. The carbon felt was pretreated before the study by being soaked and heated at a condition of 90°C with a volume of 10% hydrogen peroxide solution for 3 h, and then air-dried so as to increase the adhesion and proliferation of microbes [15].The different chambers of the SMFCs were manufactured for particular experimental requirements. Figure 1a shows that the outer dimension of a SMFC chamber for measuring the different C/N ratios and moisture content were set at 5 cm × 5 cm × 10 cm. The working volume of the SMFC system was 200 cm^3, and the electrode plate size was 4 cm × 4 cm × 0.5 cm (working area of 18 cm^2). Figure 1b shows the measurements for the pH experiments and as the pH sensors cannot be placed in the limited tank space displayed in Figure 1a, so the outer dimensions of the system chamber were changed to 15 cm × 15 cm × 10 cm, with the working

volume of the SMFC system changed to 2000 cm^3, and the electrode plate size to 5 cm × 10 cm × 0.5 cm (working area of 65 cm^2). The MFC system components were configured by placing the anode plate at the base of the system and burying the cathode plate at the interface of the solution and air. In the experiment, different substrates were added and analyzed for discussion pertaining to electricity generation.

Figure 1. Schematic diagrams of solid microbial fuel cells (SMFC): (**a**) for carbon/nitrogen (C/N) ratio and moisture content; (**b**) for pH value.

2.2. Composting Composition and Experiments

This experiment explored the effects of composting conditions on SMFC electricity generation. The fixed substrate materials were regarded as important for composting as different substrates exhibit different composting performances. This experiment chose rice husks [16], soybean residue, coffee residue, and leaf mold as the raw materials for the SMFC substrates. The selection of substrates was mainly based on cellulose, which is considered to be the most abundant biopolymer as well as an ideal source of organic matter [17].The selection of rice husks as a substrate was because rice is the staple food in Asia, and so the husks become agricultural waste in the production process. Adding rice husks to the compost in the SMFC chamber would enhance the hydraulic conductivity and the ventilation effect [18]. Additionally, soybean residue and coffee residue were chosen because soybean milk and coffee are arguably the favorite drinks of Asian nationals, thus creating a large volume of waste. Each substrate was mixed evenly at a ratio of 1:1, and factors influencing the compost such as C/N ratio, moisture content, pH value and other operational conditions were adjusted. Then, finally 200 cm^{3}of substrate would be taken out and put in the SMFC chamber to enable the exploration of the impact of operational compost factors on the power performance of SMFCs.
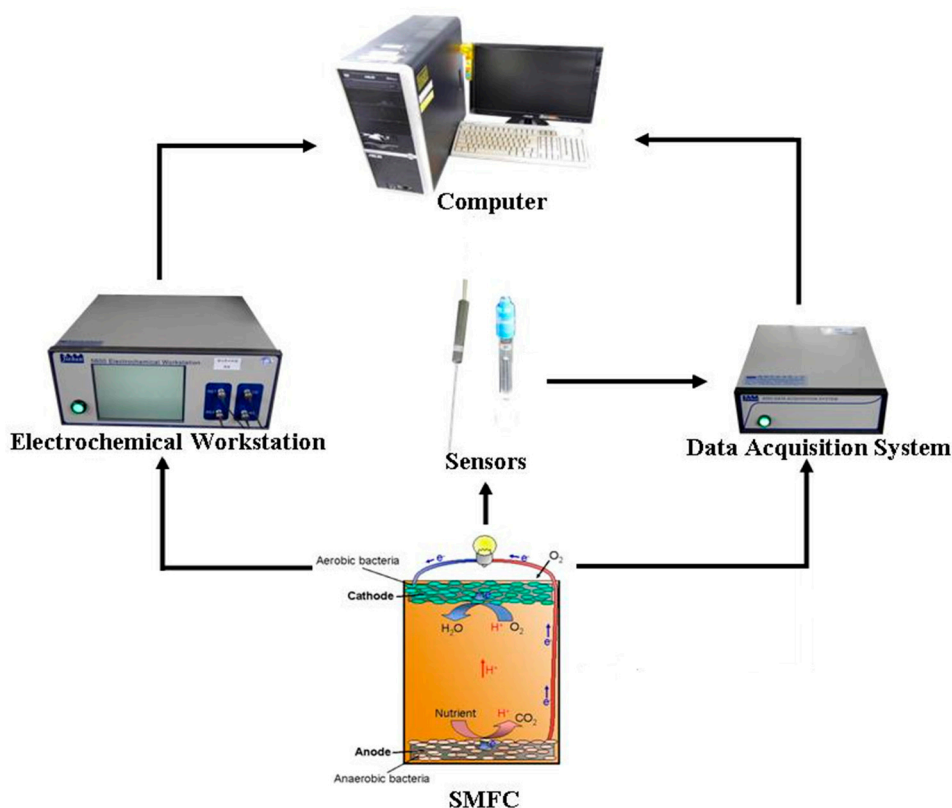
In the experiments, the composting factors were adjusted as follows. Different substrates were combined and used to change the C/N ratios [14]. Five groups of different C/N ratios (11.7:1, 27.8:1,

31.4:1, 31.7:1, 37.2:1) were experimented with to explore the effect of the C/N ratio on the power performance of SMFCs. In addition, different levels of moisture content (40%, 60%, 70% and 80%) were also trialed to investigate their impact on the power performance of SMFCs. The pH sensors were used to perceive the influence of pH value on the power performance of SMFCs during the composting process. Finally, a correlation analysis was applied to ascertain the effect of each composting factor on the SMFCs. This would prove very useful in improving the performance of SMFCs in the future.

2.3. Measurements of SMFCs

The setup of the measurement systems is shown in Figure 2. The experiments used data loggers and electrochemical analyzers to execute the electrical analysis of the SMFCs. A fixed resistor discharge (1 KΩ), polarization curve and pH were used for the analysis to assess the SMFC performance. The electrochemical analyzer (Jiehan 5600, Taichung, Taiwan) measures the polarization curves by using a dynamic potential scan and thereby obtains the limiting current and voltage of the SMFC.

On realizing the performance of the SMFC, a power, P, defined by equation of P = IV would be calculated by way of measuring the current intensity, I, and voltage, V, simultaneously in this study.

Figure 2. Diagram of the setup of the experimental measurement system.

The C/N ratio and the moisture content are defined as follows: Equation (1) shows the number of nitrogen source substances that must be added to calculate the C/N ratio:

$$K = \frac{C_1 + C_2}{N_1 + N_2} \tag{1}$$

In Equation (1), K is the C/N ratio of mixed raw materials; C_1, C_2, N_1, and N_2 are the organic carbon and nitrogen content [9] of the added organic raw materials, respectively. The C/N ratios of each material used in this experiment are shown in Table 1.

Table 1. C/N ratio of materials utilized.

Substrate	C/N	References
Soybean Residue	3.4:1	[19]
Leaf Mould	60:1	[20]
Coffee Residue	20:1	[21,22]
Rice Husk	71:1	[23]

The moisture content determination method is shown in Equation (2), using 105°C as the drying constant temperature, and a constant weight to measure the material weight loss:

$$M = \frac{W_m - W_c}{W_b - W_m} \qquad (2)$$

where M is the weight ratio of waste, W_m is the moisture content of the raw materials after mixing, W_c is the moisture content of the original waste, and W_b is the moisture content of the substrate after adjustment [15].

In the experiment of the impact of the C/N ratio on the electricity generation of SMFCs, such common household organic compounds as soybean residue, coffee residue, leaf mould, and rice husks were selected, and different C/N ratios were used to conduct the discharge study—the experimental model is shown in Figure 1a.The experiments were divided into five groups, and the substrate contents of each group are shown in Table 2.
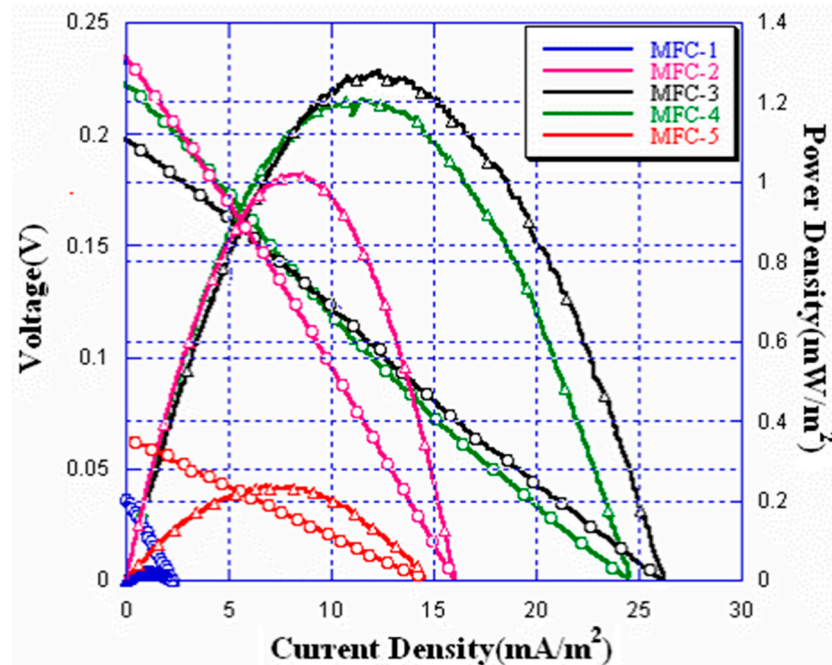
Table 2. Substrate table of each experiment.

MFC	Substrates	C/N
MFC-1	Soybean Residue, Coffee Residue	11.7:1
MFC-2	Soybean Residue, Coffee Residue, Leaf Mould	27.8:1
MFC-3	Soybean Residue, Coffee Residue, Rice Husk	31.4:1
MFC-4	Soybean Residue, Leaf Mould	31.7:1
MFC-5	Soybean Residue, Rice Husk	37.2:1

3. Results and Discussion

To explore the impact of different composting factors on the power performance of SMFCs, the C/N ratio, moisture content and pH value in the composting process, and their correlations with the electricity generation of MFCs, were examined to find the foremost correlation factor.

Figure 3 shows the experimental results of the polarization curves for different SMFCs. The results shown in Figure 3 indicate that the experimental group MFC-3 had the best electrical properties, and its C/N ratio, displayed in Table 2 was 31.4:1. An optimal power density of 1.278 mW/m^2 was obtained at a C/N ratio whose value was closest to the general compost's optimal C/N ratio of 30:1. Therefore, the results show that the optimal composting conditions are the same as the optimal power performance of SMFCs. This finding seems to be reasonable and expected because the optimal C/N ratio held in the
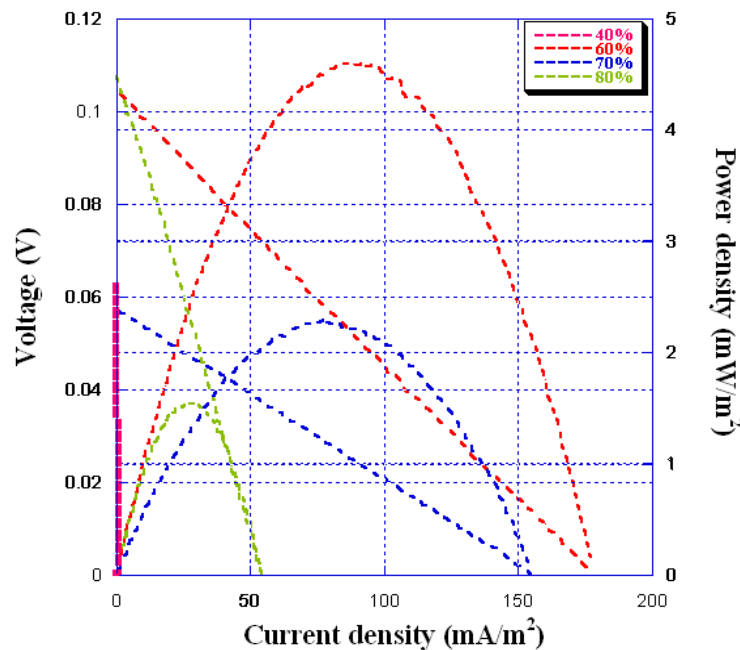
composting process or biochemical process will both benefit the microbial activity. Conversely, when the C/N ratio is too low (less than 20:1) as it was in MFC-1, microbial activity decreases because of insufficient nutrient sources. Similarly, when the C/N ratio in MFC-5 was too high (greater than 37:1), microorganisms would not complete decomposition because of excessive nutrient sources [9].

Figure 3. Effect of C/N ratio on polarization curves of the experimental groups.

The impact of moisture content on the electrical performance of SMFCs was explored in our next study. Four different of moisture content (40%, 60%, 70% and 80%) were tested at the optimal C/N ratio (31.4:1) with a substrate made up by a combination of: soybean residue, coffee residue, and rice husks in a 1:1 ratio in the experiment.
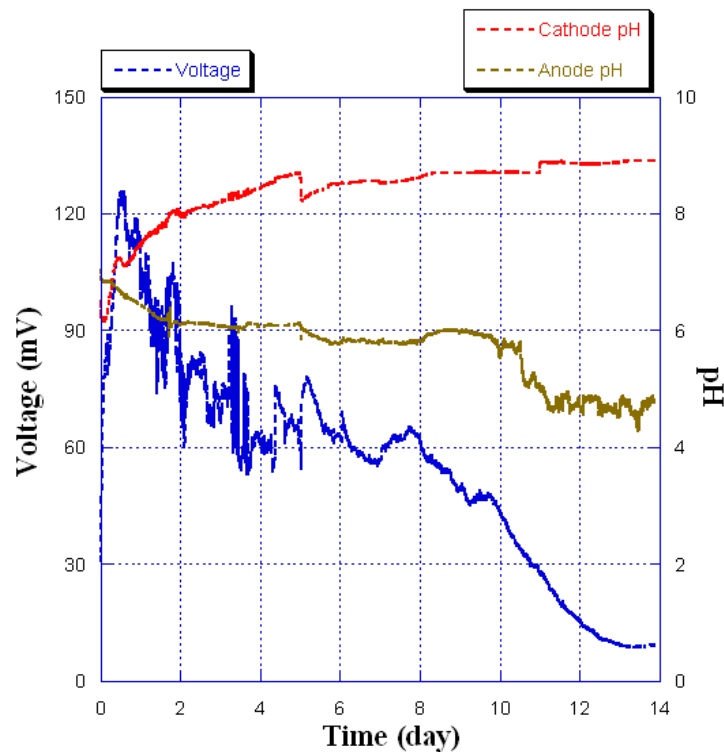
The experimental model, as shown in Figure 1a, measured the voltammetric curve of each case to analyze the impact of moisture content on the power performance of SMFCs. Results shown in Figure 4 indicate that when the moisture content was 60%, a better power density of 4.6 mW/m^2 was obtained. When the moisture content dropped to 40%, there was almost no power generation. It might be inferred that a moisture content of 40% is too low, preventing the ions from being transferred [9]. Regarding the composting, when the moisture content was less than 40%, fermentation was inhibited and microbial activity lowered [9], preventing the generation of power in the SMFC. When the moisture content was 80%, a power density of 1.55 W/m^2 attained was much worse because of the growth of anaerobic bacteria, resulting from the appearance of water logged pores in the compost. This anaerobic condition would cause the aerobic bacteria to reduce and decrease the power generation of the SMFCs [24].

Figure 4. Comparison of voltammetric curves of cells under different moisture contents.

The variations of pH values near the anode/cathode plates during the discharge process were recorded in the experimental model shown in Figure 1b. Here, the substrate used the optimal C/N ratio (31.4:1) combination (soybean residue, coffee residue, and rice husk mixed in a 1:1 ratio) and a moisture content of 60%.

Results in Figure 5 show that the pH value measured near the anode was lower, but higher for the cathode region during the discharge process. In addition, over time a decreasing trend of pH near the anode region was found due to the H^+ proton being continuously produced because of the oxidation reaction during the degradation process of the SMFCs. On the other hand, when the anode pH value declined rapidly at the final discharge stage, the voltage also fell. This phenomenon would result from the accumulation of H^+ concentrations if the hydrogen ions could not pass through the membrane quickly enough. On this physical phenomenon, some similar explanations have been addressed [6,25,26]. Rozendal *et al.* [25] indicated that when hydrogen ions cannot pass to the cathode quickly enough, the anode pH will decrease while the cathode pH will rise. The anode pH drop will affect bacterial respiration, thereby affecting the current generation. Then the cathode pH increase will cause a blockage of passing ions. Mohan *et al.* [6] also found that when the anode pH value decreased to pH = 5, the electrical property would suddenly drop, but a decrease in the pH value would directly affect the power output, and an acidic pH value would inhibit the bacterial metabolism. The experiment by Cesar *et al.* [26] illustrated that when the pH difference between the cathode and anode was greater, the electrical properties would be worse. To summarize the above mentioned literature, the conclusions are similar to those found in this study where, the experiments were conducted to achieve a correlation analysis on the variations of output voltage and changes in cathode/anode pH value. A positive correlation between the output voltage and anode pH (correlation value 0.899), and a negative correlation between the output voltage and the cathode pH (correlation value −0.765) was found. Therefore, this evidence shows that the pH factor is very important to the power performance of SMFCs, with variations in anode pH having a highly positive effect on the voltage output of SMFCs.

Figure 5. Variations of voltage output and pH value change with time at a discharge of 1 kΩ constant resistance.

4. Conclusions

This study discussed the impact of the composting conditions such as C/N ratio, moisture content and pH value on the power performance of SMFCs. When the C/N ratio was 31.4 and moisture content was 60%, an optimal power density of 4.6 mW/m^2 was obtained. In the composting process, when the pH of the substrate was maintained between 6 and 8 (which was a condition suitable to composting) there was a better power performance. From the above conclusions, it was found that an optimal composting condition would promote a better power performance in SMFCs. These finding will provide positive information when applying compost to SMFCs.

Acknowledgments

Author Contributions

Author 1 Chin-Tsan Wang designs the research, experimental concept and writes the manuscript. Author 2 Yao-Cheng Lee revises the manuscript, interpretation of the results and reply of comments. Author 3 Fan-Ying Liao performs the experiment. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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