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Proceedings of Science and Technology
ISSN (Print: 2537-0731, online: 2537-074X)
Proceedings of Science and Technology
Received: 11 October 2023, Accepted: 27 December 2023, Published online: 31 December 2023
DOI: 10.21625/resourceedings.v3i3.1035

Electrode Material Optimization for Microbial Fuel Cells Using Bamboo Charcoal Powder and Bokuju

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Abstract

Bamboo is a fast-growing plant in Southeast Asia, Africa, and Latin America. Due to its rapid growth, bamboo is considered a problem because it rapidly invades forested areas and alters the original ecosystem. On the other hand, it is regarded as a material that is readily available and very accessible in many countries and has great potential for both ecological and social purposes. Therefore, bamboo was employed as the material for the electrodes of microbial fuel cells in this study. Typically, biochar used for electrodes is chemically activated to remove impurities and increase its surface area. However, chemical treatment of biochar can have a negative impact on the activity of microorganisms. The Bamboo charcoal powder, prepared by heat-treating powdered bamboo for one hour under air at 500°C, contained about 75% carbon and had a porous structure. Therefore, the material could be used as an electrode material for microbial fuel cells without complicated and time-consuming treatment processes. Some of these treatment processes include chemical treatment, and chemically treated biochar may impact the environment. Bamboo charcoal, which does not require this chemical treatment process, is effective as an electrode material for microbial fuel cells. Bokuju, a common kind of drawing ink in Japan and mainly composed of carbon black, was used as a binder for the prepared bamboo charcoal. The reason for using powdered bamboo charcoal with Bokuju is that it is easier to obtain a solid electrode shape by a drying process. We used this electrode in a floating microbial fuel cell and optimized the ratio of Bamboo charcoal powder and Bokuju in the electrode. By evaluating the performance of the microbial fuel cell using the Bamboo charcoal Bokuju electrode, we were able to improve the effectiveness of the electrode material.

Keywords

Microbial fuel cell; Bamboo charcoal powder; Bokuju

1. Introduction

Bamboo belongs to the bamboo subfamily of the grass family. Bamboo is associated with mainly meso-humid to wet forest-type areas in temperate and tropical regions. Currently, bamboo is found primarily in Asia, America, and Africa, and it is one of the fastest-growing plants on Earth. (Ahmad et al., 2021) Bamboo has firm fibers, a compressive strength twice that of concrete, and a tensile strength almost equal to steel. (Yadav et al., 2021) In addition, bamboo is the fastest growing, so its availability has led to a wide variety of applications. (Dessalegn et al., 2022) On the other hand, being the most regenerative plant and having the characteristics of rapid growth and reproduction, bamboo changes the diversity of plant species and community structure.

Therefore, the fusion of bamboo forests may reduce food and habitat diversity and decrease bird diversity. (Xu et al., 2020) All of this raises the issue of bamboo rapidly invading forested areas and altering the original ecosystem.

Microbial fuel cells (MFCs) are environmentally friendly electrical devices that can generate energy while treating wastewater. (Boas et al., 2022) In addition, because MFCs utilize a bioelectrochemical process, they are a cost-effective and relatively simple process. (Yaqoob et al., 2021) Electrons are released at the anodes as electromotive microorganisms oxidize organic matter. (Mohyudin et al., 2022) The electrons obtained on the anode side pass through an external circuit and travel to the cathode electrode. The electrons reaching the cathode react with hydrogen ions and oxygen to produce water. (Obileke et al., 2021)

Biochar was commonly used as an agricultural additive to improve soil but has recently been used as an electrode material for MFC. (Cao et al., 2022) Biochar is readily adsorbed onto substrates, making it environmentally friendly and economical. (Li et al., 2021) Cellulose-derived carbon materials are used in various energy conversion and production technologies. (Hassan et al., 2020) (Xinran et al., 2021) Biochar is often subjected to an alkaline etching process to remove impurities and increase surface area before it can be used as an electrode. (Wang et al., 2022, Ding et al., 2022, Rawat et al., 2023) However, most reagents are toxic and corrosive. Therefore, an environmentally friendly and simple method is needed to use superior biochar from low-cost resources. (Zha et al., 2021) Therefore, bamboo charcoal, made by only heat treatment of bamboo powder, has a porous structure and a high percentage of carbon and may be used as an environmentally friendly biochar electrode for MFC.

In this study, Bokuju and Bamboo charcoal powder were used as electrode materials. Bokuju is one of the inks used in Japan and has the property of hardening when dried. Bokuju, which is mainly composed of carbon black, was used as a binder to create block-shaped electrodes. Since bamboo charcoal is a powder rather than a solid, it can be fused with liquid Bokuju, allowing the electrode to be quickly processed and transformed into a shape suitable for various situations. Optimizing the amount of bamboo charcoal relative to Bokuju in the block electrode was the objective of this study. Bamboo charcoal is high in carbon content and can be created at a low cost, making it practical for bamboo, which has become an environmental problem. The floating type MFC was used to evaluate the electrode material, and the LB medium was used as the electrolyte for the battery. The operated MFC generated electricity for about 40 days. A combination of Bokuju and Bamboo charcoal powder is proposed as a cost-effective electrode material for the MFC.

2. Experimental

2.1. Preparation of Bamboo Charcoal

Powdered bamboo (Kagoshima Co, Ltd., Kagoshima, Japan), a commonly used soil conditioner, was purchased and used in this study. Powdered bamboo was dried at 60°C overnight. The dried bamboo powder was burned at 500°C for 1 h in the air to produce bamboo charcoal. Since one of the objectives of this experiment is low cost, we aimed to carbonize the bamboo powder by calcination under air instead of nitrogen. Bamboo charcoal powder was ground in a mortar to produce an even finer powder.

2.2. Electrode Preparation

The method for preparing the electrodes was made with reference to (Hirose et al., 2021). In this experiment, electrodes for microbial fuel cells were prepared by mixing the Bamboo charcoal powder with liquid Bokuju (Kuretake Co, Ltd., Nara, Japan) and solidifying it. The electrode was quickly processed into various electrode shapes using bamboo charcoal powder and Bokuju as electrode materials. To optimize the amount of Bamboo charcoal powder and Bokuju as electrodes for microbial fuel cells, electrodes were prepared by varying the amount of Bamboo charcoal powder relative to Bokuju, as shown in Table 1. The corresponding MFCs were named from MFC 1 to MFC 5. When the ratio of Bamboo charcoal powder was higher than that of MFC 5, the electrode could not be prepared because the mixture of Bokuju and Bamboo charcoal powder became too dense. Bokuju mixed with copper powder at a 1 g to 30 ml ratio of Bokuju was used to sterilize the cathode electrode. The cathode electrode size was (2 × 2), and the anode electrode size was (1 × 1).

Table 1. The ratio of Bokuju to Bamboo charcoal powder

MFC	Bamboo charcoal powder (g)	Bokuju (ml)
MFC 1	0	4.5
MFC 2	0.4	4.5
MFC 3	0.8	4.5
MFC 4	1.2	4.5
MFC5	1.6	4.5

2.3. Preparation of LB medium

LB medium was used as the electrolyte for the microbial fuel cell. 500 ml of purified water was mixed with 5 g of tryptone, 2.5 g of yeast extract, and 5 g of sodium chloride. 500 ml of LB medium was autoclaved before being used as the electrolyte for the microbial fuel cell. The electrolyte was prepared by mixing 100 ml of LB medium prepared as described above with 500 ml of tap water and 1 ml of soil water collected from a paddy field (34°59'42.7986" N, 135°57'16.1892" E (34.9995222, 135.954497), Shiga, Japan).

2.4. MFC Structure and Operation

In this study, a floating microbial fuel cell was used, as shown in Fig. 1. The cathode electrode was placed on the float so that it was exposed to the air. The anode electrode was immersed in the electrolyte. The distance between the cathode and anode electrodes was kept constant at 35 mm. 4.7 kΩ of external resistance was connected between the electrodes of the MFC. 25 ± 1°C was used as the ambient temperature around the MFC. Tap water was added to the electrolyte of the MFC daily to maintain a constant water level, which fluctuated with drying.

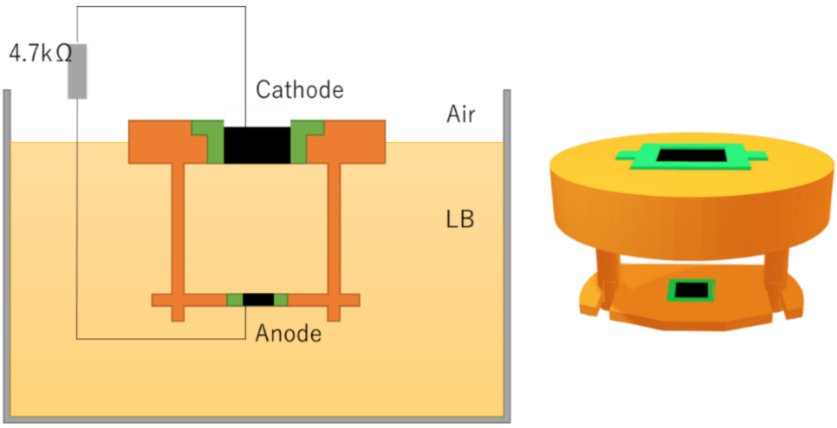
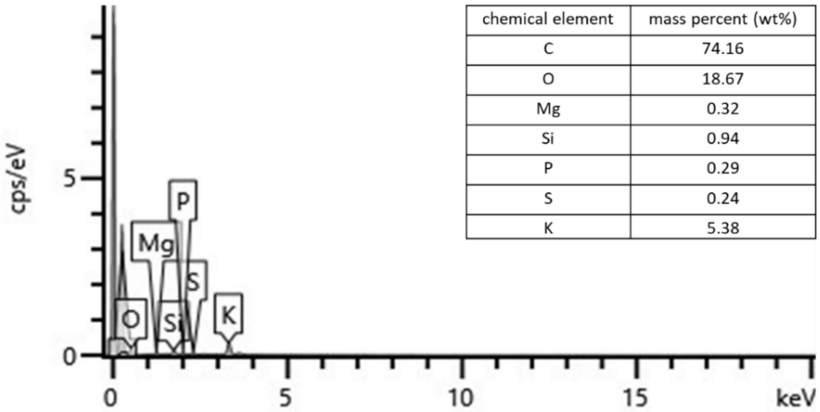


Figure 1. Floating MFC structure.

3. Experimental Results

3.1 Elemental analysis of Bamboo charcoal powder

Fig. 2 shows the elemental composition of the surface of the bamboo powder after firing (500°C), as measured using quantitative analysis of SEM-EDS. The EDS spectrum shows carbon (C) (74.16 wt.%), oxygen (O) (18.67 wt.%), potassium (K) (5.38 wt.%), silicon (Si) (0.94 wt.%), magnesium (Mg) (0.32 wt.%), sulfur (S) (0.24 wt.%), and phosphorus (P) (0.29 wt.%), and sulfur (S) (0.24 wt.%). After the sintering of the bamboo powder, it contains a large amount of carbon, which is conductive. In addition, the surface shape of the charcoaled bamboo powder was observed by Scanning electron microscopy (SEM) (Hitachi S4300), as shown in Fig. 3. It can be seen that the surface has a porous structure and a large surface area, which has great potential as an electrode material for MFC.



chemical element	mass percent (wt%)
C	74.16
O	18.67
Mg	0.32
Si	0.94
P	0.29
S	0.24
K	5.38

Figure 2. EDS spectrum of bamboo charcoal

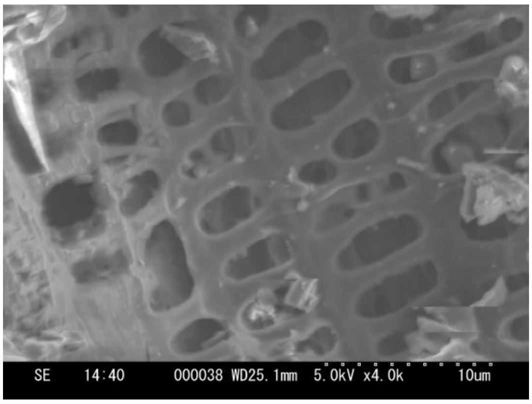


Figure 3. SEM image of bamboo charcoal

3.2. MFC Performance

Power density and current density measurements were taken to measure the battery's performance in an MFC with a Bamboo charcoal Bokuju electrode. The connected 4.7 kΩ external resistor was removed from the MFC, and a variable resistor was connected instead. The variable resistor was changed from 4.7 kΩ to 200 Ω. The voltage values of the MFC, which varied as the resistance changed, were recorded, and the power density and current density were calculated from the resistance and voltage values. The maximum value of the day among the calculated power densities was also taken, and a graph of the maximum power density over time was created, as shown in Fig. 4. The maximum power densities of MFC 1, MFC 2, and MFC 3 were as low as 0.012 μW/cm^2, 1.043 μW/cm^2, and 2.304 μW/cm^2, respectively; the maximum power density of MFC 4 was measured as high as 26.89 μW/cm^2. Furthermore, the maximum power density of MFC 5 was even higher at 38.02 μW/cm^2, and the higher the amount of Bamboo charcoal powder relative to Bokuju, the greater the power output. This indicates that Bamboo charcoal powder is an effective material for microbial fuel cells. Since Raman spectra are fingerprints of carbon-based electrodes, it is necessary to measure them as well.

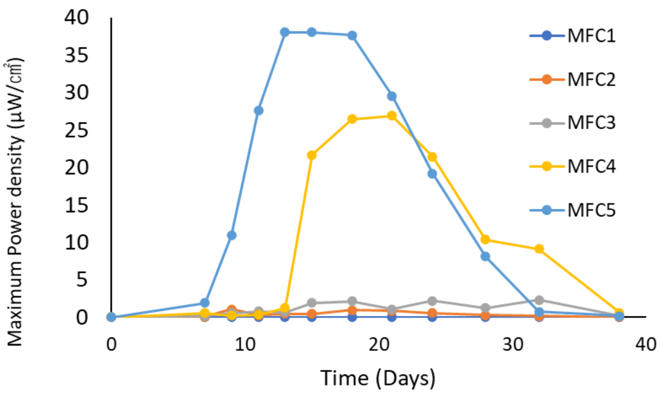


Figure 4. The maximum power density of MFCs using Bamboo charcoal Bokuju electrodes.

3.3. Elemental analysis of Bamboo charcoal Bokuju electrode surface

Elemental analysis of Bamboo charcoal Bokuju electrodes by ratio was performed using SEM-EDS, as shown in Table 2. It was found that the more ink was used, the more carbon elements were present. However, bamboo charcoal is important as an electrode material because the amount of electricity generated by MFC increases with the amount of bamboo charcoal. In the future, it is necessary to clarify by XPS and other analyses of the Bamboo charcoal Bokuju electrode and other carbon electrodes to show clear electronic interactions and synergistic effects of the bamboo charcoal powder.

Table 2. Elemental analysis of Bamboo charcoal Bokuju electrodes

MFC	**(mass%)**						
	C	**O**	**Na**	**Mg**	**Si**	**K**	**Ca**
MFC 1	78.07	18.95	0.36	0.53	0.46	1.22	-
MFC 2	77.16	19.78	0.49	0.15	0.50	0.06	1.22
MFC 3	76.10	21.61	-	-	-	2.29	-
MFC 4	73.62	22.37	0.36	0.26	0.73	2.42	0.25
MFC5	72.40	22.69	0.79	-	0.53	3.60	-

3.4 Surface observation of a Bamboo charcoal Bokuju anode

The surface of a Bamboo charcoal Bokuju electrode was observed by SEM (S-4300, Hitachi, Ltd., Japan). After the MFC 5 operation, the anode was removed from the MFC and stored in hand sanitizer at 4°C to kill and fix microorganisms. In addition, the anode was then immersed in ethanol to dehydrate the entire electrode. To improve the observability of the electrode surface, a thin gold coating was applied to the electrode surface by interposing a sputtering process. It was confirmed that biofilms of bacterial cells were formed on the anode surface, as shown in Fig. 5. The Bamboo charcoal Bokuju electrode seems to have an affinity with microorganisms.

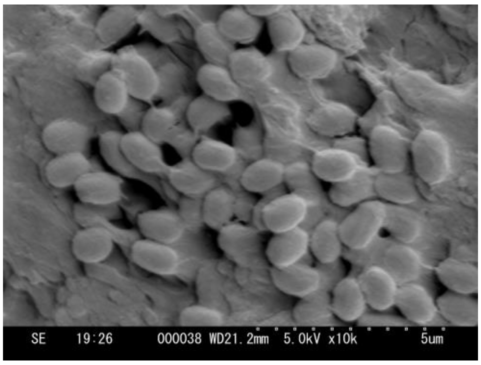


Figure 5. Electrode surface after operation of MFC4

3.5 COD change of the electrolyte in MFC

The chemical oxygen demand (COD) of the LB medium was measured before and after the operation of MFC 5. The MFC was operated at a COD of 2990 mg/l in LB medium. The COD of LB medium was 453 mg/l after 38 days of MFC operation, as shown in Fig. 6. This indicates that the decrease in the power of MFC 5 after 18 days was caused not by the deterioration of the battery but by the decrease in fuel and the limitation of microbial activity.

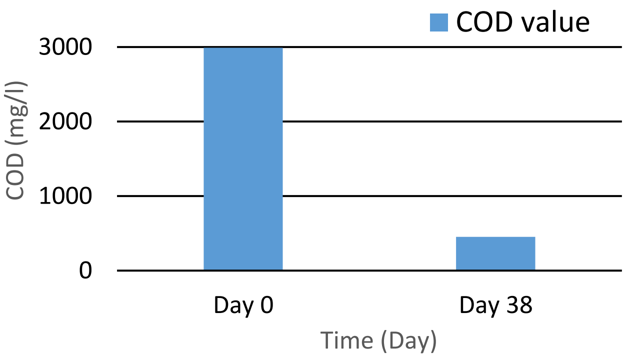


Figure 6. COD values on days 0 and 38

4. Conclusion

Bamboo charcoal powder calcined at 500°C contains 74.15% carbon and has a porous surface structure, which may be used as electrode material in MFCs. Therefore, this study examined the effectiveness of the Bamboo charcoal Bokuju electrode for MFCs. The more Bamboo charcoal powder was added to the electrode, the higher the power output of the MFC, and the maximum power density of MFC 5 with the most bamboo charcoal powder was 38.02 $\mu W/cm^2$. However, the amount of Bamboo charcoal powder in Bokuju is capped by the fabrication method limitation. Therefore, further power output of the MFC could be obtained by optimizing the firing temperature and time of the bamboo charcoal.

Acknowledgments

The abstract of this paper was presented in Advances in Energy Research, Materials Science & Built Environment (EMBE) Conference – 1st Edition which was held on the 3rd-5th of October 2023.

Funding declaration:

This research did not receive any specific grants from funding agencies in the public, commercial, or not-for-profit sectors/individuals.

Ethics approval:

Not applicable.

Conflict of interest:

The authors declare that there is no competing interest.

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