energies

MDPI

Article

A Novel Design Portable Plugged-Type Soil Microbial Fuel Cell for Bioelectricity Generation

Hoang-Uyen-Dung Nguyen, Dang-Trang Nguyen and Kozo Taguchi *

Department of Science and Engineering, Ritsumeikan University, 1-1-1 Noji-higashi, Kusatsu, Shiga 525-8577, Japan; ayma.aime@gmail.com (H.-U.-D.N.); n-trang@fc.ritsumei.ac.jp (D.-T.N.)
* Correspondence: taguchi@se.ritsumei.ac.jp

Abstract: Soil microbial fuel cells (SMFCs) are a promising cost-effective power source for on-demand electricity generation applications. So far, reported SMFC configurations are usually bulky and hard to setup. In this study, a low-cost portable plugged-type SMFC (PSMFC) was designed and fabricated for on-demand micropower generation. The PSMFC can be activated just by plugging into natural wet soil, which is easy to access in the natural condition. The PSMFC uses carbon-based electrodes for cost-effectiveness. After setting the PSMFC into the soil to activate, it started to produce electricity after 1 h and reached the power density of 7.3 mW/m^2 after 48 h. The proposed PSMFC can potentially generate electricity for remote sensors or soil sensing systems.

Keywords: plug; paddy soil; bacteria; MFC; green energy

check for updates

Citation: Nguyen, H.-U.-D.; Nguyen, D.-T.; Taguchi, K. A Novel Design Portable Plugged-Type Soil Microbial Fuel Cell for Bioelectricity Generation. *Energies* **2021**, *14*, 553. https://doi.org/10.3390/en14030553

Received: 20 December 2020
Accepted: 18 January 2021
Published: 21 January 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The soil microbial fuel cell (SMFC) is an environmentally sustainable bioelectrochemical technology that uses bacteria to convert the chemical energy from organic compounds stored in the soil to electrical energy. In the SMFC, organic matter in the anode chamber is oxidized by electrochemical microorganisms living in the soil to produce electrons and protons. These electrons and protons then migrate to the cathode, where they are reduced by oxygen to transform into water. The system is constructed for electricity generation via spontaneous redox reactions. In the past decade, SMFCs have attracted much attention as a promising technology for many environmental applications such as renewable electricity generation, pollution degradation, bioremediation, and biosensors [1–6].

Since the first SMFCs were reported in 2001 by Reimers [7], most of the tested soils in SMFCs were sediment or water-saturated soil [1,2]. Aside from the many advantages, SMFCs still have some disadvantages such as low power production, the long distance between the electrodes leads to large ohmic losses, and power generation depends on the water content and internal resistance of the tested soils [7,8].

On the other hand, microorganisms that exist in the soil play a key role in electricity generation and are affected by the initial soil physicochemical properties such as pH, temperature, moisture content, conductivity, nutrient ions, growth factors, and soil porosity [9].

The performance of a SMFC depends much on its configuration. Most recent studies have extensively focused on optimizing the SMFC configurations such as single-chamber MFC with or without membrane, column-type MFC, and dual-chamber MFC with proton exchange membrane (PEM). Some studies have attempted to decrease the internal soil resistance or electrode spacing; addressed in electrode material innovation such as using a TiO_2, Ag@g-C_3N_4 nanostructure, developed multilayer capacitive anodes to improve anode capacity, or the electricity generation performance [4,8,10–16]. Other studies have attempted to enhance the performance by adding carbon fiber into the soil to increase soil conductivity, accelerated the transport of substrates in the soil, and developed mixed culture electrochemically active biofilms [7,10,17]; however, there has still been little research reported for portable SMFC construction.

Furthermore, conventional SMFC with a column or tubular configuration assembled with the air-cathode suspended on the top of the soil and the anode buried deep inside the soil showed significant effectiveness in power production and contamination removal. However, this conventional configuration is bulky and hard to setup [18].

In this study, we fabricated a compact and portable plugged-type SMFC (PSMFC) based on low-cost materials. The PSMFC was designed as a module with the cathode and anode already mounted on the case. The cathode was put inside an enclosed chamber without touching the soil, while the anode was left exposed to the soil. The PSMFC could be easy to setup by merely plugging it into the wet soil. The proposed PSMFC was designed for on-demand electricity generation.

2. Materials and Methods

2.1. Materials

Activated carbon felt was purchased from Azumi Filter Paper Co. Ltd. (Osaka, Japan). Nafion solution (10% Nafion) was purchased from Wako Pure Chemical Industries Ltd. (Osaka, Japan). Activated carbon powder (6 μm) was purchased from UES Co. Ltd. (Osaka, Japan). Multi-walled carbon nanotube (MWCNT) dispersion coating liquid N7006L, which contains 6.1 wt% MWCNT, was purchased from KJ Specialty Paper Co. Ltd. (Tokyo, Japan). Nafion proton exchange membrane was purchased from AGC Engineering Co. Ltd. (Mihama-ku, Japan). Acrylic board (2 mm thickness) and stainless mesh (0.1 mm thickness) were bought from MonotaRO Co. Ltd. (Hyogo, Japan).

2.2. Soil Sampling

The soil utilized in this study was collected between depths of 10–30 cm from drainage near rice paddies (34°59′51.8″ N, 135°57′00.7″ E (34.997716, 135.950191), located in Shiga Province, Japan. Tested soil presented the physicochemical properties as follows: pH was 4.5, electrical conductivity (EC) was 1.36 dS/m, and total carbon (TC) was 85,200 mg/kg. In the present study, the authors could not conduct DNA sequence analyses to identify the bacterial communities that existed in the tested soil due to the lack of measurement devices.

2.3. Plugged-Type Soil Microbial Fuel Cell (PSMFC) Configuration and Operation

Figure 1a shows the structure of the proposed PSMFC. The reactors were made of acrylic boards with external dimensions of 7.5 cm height × 4.0 cm width × 2.5 cm thickness. The cathode chamber was separated from the anode chamber by a PEM. A perfluorinated polymer membrane (Nafion PEM) was selected due to its high protonic conductivity and low equivalent weight [19]. The cathode chamber was enclosed to prevent the soil water from penetrating. A small hole was opened at the top (this part was out of the soil) of the cathode chamber to expose the cathode to the open air. Carbon-based materials were used for both the anode and cathode electrodes.

Each anode electrode was fabricated by activated carbon felt, which had a surface area of 4 cm^2 and 0.5 mm thickness. The LB medium prepared with 10 g/L glucose, 10 g/L tryptone, 5 g/L yeast extract, 10 g/L yeast extract, 10 g/L NaCl, and NaOH was used to adjust the pH to 7.0. The anode electrode was dipped in 0.5 mL LB medium and then dried naturally. The LB medium loaded on the anode could facilitate the biofilm formation process, leading to fast startup time. The anode was put in contact with the soil directly.

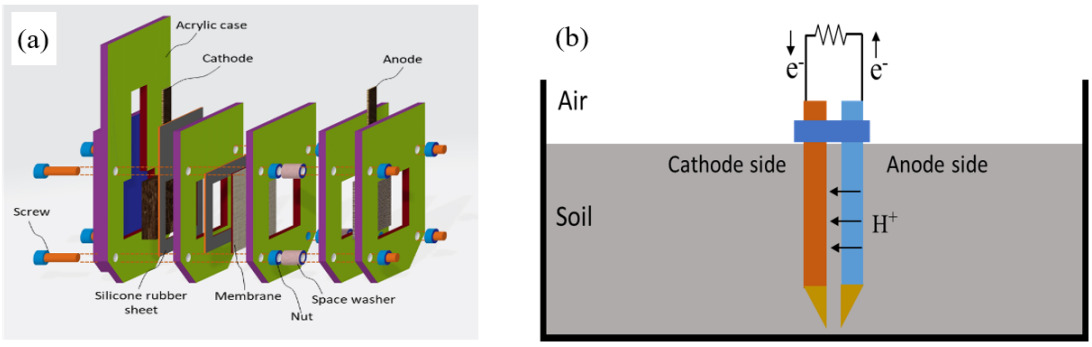

Figure 1. (**a**) Schematic of the plugged-type soil microbial fuel cell (PSMFC) structure and (**b**) schematic diagram of the experimental setup.

To evaluate the cathode electrode performance, the present study investigated two cathode patterns. The cathode of PSMFC1 was made by absorbing 2 mL of the mixture of 1 g carbon fiber (CF), 1 g activated carbon powder (ACP), 5 mL carbon nanotube, and 2 mL Nafion solution to a sponge (2 cm height × 2 cm width × 0.3 cm thickness), followed by drying at 40 °C for 24 h. The cathode of PSMFC2 was made by absorbing 2 mL of the mixture of 0.2 g CF, 0.2 g ACP, 3 mL carbon nanotube, and 1.5 mL Nafion solution to a sponge (2 cm height × 2 cm width × 1 cm thickness), followed by drying at 40 °C for 24 h. The cathode was put inside the cathode chamber.

In addition, Figure 1b shows the schematic diagram of the experimental setup of the PSMFC. Since there are many electrochemically active microorganisms that already exist in the wet soil [10], no external microorganisms were needed for the operation of this PSMFC.

Figure 2 shows the photo images of the fabricated PSMFC and its experimental setup. The stainless mesh was used as the current collector. The two electrodes were connected by a 2 kΩ external resistor. The experimental conditions were saturated water content at 30∼33 °C. All experiments were conducted in triplicate, and the data were collected and shown by average results.

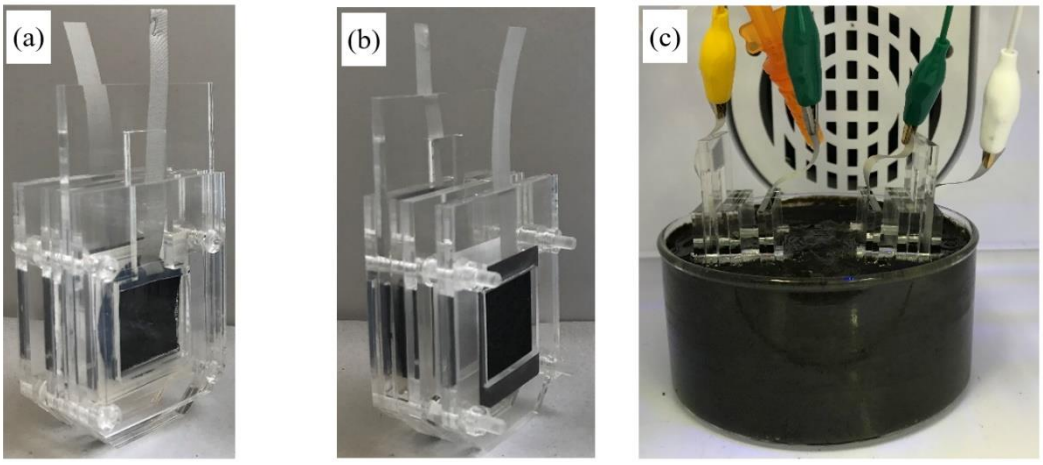

Figure 2. Photo images of the fabricated PSMFC: cathode side (**a**), anode side (**b**), and experimental setup with two PSMFCs (**c**).

2.4. Analysis and Calculation

Scanning electron microscopy (SEM) (Hitachi SU–1500) was used to examine the surface morphology of the anode. The anode after the experiment was slightly cleaned by water to remove the remaining soil on its surface. Then, it was dipped in a sterilizing solution at 4 °C for 24 h to kill bacterial cells. After that, it was continuously treated by

20%, 50%, 70%, and 99% ethanol solutions to dehydrate. Finally, it was dried at room temperature for 24 h.

The output voltage over the external resistor was measured by a data acquisition system (National Instruments NI USB–6210) sampled every 20 min for the duration of seven days. The current density (I) and power density (P) were calculated based on the measured output voltage using Ohm's law: $I = U/(RA)$; $P = UI$, where U is the measured output voltage (V), A is the anode surface area (m^2), and R is the external specific resistance (Ω). The polarization and power density curves were measured by changing the external resistance in the range of 0.3–10 kΩ.

3. Results and Discussion

3.1. Characterization of Anode Surface Morphology and Biofilm Formation

The surface morphology of the surface of the anode electrode was examined by SEM. As shown in Figure 3a, the anodic electrode's surface was porous with layers of clustered particles of activated carbon attached to carbon fibers and cellulose fibers. Although the preparation process of the samples for SEM measurement may significantly remove many cells attached to the surface of the anode, the SEM images at high magnification clearly showed biofilms of bacteria on the surface (Figure 3b,c). Previous studies have reported that a higher microporous surface could improve the biofilm formation on the anode, leading to higher current generation and power density [20,21].

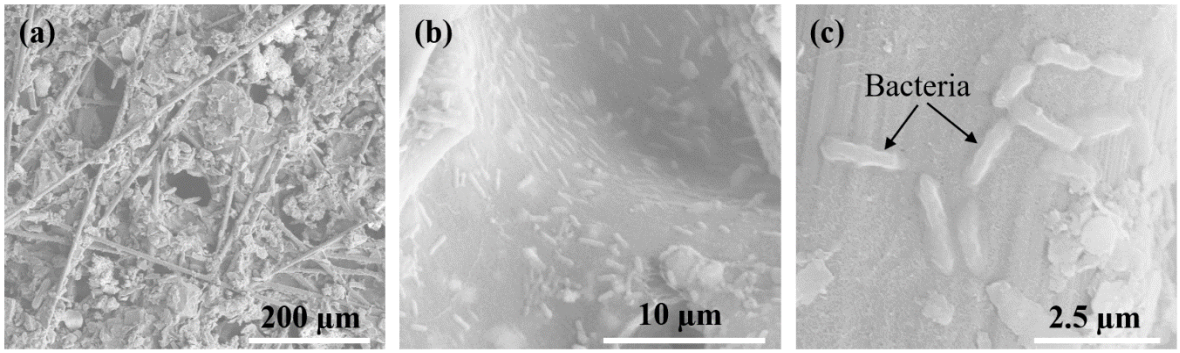

Figure 3. Scanning electron microscope (SEM) images of the surface of the anode electrode. (**a**) 150×, (**b**) 4000×, and (**c**) 12,000×.

Due to the lack of characterization devices, bacterial communities in the soil used in this study were not identified. However, according to some reported literature in the field, paddy soil contains many exoelectrogenic bacteria such as *Shewanella sp.*, *Geobacter sp.* or *Pseudomonas spp.* [9,10,13]. Therefore, it can be assumed that the paddy soil used in this study contained the same species.

3.2. PSMFC Performance and the Effect of Different Cathodes

To evaluate the performance of the PSMFC1 and PSMFC2, the output voltage was recorded over a 2 kΩ external resistor during the tested period. The current densities versus time were calculated and shown in Figure 4a. It can be seen that the current densities increased rapidly in the first 5 h and reached the peaks after about 35 h. The maximum current density of the PSMFC1 (100.12 mA/m^2) was higher than that of the PSMFC2 (81.48 mA/m^2). This result is considered a short startup time, which may be attributed to the LB medium absorbed in the anode that facilitates the biofilm formation process and microorganism activities.

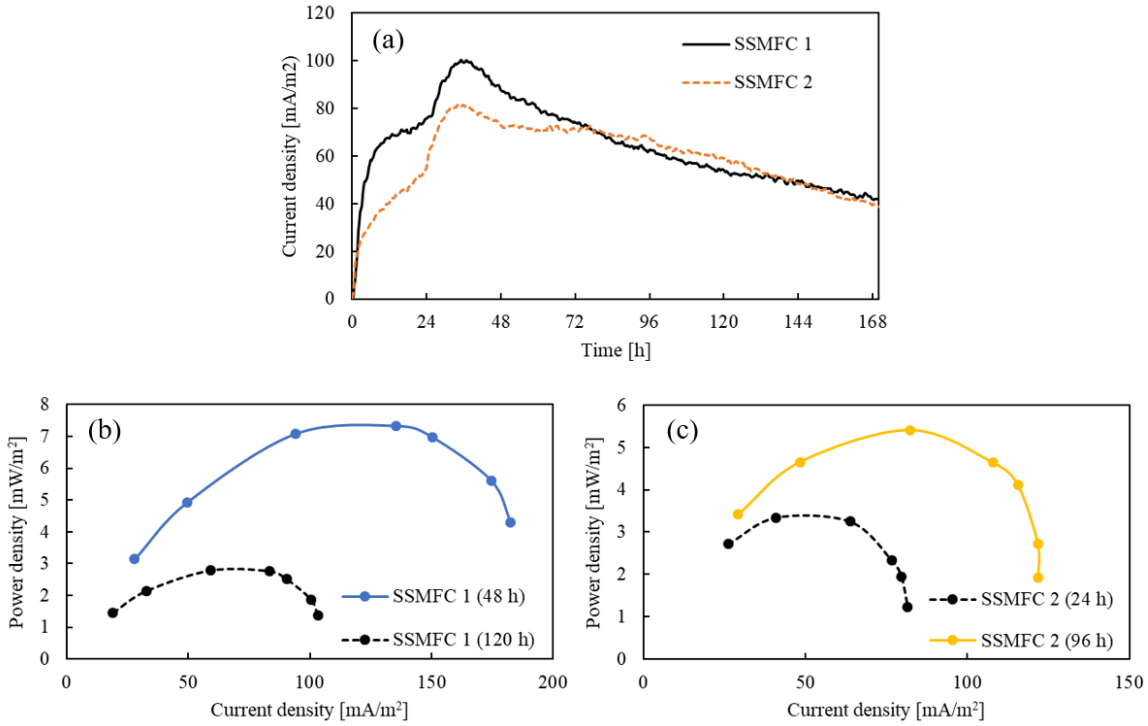

Figure 4. Electricity generation characteristics. (**a**) Polarization curve, (**b**) power density of PSMFC1 measured at 48 h and 120 h, and (**c**) power density of PSMFC2 measured at 24 h and 96 h.

After reaching the peaks, the current densities of both PSMFC1 and PSMFC2 decreased gradually. After 168 h, the current densities of both PSMFC1 and PSMFC2 showed similar values (41.85 mA/m^2 and 39.52 mA/m^2, respectively). Compared with the peaks, the degradation rates were 58% and 51% for PSMFC1 and PSMFC2, respectively. This result may be attributed to the decrease in organic matter in the soil, causing low bacterial activity. Both PSMFC1 and PSMFC2 showed similar behaviors regardless of the differences. However, the PSMFC1 showed a better output in the first 72 h.

In this study, the tested period was fixed at seven consecutive days. However, according to the experimental data shown in Figure 4a, the PSMFCs could continue to generate the output for a much longer time. The degradation of the output depends on the nutrition content of the soil and other complex factors. It may take a much longer time to determine the end of life of the PSMFCs. This problem will be taken into account in future studies.

Moreover, the power densities of the PSMFC1 and PSMFC2 were measured and are shown in Figure 4b,c, respectively. The results showed that the power density of the PSMFC1 measured at 48 h was 7.3 mW/m^2, and that of the PSMFC2 measured at 24 h was 5.4 mW/m^2. These results are in good agreement with the polarization curves shown in Figure 4a.

4. Conclusions

In this paper, a portable PSMFC was designed and fabricated. The PSMFC was fabricated using low-cost materials. By simply plugging the PSMFC into natural wet soil, it started producing electricity after 1 h and increased gradually to reach the maximum after 24–48 h. Experimental results showed that the PSMFC could produce a maximum power density of 5–7 mW/m^2. Additionally, it can be expected that more power can be obtained if the cathodic quality is further improved. With the compact and easy-to-setup design, the proposed PSMFC can potentially be used for powering remote sensors and soil quality sensing systems.

Author Contributions: H.-U.-D.N. carried out the experiment and wrote the manuscript. D.-T.N. conceived the original idea, helped with the experiment, carried data analysis, and contributed to the final version of the manuscript. K.T. conceived the original idea, supervised the research project, and contributed to the final version of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Rodrigo, J.; Boltes, K.; Esteve-Nuñez, A. Microbial-electrochemical bioremediation and detoxification of dibenzothiophene-polluted soil. *Chemosphere* **2014**, *101*, 61–65. [CrossRef] [PubMed]
2. Sherafatmand, M.; Ng, H.Y. Using sediment microbial fuel cells (SMFCs) for bioremediation of polycyclic aromatic hydrocarbons (PAHs). *Bioresour. Technol.* **2015**, *195*, 122–130. [CrossRef] [PubMed]
3. Zhao, N.; Jiang, Y.; Alvarado-Morales, M.; Treu, L.; Angelidaki, I.; Zhang, Y. Electricity generation and microbial communities in microbial fuel cell powered by macroalgal biomass. *Bioelectrochemistry* **2018**, *123*, 145–149. [CrossRef] [PubMed]
4. Wang, Y.; Wen, Q.; Chen, Y.; Yin, J.; Duan, T. Enhanced Performance of a Microbial Fuel Cell with a Capacitive Bioanode and Removal of Cr (VI) Using the Intermittent Operation. *Appl. Biochem. Biotechnol.* **2016**, *180*, 1372–1385. [CrossRef]
5. Zhang, J.; Cao, X.; Wang, H.; Long, X.; Li, X. Simultaneous enhancement of heavy metal removal and electricity generation in soil microbial fuel cell. *Ecotoxicol. Environ. Saf.* **2020**, *192*, 110314. [CrossRef]
6. Yu, D.; Bai, L.; Zhai, J.; Wang, Y.; Dong, S. Toxicity detection in water containing heavy metal ions with a self-powered microbial fuel cell-based biosensor. *Talanta* **2017**, *168*, 210–216. [CrossRef]
7. Li, X.; Wang, X.; Zhao, Q.; Wan, L.; Li, Y.; Zhou, Q. Carbon fiber enhanced bioelectricity generation in soil microbial fuel cells. *Biosens. Bioelectron.* **2016**, *85*, 135–141. [CrossRef]
8. Wang, X.; Cai, Z.; Zhou, Q.; Zhang, Z.; Chen, C. Bioelectrochemical stimulation of petroleum hydrocarbon degradation in saline soil using U-tube microbial fuel cells. *Biotechnol. Bioeng.* **2012**, *109*, 426–433. [CrossRef]
9. Zhang, X.; Li, X.; Zhao, X.; Li, Y. Factors affecting the efficiency of a bioelectrochemical system: A review. *RCS Adv.* **2019**, *9*, 19748–19761. [CrossRef]
10. Li, X.; Wang, X.; Ren, Z.J.; Zhang, Y.; Li, N.; Zhou, Q. Sand amendment enhances bioelectrochemical remediation of petroleum hydrocarbon contaminated soil. *Chemosphere* **2015**, *141*, 62–70. [CrossRef]
11. Li, X.; Wang, X.; Zhang, Y.; Cheng, L.; Liu, J.; Li, F.; Gao, B.; Zhou, Q. Extended petroleum hydrocarbon bioremediation in saline soil using Pt-free multianodes microbial fuel cells. *RSC Adv.* **2014**, *4*, 59803–59808. [CrossRef]
12. Lu, L.; Yazdi, H.; Jin, S.; Zuo, Y.; Fallgren, P.H.; Ren, Z.J. Enhanced bioremediation of hydrocarbon-contaminated soil using pilot-scale bioelectrochemical systems. *J. Hazard. Mater.* **2014**, *274*, 8–15. [CrossRef] [PubMed]
13. Wang, Y.; Chen, Y.; Wen, Q.; Zheng, H.; Xu, H.; Qi, L. Electricity generation, energy storage, and microbial-community analysis in microbial fuel cells with multilayer capacitive anodes. *Energy* **2019**, *189*, 116342. [CrossRef]
14. Khan, M.E.; Han, T.H.; Khan, M.M.; Karim, M.R.; Cho, M.H. Environmentally Sustainable Fabrication of Ag@g-C_3N_4 Nanostructures and Their Multifunctional Efficacy as Antibacterial Agents and Photocatalysts. *ACS Appl. Nano Mater.* **2018**, *1*, 2912–2922. [CrossRef]
15. Khan, M.E.; Khan, M.M.; Cho, M.H. Environmentally sustainable biogenic fabrication of AuNP decorated-graphitic g-C_3N_4 nanostructures towards improved photoelectrochemical performances. *RSC Adv.* **2018**, *8*, 13898–13909. [CrossRef]
16. Khan, M.E.; Khan, M.M.; Min, B.K.; Cho, M.H. Microbial fuel cell assisted band gap narrowed TiO_2 for visible light induced photocatalytic activities and power generation. *Sci. Rep.* **2018**, *8*, 1723. [CrossRef]
17. Khan, M.M.; Ansari, S.A.; Lee, J.H.; Lee, J.; Cho, M.H. Mixed Culture Electrochemically Active Biofilms and their Microscopic and Spectroelectrochemical Studies. *ACS Sustain. Chem. Eng.* **2014**, *2*, 423–432. [CrossRef]
18. Hsu, L.; Mohamed, A.; Ha, P.T.; Bloom, J.; Ewing, T.; Arias-Thode, M.; Chadwick, B.; Beyenal, H. The Influence of Energy Harvesting Strategies on Performance and Microbial Community for Sediment Microbial Fuel Cells. *J. Electrochem. Soc.* **2017**, *164*, H3109–H3114. [CrossRef]
19. Jayakumar, A.R. An assessment on polymer electrolyte membrane fuel cell stack components. *Appl. Phys. Chem. Multidiscip. Approaches* **2018**, *3*, 23–49.
20. Li, S.; Cheng, C.; Thomas, A. Carbon-Based Microbial-Fuel-Cell Electrodes: From Conductive Supports to Active Catalysts. *Adv. Mater.* **2017**, *29*. [CrossRef]
21. Nguyen, D.T.; Taguchi, K. Enhancing the performance of E. coli-powered MFCs by using porous 3D anodes based on coconut activated carbon. *Biochem. Eng. J.* **2019**, *151*, 107357. [CrossRef]