Electricity Generation and Growth of Hydroponic Chinese Kale in Plant Microbial Fuel Cell

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Abstract

Plant Microbial Fuel Cell (PMFC) is a source of renewable energy that converts chemical energy in organic matters to electrical energy. The process is a part of the symbiosis of plant and bacteria. The relationship between electricity generation and growth of Chinese kale was studied. The plants were grown by the hydroponic Kratky method with the addition of *Bacillus subtilis*. The anode and cathode electrodes were made of graphite felt woven with copper wires. The experimental samples were divided into four groups: PMFCs with a resistor of 10, 100, or 1000 Ω, and ones with neither electrodes nor a resistor. Over the growing period of 50 days, the results showed that the presence or absence of electrodes or a resistor had no significant effect on the heights of the plants. On day 50, the plants of the PMFCs with neither electrodes nor a resistor, however, had the total leaf lengths about 17 % longer by average, while the plants of the 1000-Ω PMFCs had the lengths about 11 % shorter by average. As the plants grew, the output voltages and power densities also increased. In conclusion, the PMFCs could simultaneously provide the electricity generation and production of hydroponic edible crop. The plant growth could also be monitored from the measured output voltages.

Keywords: Microbial Fuel Cell; Hydroponics; Kale; Bacillus subtilis; Bioelectricity.

1. Introduction

Plant Microbial Fuel Cell (PMFC) is a novel source of renewable energy and a recent variant of Microbial Fuel Cell (MFC) [1; 2]. The system operates and benefits from the symbiosis of plant and anaerobic bacteria.

Root exudates from a plant and dead plant cells, together called rhizodeposits, can be consumed by bacteria. The degradation of the organic matters yield electrons. A well-designed fuel cell system can allow flow of the electrons from anode to cathode, producing electrical current. When the plant grows well, more root exudates are released. This result in the higher bacterial growth and the higher electricity generation. As a result, the plant health can be monitored by the amount of generated electricity [3].

Plant growing in hydroponic systems is gaining popular in Thailand, because it brings high yield of crop in optimally controlled environment. Various crops can be used such as lettuces, tomatoes, and kales. The applications of PMFC with soilless plants have been extensively studied [4]. An attempt on commercial hydroponic crops, however, has not been reported.

In this study, the relationship between electricity generation and growth of hydroponic Chinese kale in PMFCs was investigated. The effect of different load resistors on the PMFCs was also considered.

2. Methods

2.1. PMFC design

A cross-sectional schematic of our PMFC is shown in Fig. 1. The studied plants were Chinese kale, grown by the hydroponic Kratky method [5] with the addition of bacteria Bacillus subtilis. The Kratky method requires no replenishment, circulation, and aeration of the nutrient solution, thus saving cost and energy. The stagnant liquid with the absence of oxygen is also necessary for anaerobic bacteria to thrive. The bacteria were selected due to their ability to enhance plant

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growth [6] and their potential in MFC [7].

The anode and cathode were made of circular pieces of graphite felt (17 cm in diameter and 3 mm in thickness). Both electrodes were woven with a current collector of pure copper wires (0.05 mm in diameter) in a mesh fashion of 1 cm × 1 cm.

The electrodes were connected via the copper wires and a resistor. The cathode floated on the liquid surface with an aid of small pieces of polystyrene foam. The anode was anchored to the cathode with plastic tubes, maintaining a distance of 10 cm.

2.2. Experimental procedure

Sixteen plant samples were divided into four groups (four plants each)W PMFCs with a resistor of 10, 100, or 1000 Ω, and ones with neither electrodes nor a resistor (a control group).

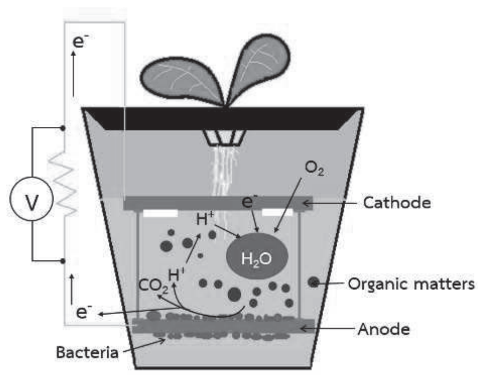

Fig. 1. Schematic of our PMFC.

As the hydroponic medium and as the electrolyte, the modified Hoagland nutrient solution was prepared and mixed with the bacteria and 10-mM acetic acid and aerated for 20 days. The mixture was then poured into sixteen buckets, each containing one young plant (about 2 weeks old). The starting volumes of the solutions were about 4.7 L, decreasing over time.

The solutions were adjusted to an electrical conductivity (EC) of about 2 mS/cm and a pH of about 5.5-6, which were appropriate for growing hydroponic kales [8]. The values were adjusted and maintained throughout the experiment by adding potassium hydroxide or nitric acid if necessary.

The plants were grown and observed for 50 days. The output voltages and currents of all the PMFCs were measured by a multimeter (FLUKE 289, USA) every day. The heights and total leaf lengths of the plants were also recorded.

2.3. PMFC performance analysis

The PMFC performance was evaluated using two parameters; output voltage and power density [1]. The power density was calculated on the basis of the projected anode surface area by,

$$P_{An} = \frac{E_{cell} I_{cell}}{A_{An}} \qquad (1)$$

where

P_{An} = power density per anode area

E_{cell} = measured output voltage

I_{cell} = measured output current

$\mathrm{A_{An}}$ = anode surface area

For our PMFCs, the anode area was about 230 cm^2.

To compare the results, the curve fitting techniques (linear and cubic regressions) were applied to determine the trendlines of the heights, total leaf lengths, output voltages, and power densities over the growth period of the plants.

3. Results and Discussion

Fig. 2(A) and 2(B) shows the heights and the total leaf lengths of the kale plants of the four experimental groups with different resistor loads over the growing period of 50 days, respectively.

Over the entire growing period, the plants of the four groups had similar heights. This means that the difference in the resistor loads had no significant effect on the heights of the growing plants.

In contrast, although at the beginning the total leaf lengths of the plants of the four groups were similar, at the late growing period the difference started to appear. The plants of the control group seemed to have the highest lengths, while the plants of the PMFCs with a resistor of 1000 Ω had the lowest. On day 50, the last day of growing, with respect to the overall average of the total leaf lengths of all the plants, the plants of the control group had the higher leaf lengths by about 17 %, while the plants of the 1000-Ω PMFCs had the lower leaf lengths by about 11 %.

oxidation and reduction reactions, and ion movement between the electrodes).

Also, the higher the resistor load was, the greater the effect of the load on the plant growth was, particularly on the leaf length. Perhaps the plants required the ionic nutrients in the growth of the leaves more than that of the stems. The greater resistor load means the higher impeding force to the flow of the electrons. This could induce the higher usage of the ionic nutrients for the PMFC processes to maintain the electricity generation, and thus competing with the nutrient consumption by the plants.

Fig. 3(A) and 3(B) shows the measured output voltages with respect to the heights and the total leaf lengths of the kale plants of the three groups with different resistor loads, respectively.

As the plants grew, the output voltages also increased. The rates of the increasing voltages were low at first when the plants were small, but the rates became larger when the plants grew bigger. This implies the more effective PMFC processes.

Assuming that all the PMFCs should produce similar quantities of the electrical currents, one would expect the 1000-Ω PMFCs to yield the highest voltages, based on the Ohm's law. However, despite the difference in the resistor loads, all groups of the plants produced similar trends of the output voltages. One explanation is that the internal resistances of the PMFCs were so large that it caused the huge loss of energy and yielded exceedingly low current [9]. In other words, the external resistances had little effect on the systems, since they were much smaller compared to

On the contrary, the similar result was not observed in the plots of the power densities with respect to the leaf lengths, in Fig. 4(B). At the same height, the plants of the 1000-Ω PMFCs had the shorter leaf lengths than the others, thus the lower power densities. At the same leaf length, however, all the PMFCs yielded the similar power densities. Additional analyses on the leaf quality (e.g., the color or the levels of nutrient elements) may provide better understanding of the significance of the leaf on the PMFC power output.

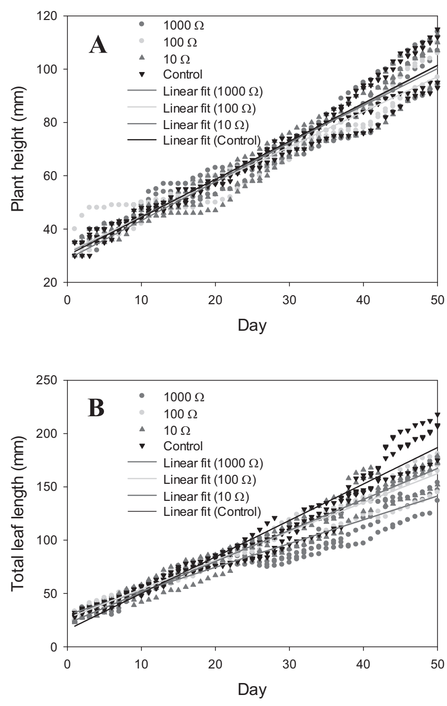

Fig. 2. (A) The heights and (B) the total leaf lengths of the kales in the four groups of PMFCs with different resistorloads. The linear curve fitting was applied (the R2 values are between 0.883-0.966).

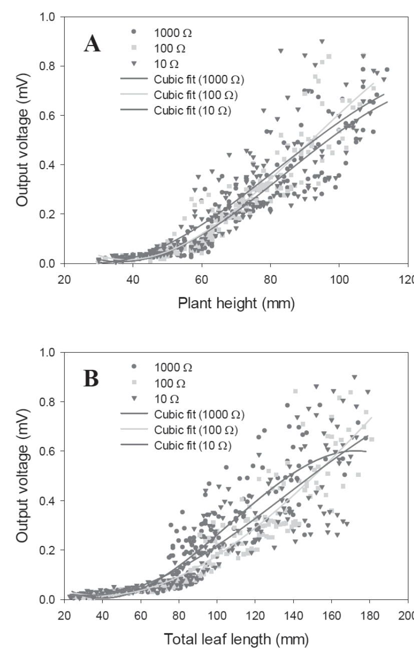

Fig. 3. The output voltages with respect to (A) the heights and (B) the total leaf lengths of the kales in the PMFCs with different resistor loads. The cubic curve fitting was applied (the R2 values are between 0.783-0.888).

4. Conclusion and Recommendations

As the plants grew, the measured output voltages and the power densities of the PMFCs also increased. Both the voltages and the power densities, however, were expected to reach the plateaus when the plants reached maturity. The longer observation period may be required.

The presence of the electrodes and resistor had no effect on the growing height of the Chinese kale plants. Nevertheless, the plants of the PMFCs with neither electrodes nor a resistor had the slightly longer total leaf lengths, while the plants of the 1000-Ω PMFCs had the shorter lengths. This knowledge may help to decide the choice of crops (emphasizing the leaves or the stems) and the resistor load size to achieve the optimum of both electricity generation and crop production.

The goal of this study was not the optimization of the power output but to study the relationship between the plant growth and the electricity generation. Development of most PMFCs is currently in research stage. They yield power output and efficiency far lower than the more established renewable systems, for instance, wind turbines or solar panels. To be economically feasible, PMFCs should yield the power density in the order of milliwatts per square meter or higher [4]. The plants in this study were also relatively underdeveloped. A better design of the system (e.g., decreasing the distance between the electrodes) is needed to reduce the large internal resistance. Further investigations on the choice of plant, the electrode materials, and the higher organic loading in addition to the nutrient solution may be necessary.

Acknowledgements

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References

[1] Logan, B. E., Hamelers, B., et al. (2006) Microbial fuel cells: methodology and technology. Environmental Science & Technology, 40(17), 5181-5192.

[2] Strik, D. P. B. T. B., Hamelers, H. V. M., et al. (2008) Green electricity production with living plants and bacteria in a fuel cell. International Journal of Energy Research, 32(9), 870-876.

[3] Brunelli, D., Tosato, P., et al. (2016) Flora health wireless monitoring with plant-microbial fuel cell. Procedia Engineering, 168, 1646-1650.

[4] Nitisoravut, R., & Regmi, R. (2017) Plant microbial fuel cells: A promising biosystems engineering. Renewable and Sustainable Energy Reviews, 76, 81-89.

[5] Kratky, B. A. (2009). Three non-circulating hydroponic methods for growing lettuce. Paper presented at the International Symposium on Soilless Culture and Hydroponics, Lima, Peru.

[6] Lee, S., & Lee, J. (2015) Beneficial bacteria and fungi in hydroponic systems: Types and characteristics of hydroponic food production methods. Scientia Horticulturae, 195, 206-215.

[7] Hassan, H., Schulte-Illingheim, L., et al. (2016) Degradation of 2,4-dichlorophenol by Bacillus Subtilis with concurrent electricity generation in microbial fuel cell. Procedia Engineering, 148, 370- 377.

[8] Singh, H., & Bruce, D. (2016). Electrical conductivity and pH guide for hydroponics. Retrieved from https://www.researchgate.net/publication/309293679_Electrical_Conductivity_and_pH_Guide_fo r_ Hydroponics

[9] Klaisongkram, N., & Holasut, K. (2015) Electricity generation of Plant Microbial Fuel Cell (PMFC) using Cyperus Involucratus R. KKU Engineering Journal, 42(1), 117-124.