Chapter 4
Current Advances in Paddy Plant Microbial Fuel Cells

Kiyoshi Omine, Santos D. Chicas, and Venkataraman Sivasankar

4.1 Introduction

Microbial fuel cells (MFCs) are bioelectrochemical cells that convert microbial reducing power into electrical energy that is green (Logan and Regan 2006). Attempts have been made to apply MFC systems to recover electric power from marine and riverbeds termed as sediment MFCs (SMFCs) (Schamphelaire et al. 2008). MFC as a hybrid composting method, which reuses kitchen waste as raw material, has also been proposed (Moqsud et al. 2014).

Plant microbial fuel cells (PMFCs) are a recently developed technology that uses organic rhizodeposits, comprising of root exudates and dead root cells, as the electron donor for heterotrophic microorganisms in the plant rhizosphere (Strik et al. 2008). Plants excrete photosynthesized organic compounds from roots. Those organics are used by microbes for electricity generation in PMFCs. PMFCs are remarkably sustainable because they have a clean conversion without emissions and have no competition for arable land or nature. PMFCs can also be implemented in rice paddy fields combining food and electricity production and so circumventing the competition with food production (Kaku et al. 2008).

Graphite is often used as cathode material in a PMFC. However, the reduction of oxygen on graphite is slow and limits the power output of the PMFC. Electrocatalysts like platinum are able to catalyze the reduction of oxygen. The high costs and the potential poisoning compounds in the solution make platinum undesired to be applied in the PMFC.

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In this study, a performance of paddy plant microbial fuel cell (PMFC) is evaluated by experiments using container of bucket and PET bottle. Two types of electrodes, namely, carbon fiber and activated bamboo charcoal, are used on paddy PMFC. Influences of electrode material and existence of iron wire attached to anode on voltage generation are investigated. The influence of connections in series or parallel, using small-sized PET bottle (500 mL), is also investigated.

4.2 Test Materials and Methods

Two types of electrodes were used on the PMFC. Carbon fibers do not have any negative effect on the growth of paddy roots (Moqsud et al. 2015). However, it is considered that carbon fiber is not suitable for the anode, because the roots of paddy are closely attached with the carbon fiber, thus making it difficult to be removed. In this study, carbon fiber (Toho Rayon Co., Ltd., Tokyo) was used only as a cathode. Activated bamboo charcoal (KPC Co., Ltd., Shiga Prefecture, Japan) was used as anode or cathode. These electrodes are good at conducting electricity with an electrical resistance of 5 ohms. Figure 4.1 shows the electrode materials of cathode and anode. The activated bamboo charcoal sizes were around 120 × 50 mm and 50 × 40 mm, and the carbon fiber mass was 10 g; these were connected to a stainless wire. Power generation of soil microbial fuel cell (SMFC) using organic waste increases by wrapping iron wire on the activated bamboo charcoal anode (Moqsud et al. 2013). The activated bamboo charcoal with iron wire was also used in this experiment to investigate its effect on power generation of PMFC.

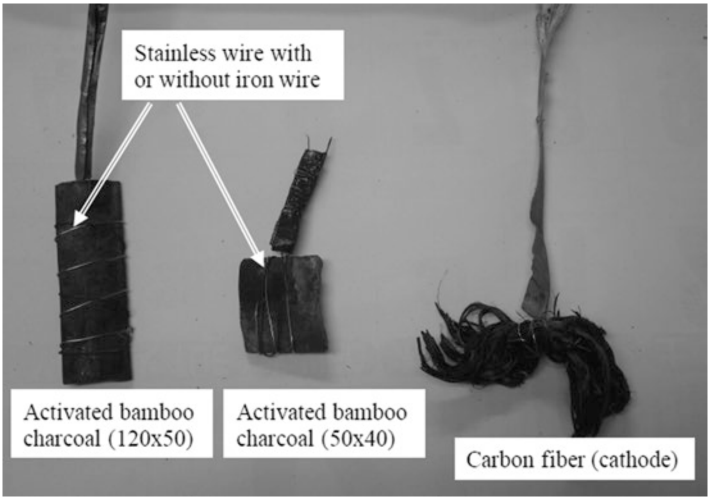

Fig. 4.1 Electrode materials of cathode and anode

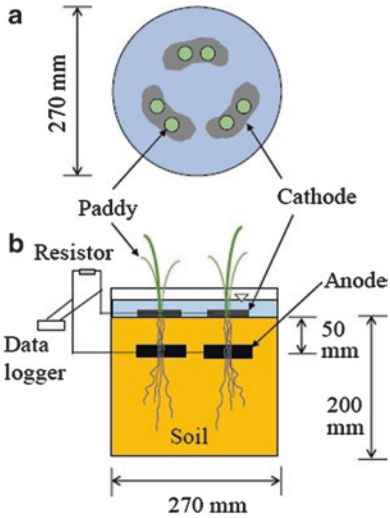

Fig. 4.2 Plan (a) and cross section (b) of the experimental device using bucket of 13 L

Table 4.1 Test conditions on paddy plant MFC using bucket

No.	Plant	Fertilizer	Cathode	Anode
1	Without	Without	Carbon fiber	Activated bamboo charcoal
2	Paddy	Chemical	Carbon fiber	Activated bamboo charcoal
3	Paddy	Organic	Carbon fiber	Activated bamboo charcoal
4	Paddy	Organic	Carbon fiber	Activated bamboo charcoal
5	Paddy	Organic	Carbon fiber	Activated bamboo charcoal with iron wire
6	Paddy	Organic	Carbon fiber	Activated bamboo charcoal with iron wire
7	Paddy	Organic	Carbon fiber	Activated bamboo charcoal with iron wire
8	Paddy	Organic	Carbon fiber	Activated bamboo charcoal with iron wire
9	Paddy	Organic	None	None

No.5–No.8: same conditions

Schematic diagram on experimental device of the PMFC using bucket of 13 L is illustrated in Fig. 4.2. Test conditions of the PMFC are shown in Table 4.1. The soil was prepared by mixing clayey soil, sandy soil, culture soil, and leaf mold. Eight buckets were prepared for the PMFCs. Bucket No. 1 was not planted for comparing the electricity generation with or without plant. There was no fertilizer mixed in this bucket. Bucket No. 2 was prepared by mixing chemical fertilizer of 5 g into the soil. Bucket Nos. 3–8 were prepared by mixing organic fertilizer of 30 g. The carbon fiber was used for all buckets as cathode. The activated bamboo charcoal was used for bucket Nos. 1–4. The activated bamboo charcoal with iron wire was used for bucket Nos. 5–8 for the purpose of increasing the performance of the PMFC. Bucket Nos. 3–4 and bucket Nos. 5–8 were prepared as replications of the same conditions, respectively.

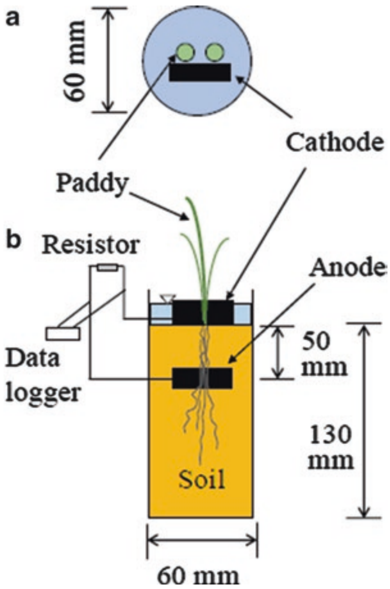

Fig. 4.3 Plan (a) and cross section (b) of the experimental device with PET bottle of 0.5 L

Table 4.2 Test conditions on paddy plant MFCs of five PET bottles' connection in series or parallel

	Plant	Fertilizer	Cathode	Anode
Case 1	Paddy	Organic	Activated bamboo charcoal	Activated bamboo charcoal
Case 2	Paddy	Organic	Activated bamboo charcoal	Activated bamboo charcoal with iron wire

Three anodes made of the activated bamboo charcoal in size of 120 × 50 mm were inserted into the soil, and three cathodes made of the carbon fiber in mass of 10 g were placed on a surface of the soil. The anode area covers around 0.006 m^2 inside the soil of the PMFC. The anode was set approximately 50 mm below the surface of the soil, while the cathode was placed immediately above the soil surface, but under the water. These electrodes were connected via lead wires. Both the anode and cathode were connected to a data logger. The data logger is set to measure the voltage in every 5-min interval.

Additionally bucket No. 9 with organic fertilizer and without electrode was prepared. The rice plants were planted in the soil in each bucket except for bucket No. 1. Black rice (ancient rice) was selected, because the black rice is resistant to disease and easy to grow.

In order to investigate the influence of electrode material and voltage generation by difference of connection, small-sized paddy plant MFC was prepared. Schematic diagram on experimental device of the PMFC using PET bottle of 500 mL is illustrated in Fig. 4.3. Test conditions of the PMFC are shown in Table 4.2. The same soils described above mixed with 6 g of organic fertilizer were used in each PMFC.

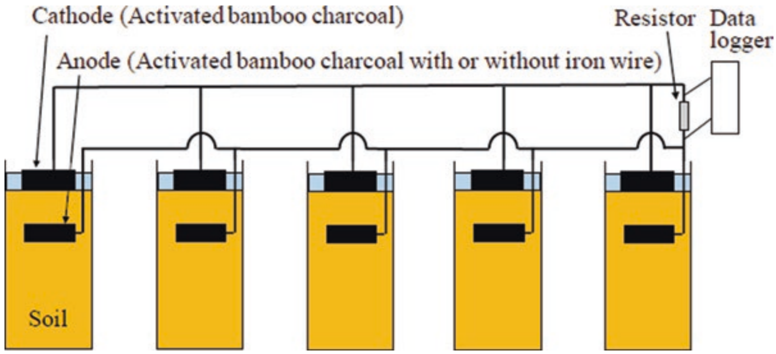

Fig. 4.4 Plant MFCs of connection in parallel using five PET bottles of 0.5 L

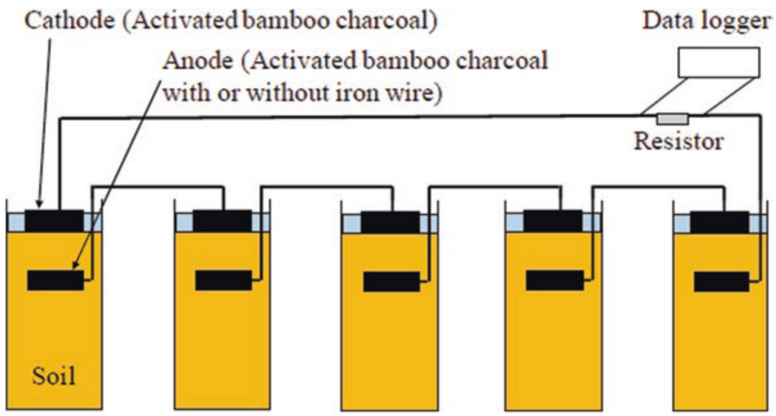

Fig. 4.5 Plant MFCs of connection in series using five PET bottles of 0.5 L

The activated bamboo charcoal was used for both electrode materials, anode and cathode. Two types of PMFCs using anodes with and without iron wire, Case 1 and Case 2, were prepared, respectively.

The activated bamboo charcoal in size of 50 × 40 mm was inserted into the soil, and the same size of the electrode was placed on the surface of the soil. The anode area covers around 0.002 m^2 inside the soil of the PMFC. The anode was set approximately 50 mm below the surface of the soil, while the cathode was placed immediately above the soil surface, but under the water. Electrodes of five PMFCs were connected in parallel or series via lead wires to a data logger. Figures 4.4 and 4.5 show PMFCs of the connection in parallel or series using five PET bottles of 500 mL, respectively. The data logger is set to measure the voltage in every 5-min interval. The black rice plant was planted in the soil.

4.3 Results and Discussion

4.3.1 Experiment Using Bucket of 13 L with Carbon Fiber and Activated Bamboo Charcoal as Electrodes

Paddy plant MFCs were performed during the rice cropping season (from June to August) in Nagasaki University Bunkyo-machi campus, Japan. Figure 4.6 illustrates the variations of temperature and daylight hours during this period in Nagasaki City (Japan Meteorological Agency). Maximum and minimum temperatures in this period were 37 and 16 °C, respectively. Average temperature in this period was 26.5 °C. Average daylight hour was 6.4 h. On the whole, there were many sunny days. The weather condition during the study period was good for growing paddy plants.

Figure 4.7 illustrates the variation of voltage generation with time in rice PMFCs in different buckets. Rice seedlings were planted to the buckets on June 9, 2017, and data were collected from June 17, 2017. The voltage generation on the case of without paddy plant (No. 1) increased gradually from June 15 and reached to 0.2 V. After that, the value increased and decreased. It was observed that algae grew in the bucket. This might have occurred due to the presence of nutrients in the culture soil. The result suggests that the voltage of bucket No. 1 was generated due to the presence of algae. The voltage generation for the case of bucket No. 2 with chemical fertilizer reached to 0.5 V initially, and then the value decreases gradually. This occurred as a result of the chemical fertilizer which works quickly, but the effect does not continue for long term.

Bucket Nos. 3–4 were prepared by mixing organic fertilizer as replications of the same conditions. The voltage generation for bucket No. 3 increased up to 0.37 V, but

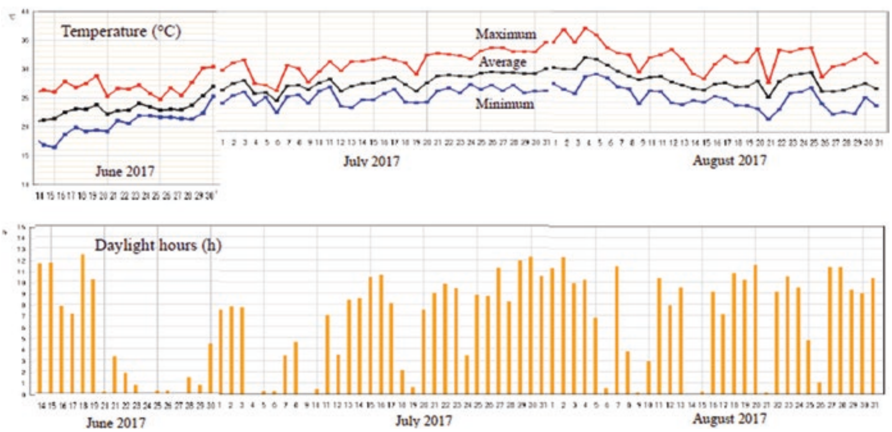

Fig. 4.6 Variations of temperature and day light hours in Nagasaki City (Japan Meteorological Agency)

after that, it dropped down. This might have occurred due to a defective connection. On the other hand, the voltage for bucket No. 4 increased gradually, and the value changed considerably. Maximum voltage reached at 0.83 V on July 31, 2017. It was the highest so far in PMFC research (Moqsud et al. 2015; Liu et al. 2013; Strik et al. 2008).

Bucket Nos. 5–8 with the activated bamboo charcoal with iron wire were prepared by mixing organic fertilizer as replications of the same conditions. The voltage for bucket Nos. 5–8 increased gradually, and the results were also similar. Maximum voltage reached at 0.68 V on August 24, 2017. It was observed that the voltage for bucket Nos. 5–8 is more stable when compared with that of bucket Nos. 3–4. However, it is not easy to get stable voltage on PMFCs.

Figure 4.8 shows the growth of paddy plant with time in different buckets. The growth of the plant for all buckets increased gradually, and the length became more than 800 mm. Growing speed of bucket Nos. 3–8 with organic fertilizer is relatively high comparing that of bucket No. 2 with chemical fertilizer. It was also observed that the growth of bucket Nos. 5–8 with iron wire is enhanced. It may be considered that iron was supplied to the plant as nutrition.

Figure 4.9 shows growth of paddy plant in different buckets. Additionally, paddy seedling was planted to bucket No. 9 with organic fertilizer and without electrodes. It was found that the electrodes do not influence the growth of paddy plant.

Figure 4.10 illustrates variation of voltage with duration and influence of solar radiation during July 14–24, 2017. Bucket Nos. 1, 2, 4, and 5 were selected. The solar radiation shows clear peak value in daytime, and the value becomes zero during nighttime. The voltage of all buckets also showed clear peak value in daytime. Bucket No. 5 with organic fertilizer and iron wire showed high voltage when compared with that of other buckets in this period. It is considered that iron wire contributed to the increase in voltage. However, it was found that bucket Nos. 1, 2, and 4 kept the voltage between 0.1 and 0.2 V even at nighttime. It is not certain why these differences occurred.

4.3.2 Experiment Using PET Bottle of 500 mL with Activated Bamboo Charcoal for Anode and Cathode

PMFCs using PET bottle of 500 mL were performed for investigating influences of electrode material and voltage generation by difference of connection. Activated bamboo charcoal was used for both electrode materials, anode and cathode. Two types of anodes with and without iron wire were prepared. Five PMFCs were connected in series at first, and these PMFCs were reconnected in parallel later. Figure 4.11 illustrates variation of voltage on PMFCs in a series connection during July 15–22, 2017, and the influence of solar radiation. Average voltage values of PMFCs in series connection with or without iron wire were 3.12 V and 1.19 V, respectively. It is obvious that the voltage generation of plant MFCs increased by

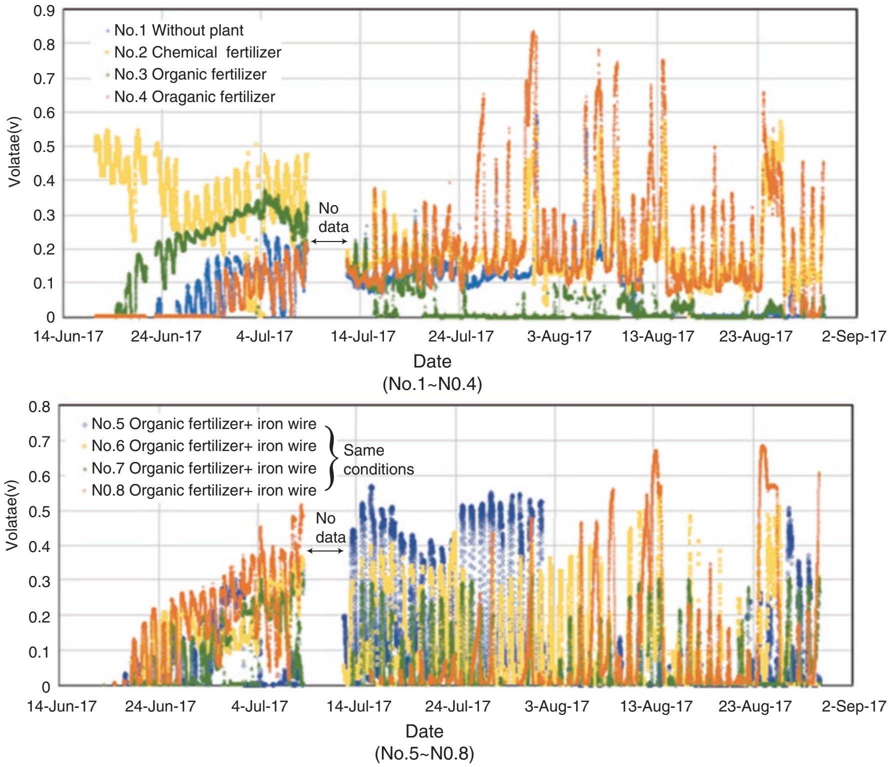

Fig. 4.7 Variation of voltage generation with time in different buckets

using anode with iron wire. This resulted in a voltage increase. A similar effect of iron wire was also found in soil MFC using organic wastes (Moqsud et al. 2013). Furthermore, it is remarkable that PMFCs generated voltage continuously even at nighttime. Sometime the voltage changed, but no effect of solar radiation was observed.

Figure 4.12 illustrates variation of voltage on PMFCs in parallel connection during July 25 to August 6, 2017. Similar trends in influences of iron wire and material of cathode were also found on PMFCs in parallel connection.

Average voltage values of PMFCs in parallel connection with or without iron wire were 0.517 V and 0.332 V, respectively. Average voltage of PMFCs in parallel connection was lower than that in series connection. Ideally, a voltage of five batteries in series connection becomes five times of that of a battery, and a voltage of batteries in parallel connection is the same. The voltage ratios of series and parallel connections on PMFCs using cathode with or without iron wire were 6.0 and 3.6, respectively. The results indicate that the voltage generation of PMFCs increased effectively by using iron wire.

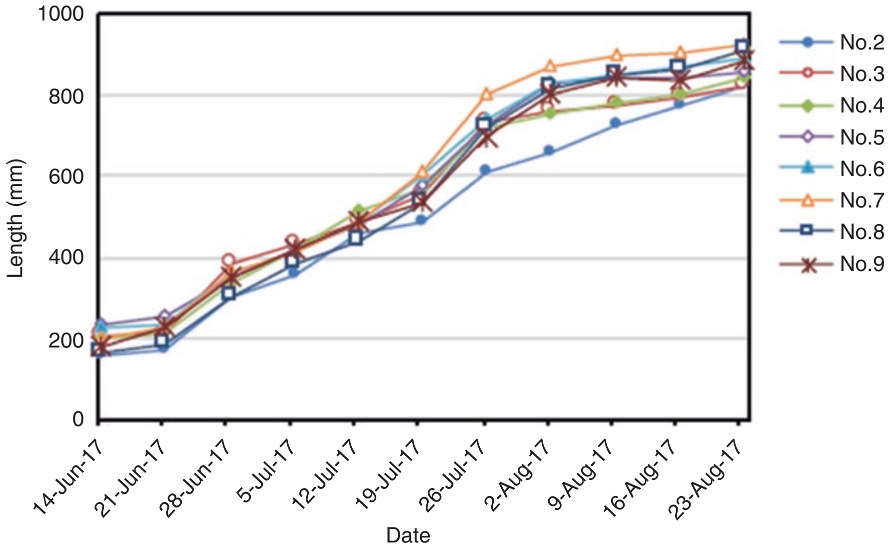

Fig. 4.8 Length of paddy plant with time in different buckets

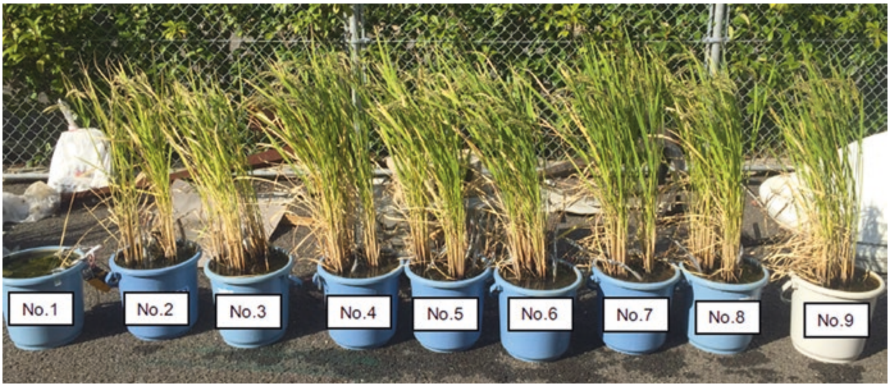

Fig. 4.9 Growth of paddy plants in different buckets

Figure 4.13 shows the growth of paddy plant using PET bottle of 500 mL in the case of anode with iron wire. Figure 4.14 illustrates the length of paddy plant with time and influence of anode with or without iron wire. The values were measured as an average of five PET bottles of 500 mL for each case. Both paddy plants grew gradually to approximately 600 mm by the end of July 2017. After that, the growth of the plants slowed down. The rice plants using bucket grew more than 800 mm in length as shown in Fig. 4.8. It is therefore considered that the lower growth of the stem is due to the small size of the PET bottle, which limited root growth. Finally, the length of the paddy plant in the PMFCs with iron wire was longer than without iron wire. Despite the small-sized condition, it was determined that PMFCs using PET bottle can generate relatively large voltage.

Electrode output is measured in volts (V) against time. The current I in amperes (A) is calculated using Ohm's law, $I = V/R$, where V is the measured voltage in volts (V) and R is the known value of the external load resistor in ohms. From this it is possible to calculate the electric power output P in watts (W) of PMFCs by taking the product of the voltage and current, i.e., $P = I \times V$. For obtaining a maximum power of PMFCs, the values of voltage are measured using different resistances.

Figure 4.15 shows the relationship between voltage and current in the PMFCs of five PET bottles in a series connection on July 20, 2017. It was found that the relationship was almost linear. The intercept and inclination of the line represent electromotive force and internal resistance for the MFCs, respectively. It represents that the PMFCs with a good performance indicate high electromotive force. The test results obtained from Fig. 4.15 are given in Table 4.3. The electromotive force of five PMFCs in series connection with iron wire was 3157 mV. The internal resistance of PMFCs was relatively high, because PMFCs were connected in series. Maximum electric power is calculated from the linear relationship between voltage and current. The maximum power per anode area is 40.3 mW/m^2 for the PMFC with iron wire.

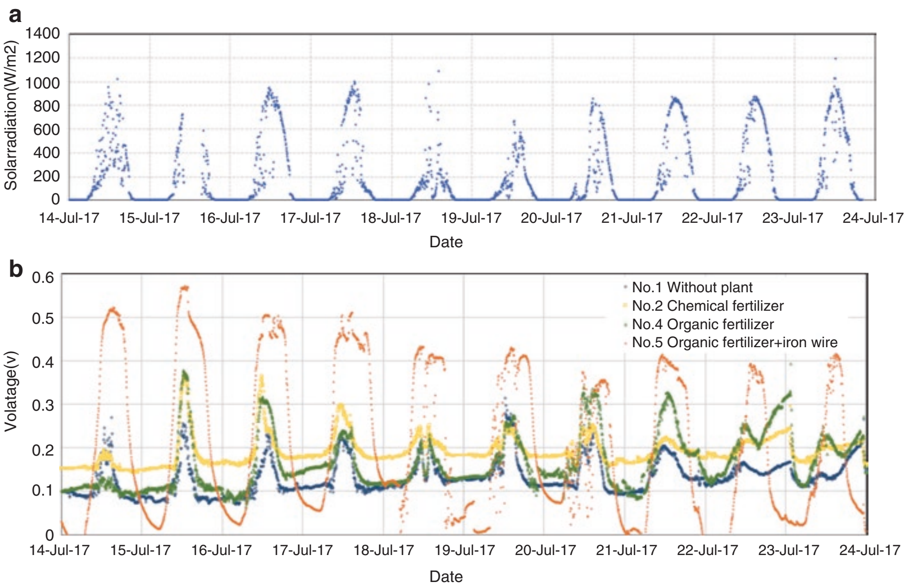

Fig. 4.10 Variation of voltage and duration and influence of solar radiation. (a) Solar radiation; (b) voltage radiation

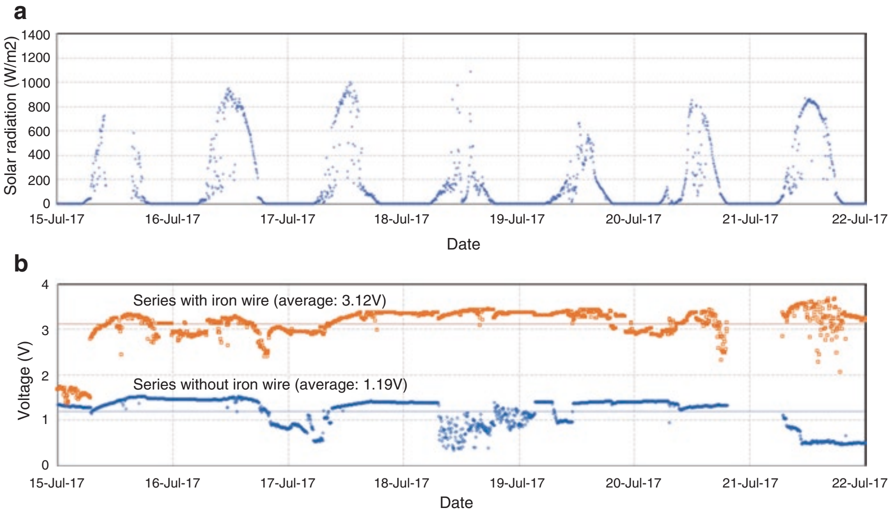

Fig. 4.11 Variation of voltage with duration on PMFCs in series connection using anode with or without iron wire and influence of solar radiation. (a) Solar radiation; (b) voltage radiation

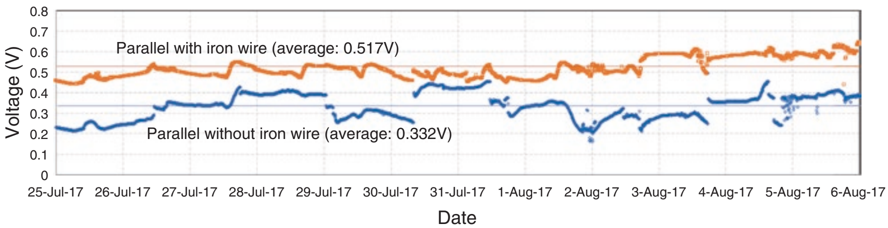

Fig. 4.12 Variation of voltage with duration on PMFCs in parallel connection and influence of anode with or without iron wire

4.4 Conclusions

The following conclusions were obtained from this study.

In the experiments of the paddy plant MFCs with anode of activated bamboo charcoal and cathode of carbon fiber using bucket of 13 L:

1. The result suggests that the voltage of the case without plant was generated due to the presence of algae. The voltage generation of the case with chemical fertilizer increased fast and reached to 0.5 V. It is considered that chemical fertilizer works quickly but the effect does not continue for long.
2. The voltage of the case with organic fertilizer increased gradually, and maximum voltage reached was 0.83 V. It was the highest so far in PMFC research. The voltage of the case with organic fertilizer and using anode with iron wire increased gradually, and maximum voltage reached was 0.68 V. It was observed that the

Fig. 4.13 Growth of paddy plant using PET bottle of 0.5 L

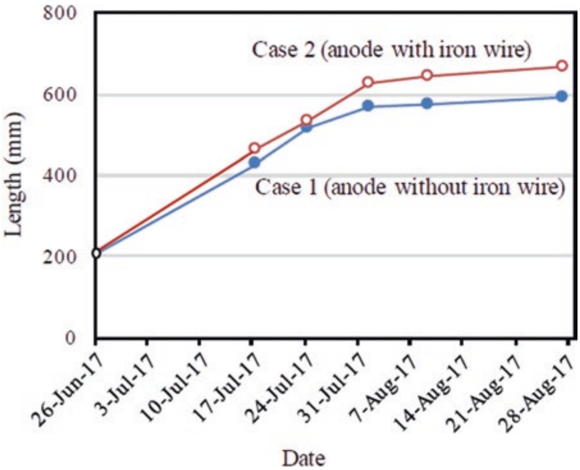

Fig. 4.14 Length of paddy plant with time and influence of anode with or without iron wire (average of five PET bottles of 500 mL for each case)

voltage of this case is more stable compared with that of the case without iron wire. However, the voltage on the PMFCs depends on sunlight.

3. It was found that the electrodes in PMFCs do not influence the growth of paddy plant. It was also observed that the growth of paddy plant is promoted when iron wire is used. This suggests that iron was supplied to the plant as nutrition.

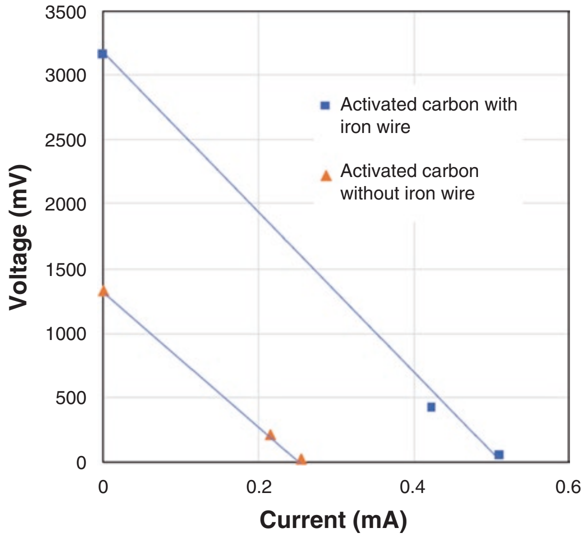

Fig. 4.15 Relationship between current and the voltage of paddy MFCs

Table 4.3 Test results on PMFCs in five PET bottles' series connection

	Electromotive force	Internal resistance (Ω)	Maximum power per area of anode (mW/m^2)
Case 1	1334	5252	8.5
Case 2	3157	6178	40.3

In the experiments of the paddy PMFCs with activated bamboo charcoal in both anode and cathode using PET bottle of 500 mL:

4. Five PMFCs were connected in series or parallel. It was observed that the voltage generation of plant MFCs increases by using anode with iron wire. It became more than 2.5 times in series connection.
5. It was remarkable that voltage of PMFCs generates continuously even at nighttime. Sometime the voltage changed, but no effect of solar radiation was observed.
6. The maximum power per anode area of 40.3 mW/m^2 was obtained on the PMFCs with iron wire in series connection.

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