

SCIENTIFIC ARTICLE

Efficiency of *Spathiphyllum* spp. as a plant-microbial fuel cell

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Abstract

The purpose of this study was to investigate the utility of an ornamental plant, *Spathiphyllum* spp., as a plant-microbial fuel cell (Plant MFC) to produce voltage and current. This study also evaluated the effect of the Plant MFC on water use efficiency and plant growth. The experiment used four experimental groups: used MFC without plant (Soil MFC), used MFC with plant (Plant MFC), unused MFC without plant (Soil Pot), and unused MFC with plant (Plant Pot). Plant MFC generated higher voltage and current levels than Soil MFC. The average voltage of Plant MFC and Soil MFC was 0.475 V and 0.375 V, respectively, and the average current was 0.110 mA and 0.030 mA, respectively. Plant MFC using *Spathiphyllum* spp. produced a constant voltage output, with a deviation of 0.027 V during the four-month indoor experiment. The difference between the maximum and minimum voltage during the day was as small as 0.015 V, which supports the utility of Plant MFC as a stable power source. Volumetric soil moisture content, chlorophyll fluorescence (Fv/Fm), photosynthesis rate, leaf area, fresh weight, and dry weight of Plant MFC and Plant Pot were measured. There was no significant difference in any values, and volumetric soil moisture and plant growth were not affected by the utilization of Plant MFC. Thus, a Plant-MFC using *Spathiphyllum* spp. can play the same ornamental role as conventional plants and at the same time be used as a sustainable bioelectricity source.

Keywords: bioelectricity, energy harvesting, photosynthetic MFC, renewable energy, sustainable energy.

Resumo

Eficiência de *Spathiphyllum* spp. como célula de combustível microbiana de planta

O objetivo deste estudo foi investigar a utilidade de uma planta ornamental, *Spathiphyllum* spp., como célula de combustível microbiana de planta (CCM de Planta) para produzir tensão e corrente. Este estudo avaliou também o efeito da CCM de Planta na eficiência do uso da água e no crescimento da planta. A experiência utilizou quatro grupos experimentais: CCM usada sem planta (CCM de Solo), CCM usada com planta (CCM de Planta), CCM não usada sem planta (Vaso com Solo) e CCM não usada com planta (Vaso com Planta). A CCM de Planta gerou níveis de tensão e corrente mais elevados do que a CCM de Solo. A tensão média da CCM de Planta e da CCM de Solo foi de 0,475 V e 0,375 V, respectivamente, e a corrente média foi de 0,110 mA e 0,030 mA, respectivamente. A CCM de Planta usando *Spathiphyllum* spp. produziu uma saída de tensão constante, com um desvio de 0,027 V durante a experiência de quatro meses em ambiente protegido. A diferença entre a tensão máxima e mínima durante o dia era tão pequena quanto 0,015 V, o que apoia a utilidade da CCM de Planta como uma fonte de energia estável. Foram medidos o teor de humidade volumétrico do solo, fluorescência da clorofila (Fv/Fm), taxa de fotossíntese, área foliar, peso fresco e peso seco da CCM de Planta e do Vaso com Planta. Não houve diferença significativa em nenhum dos valores, e a humidade volumétrica do solo e o crescimento da planta não foram afetados pela utilização da CCM de Planta. Assim, uma CCM de Planta usando *Spathiphyllum* spp. pode desempenhar o mesmo papel ornamental das plantas convencionais e ao mesmo tempo ser utilizada como uma fonte de bioeletricidade sustentável.

Palavras-chave: bioeletricidade, captação de energia, CCM fotossintética, energia renovável, energia sustentável.

Introduction

The world's population is steadily increasing. Consequently, consumption of fossil fuels is also increasing, leading to worldwide concerns about fossil fuel shortages.

Alternative energy sources are needed due to environmental problems associated with the use of fossil fuels, including CO₂ emission, global warming, and pollution. Solar cells and wind power are alternative energy sources with unlimited supply (Erickson and Jennings, 2017; Zhang

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et al., 2017; Guo et al., 2018). In addition, research into various biotechnologies that will provide alternative energy sources and reduce greenhouse gas emissions is ongoing. One such technology involves the use of microbial fuel cells (MFCs) as a sustainable and environmentally friendly power source (Tommasi and Lombardelli, 2017; Hung et al., 2019; Elshobary et al., 2020). In an MFC, microbial catalysts oxidize organic matter to generate water and electricity through the flow of electrons and hydrogen ions between the anode and cathode (Abourached et al., 2016; Xu et al., 2016; Shuba and Kifle, 2018).

A Plant-MFC is powered by plant photosynthesis. The organic matter that is produced by photosynthesis moves from leaves to roots. Roots exude organic matter into the soil. Microorganisms living in the soil continuously decompose the exuded organic matter. Finally, electrical energy is generated through such processes (Nitorisavut and Regmi, 2017; Sathish-Kumar et al., 2017; Chicas et al., 2018; Kabutey et al., 2019).

Fu et al. (2009) investigated the impact of biomass and light intensity on Plant-MFC performance by using the microalgae *Spirulina platensis* to generate electricity day and night. They also examined the relationship of open circuit voltage and light intensity with optimal biomass area density. Fu et al. (2010) also assessed the possibility of using a Plant-MFC as an ordinary battery, which is ready-to-use and portable, by investigating the electrical response of the microalgae *Spirulina platensis*. Voltage was immediately generated as soon as *Spirulina platensis* attached to the anode (+). As is the case with batteries, Plant-MFCs produced a high voltage when connected in series. Plant-MFCs also generated a high current when connected in parallel. Helder et al. (2013) found that most electricity is produced at the top of the system, with less internal resistance and the largest number of roots. Im et al. (2014) studied the size of electrodes and reported that the amount of electric power produced decreases when the internal resistance is increased by a long distance between electrodes or small electrode size. Sophia and Sreeja (2017) found that addition of three species (*Brassica juncea*, *Trigonella foenumgraecum*, and *Canna Stuttgart*) to compost is related to the production of bio-energy. Those authors showed that both plant species and compost added to soil are closely related to the amount of electric power that is produced. In addition to plant species, a few other factors can also influence power generation by Plant-MFC, including the distance between plant roots and electrodes, the material used for the electrodes, and the precise composition of the Plant-MFC (Ahn et al., 2014). Deng et al. (2012) also reported on power production by a Plant-MFC, and looked at configurations, plant types, anode and cathode materials, bacterial communities, possible applications, and future directions for the technology. And

they suggested that green energy can be used in many areas. Lin et al. (2015) tested a self-powered and wireless environmental monitoring system that uses soil energy. Sudirjo et al. (2019) created a Plant-MFC application for the maintenance of rice paddy fields and the growth and production of rice crop. Brunelli et al. (2016) and Rosa et al. (2019) reported the possibility of wireless and battery-less monitoring of plant health status and environmental data using a Plant-MFC. This system is renewable and cost-effective; an atmospheric humidity sensor, microcontroller, and low-energy Bluetooth transmitter are connected to the Plant-MFC, and there is no need to change any batteries. The monitoring system can generate energy through a reaction between soil moisture and microorganisms. Eco-friendly energy sources such as solar power, wind power, and MFCs can generally be applied in specific areas, such as monitoring in different field environments, because they supply power to remote sensors without necessitating regular battery changes, although their energy conversion efficiencies are low (Lin et al., 2015; Alsharif et al., 2018; Xu et al., 2019). Therefore, continued research on such eco-friendly energy sources is required.

The decline in green space associated with urbanization is increasing the demand for ornamental plants, leading to increased rooftop greening, wall greening and indoor gardening. Previous studies have focused on the energy efficiency of Plant-MFCs. However, research on the effects of Plant-MFCs on plant growth is lacking.

This study investigated the possibility of using an ornamental plant, *Spathiphyllum* spp., as a Plant-MFC. The voltage and current production of the Plant-MFC and the effects of Plant-MFC on the water use efficiency and growth of the plant were evaluated.

Materials and Methods

Spathiphyllum patinii was used as plant material in this study. *Spathiphyllum* spp. is a houseplant of Araceae family. *Spathiphyllum* spp. has been used in various studies for purifying indoor air by removing gaseous pollutants, such as volatile organic compounds, and particulate pollutants, such as PM₁₀ and PM_{2.5}. It has also been studied for improving indoor temperature and humidity (Hörmann et al., 2018; Kwon and Park, 2018; Parseh et al., 2018).

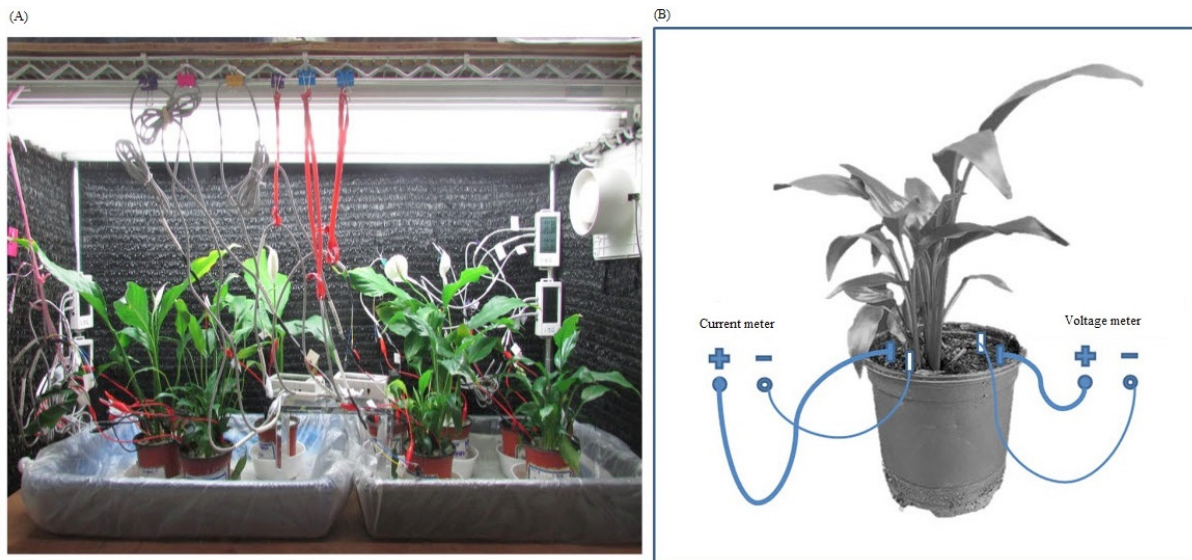
Individual *Spathiphyllum* spp. plants, all with the same plant height, number of leaves, and a fresh weight of 50 g, were selected for this study. They were then planted in perlite (Paraso, Kyungdong One, South Korea) on a plastic pot with a diameter of 10 cm to minimize the effects of soil organic matter. Chemical of perlite was tested by the Rural Development Administration method (Lee et al., 2006) (Table 1). We did not add fertilizer, and we only watered the plants during the experiment.

Table 1. Chemical properties of perlite used in this study

pH	EC	OM	T-N	Av-P ₂ O ₅	CEC	Ex-K	Ex-Ca	Ex-Mg
	(dS m ⁻¹)	(%)	(%)	(mg kg ⁻¹)		(Cmol ⁺ kg ⁻¹)		
5.80	0.01	0.98	0.01	15.3	0.78	0.04	0.02	-

A fluorescent lamp was used as a light source. The experiment was performed after photoadaptation with an intensity of about 40 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPFD and establishment of a light cycle of 12/12 h (day/night). We used a sub-irrigation system to maintain a constant soil moisture level. The soil moisture content was measured using an FDR sensor (ML2x, Delta-T Devices, UK). A single chamber was used for the Plant-MFC. A plate-shaped electrode with a width of 1 cm and a length of 2.5 cm was used. Copper (Cu) was used for the positive electrode (+), zinc (Zn) was used for the negative

electrode (-), and the electrode spacing was fixed at 1 cm. Silicon coupling rings were used for each pot to maintain constant depth and distance. To assess the maximum output, the Plant-MFC voltage was measured in an open circuit not connected to any resistance. The current was measured in a short-circuited condition to obtain the maximum current. Open circuit voltage and short circuit current were continuously measured during the experimental period using data loggers such as Onset HOBO model UX120-006M and Onset Computer Corporation-USA (Figure 1).

**Figure 1.** Experimental setup. (A) Photograph of the Plant-MFC, (B) Voltage and current measurements of the Plant-MFC.

The present experiment examined four different groups: 1) Soil-MFC, which was only soil without plants, 2) Plant-MFC, which had plants, 3) Soil Pot, which had neither plants nor an MFC, and 4) Plant Pot, which had plants that were not used as an MFC. We compared voltage and current generation between Soil-MFC and Plant-MFC to test whether the presence of the plant was associated with changes in voltage and current production. Additionally, to determine the effect of Plant-MFC installation on plant growth, we examined chlorophyll fluorescence (Fv/Fm), photosynthetic rate, leaf area, fresh weight, and dry weight of both the aboveground and underground portions

of the plant. We measured Fv/Fm and photosynthetic rate every two weeks. Fv/Fm was assessed with a chlorophyll fluorescence analyzer (PAM2000, Walz, Germany) after treatment with a darkness adaptive clip for 30 minutes. Photosynthetic rate was measured between 10:00 AM and 1:00 PM using a photosynthetic analyzer (Li-6400, Li-COR Inc., USA) under the following leaf chamber conditions: light intensity of 40 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPFD, air flow rate of 250 $\mu\text{mol}\cdot\text{s}^{-1}$, temperature of 25 °C, and carbon dioxide concentration of 400 $\mu\text{mol CO}_2\cdot\text{mol}^{-1}$. We measured leaf area and both fresh and dry weight of plant shoots and roots at the end of the experiment.

Dry weight was measured after the plant was dried for 70 hours in a hot air-circulating dryer at 70 °C (HB-502M, Hanbaek Science, South Korea). Leaf area size was measured using a leaf area meter (Li-3000A, Li-COR Inc., USA). The experiment was performed in an indoor laboratory over the course of four months, from May to September 2016.

An experiment was repeated three times within each group. We used the SAS 9.3 program (SAS Institute Inc., USA) for all statistical analyses. Statistical significance was considered at $p < 0.05$, which was taken to indicate

meaningful differences between treatment averages using Duncan's multiple range test (DMRT).

Results and Discussion

Comparison of Plant-MFC and Soil-MFC in Terms of Voltage and Current

Plant-MFC produced higher voltage and current than did Soil-MFC (Figure 2). An average Plant-MFC voltage and current were 1.27 times and 3.7 times higher than that of Soil-MFC, respectively.

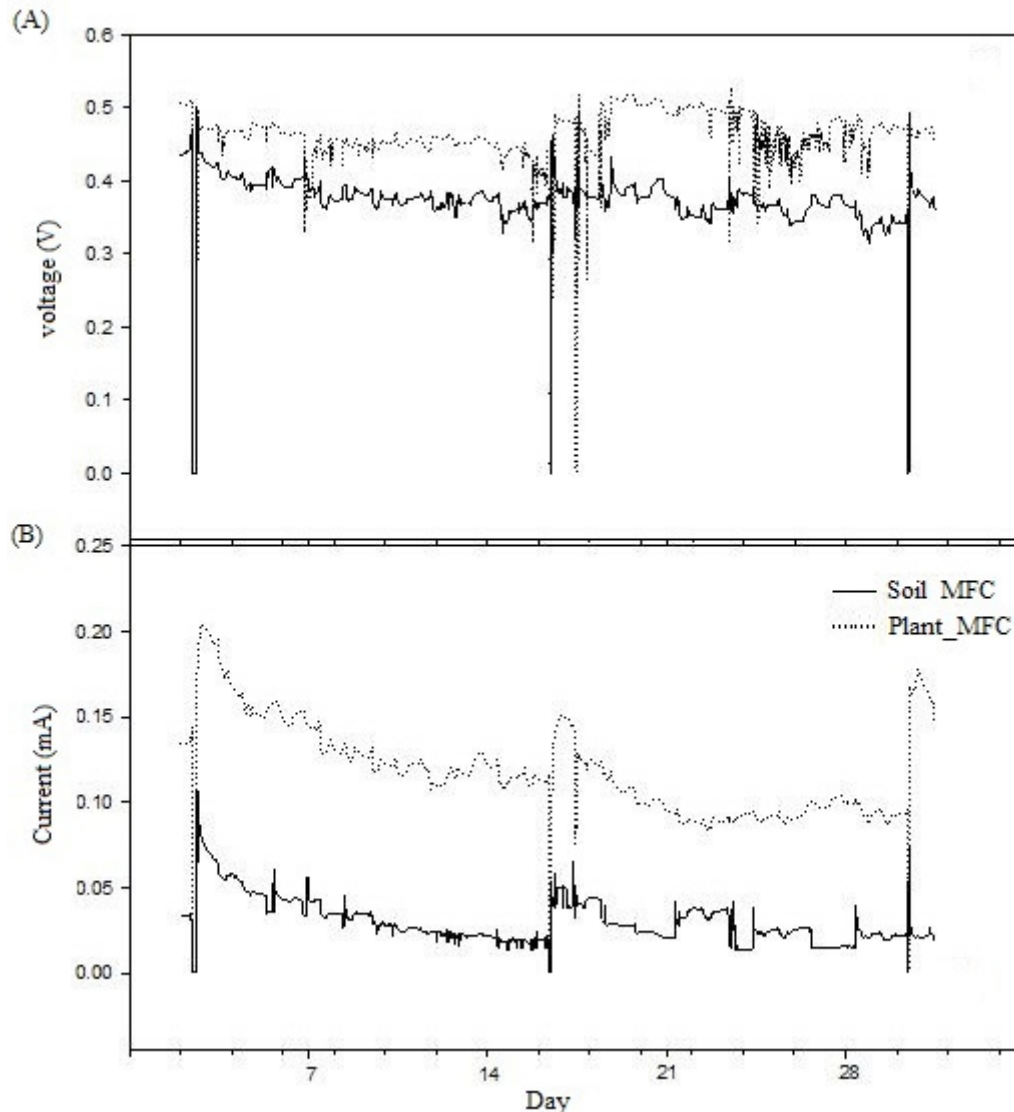


Figure 2. Comparison of voltage. (A) and current (B) generation between Soil-MFC and Plant-MFC ($n = 3$). The severe fluctuations in the center of the graph reflect the process of disconnecting and reconnecting the MFC for physiological measurement purposes.

Such findings are consistent with the results of Ahn et al. (2014) and Regmi et al. (2018), who showed that the voltage and current of Plant-MFC were higher than those of Soil-MFC (unplant-MFC) in their experiment using *Oryza sativa* and vetiver plants as a Plant-MFC. Certain root by-products that emerged in the process of photosynthesis might have affected MFC voltage and current generation. In a Plant-MFC experiment using *Oryza sativa* in the field, there was almost no difference in the voltage of the MFC according to the presence of plants for one month after transplantation of *Oryza sativa*. However, there was a difference in voltage since August, during the period in which *Oryza sativa* showed rapid growth. This difference depended on the presence of plants (Ahn et al., 2014). The degree of voltage fluctuation was substantial during the experimental period of four months, beginning in August.

Spathiphyllum spp. grew for four months in an indoor setting. However, it did not grow as much as *Oryza sativa*. The voltages of Plant-MFC and Soil-MFC were

0.465 ± 0.027 V and 0.373 ± 0.018 V, respectively, during the experimental period, indicating relatively constant voltage generation. The only exception was during the two days in which the Plant-MFC was separated from the data logger in order to measure growth and soil moisture. Plant-MFC was reconnected to stabilize the voltage.

The average voltages of Plant-MFC and Soil-MFC over the course of ten days (July 4-8 and July 16-20, when voltage and current were relatively constant) were 0.475 ± 0.030 V and 0.375 ± 0.013 V, respectively. According to the study on enhanced bio-electricity generation in a plant microbial fuel cell with electrochemically modified carbon fiber brush anode, it was reported that *Dracaena braunii* and *Epipremnum aureum* generated the respective peak voltage of 0.432V and 0.620V within a similar voltage range (Sarma and Mohanty, 2018).

The average currents for the same period were 0.110 ± 0.018 mA and 0.030 ± 0.006 mA, respectively (Table 2).

Slightly different voltage and current values were seen at different time points in a single day (Figure 3).

Table 2. Average voltage and current according to MFC type (n =10).

Plot	Voltage (V)	Current (mA)
Soil-MFC	0.375 ± 0.013 b ^z	0.030 ± 0.006 b
Plant-MFC	0.475 ± 0.030 a	0.110 ± 0.018 a
Significance	***	***

^z Means separation with columns according to Duncan's multiple range test, $p = 0.05$.

ns = non-significant;

***, ** = significant at $p = 0.05$, 0.01 , and 0.001 , respectively.

This may be related to the fact that the light was on between 8:00 AM and 8:00 PM during the experiment and the central air conditioner was operated between 12:00 PM and 05:00 PM. The 10-day average voltage gradually increased starting from 8:00 AM, when the light was turned on. However, it decreased after 12:00 PM, when the air conditioner was switched on. The voltage increased again after 5:00 PM, when the air conditioner was turned off. It then gradually decreased after 8:00 PM, when the light was turned off (Figure 3A). Current fluctuation displayed a similar pattern as voltage (Figure 3B). Bombelli et al. (2013) and Regmi et al. (2018) reported that the fluctuation of voltage by time within a day is caused by the effect of root exudates produced by photosynthesis. The present study indicates that the voltage fluctuation of Plant-MFC by time may be more strongly related to temperature change due to the operation of a fluorescent lamp and an air conditioning unit than the effect of root exudates, as suggested by Ahn et

al. (2014). Plant-MFC and Soil-MFC showed similar trends in voltage fluctuation over time. In the rooftop experiment conducted by Helder et al. (2013), Plant-MFC was influenced by temperature. Voltage production decreased at low temperature. Plant-MFC using *Oryza sativa* showed considerable variation in day and night voltage due to diurnal variation in temperature (Ahn et al., 2014). The voltage gap between day and night was about 0.05 V in experiments using *Phalaris arundinacea* and *Glyceria maxima* (Blossfeld et al., 2011). The current experiment, which maintained a constant indoor temperature of 25 °C, revealed that the difference between the highest and the lowest daily voltages was only 0.015 V, indicating that the variation in voltage of an indoor Plant-MFC is smaller than that of an outdoor Plant-MFC. This finding implies that light intensity and temperature can affect the activities of microorganisms and photosynthetic activities of plants, thus influencing the volume of electricity produced.

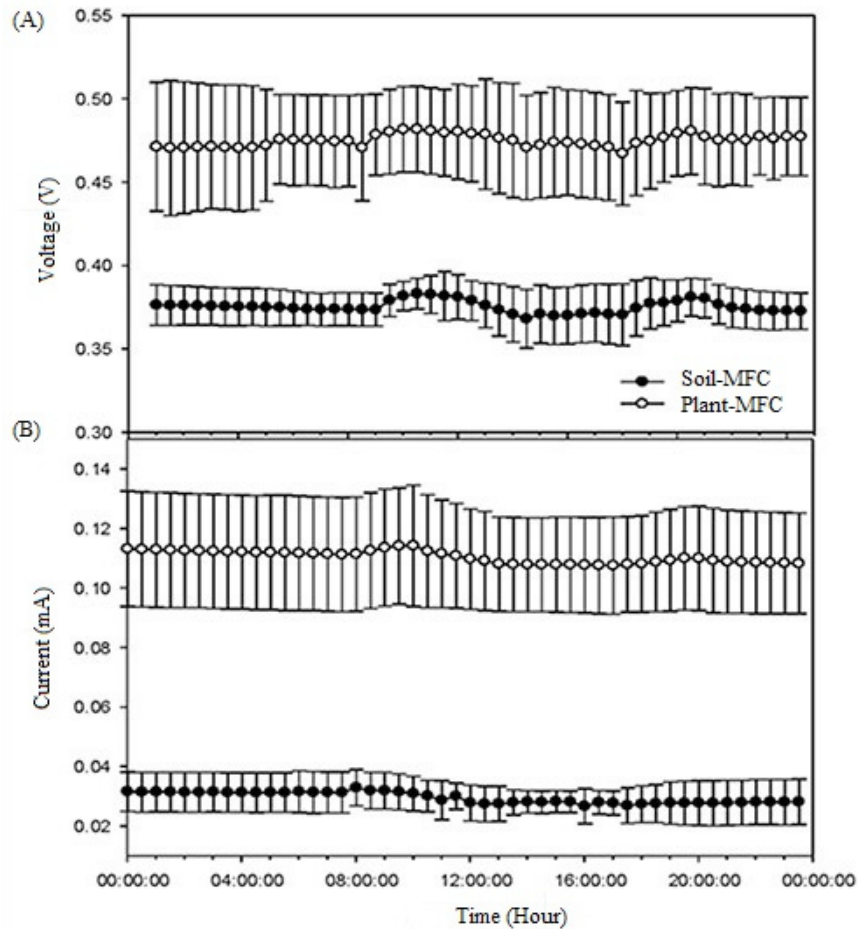


Figure 3. Daily fluctuation in voltage. (A) and current (B) between Soil-MFC and Plant-MFC. Values are means \pm SE (n = 10).

Effect of Plant-MFC on the water use efficiency and growth of plants

Previous research mostly used wastewater for MFC experiments, and focused on Plant-MFCs using *Oryza sativa* or other wetland plants. This may be related to the fact that water is important for microorganisms to ionize organic matter and transfer electrons and hydrogen ions to the electrodes. The levels of soil moisture of the Soil pot and the Soil-MFC were almost the same. Soil moisture of the Soil pot was between 58.17 and 71.60%, and that of the Soil-MFC was between 57.70 and 65.70% when we watered them the same amount. Likewise, soil moisture of

Plant pot was between 34.23 and 46.40%, and that of Plant-MFC was between 34.67% and 42.53%. In other words, the levels of soil moisture between Plant pot and Plant-MFC were also almost the same. Therefore, no significant difference in the level of soil moisture was found according to the use of MFC. However, soil moisture of Plant pot and Plant MFC was in the range of between 34.67 and 46.40%, and the soil moisture of Soil pot and Soil MFC was between 57.70 and 71.60%, indicating a significant difference in the level of soil moisture according to the presence of plants. This finding may be due to evapotranspiration of the plant (Table 3).

Table 3. Volumetric soil moisture content (%; n = 3).

Plot	1 day	15 days	30 days	45 days
Soil Pot	58.17 a ^z	71.60 a	68.67 a	68.37 a
Plant Pot	37.80 b	46.40 c	39.97 c	34.23 b
Soil-MFC	57.70 a	65.70 b	64.17 b	63.80 a
Plant-MFC	34.67 b	40.03 d	41.53 c	35.80 b
Significance	***	***	***	***

^z Means separation with columns according to Duncan's multiple range test, $p = 0.05$.

ns = non-significant;

***, ** Significant at $p = 0.05, 0.01, \text{ and } 0.001$, respectively.

There was no significant difference in soil moisture content between Plant-MFC and Plant Pot on June 29 or August 11. However, a significant difference appeared on July 13 and July 28. This may be due to the difference in plant growth caused by flowering of each plant. Paredes and Quiles (2017) reported that *Spathiphyllum lanceifolium* showed an Fv/Fm value of 0.7-0.8 at a shade light intensity of 800 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPFD. Kwon and Park(2018) used *Spathiphyllum spp.* in their study for particulate matter removal of an indoor plant according to light intensity to measure photosynthetic rates, and reported

a photosynthetic rate of 4.4 at 60 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPFD. In this study, it was found that those plants with the above range of Fv/Fm values and photosynthetic rates at 40 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPFD showed normal growth. No significant difference was found in Fv/Fm or photosynthetic rate (which were taken as measures of plant stress caused by being used as a Plant-MFC) between Plant-MFC and Plant Pot (Table 4).

Leaf area, fresh weight, and dry weight values after the end of the experiment did not significantly differ between Plant-MFC and Plant Pot (Table 5).

Table 4. Change of Fv/Fm and photosynthetic rate in Plant Pot and Plant-MFC (n = 3).

Plot	Fv/Fm		Photosynthetic rate ($\mu\text{molCO}_2\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	
	1day	30days	1day	30days
Plant Pot	0.683 a ^z	0.762 ab	2.58 a	3.21 a
Plant-MFC	0.706 a	0.733 b	1.81 a	3.36 a
Significance	ns	ns	ns	ns

^z Means separation with columns according to Duncan's multiple range test, $p = 0.05$.

ns = non-significant;

***, ** Significant at $p = 0.05, 0.01, \text{ and } 0.001$, respectively.

Table 5. Comparison of leaf area, fresh weight, and dry weight between Plant Pot and Plant-MFC (n = 3).

Plot	Leaf area (cm^2/shoot)	Fresh weight (g/shoot)	Dry weight (g/shoot)
Plant Pot	436.1 a ^z	40.53 a	7.60 a
Plant-MFC	424.4 a	48.17 a	10.17 a
Significance	ns	ns	ns

^z Means separation with columns according to Duncan's multiple range test, $p = 0.05$.

ns = non-significant;

***, ** Significant at $p = 0.05, 0.01, \text{ and } 0.001$, respectively.

Therefore, no significant change in soil moisture content or plant growth was observed, even if the plant was used as a Plant-MFC. To increase Plant-MFC efficiency, further studies are needed to examine the relationship between the aboveground and underground portions, selection of appropriate plant species, soil type, and light intensity.

Conclusions

Compared to the outdoor environment, the characteristics of the indoor environment, such as light, temperature, and humidity, remain relatively constant, so the growth of *Spathiphyllum* spp. for indoor landscaping progresses slowly, and when it is used as a Plant-MFC, there are slight fluctuations in daily and monthly voltage and current. In addition, when comparing plants used as Plant-MFCs and general potted plants, we found no significant differences in water use efficiency and growth. Thus, a Plant-MFC using *Spathiphyllum* spp. can play the same ornamental role as conventional plants and at the same time be used as a sustainable bioelectricity source.

Author Contribution

KJK: data analysis and manuscript preparation; **BJP:** design of this experiment and manuscript review.

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