Power generation in a plant-microbial fuel cell assembly with graphite and stainless steel electrodes growing *Vigna Radiata*

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Abstract. Plant-microbial fuel cells (PMFCs) are an interesting renewable energy technology that has the potential to generate clean electricity without competing with agriculture for land space. In this study, the electricity generation potential of mung beans (*Vigna radiata*) in a PMFC set-up with different electrode materials was explored. Three types of set-ups were prepared with five replicates each: PMFCs with stainless steel electrodes, PMFCs with graphite electrodes, and control pots without electrodes. This experimental set-up allowed for the evaluation of the better electrode material, and whether the PMFC environment harms or benefits the plants. The voltage gathered suggests that the potential difference generated in the PMFCs with differing types of electrodes were statistically the same ($\alpha = 0.05$). The same can be said for power and power density, although the system with stainless steel electrodes generated more power towards the end of the experiment. It was also evident that PMFCs with stainless steel electrodes experienced prolonged time lags due to the reduced biocompatibility of stainless steel. Polarization studies showed that a single PMFC is capable of generating power densities of 0.35 mW/m$^2$ and 0.12 mW/m$^2$ for stainless steel and graphite systems, respectively. The increased power density of PMFCs with stainless steel indicate the lowering of internal resistance brought by the stainless steel. Plants in the PMFCs set-ups were seen to grow faster, taller, and have higher pod output than those in the control set-up. These results indicate that the PMFC technology can be implemented in agricultural land for the continuous generation of passive electricity while growing food crops, eliminating the competition between energy generation and agriculture.

1. Introduction

The relentless energy crisis and environmental issues have prompted studies on diverse technologies as a source of alternative renewable energy [1]. An extended discipline of Microbial Fuel Cells (MFCs) that uses plants as the source of microbial organisms and converts chemical energy to electrical energy is the *Plant-Microbial Fuel Cell* (PMFC). This technology has gained attention and has been continuously studied for the last decade in which claims to produce non-destructible and sustainable green electricity via living plants [2]. Sustainable renewable energy is the next generation
of energy transition and P-MFCs has great competency in reducing the dependence on the destructive use of fossil fuels. This bio-electrochemical system generates electricity concurrently without the need of disrupting the living plants thus defeating competition between arable lands for food production power generation plants that beguiles deforestation. It also eliminates the need of additional energy input from external sources as other biomass resources and renewable energy requires. With this alternative, the transport of biomass is no longer needed in which avoids the depletion of nutrients in the ecosystem [3]. PMFC technologies are based on the principle of rhizodeposition, which is the excretion of organic compounds from the roots that is the source of electrons and electricity generation by electrochemically active bacteria in a microbial fuel cell [4]. The PMFC is a version of a MFC where the system makes use of living plants as the source of microbial matter. Its roots are located within the anodic region assumed to be an anaerobic environment within the structured fuel cell allowing the system to act as a bioreactor that enables the conversion of chemical energy to green electrical energy. The requisite elements for Plant-Microbial Fuel Cell assembly are the electrodes, a membrane separator, an external circuit connecting the two electrodes and a resistor.

For Plant-Microbial Fuel Cells, present studies have demonstrated current production associated with plant rhizodeposits using plants from flower bearing species such as Ipomoea aquatica, Typha latifolia and Canna indica and plants from grass species such as Oryza sativa, Glyceria maxima, Spartina anglica, Arundinella anomala, Lemna minuta and Arundo donax [5]. The grass species in particular have shown to be useful for electrical power generation [6]. Previous researches focused on power production by the optimization of the reactor design and configurations, plant selection or nutrient media [6] and the development of bio-electrocatalytic interfaces [7].

Prior the launch of PMFCs to an industrial scale, numerous aspects of its study requires further undertaking. Several limiting factors present great challenge toward the engineered and commercialized application of a MFC Technology [8]. From poor electro-active bacteria kinetics, insufficient understanding of the electron transfer mechanism within the cell, the influence of complex environmental conditions and its effect on the microbial colonization and the knowledge of microbial community structures remains a large chunk of uncertainty in the study of PMFC systems [7]. For most PMFCs executed in laboratory conditions, energy sustainability and durability have yet to be achieved as the electrical power generated is considerably very low that lacks sufficiency to drive electronic devices available today [9]. The search for effective architecture and materials that will enable high generation of electrical energy in a PMFC system is constant as there are very few existing studies on the use varying electrode materials and their resulting performance in the power generation. In addition, the performance exhibited by the PMFCs are significantly affected not solely by the internal system but also by its external environment as well. This has not been considered thoroughly in the previous studies. Up to this date, a variety of selection of plant species and methods of creating PMFC assemblies and configuration are continuously studied in order to improve and industrialize this technology for green electricity generation.

The objective of this study is to design and construct a Plant-Microbial Fuel Cell assembly using graphite rods and stainless steel mesh as the electrode materials with Mung beans (Vigna radiata Wilzeck). Through the comparisons of the electrical potentials, the capability of electricity generation using the fuel cell chamber design utilizing different electrode materials was to be identified. This will discern which electrode material is more effective for the design system. Also, this study aims to evaluate the effect on PMFC elements in the growth and development of the model plants to evaluate whether a PMFC can be used to simultaneously generate electricity and produce biomass.

2. Materials and methods

2.1. PMFC assembly and set-up
Each single-chambered PMFC was composed of the electrodes, a resistor load, a semi-permeable membrane, the soil and the plant specimen. The stainless steel mesh and graphite rods were used as the electrode materials for the system. The resistor used had the load of 2000-Ω. A layer of
cheesecloth was used as the membrane separator and copper wires were used as the external conductor that connected the electrodes with the resistor load.

The overall exterior that contained the assembly was made from polycarbonate plastic. Each fuel cell had the dimensions of 6-in x 6-in x 12-in (L x W x H). Two holes big enough for copper wires to pass through were made on one side of the customized pots with respect to the position of the electrodes. Additional holes were made on the bottom of the pot for drainage. From bottom to top of the container, the cell consists of 1-inch layer of garden soil, the cathode electrode, 5-inch layer of garden soil, the cheesecloth membrane cut in accordance with the dimensions of the pot, 4-inch garden soil, the anode electrode and finally the plant. The container was completely filled with soil which was patted thoroughly in every layer (Figure 1).

Figure 1. PMFC assembly with stainless steel (left) and graphite (right)

Green Mung Beans (Vigna radiata Wilczek) seeds that were sourced from the local market in Intramuros, Manila was the selected plant specimen for this experiment. The specimens were grown from seedlings in a soil medium composed of coconut coir and garden soil potting mixture sourced from Los Baños, Laguna. No additional nutrient media was used for planting. For outdoors planting, the seeds were required to be buried about 1-inch deep covered in soil as these particular seedlings require darkness to germinate. The seeds were planted on seed trays and were exposed to 8 to 10 hours of sunlight daily. The plant grow-out lasted for thirty days. During this period, plant care involved light watering to keep the seed bed moist to enhance the germination process. On the last day of plant grow-out period, the plants were transferred in the P-MFC set-up and were left for ten days to allow the microbial organisms to settle and consolidate with the soil. Continuous plant care was conducted. Upon plant transfer, the roots of the plant were fully covered with soil to avoid the plant from drying-out.

2.2. Collection and treatment of data
Voltage was recorded against an external resistor six times a day for 30 days straight using a digital multimeter (RS Pro RS14). Soil pH meter, hygrometer, and thermometer were used to monitor growing conditions. Current ($I = V/R$), power ($P = IV$), and power density ($P_D = P/A$) were computed from voltage readings taken against a 2000-ohm resistance.

2.3. Polarization
The polarization studies were conducted to indicate the power output of a certain fuel cell system under various resistor loads that are exhibited by polarization curves. This type of study is the most common method in testing a fuel cell’s performance and determination of the optimum condition that it can achieve and is represented by a polarization curve that contains linear data that relates the power density and the current density. This allows comparisons with existing publications of fuel cell technology. The polarization studies conducted used sixteen different resistor loads varying from 5 Ω to 50,000 Ω. The voltage reading using each of these resistors were individually were recorded and compared to one another by producing a polarization curve showing the behavior of power generated
of a fuel cell chamber with respect to the step-wise incline of resistor loads. Current density was plotted against power density to complete the polarization curve.

3. Results and discussion

3.1. Voltage, power, and power density
The measured voltage and calculated power and power density are shown in Figures 2 and 3 below.

![Figure 2. Voltage readings versus time](image1.png)
![Figure 3. Power and power density versus time](image2.png)

There is no significant difference between the power and power density of both PMFC set-ups containing different electrodes ($\alpha = 0.05$). However, it is important to note that the PMFCs with stainless steel electrodes attained higher absolute power and power densities towards the end of the experimental period. The time lag for stainless steel systems was larger than that with graphite, presumably because of the inhospitable nature that stainless steel provides for bacteria (biocompatibility). The slow incline at the initial phase is due to the settlement of rhizodeposits where it is in the process of binding uniformly with the new soil. Right after, anaerobic reactions occur allowing the production of electron donors enabling the transfer of electrons that leads to the generation of electrical energy. The steady incline of power density generated means that the system is at a state of equilibrium and the environmental conditions are stable enough for the electricity generation.

3.2. Polarization
A polarization curve is made of the values of power densities under varying resistor loads. Through this fuel cell chamber’s designed system will identify which resistor load will produce the optimum performance. The polarization studies conducted was done on the 30th day of data collection. At this point, the plant has reached maturity and is already bearing fruits.

By increasing the load stepwise, the polarization studies produced parabolic trends pinpointing the absolute maximum power generated found at the parabola’s peak. This is the preferable resistance value to enable optimum conditions of the designed microbial fuel cells [10]. For the stainless steel systems, the maximum power density attained was 0.35 mW/m² under the resistance of 8200 $\Omega$. This is 40% more than the power density using the default resistor of 2000 $\Omega$ which was 0.25 mW/m². This means that the applied external resistance was lower than that of the internal resistance, resulting to a lower yield. On the other hand, PMFCs with graphite electrodes obtained the maximum power density of 0.12 mW/m² under a resistance of 10000 $\Omega$ which is 50% larger than the power density under a resistance of 2000 $\Omega$ (0.08 mW/m²). Overall, PMFCs with stainless steel electrodes obtained maximum power densities that are about 200% larger than graphite electrodes. Even though graphite
is more biocompatible, stainless steel electrodes have lower resistances and thus contribute to the lower resistance of the PMFCs, thereby translating to higher power and power densities.

Figure 4. Polarization curves for PMFCs with stainless steel (●) and graphite (■) electrodes

3.3. Growth and development of plants
A separate set of trials (control) were made duplicating the entire PMFC set-up, only this time without electrodes. All replicates were exposed to the same conditions as those with electrodes. It is of interest whether the electricity generation of the PMFC has a positive or negative effect on the plants’ growth. It was evident during the experimentation process that plants growing in the fuel cell assemblies with the electrode materials in their system showed more abundance and better growth as compared to the ordinary trial as the plants growing with the electrode elements appeared to be healthier and stronger. In the duration of the experiments, the trials with the electrode materials was observed to have greener leaves with taller, thicker and sturdier stems as compared with the control with brownish pale-green leaves and thinner stems. The maximum height of control was only about half the height of the plants with the electrode material. Upon monitoring, the highest average height measured for the plants in the PMFC trials reached 42 cm in height, while the height of those in control seemed stunted reaching to its highest average height of 22 cm. Fruit pods in the control were smaller compared to the pots with electrode material; the average length of the mung bean pods were about 8-cm in length for PMFC trials wherein the plants in a non-fuel cell environment was only about 4 to 5 cm long. In terms of maturity, the control plants matured later by two weeks than all the experimental trials conducted. The results of this study are in agreement with the results from a previous research [11] wherein the plants grown under polarized conditions (in PMFCs) have higher levels of intracellular nutrients compared to the control (no electrodes). One explanation could be the enhanced metabolic process of the plants stimulated by the electricity flow through the system, which caused the plant to accumulate more of its photosynthetic products [12]. This also leads to enhanced rhizodeposition, which explains the maintenance of power generation even with fluctuating sunlight levels.

3.4. Scale-up potential
The choice of the plant specimen was upon consideration of accessibility and availability in the area. Mung bean is included in the 21 major crops produced in the Philippines and according to the Philippine Statistics Authority’s quarterly bulletin of the major vegetables and roots crops in the quarter of April to June 2018, the production of Mung bean had increased by 3.3% compared to the
same quarter of the previous year, 2017. This translates to 24,800 metric tons of mung bean per annum. Approximately, for a yield of 1000 kg/ha, mung bean production would cover about 24,800 hectares of land which has the potential to generate about 760 MWh/y of passive electricity solely from the farming of mung beans. This can be made possible through stacking, as illustrated in a previous study [13].

4. Conclusions
The possibility of concurrent food and power generation is confirmed with the designed single-chambered PMFC for both systems utilizing graphite and stainless steel electrodes with \textit{V. radiata}. However, the low levels of generated power density remains a challenge as it remains to be insufficient for applicable use. This may be due to the cell configuration and the used resistance within the system.

Polarization studies suggested that optimum levels of power density could be achieved by using resistor loads of 8200 $\Omega$ and 10000 $\Omega$ in stainless steel and graphite systems respectively. Executing the designed P-MFC under this resistor loads may produce power density up to 50% larger than the current power generated.

Through comparison between plants growing in the PMFC set up and normal plant set-up (control) without PMFC elements, the plants appear to be healthier and has more rigorous growth in contrast to the control with stunted growth and smaller pods. This is on the note that all plants are exposed to same environmental conditions.

With the land covered by the Mung bean production in the country, this study proves that it has high potential as a sustainable alternative green energy resource if only it can surpass the challenges of low power density production. Future studies must be focused on the amplification of power generated by the system to fuel the hopes on one day being able to generate clean electricity alongside agriculture.

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