

Stacking of aquatic plant-microbial fuel cells growing water spinach (*Ipomoea aquatica*) and water lettuce (*Pistia stratiotes*)

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Abstract. Plant-microbial fuel cells (PMFCs) are a sub-branch of a class of promising bioelectrochemical systems which are capable of simultaneously supplying biomass and renewable energy from photosynthesis and root exudation. In this study, the possibility of power amplification through stacking was tested. *Ipomoea aquatica* and *Pistia stratiotes* were used as model plants in this study because their biomass is valued as food for humans and livestock, respectively. In a brief 7-day experiment, maximum power densities of 6.35 mW/m^2 for *I. aquatica* and 3.54 mW/m^2 for *P. stratiotes* were obtained from aquatic PMFC assemblies. No significant difference in voltage was observed between the two plants, although the current and power output of *I. aquatica* were significantly higher than that of *P. stratiotes*. Connecting three cells in series resulted to three times higher voltage but the same current, and connecting three cells in parallel resulted to three times higher current but the same voltage for both plants. Power was also amplified by stacking. There is no significant difference in the power produced by the cells connected in series or parallel. Power density remained constant due to the increase in surface area of electrodes used upon stacking. These results are consistent with the rules of electric circuits and would become a valuable tool in the computational design of larger systems with numerous cells that can supply a large part of our electricity demands. For future studies, assemblies with more cells are recommended to establish the upper limit of the validity of the series/parallel models and can be tested with other plants.

1. Introduction

Continuously increasing energy demands due to an increasing population and the conscious need to cut back on non-renewable energy sources have driven the need to explore new ways of extracting electricity from renewable sources. In the past, biomass energy had been considered because of its abundance. However, extracting energy from biomass may hamper and compete with food production [1]. Furthermore, energy-intensive processes are oftentimes required to extract energy from biomass in the conventional sense, leading to a large energy penalty and minimal net energy output.

A plant-microbial fuel cell (PMFC) has the capability to simultaneously produce biomass and electricity. During photosynthesis, plants discharge a part of what they produce in their roots where bacteria break the nutrients down in a redox reaction, triggering the transfer of electrons. If placed strategically, electrodes can be used to capture these electrons and produce an electric current [2]. A



PMFC produces electricity without hampering the growth of the plant, thus, it can be implemented in agricultural systems to simultaneously produce food and electricity. Several studies have investigated the power production of some plants such as *Oryza sativa* [3], *Glyceria maxima* [2], *Brassica juncea* [4], *Canna indica* [5], and many more. Majority of previous studies have focused on wetland plants for their application in simultaneous water treatment and electricity production, while few studies had considered using plants valued as food (for humans or livestock) in PMFCs, such as water spinach (*I. aquatica*) and water lettuce (*P. stratiotes*).

As promising as it sounds, PMFCs are yet to achieve the predicted maximum power output of 3.2 W/m² [6]. A proposed solution is to stack individual PMFCs to amplify the power produced. In theory, connecting individual cells in series or parallel will amplify voltage and current, respectively. It is not clear if the same is true for biochemical systems.

This study aims to determine the power production of *I. aquatica* and *P. stratiotes* in separate stacked design of hybrid (aquatic/terrestrial) plant-microbial fuel cell (PMFC) assemblies. This will demonstrate the capability of the aforementioned system to concurrently produce biomass and bioelectricity. Furthermore, the effect on power generation upon stacking multiple cells is also of interest.

2. Materials and methods

2.1. PMFC design and set-up

The main PMFC assembly was made of ordinary glass and was designed to hold 9 individual cells as shown in figure 1(a). Two assemblies were provided for the two plants on interest. Each cell was fitted with a fine-meshed cotton cloth separator, with dimensions similar to its cross-section (figure 1(b)). Two graphite rods ($A = 4.85 \times 10^{-4} \text{m}^2$) were used as electrodes; the cathode was secured to the bottom of the container while the anode was secured near the dense roots of the plants. Holes were drilled on the sides of the cells to enable stranded copper wires to go through and were made water proof by hot glue. Junctions between the graphite electrode and the copper wires were also sealed to prevent the exposure of copper.

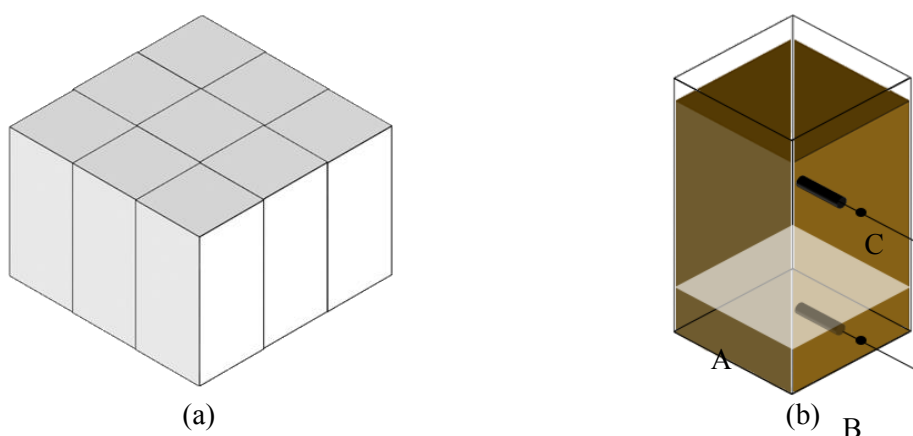


Figure 1. (a) Design of stacked PMFCs (L x W x H: 18 in x 18 in x 12 in) and (b) Layout of the individual cells (A - cloth separator; B - cathode; C - anode).

The cotton cloth separator was placed 2 inches from the bottom of the container and was secured to the sides of the container. An economical separator was used instead of a proton-exchange membrane to reduce the cost associated with the set-up. *I. aquatica* seeds were sourced from Ramgo International Corporation and were first grown on wet soil for 20 days before transferring to the PMFC assembly to make sure that the plants have grown an ample root system. *P. stratiotes* were sourced from a watershed in Taguig, Philippines. Similar-sized medium plants were picked for the experiment and

were immediately placed on their corresponding assembly. Both assemblies were placed in an area of direct sunlight in early morning with partial shading from noon and afterwards. This is to prevent the cells from overheating which may affect the health of the plants.

2.2. Operation and measurement

Prior to the measurements, the assemblies were not disturbed for 10 days to let the rhizosphere recover and stabilize. Loss in water due to evapotranspiration was replaced every morning. A multimeter was used to measure the open circuit voltage and current of the individual cells every 2 pm for seven days. Also, three sets of three cells were connected in series and parallel to measure the effect on voltage and current. Overall, three trials were made for each stacked measurement of voltage and current, and nine trials were made for individual cells for each plant. Temperature and humidity were noted for the seven-day experiment and both were found to be essentially consistent throughout. New biomass formation was also observed and noted for all plants in the study.

3. Results and discussion

3.1. Power generation of individual cells

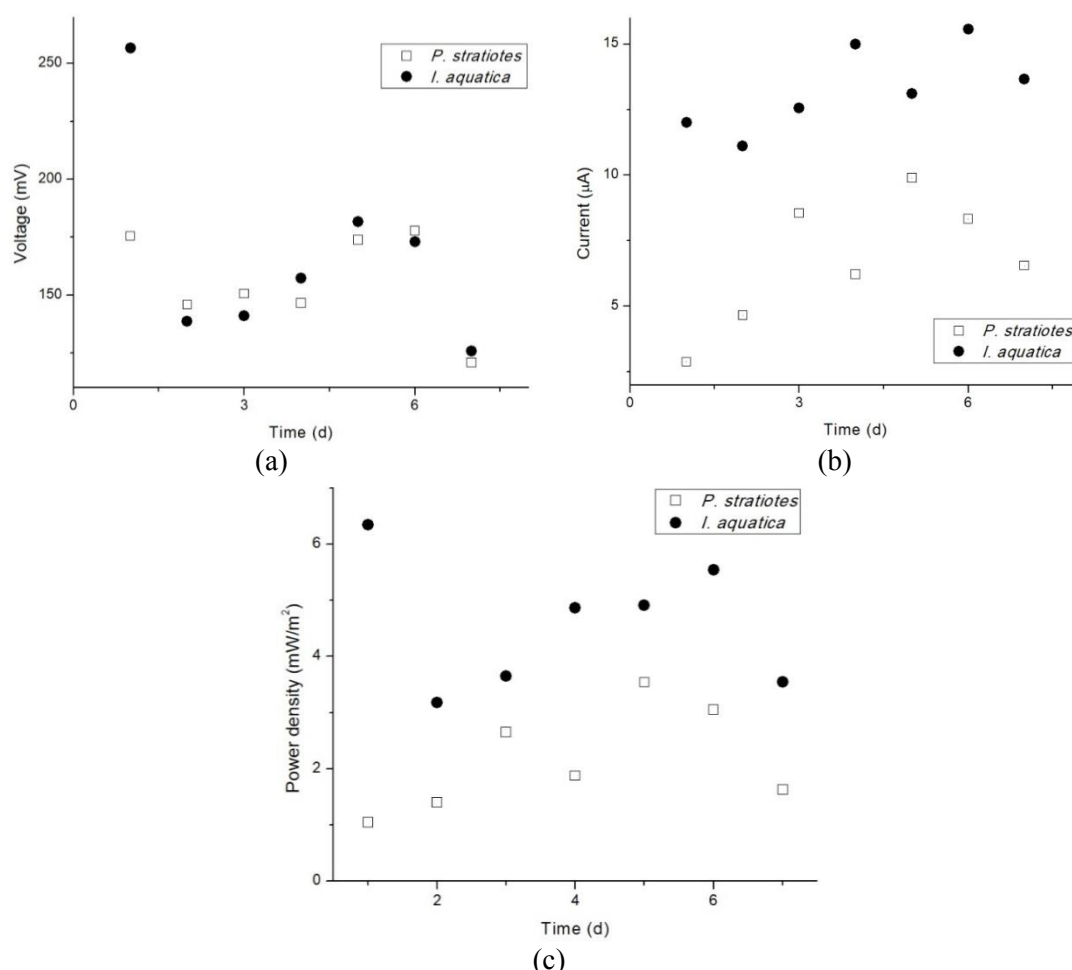


Figure 2. (a) Average voltage readings of individual cells, (b) Average current readings of individual cells and (c) Average calculated power densities of individual cells.

The obtained open current voltage and current and the calculated power density (power produced per

unit area of anode) for both *I. aquatica* and *P. stratiotes* are shown in figure 2. A two-tailed t-test ($\alpha = 0.05$) was done to compare if there is a significant difference between the obtained values for each plant. There was no significant difference in the voltage output of the two plants. However, the current and power density of *I. aquatica* was found to be significantly higher than those of *P. stratiotes*. With temperature, humidity, and illumination kept the same for both assemblies, the most feasible explanations for the discrepancy in values are the difference in physiologies and bacteria population.

The power output of a PMFC is directly affected by both the bacteria in the rhizosphere and the amount of exudates excreted by the plant [7]. The amount of exudates can also be traced to the photosynthetic activity of a plant, thus, more exudates will be released as the plant grows actively. This concept can be taken advantage of in PMFCs. Both *I. aquatica* and *P. stratiotes* are fast growing aquatic plants, and the active increase in biomass translates directly to an active supply of electricity if harvested properly [5].

The maximum obtained power densities for *I. aquatica* and *P. stratiotes* are 6.35 mW/m^2 and 3.54 mW/m^2 , respectively. These are the first reported power density values of human and animal feed crops. These results are the first step in acknowledging the possibility of simultaneous food and electricity production without the usual drawbacks in conventional renewable energy installations such as high initial investment, competition with agriculture for arable land, and high carbon footprint [1].

3.2. Effect of stacking on power generation

In electrical circuits, series and parallel connections of individual cells are used to amplify voltage and current, respectively. That concept was applied to PMFCs. The results and comparisons for *I. aquatica* are shown in figure 3.

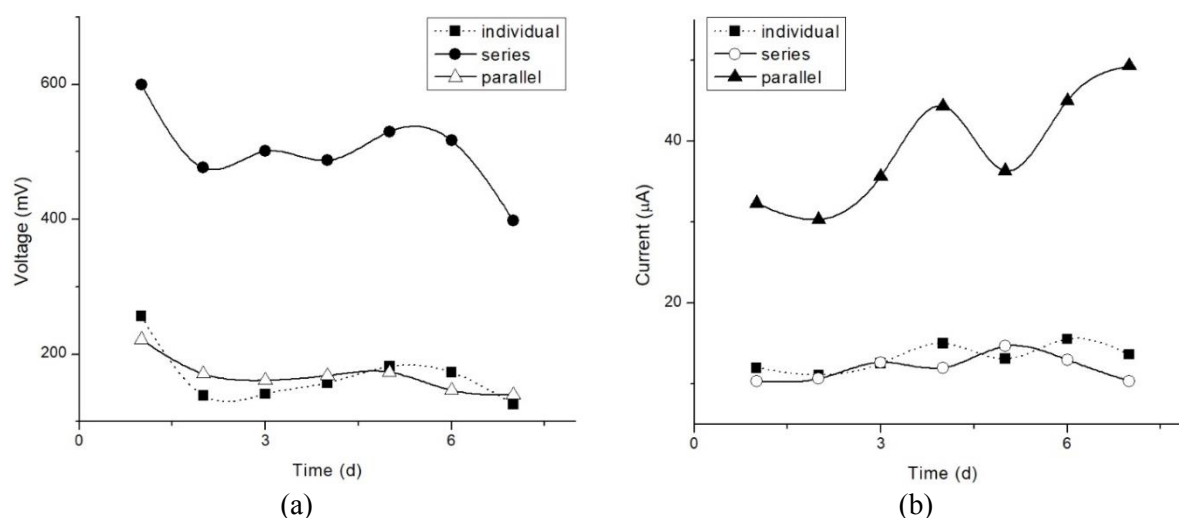


Figure 3. (a) Average voltage reading of individual cells compared to those connected in series and parallel and (b) Average current reading of individual cells compared to those connected in series and parallel.

The cells connected in series displayed additive voltages with constant current, proving that the individual cells can be considered as electrical components when predicting the power output of a PMFC cluster assembly. For cells connected in parallel, the current was triple of the individual values while the voltage remained the same, the average voltage of individual cells. The difference is shown clearly on figure 3. The same pattern was seen from *P. stratiotes*.

Upon computation and comparison of the obtained power density, no significant difference was seen between the power density of cells connected in series and in parallel, and to the individual cells.

This is due to the equalization of power produced to the available surface area of the electrodes, which is thrice as much. Therefore, power density can be seen to remain constant even upon stacking. However, this should not be confused with power; the power increases upon stacking. For instance, the average power produced by a single *I. aquatica* cell was 2.22 μW and it increased to an average of 6.47 μW upon connecting three cells in parallel. The resulting power was 3 times the original, as expected.

The principle of stacking and its effect on voltage, current, and power is expected to apply even for a great number of cells connected. However, since the system is biological in nature, that concept might only work up to a certain maximum number of cells. It is then recommended to further investigate with more cells to verify its validity. Also, the combination of series and parallel connections within one assembly can further be investigated.

4. Conclusions

The study has successfully reported values for the maximum power densities of *I. aquatica* and *P. stratiotes* in aquatic PMFC assemblies as 6.35 mW/m^2 and 3.54 mW/m^2 , respectively. Also, the proposed design of a PMFC assembly with separate individual cells were tested.

Stacking of individual cells by connecting them in series and parallel resulted to an additive voltage but constant current and additive current but constant voltage, respectively. This obeys the rule of electronic circuits, even though the system at hand is biological in nature. The power upon stacking is also amplified, roughly equal to the power of an individual cell multiplied to the number of connected cells regardless of connection (series or parallel). However, the power density of an individual cell is similar to the power density of stacked cells due to the larger total surface area of electrodes used in stacked cells.

Overall, a PMFC assembly dedicated to produce both biomass for food and bioelectricity as an energy source is not a far-fetched idea and still has a lot of potential for development.

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