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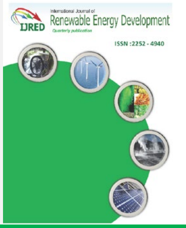

Research Article

Design and Testing of 3D-Printed Stackable Plant-Microbial Fuel Cells for Field Applications

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Abstract. The prevalence of non-renewable energy has always been a problem for the environment that needs a long-term solution. Plant-Microbial Fuel Cells (PMFCs) are promising bioelectrochemical systems that can utilize plant rhizodeposition to generate clean electricity on-site, without harming the plants, paving the way for simultaneous agriculture and power generation. However, one of the biggest hurdles in large-scale PMFC application is the diffused nature of power generation without a clear path to consolidate or amplify the small power of individual cells. In this study, stacking configurations of 3D-printed PMFCs are investigated to determine the amplification potential of bioelectricity. The PMFCs designed in this study are made of 3D-printed electrodes, printed from 1.75 mm Proto-pasta (ProtoPlant, USA) conductive PLA filament, and a terracotta membrane acting as the separator. Six cells were constructed with the electrodes designed to tightly fit with the ceramic separator when assembled. An agriculturally important plant (*S. Melongena*) was utilized as the model plant for testing purposes. Stacking of cells in series had resulted in severe voltage loss while stacking of cells in parallel preserved the voltage and current of the cells. Cumulative stacking verified the increasing voltage losses as more cells are connected in series, while voltage and current were generally supported well as more cells were connected in parallel. Combination stacks were also investigated, but while 2 sets of 3 cells in parallel stacked in series generated proportionately larger power and power density compared to individual cells, the drop in current density suggests that pure parallel stacks are still more attractive for scaling up, at least for the proposed stake design in this study. The results of this study indicated that the scale up of PMFC technology is possible in field applications to continuously generate electricity while growing edible plants.

Keywords: 3D-printing, stacking efficiency, electrodes, separator, electrochemistry

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1. Introduction

Increasing the proportion of renewable energy usage provides the most sustainable potential to advance the world's energy revolution. Plant Microbial Fuel Cells (PMFCs) are an emerging solution to advancing energy transformation from natural resources, with its capability to generate clean energy simultaneously with other important processes such as agriculture, remediation, water and wastewater treatment, among others (Tetteh *et al.*, 2019; Naranya Prasad and Kalla, 2021). This technology is closely based on the concept of microbial fuel cells, which convert chemical energy to electrical energy by the metabolism of electrogenic microorganisms (Zain *et al.*, 2015). Plants generate root exudates as a byproduct of photosynthesis (Aulakh *et al.*, 2008), and this release of organic matter to the soil serves as the substrate that bacteria can use to directly generate electricity (Huang *et al.*, 2021). Previously, marsh grasses were the most dominant plants to be tested with this technology due to their high biomass production, salinity tolerance, easy cultivation, and adaptability to the system (Nitisoravut & Regmi, 2017). Recently, PMFC technology is increasingly used in agricultural systems where the model plant used also produces harvestable biomass on the shoot part, allowing for simultaneous electricity and food production (Apollon *et al.*, 2021). A key part of enhancing the bioelectricity generation side is by optimizing the design and material selection, which is the key focus of this study.

Electrode materials bear a great significance in regulating power in PMFCs; carbon-based electrodes are commonly used due to their good conductivity, low cost, and availability. Some also used stainless steel as an alternative for these carbon-based materials for improving conductivity (Peng *et al.*, 2016). Naturally, using suitable electrode materials will improve power output. In terms of design, PMFC power generation capacities will vary on how the bioelectrochemical system was built. One study used a tubular design that consists of concentric coaxial anode, membrane, cathode, and silicone tube and installed in a wetland environment (Wetser *et al.*, 2017). The conditions of the environment allowed for consistent gas exchange in the cathode while the entire system was kept functioning by moisture in the soil. However, even though the tubular system was optimized for use in that environment, it still suffers from limiting factors such as moisture-dependent system conductivity and ion transport constraints, unlike in Microbial Fuel Cells where the substrate comes from an aqueous media (Shaikh *et al.*, 2021). Designs that address this limitation will be key in advancing the

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applicability of PMFC systems. Incorporating additive manufacturing will also ensure uniformity my allow for standardization in MFC or PMFC performance (You *et al.*, 2017; You *et al.*, 2020).

Assuming that the design constraints are solved, another factor to consider in improving PMFC performance is its ability to scale up. From an allometric analysis, it was shown that MFC scale-up would be more efficient if individual units are kept small, but several would be stacked together to amplify their power output (Greenman & Ieropoulos, 2017). The same can be applied for PMFCs which work on the same principle. Stacking studies done on PMFCs remain limited, as design constraints also play a role in creating consistent units purposefully designed to be stacked. From previous PMFC stacking studies, inconsistencies were found on how series and parallel stacks behave. In an earlier study, it was shown that open circuit stacks of aquatic PMFCs using *Ipomoea aquatica* and *Pistia stratiotes* followed the conventional stacking laws of batteries (i.e., series connection generate higher voltages) (Pamintuan *et al.*, 2018). A follow up study utilizing terrestrial PMFCs with *Vigna ungiculata* in polarized circuits revealed the opposite; serially stacking PMFC units resulted in lower voltages compared to individual cells. Parallel stacks seem to be better in preserving voltage and current of stacks (Pamintuan *et al.*, 2020). The key difference between the two is the medium used, which affects rates of ion transport and overall resistances in the system.

This study aims to design and test the stacking performance of 3D-printed stackable PMFC stakes for field applications. With the design of 3D printable PMFCs, units can be created equally for consistency. This study can help establish and normalize printable PMFC designs that are easy to construct which could contribute to the wider adaption of PMFCs in the consumer market. It is promising even if it historically has low level power generation because of its ability to continuously generate power while still enabling food production, as well as other functions. The specific objectives are: to measure the power generation of the designed PMFC units, and to determine their stacking potential under different configurations. The plant used in this study was Solanum melongena, more commonly known as eggplant. Apart from being one of the most popular crops grown for domestic consumption in the Philippines, this plant can also be grown during any month of the year while allowing for multiple harvests, increasing the time it spends in the soil with the PMFC.

2. Materials and Methods

2.1 Design and construction of 3D-printed electrodes

In this study, the electrodes were designed using Fusion 360 for the PMFC stacks. The general shape of the electrodes were based on the shape of the terracotta membrane, which was used without modification. The general structure of the system was adopted from the stake design of the terracotta membrane, which makes it easier to deploy in the soil. Another benefit to the current design is its ability to hold and slowly release water, making sure that there is constant indirect electrochemical contact between the anode and cathode.

Figure 1 shows the design and dimensions of the cathode that was placed inside the terracotta membrane. The wall has an approximate thickness of 1 mm. It has a total surface area of 0.01999 m^2. The size of the cathode was strictly controlled since the it should be in direct contact with the membrane; the cathode was made to tightly fit inside the terracotta stake. Small holes were provided all over the cathode to increase its total surface area.

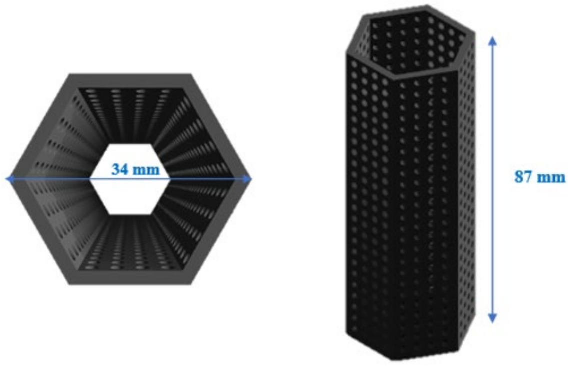


Fig 1. Top view (a) and isometric view (b) of the 3D-printed PMFC cathode

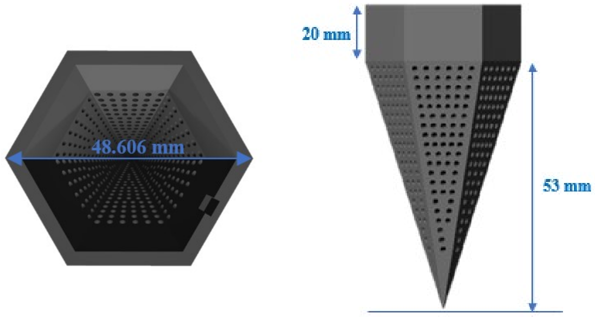


Fig 2. Top view (a) and front view (b) of the 3D-printed PMFC anode

Figure 2 shows the design of the anode. It was designed to attach to the pointy lower half of the terracotta stake. Following the same guideline for cathodes, then anode must have good contact with the clay stake. Thicker walls (2.5 mm) were used for the anode to preserve its structural integrity in the soil. The calculated external surface area of the anode is 0.005543 m^2. The cathode-to-anode surface area ratio is 3.6. Based on previous studies on compartmentalization, higher ratios (larger cathodic area) tend to increase PMFC activity by compensating for the slower cathodic half-reaction (Pamintuan *et al.*, 2020; Ueoka *et al.*, 2016). Protopasta (Protoplant, USA) conductive polylactic acid (PLA) filament with diameter of 1.75 mm was used to print the electrodes in a Creality Ender 3 Pro 3D printer. A 0.4 mm brass nozzle was used, with 0.2 mm print layer height and 100% infill. The assembled PMFC is shown in Figure 3. The terracotta membranes were obtained from a general-purpose store, which are used as watering stakes for controlled release of water to the soil. The terracotta stake acts as both membrane separator (Winfield *et al.*, 2016) and water reservoir in this design, with a measured water retention capability of around 52 hours (from filled to drained).

2.2 Operation and measurements

The plants used for this study are mature *S. melongena* (60 days after transplant) planted in continuous clay-loam soil. The PMFC stakes are inserted into the soil, 5 cm away from the base of their partner plants. The 6 plants are spaced 30 cm apart of each other, forming 2 rows of 3 cells each (Figure 4).

The PMFC stakes were never allowed to dry, as the stakes are continuously filled with tap water every day. Voltage against 1000-ohm resistance was measured (A830L digital multimeter) for all cells once a day at 12 nn for 20 days, after an acclimatization period of 7 days to ensure that the reactors are working properly.

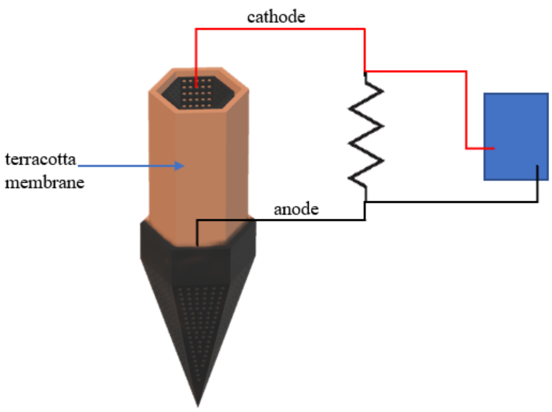


Fig 3. Assembled individual PMFC showing the 3D-printed anode and cathode and terracotta membrane

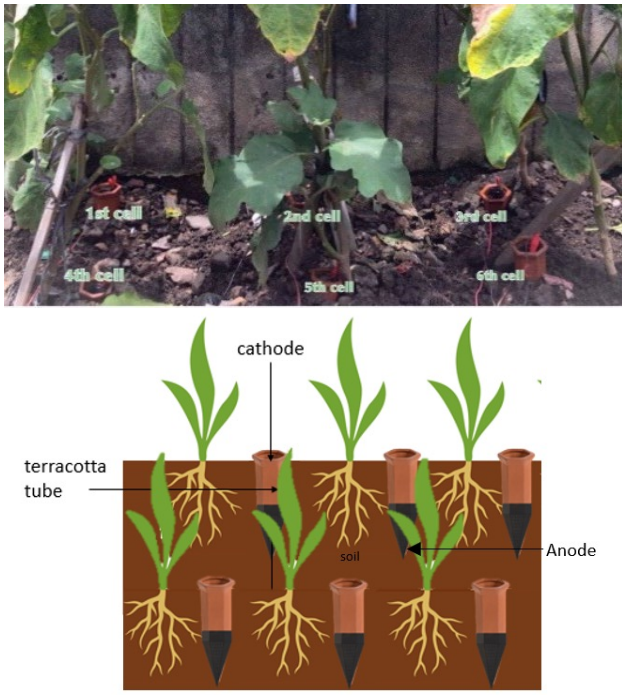


Fig 4. Illustration and actual set-up of 3D-printed PMFCs in soil with *S. melongena*

Current ($I=V/R$), power ($P=V^2/R$), and power density ($P_D=P/A$) were computed. The area considered for power density calculations was the external surface area of the anode, for normalization of power generation. The measured individual voltage and current were used as baselines for comparing the changes in output when cells are connected in various stacking configurations.

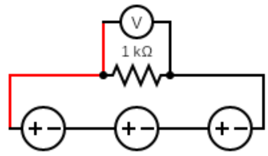
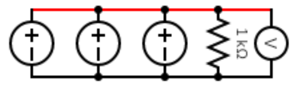
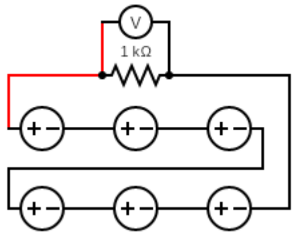
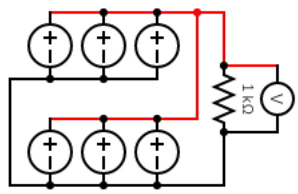
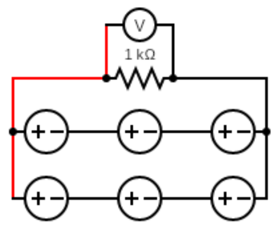
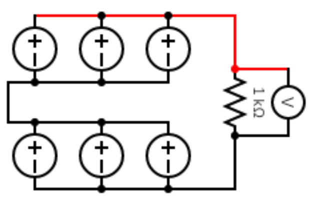
2.3 Stacking efficiency studies

Stacking efficiency studies were performed by connecting the 6 cells in different configurations, and comparing their output with the baseline (average of individual outputs). The stack tests done are listed in Table 1.

The voltage of the stacks was also measured against a 1000-ohm resistor. For pure series and parallel stacks, multiple readings were taken for different cells connected (i.e., 1-2-3, 4-5-6, 1-4-6, etc.). This serves to even out inconsistencies and produce an average that can be compared to the individual cells. The percent variability between different connections ranges from 2% to 10%.

Furthermore, cumulative stacking was also performed. This was done by incrementally increasing the number of cells connected in pure series and parallel stacks (i.e., 1, 1-2, 1-2-3, 1-2-3-4, etc.). This can potentially show the progression of voltage losses in the stack, as well as malfunctioning cells. The following combination stacks were also conducted and observed: 2 sets of 3 cells in series stacked in parallel (2S-P), and two sets of 3 cells in parallel stacked in series (2P-S). These hybrid connections aim to combine the strengths of either pure stack. Polarization tests were conducted to determine the voltage response of individual cells and their stacks to changing external resistance (0.51, 1, 5.1, 10, 20, 30, 43, and 51 kΩ).

Table 1
Summary of PMFC stacks investigated; positive terminals are designated as cathodes; negative terminals are designated as anodes

Description (code)	Illustration
3 cells in series (3S)	
3 cells in parallel (3P)	
6 cells in series (6S)	
6 cells in parallel (6P)	
2 sets of 3 cells in series, in parallel (2S-P)	
2 sets of 3 cells in parallel, in series (2P-S)	

3. Results and Discussion

3.1 Series, parallel, and combination stacks

The daily average voltage of the individual cells along with the varying pure stacks of series and parallel are shown in Figures 5 and 6. The voltage and the current readings of individual cells reached a plateau with readings hovering along an almost constant value once the readings stabilized. The voltage and current of the series stacks are almost the same as the voltage and current of the individual cells, as seen in the often overlap in the graphs. The constant deviation comes from the voltage and current of parallel stacks, which are significantly larger than the individual and serial stacks (α = 0.05). While the figures already show different behaviors than what was previously reported in PMFCs, variations in stacking response could be attributed to design factors and not necessarily a generalization for all PMFCs.

Previous studies focusing on stacking of PMFCs demonstrated the multiplicity of voltage in series connection, and current in parallel connection which is similar to the behavior of batteries (Pamintuan, Ancheta *et al.*, 2020; Pamintuan *et al.*, 2018). However, it should be noted that previous studies utilized a different design and configuration of PMFCs; much focus has been given on internalized configurations, which is when PMFC parts and materials are inside a container with the substrate (such as a pot with soil or water). The current study utilizes an externalized configuration, where the PMFC is an assembled set-up and the plant and substrate are external to all the working parts of the PMFC, similar to a tubular wetland PMFC previously reported (Wetser *et al.*, 2017). This change in configuration allows for more flexibility in deployment and retrieval, and it also doubles as a water reservoir for continuous passive watering of the soil. The preliminary findings on stacking stated here can serve as a starting point for further optimization of stack power output.

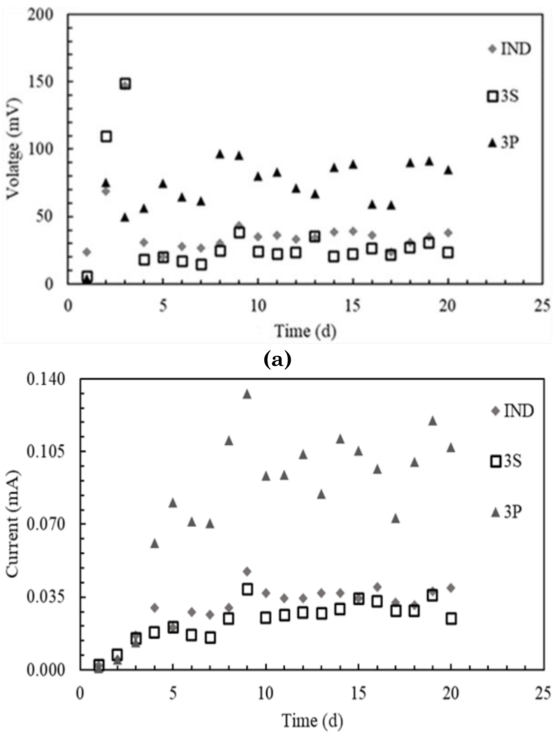


Fig 5. Daily average voltage (a) and current (b) comparison of individual PMFCs to those stacked in 3 cells in series (3S) and parallel (3P)

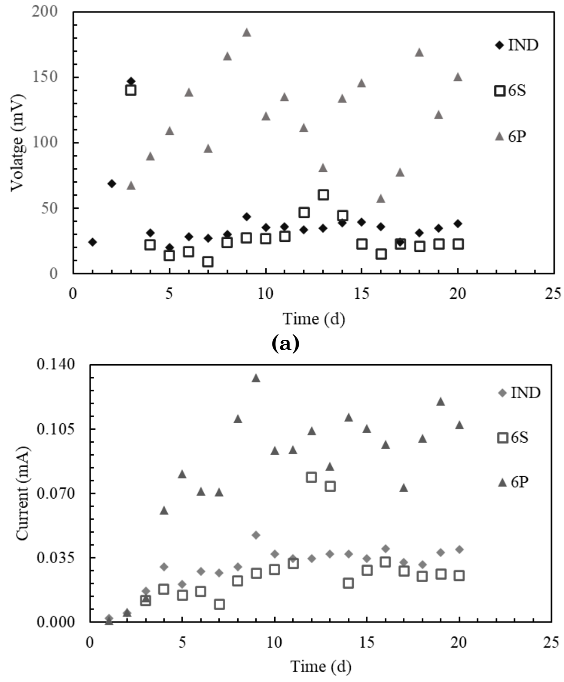


Fig 6. Daily average voltage (a) and current (b) comparison of individual PMFCs to those stacked in 6 cells in series (6S) and parallel (6P)

In any bioelectrochemical system, voltage losses or voltage reversal is the primary reason behind the inability to reliably scale up (Kuchi *et al.*, 2018; Liu *et al.,* 2015). In MFCs, voltage reversal is brought by the limitation in substrate, as demonstrated in fed-batch MFCs (Oh & Logan, 2007). Near the end of the cycle where much of the organic matter in the water has been consumed, the MFC in the experiment began to produce a negative voltage, which means that the serial stack of MFCs would end up having a lower overall voltage because the negative cell potential of one of the cells in the stack would cancel out some of the positive potential generated from other cells. This is easily remedied in MFCs by having a continuous mode of operation to make sure that there is always ample organic matter in the wastewater stream for the bacteria to consume. However, in PMFCs, the availability of the substrate is dependent on the photosynthetic activity of the plants, plus the locally or innately present organic matter in the soil. This makes PMFCs more prone to voltage reversal. From the stacking results, parallel arrangements give more potential for scale up because those stacks are not affected by one or two cells experiencing voltage reversal. Several instances from the measurements revealed that even if one of the three cells stacked in parallel has a lower voltage registered, the parallel stack still registers a higher voltage than what is expected. This could be attributed to the levelling effect of parallel connections where the electrons generated from one cell could supplement a need for other cells because they are free to move between electrodes of different cells. In series connections, a faulty cell hinders electron transfer for the entire stack, leading to lower voltage and current readouts (Figures 7 and 8).

In Figure 7, a large gap between the actual and expected voltage of the three cells connected in series is observed; the actual reading is 72% lower than the expected value. Meanwhile, the voltage of the three cells in parallel is 81% higher than the expected value. In terms of current, the reading for 3 cells in series does not significantly vary with the expected value, while the current readings of 3 cells in parallel are 9%

lower than the expected (α = 0.05). The same behavior is noted for 6 cells stacked in series and parallel, but the discrepancy in voltage of series stacks is further magnified. This is to be expected based on the previous discussion on voltage reversals; more cells stacked in series means that there are more points of failure in the stack.

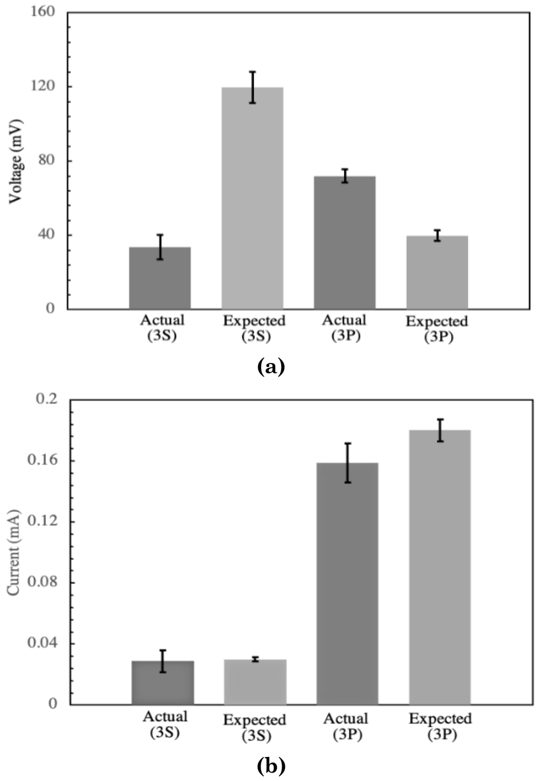


Fig 7. Average voltage (a) and current (b) of 3 cells connected in series and parallel compared to the expected values

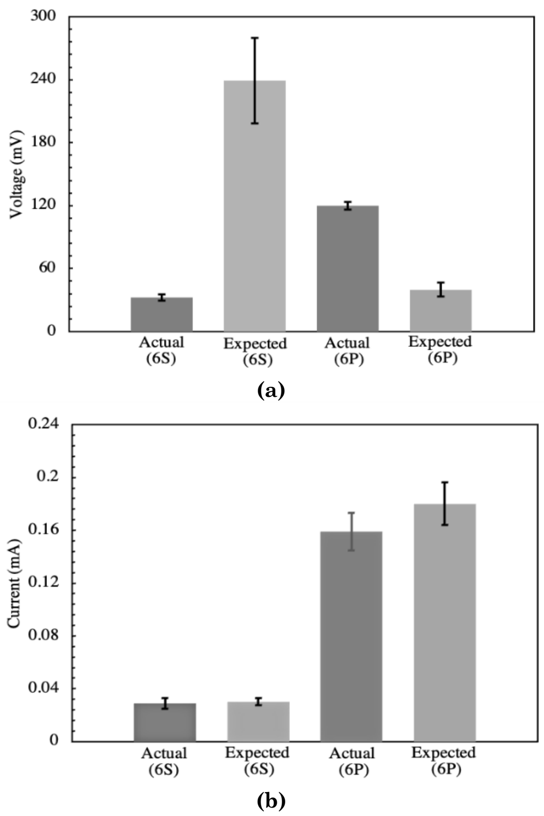


Fig 8. Averaged voltage (a) and current (b) of 6 cells connected in series and parallel compared to the expected values

On the other hand, more cells stacked in parallel provides more support for other cells that may fail, as shown in Figure 8. However, the main drawback of more cells stacked in parallel is its ability to transport electrons. More cells connected means a larger resistance is also introduced, especially since the conductive PLA filaments used as electrodes are relatively more resistive compared to traditional electrodes like stainless steel and carbon-based materials. This could also explain the difference between the results of this study compared to other stacking studies utilizing different electrodes and design configurations.

So far, the results have shown both the upsides and downsides of series and parallel connections in this particular 3D-printed design of PMFC. Since the voltage suffers greatly in serial stacks and current gradually declines in parallel stacks, a combination of the two may hold the answer to magnifying both. Combining series and parallel stacks in different orders can supplement the weakness of one type of connection. In Figure 9, the results show that the voltage reversal experienced in serial stacks can be mitigated by first forming smaller parallel stacks, before connection those parallel stacks in series (2P-S). In doing so, voltage vas amplified (313% larger than expected), while current loss remains similar to the pure 6P stack. The advantage of the hybrid stack 2P-S is it produces higher stack voltage compared to either 6P or 6S. On the other hand, the hybrid stack 2S-P suffers from the same problems of pure 6S stacks because the serial connections were done first before parallel, leading to voltage losses before it can be restored by parallel connections. 2S-P stacks generate about the same voltage as a 6S stack but it performs worse in current generation. These results further solidify the usefulness of parallel stacks in this PMFC configuration, and how series stacks can help increase voltage output, as long as parallel connections are made first.

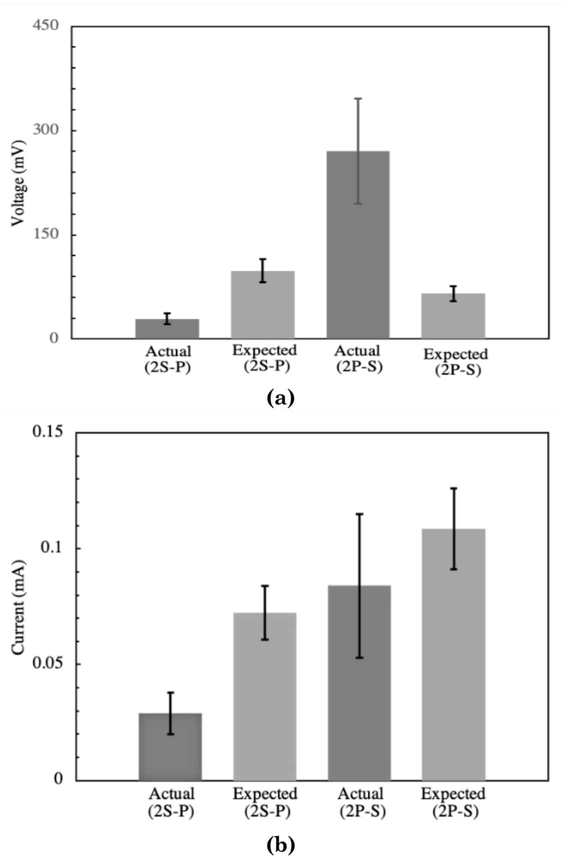


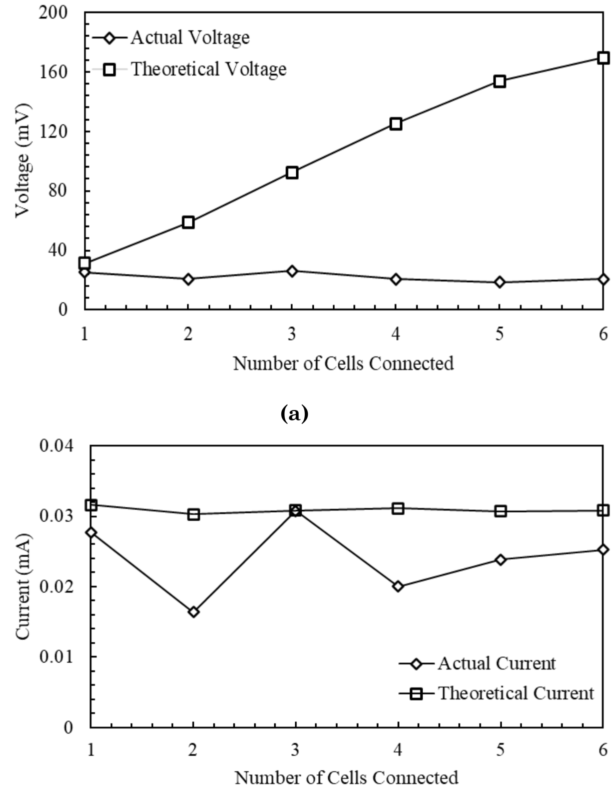
Fig 9. Averaged voltage (a) and current (b) of 2 sets of 3 cells in series connected in parallel (2S-P) and 2 sets of 3 cells in parallel connected in series (2P-S)

The difference in characteristics of PMFCs to batteries sets the difference in actual and theoretical value results. Batteries store energy, while PMFCs are generally thought to be generators. The results shown here suggests that PMFCs can also have a storage capacity due to the deviation of its behavior from batteries, making it a hybrid between batteries and generators. Some studies have shown that PMFCs can also store the energy on its own, particularly through capacitive bioanodes and the capacitance of biofilms themselves. A previous study has shown that biofilms can store charges, but the capacitance of the biofilm linearly decreases as its thickness increases (Maurício *et al.*, 2006). The soil being a mixture of organic and inorganic materials including water also contributes to the system's capacity to store charges. In MFCs, it has been shown that electrode systems can be modified with polymers to become capacitive bioelectrodes, giving them the ability to hold charges (Deeke *et al.*, 2012; Heijne *et al.*, 2018; Sindhuja *et al.*, 2019). All these combined with the results from this study suggests that PMFCs can hold charges, and these stacking studies can help maximize the charge-holding potential of these systems to benefit scale-up and large-scale implementation.

3.2 Cumulative stacking

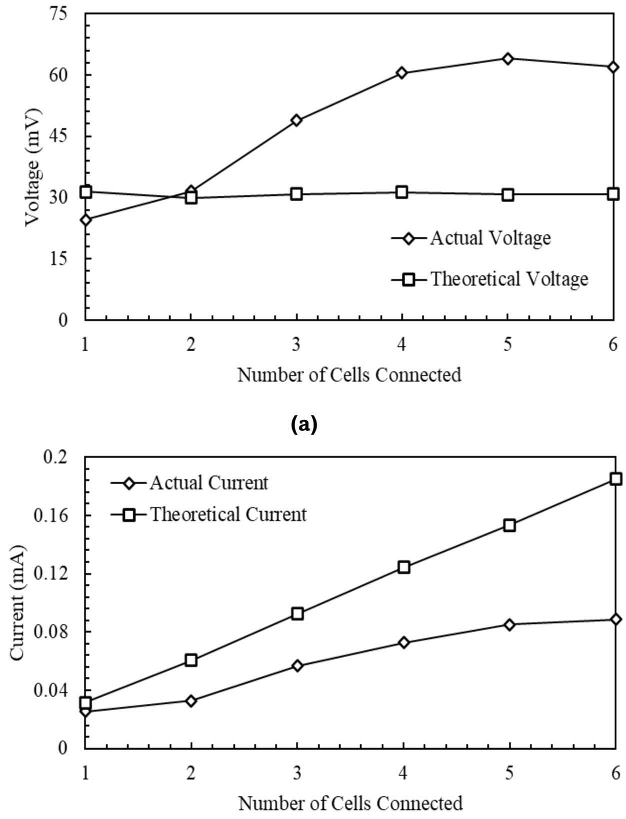
To further investigate the behaviors of cells in series and parallel stacks, cumulative stacking tests were performed by incrementally increasing the number of cells connected. From Figures 10 and 11, there is an appreciable amount of voltage loss in series stacking, while the stack voltage appreciates in parallel stacking, complimenting the results earlier presented. Aside from voltage reversal, another possible reason is the current mismatch in the cells that results in power reduction and voltage disparity in stacks. In terms of current, both series and parallel stacks display a trend wherein current increases as more cells are connected but it struggles to keep up with the expected value, further proving the previous results from 3P and 6P. This is directly caused by the electrode material and the external circuit; one possible approach to remedy this is by using a different electrode material with better conductivity to better handle higher current densities from more cells connected (Gurung & Oh, 2012; Gajda *et al.*, 2020).

To better understand the effect of connecting more cells in series and parallel, the power and power densities of the stacks are presented in Figure 12. The absolute power generated is only amplified in parallel stacks, and the power generally increases as more cells are connected in parallel. In serial stacks, the power generally decreases as more cells are connected. These are consistent with observations on voltage and current as parallel stacks can modestly conserve current while amplifying voltage. However, the true value of stacking can be appreciated in terms of power density, a true metric for scale-up. In power densities, the power generated is normalized in terms of area; in this case, the area used is the external anodic surface area to represent the changes in power generation in terms of increasing resistance. The power density of serial stacks experienced a rapid decline as the decrease in absolute power is compounded with an increase in surface area. On the other hand, the parallel stacks give a promising outlook as the power density is shown to increase even when increasing the number of cells stacked together. This shows that a scale-up is possible with parallel stacks. However, it should be noted that the power density eventually decreases beyond 4 cells connected in parallel, as the absolute power also becomes stagnant at that point. This is the same behavior encountered in compartmentalization studies in MFCs and PMFCs (Pamintuan, Bagumba *et al.*, 2020; Pamintuan, Reyes, *et al.*, 2020).



(b)

Fig 10. Response of voltage (a) and current (b) to cumulative stacking in series

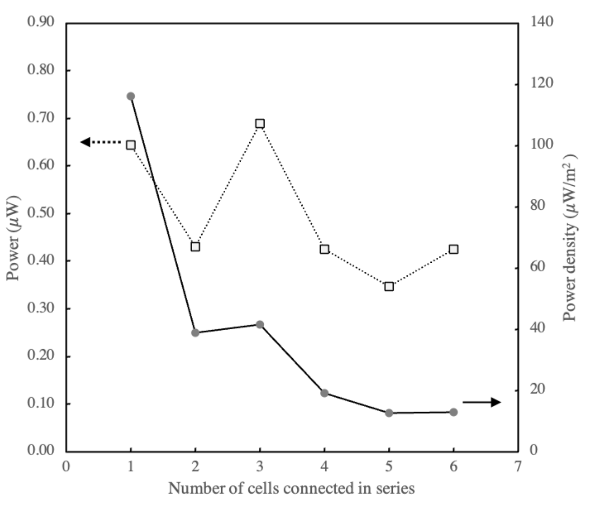


(b)

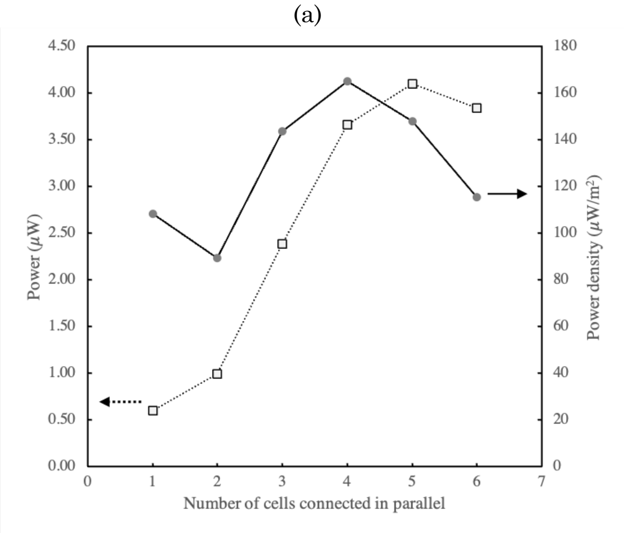
Fig 11. Response of voltage (a) and current (b) to cumulative stacking in parallel

Ultimately, strategic stacking of the designed PMFC stakes showed that it is indeed possible to amplify the power and power density of such cells, within reasonable limits. For further investigation, it may be possible to incorporate individual controllers of voltage and current of the designed PMFC stakes, such as resistor control and energy harvesting circuits (Kim & Chang, 2018; Nguyen *et al.*, 2019; Osorio de la Rosa *et al.*, 2019) before stacking the cells.

Cumulative parallel stacking produced larger stack voltages than predicted. The stack voltage should be equal to the average voltage of the cells in a parallel connection. Still, the results are consistent with stacking 3 and 6 cells in parallel for all trials and combinations. The results suggest that parallel stacking prevents voltage loss but is unstable in generating high currents as the cells increase. The same goes with the current, it is higher than the cells stacked in series, and it generates stable current as the stacking of cells increases (starting in cell 3 through cell 6). From the studies of other bioelectrochemical systems like MFCs, serially stacked MFC systems or units could provide a higher voltage (Selvasembian *et al.*, 2021; He *et al.*, 2017). Still, it has often been proven to be difficult and ineffective due to the voltage reversal or the reverse polarity, which results in the fuel shortage of the individual units and leads to significant overall voltage decay (Molognoni *et al.* 2021).



(a)



(b)

Fig 12. Power and power density tradeoffs for cumulative stacking of PMFCs in series (a) and parallel (b)

Voltage reversal in a stacked microbial fuel cell is a significant challenge because its definite cause and occurrence process is uncertain (An and Lee 2014). In this case, a significant voltage difference and reversed cell polarity when using the series-stack connection in BES. It is referred to as "voltage reversal," in which an anode becomes a cathode or vice versa that can occur due to a non-spontaneous anode overpotential in a unit cell with lower anode kinetics than the other cells (Peter Aelterman *et al.* 2006). The voltage reversal was caused by fuel deprivation, which decreased bacterial activity. As seen by a relative drop in cell performance following a cycle of starvation, voltage reversal had a detrimental effect on bacteria on the anode of the compromised cell or no feeding. Voltage reversal management will be critical for the long-term functioning of microbial fuel cells in series. While a cell's immediate "feed intake" can restore positive voltage generation, the long-term effect of charge reversal is bacteria inactivation, prompting the short-circuiting of compromised cells to sustain stack electricity output (Yang *et al.* 2018).

3.3 Comparison of power, power density, and current density

Stacking cells together results to an overall increase in the available surface area for electrochemical reactions, but it also increases the overall resistance of the system which will have definitive effects on the power generation. Figure 13 summarizes the power and current density comparison for all stacks studied to have a broad view of the trade-offs in stacking PMFC stakes.

In general, all pure serial stacks (3S and 6S) as well as series-forward stacks (3S-P) all failed to amplify the power and power density of the system. These connections ended up doing more harm by lowering the overall power density from the added surface area of electrodes without the proportionate increase in power output. On the other hand, the stacks 6P and 2P-S successfully increased both power and power density of the individual cells. However, both successful stacks displayed slightly lower current densities compared to individual cells, pointing to the flaw of electrodes used in the system. The 3D-printed conductive PLA electrodes are failing to carry higher current densities, thereby limiting the maximum capability of the stacks. It is therefore recommended for the electrodes to first undergo pre-treatment such as mechanical or chemical modifications before being used as electrodes to improve the performance of PMFCs (Slate *et al.*, 2021; Rocha *et al.*, 2022).

3.4 Polarization

Polarization tests were performed once a week for 20 days as the individual cells' voltage and current reached the stable value. The 510 Ω ~ 51 kΩ (510R, 1K, 5.1K, 10K, 20K, 30K, 43K, 51K) resistors load are plotted with their corresponding voltage (mV) and current (mA) reading. Figure 14 summarizes the response of all studied systems under varying values of resistors.

The polarization curves follow a parabolic trend by increasing the resistor load as it reaches its peak. Through this, the resistor load that allowed the optimum performance of the PMFCs was determined. The voltage recorded ranges from 25 mV to 442.5 mV for all the studied systems. And for current, it ranges from 0.02 mA to 0.114 mA. It is observed from the graph that when the value of the resistance increases, the value of the voltage no longer increases, but its value is close to the maximum voltage obtained (open circuit voltage).

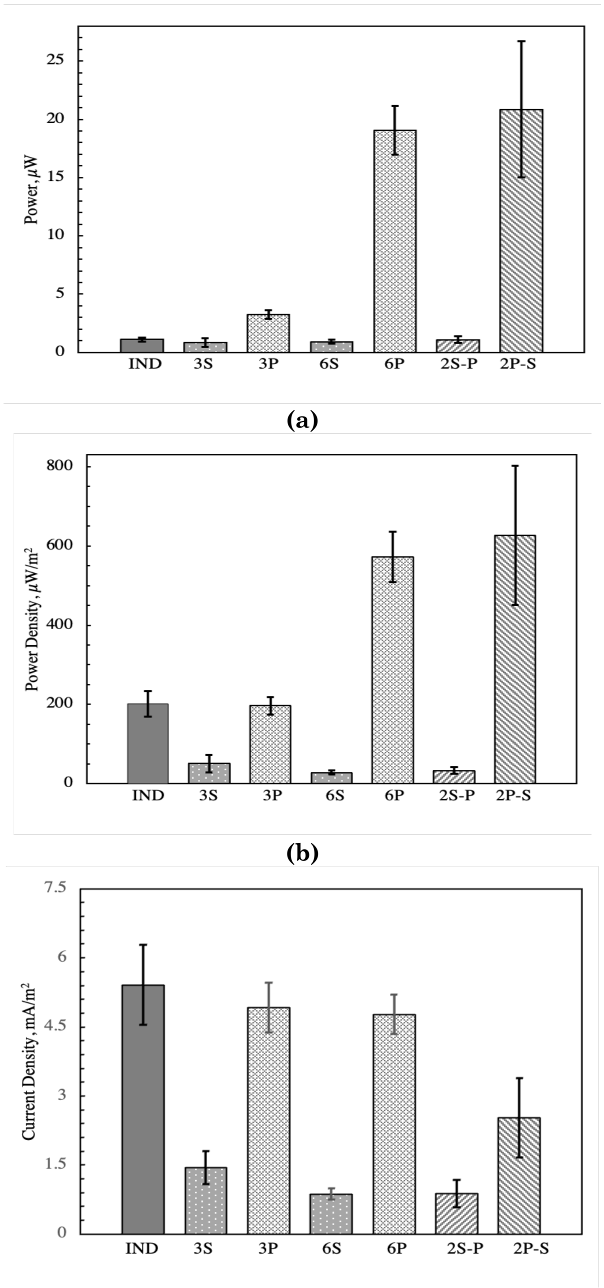


Fig 13. Power (a), power densities (b), and current densities (c) of all studied stacks

The established stacking efficiencies for series and parallel stacks all broke down at higher resistances. At the external applied resistance of greater than 20 kΩ, parallel stacks do not outperform individual cells. This can be explained by an imbalance in the resistances as individual cells only have an internal resistance of 10 kΩ measured from polarization curves. Applying an external resistance much greater than the internal resistance results to an appreciable loss in voltage and ultimately power (Nikhil *et al*., 2018; Aaron *et al*., 2011).

This is further compounded by the departure of the resistance of PMFC stacks from the expected values. The overall resistance of 3S and 6S stacks are at 5 kΩ, half of an individual cell, whereas it is expected that the resistance of units connected in series are additive. On the other hand, 3P and 6P stacks all have effective internal resistances of 10 kΩ, the same as an individual cell, where it is expected that the stack resistance is the reciprocal of the sum of reciprocals of the individual resistances.

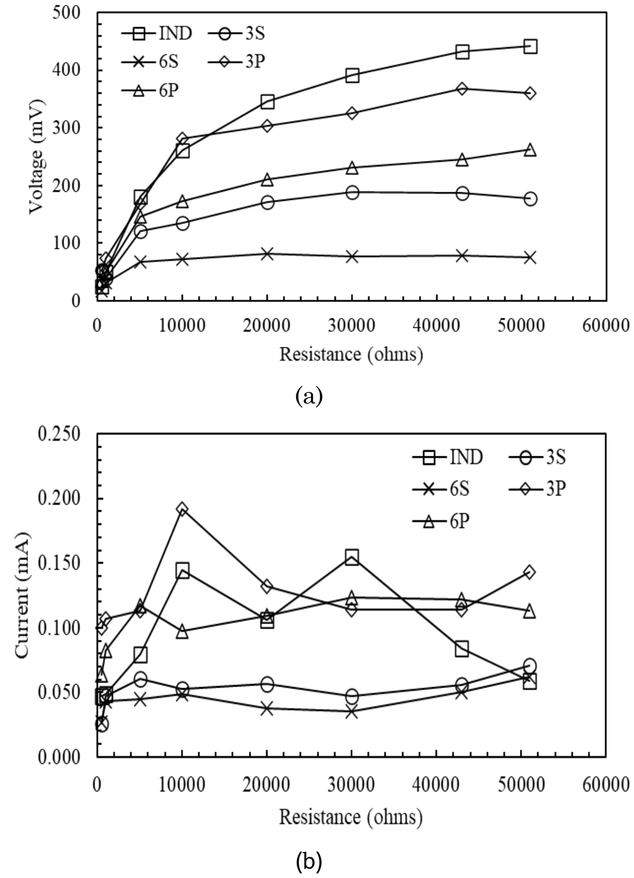


Fig 14. Response of voltage (a) and current (b) of all studied systems with varying external resistance

These departures in stack resistances further presents another complication in attempting to standardize the scale-up methodology for PMFCs. This behavior has not been seen in MFC studies. One possible explanation for this behavior is the lower electrical conductivity of the electrodes used here, or the additional capacitance of the system (Lu *et al.,* 2015; Maddalwar *et al.,* 2021). Either way, further studies need to be focused on demystifying this behavior in PMFCs.

4. Conclusions

Different tests and stacking efficiency studies showed low energy generation levels that remain insufficient for field or large applications. This points to the cells' uneven voltage values that affect the other PMFCs to generate larger yields within the system. Nonetheless, all the performed stacking efficiency studies and combinations revealed that the parallel connections of PMFCs ultimately provide higher power and power densities than those in varying combinations of series connections. More importantly, parallel connections are able to amplify the power of individual cells. Voltage reversal greatly affects series stacks, while having minimal effect in parallel stacks. We can take advantage of this behavior in combination stacks with parallel connections first, then connecting those in series to further amplify the voltage of the stack.

The designed PMFC in this study has inherent advantages, such as uniformity of units, stackability, and ease of use due to its stake design and 3D-printed parts. However, the 3D-printed electrodes showed some disadvantages particularly on its conductivity and ability to carry current; even the best stacking configurations tested in the study were struggling to conserve or amplify the current of individual cells because of this limitation from the electrode. It is recommended to pursue more studies in this field to produce better PMFC designs that can easily be manufactured while being able to stack efficiently, for a future that allows for simultaneous food production and electricity generation in the field.

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