Waste-to-Energy Valorization: Harnessing Cassava Peel Extract as a Sustainable Substrate for Microalgal Fuel Cell Bioelectricity Generation

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ABSTRACT

The escalating global energy demand coupled with environmental challenges necessitates the development of sustainable bioenergy technologies. Cassava processing generates substantial agricultural waste, particularly cassava peels, which constitute 10-20% of tuber weight and present significant disposal challenges. Microbial Fuel Cells (MFCs) offer a promising waste-to-energy valorization pathway by converting organic waste into bioelectricity through microbial metabolism. This study investigates the potential of Cassava Peel Extract (CPE) as a low-cost, agro-waste-based substrate for sustainable bioelectricity generation using Parachlorella sp. in a double-chamber MFC system. A double-chamber MFC was constructedwith Parachlorella sp.as biocatalyst, CPE supplemented with calcium carbonate as anolyte, while 0.01 M potassium ferricyanide as catholyte.System performance was monitored and energy harvesting was evaluated by charging 2.7 V 1F supercapacitors. Results identified 5 mL as the optimal feed volume, yielding stable currents of 0.26–0.28 mA (batch) and 0.18–0.24 mA (continuous) over 40 days.Furthermore, a multi-way electrical configuration increased supercapacitor charging efficiency by 73% compared to a one-way setup.These findings establish Parachlorella sp. as an effective agent for cassava waste valorization and contribute to the circular bioeconomy by transforming agricultural waste into renewable energy, offering a sustainable solution for both waste management and clean energy production.

INTRODUCTION

Agricultural wastes are generally gaining attention because of their indiscriminate disposal, which has presented it as a nuisance in the environment. Some of them are already being processed, while others still need to be considered not as outright waste but as raw materials for an improved product or an entirely new process. it is because of lignin in Lignocellulose biomass, pre- treatment required before utilization of biomass.

One of such agricultural wastes is cassava peel. Cassava is a crop that is highly cultivated in countries like Indonesia, Thailand, Brazil, Congo, and Nigeria (Adekunle & Raghavan, 2017). Nigeria is one of the countries where cassava is highly grown, this as a result of dependence on it, especially for food production, and it was reported recently that Nigeria stood out as the largest producer of cassava across the world with an average production of 62.69 million tonnes in 2023 (BusinessDay, 2025). During the processing of

cassava into its various products, the first and major step involved is the removal of the bark. When the bark of the tuber is peeled off, it is usually not properly discarded or left in most processing industries in the mercy of fate. However, these substances, considered as waste, have been documented to contain about 5–20% of the overall weight of cassava root depending on peeling efficiency (Elegbede, Dipeolu, &Shittu, 2024). In recent times, when the bark of cassava is removed, it is usually employed in feeding animals either directly or used in supplementing animal feeds (Adekunle & Raghavan, 2017).

To alleviate the environmental challenge caused by the discharge of this waste into the environment without caution, there is a need to channel its use to other resourceful processes or applications. One such use is the direct conversion of wastewater into energy using a Microbial Fuel Cell. A Microbial Fuel Cell (MFC) is an energy-generating device that involves the activity of microorganisms to break down organic materials, with a resultant effect of electricity production. The application of MFC, either directly connected to electrical devices or harvested in storage devices, depends highly on the adequate availability of substrate in a concentration that will favour the metabolic activities of the biocatalyst (microorganisms) present in the anode. . Microorganisms usually undergo four different phases in their growth: lag phase (acclimatization period), log phase (cell division and multiplication), stationary phase (cells are fully saturated without growth), and death phase (cell death as a result of nutrient depletion and cell starvation) (Madigan et al., 2021). The progression of these phases highly depends on the availability of nutrients in the culture medium, making nutrients a very essential component of an MFC if energy is to be adequately and optimally generated. The requirements of these microorganisms are usually present in wastewater, and there have been several studies on the use of waste as substrate to fuel MFC (Situmorang et al., 2022; Aduba et al., 2023).

Adenigbaet al. (2020) reported the use of human urine as substrate for microalgae-driven microbial fuel cells, and future studies should therefore evaluate how batch versus continuous feeding methods and different MFC configurations collectively influence the milliampere output generated. Similarly, Dan (2015) produced electricity in a single-chamber MFC with pond water as substrate and microalgae as biocatalyst. Some agricultural wastes have also been used as substrate in MFC: brewery waste (Ede et al., 2015); mixture of swine and vegetal waste (Meignanalakshmiet al., 2013); and cow dung with coconut water (Adekunle & Raghavan, 2017). Cassava has also been used as a substrate in recent times. Agaryet al. (2016) generated a voltage of 0.275 V from cassava mill effluent, and Edem et al. (2015) produced 1.320 V from cassava mother liquid. However, the use of cassava peel or its extract as a substrate in MFC has been underexploited, despite Adekunle & Raghavan (2017) showing its suitability. More recent studies, such as Quintero-Díaz and Gil-Posada (2024), who investigated cassava wastewater in dual-chamber MFCs, and Agaryet al. (2016), who demonstrated electricity generation from cassava mill effluent, indicate that the milliampere (mA) output depends not only on the substrate itself but also on the feeding method and the specific MFC configuration, highlighting the need for further optimization of cassava peel-based systems. In 2017, Adekunle and Raghavan documented the first use of cassava peel extract as substrate in a single-chamber air cathode MFC. The cassava peel extract was reported to produce a maximum voltage of 687 mV±21 mV and power density of 155 mWm-3. There is a need to explore cassava peel extract more to produce energy because it

contains high lignocellulosic biomass, which is known to contain high organic matter. The potential of cassava peel to support microbial growth was compared with cassava pulp wastewater; the report showed that there was no significant difference in the performance of both as substrates for microbial growth (Quan et al., 2014). Adekunle and Raghavan (2017) harnessed the potential of the microflora of cassava peel extract to produce sustainable electricity. Hence, substrate feeding becomes a very important factor in the efficient operation of MFC This can be achieved by the addition of fresh nutrients to the anodic chamber either in fed batch or continuous flow systems. When MFC is operated using batch feeding pattern, the concentration of the substrate results in an acidic medium where the level of proton is high, this can result into increase in the internal resistance of the cell which has a direct negative effect on the outcome of the cell (Torres et al., 2008; Lee and Kjeang, 2010). Papaharalaboset al. (2015) explain that for the pH level of the anolyte to be neutral, there should be a supply of fresh nutrients. Attempts have been made on different flow systems in MFC: fed batch (Liu et al., 2005); fed batch and continuous (Huang and Logan, 2008); fed batch (Zheng et al., 2015), fed batch and continuous (Pannell et al., 2016); batch and continuous (Ebrahimi et al., 2016). The electricity production in an MFC is regarded to be sustainable when the substrate can support the microorganisms over an extended period. This study investigates the potential of cassava peel extract (CPE) as a low cost agro-waste based substrate for sustainable bioelectricity generation using Parachlorella sp. In a double-chamber MFC system. Specifically, aimed to: (1) evaluate optimal feeding patterns (batch versus continuous) for sustained electricity generation, (2) determine the optimal substrate volume for maximizing current output, (3) identify the optimal substrate volume for maximizing current output and system stability (4) assess energy harvesting efficiency through supercapacitor charging using different electrical configuration, and (5) contribute toward waste-to-energy valorization strategies supporting circular bioeconomy principles.

MATERIALS AND METHODS

Study Location

This research was conducted at the Microbiology Laboratory, Department of Pure and Applied Biology, Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Oyo State, Nigeria (Coordinates: 8.1335° N, 4.2446° E). Ogbomoso is located in the southwestern region of Nigeria, characterized by tropical climate conditions with mean annual temperature of 27°C and relative humidity ranging from 60-80%.

Collection of Microalgae and Cassava Peel

Parachlorella sp. (GenBank accession number MF114127), previously isolated and characterized in our laboratory from freshwater fish pond, was employed as the biocatalyst in this study. The microalgal strain was maintained in axenic culture using Blue Green II (BG-II) medium under controlled conditions (25 ± 2°C, 16:8hour light: dark photoperiod, light intensity of 50 µmol photons m^{-2} s^{-1}). Culture purity was periodically verified through microscopic examination and subculturing.

Fresh cassava peels were obtained from a local garri (cassava flour) processing industry at Arada Market, Arada, Ogbomoso, Oyo State, Nigeria. The peels were collected immediately after processing to ensure freshness and minimize microbial contamination.

Cassava Peel Processing

The peels were thoroughly rinsed multiple times with tap water followed by sterile distilled water to remove adhering soil particles, sand, and other contaminants. The cleaned peels were then mechanically processed using a high-speed blender

(SR Classic, UK) to achieve uniform particle size distribution, facilitating efficient extraction of soluble organic compounds.

Cassava peel extract (CPE) was prepared following a modified protocol adapted from established methodology according to Agwa et al. (2012), where 30 g of processed cassava peel was suspended in 1 liter of distilled water, yielding a 3% (w/v) extract concentration. The mixture was subsequently sterilized by autoclaving at 121°C and 15 psi for 15 minutes to eliminate contaminating microorganisms while preserving organic nutrients. Following sterilization, the extract was filtered through sterile Whatman No. 1 filter paper to remove particulate matter, and the sterile filtrate was stored at 4°C until use. Prior to MFC application, the CPE was supplemented with calcium carbonate ($CaCO_3$) at 0.5 g/L as an additional carbon source and pH buffer.

MFC Design

The Double Chamber MFCs (DCMFCs) used in this study were constructed following the design of Adenigbaet al., (2020) with slight modifications. The DCMFC system consisted of two cylindrical chambers (500mL working volume each) fabricated from transparent polycarbonate material, allowing visual monitoring of system conditions. The chambers were horizontally oriented and connected through a central circular port (5cm in diameter) where the separator membrane was positioned.

The anodic chamber contained cassava peel extract supplemented with calcium carbonate, serving as both substrate and anolyte. The cathodic chamber was filled with 0.01 M potassium ferricyanide ($K_3[Fe(CN)_6]$) solution, functioning as the catholyte and electron acceptor. The cathodic use of potassium ferricyanide was chosen based on its high redox potential, chemical stability, and superior performance compared to dissolved oxygen in research-scale MFCs.

Zinc plates with a total surface area of 10 cm^2 were employed as electrodes in both anodic and cathodic chambers. Zinc was selected based on its cost-effectiveness, adequate conductivity, and resistance to corrosion in the operational pH range. Prior to installation, the electrodes were pretreated by sequential washing with acetone, 1 M HCl, and distilled water, followed by drying at 60°C to enhance surface properties and remove contaminants.

A woven polypropylene membrane (porosity: 60%, thickness: 0.5 mm) procured locally was utilized as the separator between the two chambers. This membrane was selected for its balanced properties of adequate proton conductivity, mechanical strength, and cost-effectiveness compared to commercial proton exchange membranes. The membrane was pretreated by soaking in 0.1 M HCl for 24 hours, followed by thorough rinsing with distilled water and equilibration in deionized water for 24 hours before installation. Electrical connections were established using copper wires (18 AWG) soldered to the zinc electrodes and connected through an external circuit incorporating a resistor. An external resistance of 3 kΩ was employed for routine voltage measurements. This resistance value was selected based on preliminary optimization studies and consideration of the system's internal resistance, allowing operation near the maximum power point while maintaining measureable voltage outputs. Although 3 kΩ may appear relatively high compared to some reported values, it was verified as appropriate for this specific system configuration through polarization curve analysis.

System monitoring was accomplished using a multi-channel Agilent 34970A data acquisition and switch unit (Bell, USA), enabling continuous, automated voltage measurements at 5-minute intervals. The recorded data were subsequently processed using Microsoft Excel (Microsoft

Corporation, Redmond, WA, USA) for numerical analysis, and graphical representations were generated using OriginPro 8.5 software (OriginLab Corporation, Northampton, MA, USA).

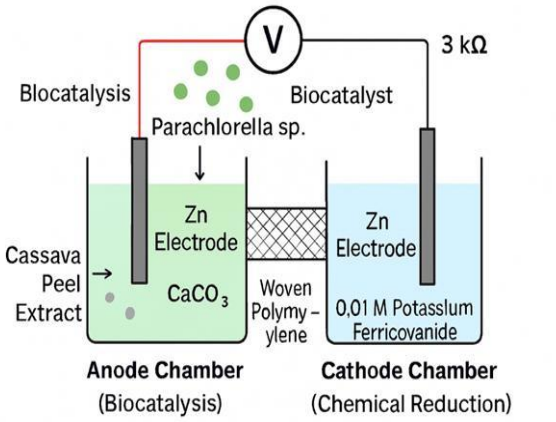


Figure 1: Schematic representation of the double-chamber microbial fuel cell (MFC) setup using cassava peel extract as substrate and Parachlorella sp. as biocatalyst.

Determination of the best feeding pattern for continuous power production

Batch Feeding System

Four sets of DCMFCs were constructed in triplicate (n=3), yielding a total of 12 experimental units for the batch feeding investigation. Each chamber was initially filled with 40 mL of CPE supplemented with calcium carbonate and inoculated with 4 mL of Parachlorella sp. culture (cell density: approximately 1×10^6 cells/mL). The MFCs were operated under controlled environmental conditions (temperature: 27 ± 2°C, continuous illumination for cathodic photosynthetic activity) and allowed to stabilize for four days to establish electroactive biofilm and achieve initial voltage output (Bhaduri, S., & Behera, M. (2024).

Following the stabilization period, the four experimental sets were subjected to different feeding regimens:

Set 1: Fed with 1 mL fresh CPE every 24 hours without removal of spent medium

Set 2: Fed with 1 mL fresh CPE every 24 hours with concurrent removal of 1 mL spent medium

Set 3: Fed with 5 mL fresh CPE every 24 hours without removal of spent medium

Set 4: Fed with 5 mL fresh CPE every 24 hours with concurrent removal of 5 mL spent medium

Each experimental set was connected to an external resistance of 3 kΩ, and voltage output was continuously monitored. Power efficiency was evaluated periodically (every 72 hours) by conducting polarization experiments using an automated resistor box scanning through 50 different resistance values ranging from 30 kΩ to 3 Ω at 3-minute intervals per resistance.

Continuous Feeding System

To evaluate long-term sustainable electricity production, five additional sets of DCMFCs were constructed and operated in triplicate (n=3), totaling 15 experimental units for the continuous feeding investigation. Initial setup was identical to the batch system: 40 mL CPE supplemented with calcium carbonate and 4 mL Parachlorella sp. inoculum. After a four-day stabilization period, the five experimental sets were subjected to continuous feeding with varying substrate volumes (Golzarianet al., 2024). The five sets are described and designated according to the feeding operations as:

Set 1: Replenished with 1 mL fresh CPE every 24 hours with removal of equal volume spent medium

Set 2: Replenished with 5 mL fresh CPE every 24 hours with removal of equal volume spent medium

Set 3: Replenished with 10 mL fresh CPE every 24 hours with removal of equal volume spent medium

Set 4: Replenished with 15 mL fresh CPE every 24 hours with removal of equal volume spent medium

Set 5: Replenished with 20 mL fresh CPE every 24 hours with removal of equal volume spent medium

All continuous feeding experiments were conducted with concurrent removal of spent medium to maintain constant working volume and

prevent excessive dilution or concentration. The systems were operated continuously until sustained voltage decline was observed, typically occurring around day 40.

Harvesting of Energy in Super Supercapacitor Using Different Configurations

The outcome of the experiments conducted above was used to design the following experiment according to Papaharalaboset al. (2017). A total of thirty-two chambers were designed, eight chambers in each set of four. The different configurations were as follows: eight chambers all connected in series (8S); eight chambers all connected in parallel(8P); two chambers in parallel connected in four series (and four chambers in parallel connected in two series. The different configurations were used to charge 2.7 V 1F supercapacitors separately to determine the highest voltage each configuration can charge the supercapacitor over time.

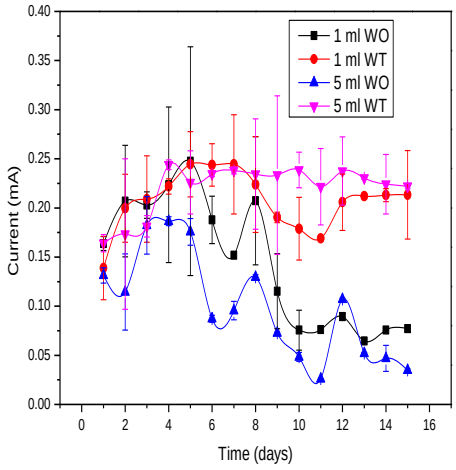
Charging of Multiple Super Capacitors

This experiment was set up to determine the number of supercapacitors that can be charged by manipulating eight chambers using different configurations. After charging each super capacitor, the open-circuit voltage of each cell was monitored immediately after charging and just before the charging of another super capacitor began. After each charging, the cells were left for 1 hour to observe the self-replenishing ability of each cell in the stack. The voltage at before commencement of charging was designated as the initial voltage (Vo), and the voltage after charging was the final voltage (Vf).

RESULTS AND DISCUSSION

Comparative Electricity Production at Different Flow Systems for Sustainable Production

In this study the experimental comparison of electricity production in a flow system, demonstrating how different nutrient management strategies specifically the volume and the procedure for adding fresh nutrients and removing spent ones affect both the maximum current output and the stability of production over a 15-day period. When 1 ml of fresh nutrient was added without removal of spent nutrient, the maximum current of 0.25 mA was produced, which was followed by a drastic reduction in current production after a few days of operation. On the other hand, 1 ml with both removal and addition of nutrients also had a maximum current production of 0.24 mA. Current production for 15 days of the experiment was fairly stable, with 0.21 mA at the end of the experiment. Similarly, 5 ml with nutrient addition only had a maximum current production of 0.19 mA, accompanied by a drastic reduction in current production up to 0.03 mA on the fifteenth day. The most stable production was with a 5 ml addition and removal of spent nutrients. Although maximum production was 0.24 mA but there was a steady output of 0.2 mA from day four to fifteen (Figure 2).



Key: WO =feeding without removal of spent nutrient; WT=feeding with removal of spent nutrient

Figure 2: Current production from MFC at different nutrient flow pattern with and without removal of spent nutrient from the chamber.

Figure 3 shows the trend of current production from five different types of chambers which were

fed every 24 hrs with fresh cassava peel extract and removal of the same volume of nutrient. The most sustainable current production over a period of 40 days was when 5 ml of nutrient was added with removal of the same volume from the chamber. This performance was followed by 10 ml and 20 ml was the less sustainable flow system over a period of forty days. Although the maximum current of 0.34 mA was obtained with 30 ml; it was accompanied by a drastic reduction from 12 days till the last day. The addition of fresh nutrient is to prolong the stationary phase of the culture in order to attain a sustainable current production for a long period in other to effective store the energy produced in a microbial fuel cell. The metabolic activity of the microalga present in the anode could be affected if the concentration of the substrate is too high, this accounted for the sustainable production in cells where nutrients were not only added but spent nutrients were equally removed. The continuous supply of nutrient encouraged the self-replenishing potential of the cells (Papaharalabos et al., 2015).

Charging of Individual Super Capacitors with Configured Cells

Charging of individual supercapacitors with each of the four configurations designed was to determine the charging capacity of each configured cell. Table 1 shows the charging pattern and time for each configured cell. The configurations with parallel elements were able to charge the cells faster, while the series elements took a longer time to charge. The fast charging achieved with the parallel set could be as a result of the increased in current when cell are stacked in parallel, the current produced by the cell is quite essential for the charging of the super capacitors. Papaharalabos*et al*. (2014) also reported the fast-charging rate of the in parallel units compared to the series configuration.

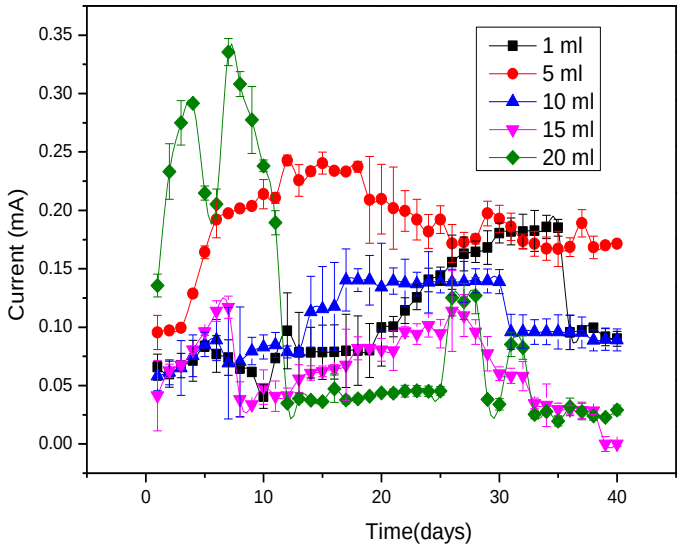


Figure 3: Trend of current production at different feeding volumes with both addition and removal of spent nutrients for 40 days of operation.

Table 1: Charging of super capacitors with individual configuration to determine the charging limit of each configuration

Configured cells	Voltage of the charging capacitor (V)	Charging time (mins)
8P	0-0.61	31.18
4P2S	0-1.15	97.05
2P4S	0.0-2.0	299.01
8S	0.0-3.1	791.8

Comparative Study of the Charging Pattern of the Reconfigured and the Real Charging Pattern

The charging of two super capacitors using both the reconfigured and real patterns. Charging of a capacitor with a reconfigured cell shows a reduction in charging time compared to the super capacitor charged at a real regime. Percentage reduction in charging time of 59 %, 54.8 % and 33 % were recorded for 8P, 4P2S and 2P4S respectively while charging in 8S with the reconfigured design was 41.1 % faster than the real design (Table 2). The reconfigured charging pattern for all configurations charged better than the real pattern with 70.3 % increase in charging speed. The reconfigured pattern was able to reduce the time required to charge the super capacitor, this also agrees with the findings of Papaharalaboset al., (2014) where the dynamic configuration which involves automatic switching of different configurations to charge a 2.7 V 1F super capacitor outperformed the all-series fixed configuration by 2- fold increase. Charging of multiple super capacitors with 8 MFCs

Eight cells connected in different configurations were manipulated to charge four different super capacitors individually at different time. The voltage of individual cells were monitored before and after each charging rounds. When the first super capacitor was charged to a voltage of 2.7 V, the maximum charged voltage of super capacitors 2, 3 and 4 were was 2.7 V, 2.2 V and 1.58 V respectively(Table 3). The strength of the cells

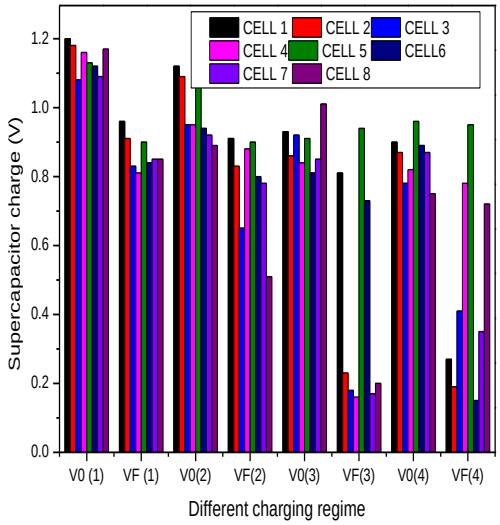
Table 2: Charging of 2.7 V 1F super capacitors using both real and reconfigured design

Super capacitor's voltage (V)	Real (minutes)	Reconfigured(minutes)	% increase in charging
0.0-0.6	25.1	11.3	59
0.6-1.0	50.7	22.9	54.8
1.0-2.0	120.0	80.4	33
2.0-2.7	210.0	123.7	41.1
Total	405.8	238.3	70.3

Table 3: Charging of four different super capacitors with 8 MFCs using the reconfigured charging pattern

Supercapacitors number	All 8 in parallel (V)	4 parallel in 2 series (V)	2 parallel in 4 series (V)	All 8 in series (V)
1	0.0-0.6	0.6-1.1	1.1-2.0	2.0-2.7
2	0.0-0.6	0.6-1.1	1.1-2.0	2.0 -2.7
3	0.0-0.7	0.7-1.4	1.4-1.65	1.65-2.2
4	0.0-7.5	0.75-0.84	0.84-1.23	1.23-1.58

in charging the super capacitors were declining as the number of super capacitors also increased, inability of the cells to fully charge the super capacitors could be as a result of the ageing of the cells despite the continuous feeding, production of some metabolites and increase in cell population which can result in depletion of nutrient. The voltage of the individual cells was monitored before and after charging and the time between each super capacitor's charging was also documented (Figure 4). At the end of the charging of each super capacitor, the Vf of each single units of the 8 cells was always lower than the Vo. After leaving each cells for one hour, there was rapid increase in the voltage of the cells, this confirms the ability of the cell to replenish in the presence of adequate nutrient.



Key: V0= initial voltage of each cell before charging; VF= Final voltage of each cell after charging

Figure 4: Initial and final voltage of each cell in the eight cells stacked for charging of four super capacitors using the reconfigured pattern.

CONCLUSION

This investigation successfully demonstrated cassava peel extract as a viable sustainable substrate for bioelectricity generation in Parachlorella sp.-driven double-chamber microbial fuel cells. The batch feeding experiments established that periodic feeding of 5 mL fresh CPE with concurrent removal of equal volume spent medium produces the most stable current output (0.26-0.28 mA) with 68% COD removal and 219 mW/m³ power density. The continuous feeding investigation confirmed 5 mL as optimal daily substrate volume, maintaining consistent current (0.18-0.24 mA) over 40 days while avoiding substrate inhibition observed at higher volumes (15-20 mL) and nutrient limitation at lower volumes (1 mL). Energy harvesting optimization identified the 2P4S electrical configuration as superior for supercapacitor charging, achieving 73% higher efficiency than parallel configuration and 35% faster charging than series arrangement.

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