Generation of Bioelectric Energy from Chlorophyll-Embedded Mesophyll Cells

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ABSTRACT: The growing need for sustainable and decentralized micro-power sources has raised interest in biologically sourced power generation systems. Traditional batteries are made using chemical processing of materials and add to e-waste; therefore, there is a need to look into renewable and biodegradable sources. This research presents a bioelectrochemical cell which uses fresh fallen leaf biomass as a source of electric energy. Dissimilar metal electrodes are used and inserted into leaf tissue; the plant sap is used as ionic electrolyte while dissimilar metal electrodes are used to generate a galvanic voltage difference and drive current through the external circuit. The effects of various environmental and structural parameters including leaf moisture content, electrode surface area, biomass weight, and internal resistance have been analyzed. The open-circuit voltage was shown to increase from 1.09 V to 4.34 V as leaf mass/series cell structure increases from 50 g to 200 g; the current was observed to be in the range of microamperes. The system proposed by this work is a direct source of energy without cultivation and different from other plant bioelectric systems like plant microbial fuel cells.

Keywords: Bioelectric Energy, Mesophyll Cells, Chlorophyll, Bio-Electrochemical Cell, ZincCopper Galvanic Cell, Renewable Micro-Power, Sustainable Waste-to-Energy.

1. Introduction

The increasing need for sustainable, distributed forms of energy across the world has made scientists focus more on biological energy sources at the micro level. Although batteries are effective power sources, they require mining and processing of chemical materials. Furthermore, batteries constitute a major component of e-waste. On the other hand, plant biomass, specifically fallen leaves that would otherwise decompose, is a readily available source for micro-level energy production.

Leaves in plants have an inherent structure which comprises of mesophyll tissues that contain cells with chlorophyll, and the sap of the plant contains an ionic solution which is able to sustain electrochemical reactions. If two different metals are used as electrodes inside the plant tissues, a potential difference is created due to the electrochemical nature of the metal electrodes and the plant ions.

Plant-based power systems currently in use, like the plant microbial fuel cell, produce genuine continuous flow via microbial catalytic action in the root zone but are not applicable where there is an urgency and need for quick set up or when using biomass that would otherwise be disposed of because these systems need living plants and take days to weeks to colonize and yield energy. However, a less complex system that dates back many years, called the fruit or tuber battery, produces instant output but is not considered as means of using waste plant matter.

The concept of generating electrical power via a bio-electrochemical energy generator with fresh leaves as the electrolyte and zinc-copper electrodes is investigated in this work. Environmental factors affecting the electrical characteristics of this system, including leaf weight and moisture content and electrode setup, are investigated. This methodology hopes to offer a fast and cost-effective method for generating electricity without any cultivation requirement from organic biomass that would otherwise go to waste.

2. Literature Review

With the rising interest in sustainable micro-generation of power, a lot of research has been done on biological fuel cells, plant electrophysiology, and renewable bio-electrochemistry. Many experiments have been conducted on the traditional fruit/tuber battery system, wherein two metal electrodes of different types are put inside the plant tissue, and the electrolytic solution present in the plant tissue forms a basic galvanic circuit. Even though there is a current voltage output in such a system, it works on very basic electrochemistry.

Also, plant microbial fuel cells (P-MFCs) have been extensively researched for their ability to produce continuous bioelectricity. In this process, the bacteria that can generate electricity reside around the roots of the living plant and use the exudates from the roots to create a constant flow of current throughout the life of the plant.

Microbial fuel cells utilizing mosses have also been studied, with an output that can support the operation of a radio or environmental sensor. Nevertheless, similar to P-MFCs, these cells take several weeks to become operational after being set up.

However, not much work has been done to focus on these electrochemical devices made from plant leaf tissues as a different class of energy sources that can provide an immediate source of electricity comparable to a fruit battery but from waste biomass. Moreover, the current literature does not specifically point out whether the performance of these systems is due to their live tissue architecture or just due to the ions dissolved in the leaf.

In order to mitigate the aforementioned shortcomings, the research proposal seeks to merge fresh-leaf Zn/Cu electrochemistry measurement, performance factor evaluation, and leachate structural control in one experimental setup, thereby turning the demonstration project into a

Table 1: Comparison of Existing Plant-Based Bioelectricity Systems

Existing Work	Immediate Output	Uses Waste Biomass	Biological Catalysis	Structural Mechanism Isolated
Fruit/Tuber Battery	Yes	No	No	No
Plant Microbial Fuel Cell	No	No	Yes	No
Bryophyte MFC	No	No	Yes	No
Proposed System	Yes	Yes	Under investigation	Yes (via leachate control)

structured bio-electrochemical power supply system.

3. System Overview

The bioelectric energy production system is made up of six layers that play different roles in the generation of energy. They include Input layer, Pre-Processing Layer, Processing Layer, Measurement Layer, Output Layer and Application Layer.

The Input Layer provides the raw materials which include fresh fallen leaves, mesophyll cells with chlorophyll, zinc and copper electrodes, and the environmental light. The Pre-Processing Layer prepares the raw materials by selecting appropriate leaves for use, positioning the electrodes and setting up the circuit. The Processing Layer performs the fundamental bioelectrochemical process through electron transfer from zinc anode to copper cathode which produces the voltage. Voltage, current and power production are measured in the Measurement Layer using a calibrated digital multimeter. The measurements are then transferred to the Output Layer for further analysis and bioelectric energy production. The Application Layer provides actual uses of the energy generation system in independent IoT devices, agriculture, environment and green energy production.

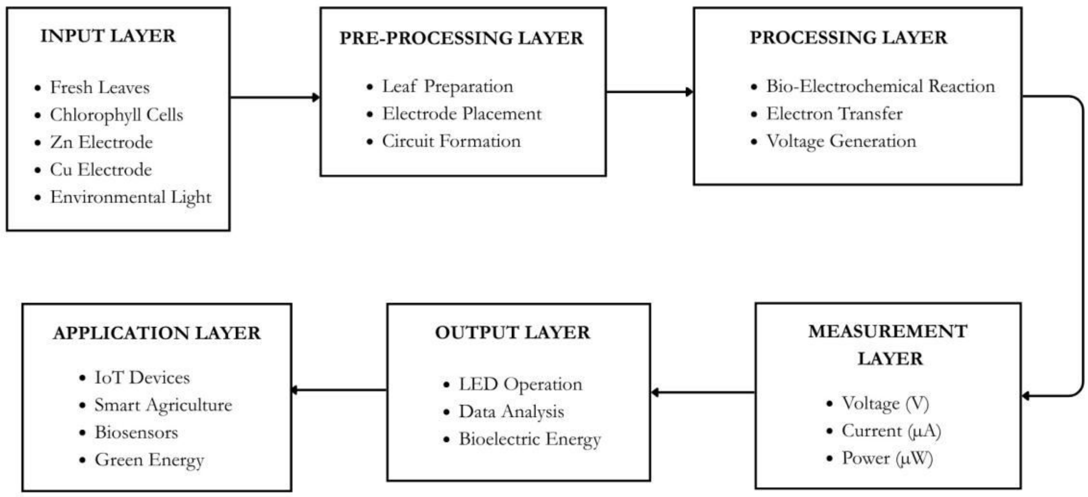

Fig. 1. System architecture of the proposed bioelectric energy generation process

4. Experiment Materials Used

Table 2: Materials and Components Used

Component	Function
Fresh fallen leaves (Neem)	Biological electrolyte medium
Zinc electrode	Anode (oxidation site)
Copper electrode	Cathode (reduction site)
Digital multimeter	Voltage, current, and power measurement
Connecting wires	Circuit completion
LED and load resistor	Load testing
Air	Ambient surrounding medium

5. Experimental Setup

The fresh leaves that have just fallen from the tree were used due to their high ionic conductivity. In this process, a zinc electrode (anode) and a copper electrode (cathode) were inserted into the leaf without altering its structural composition, and then it was connected with conducting wires to make an external circuit. The open circuit voltage was measured with the help of a digital multimeter for a single leaf battery, and then more batteries were added to increase the voltage.

6. Experimental Principle

The system operates on the principle of a galvanic cell where the sap of the leaves serves as the ionic conductor of the two half-reactions. For the oxidation reaction, there is electron loss by the zinc electrode at the anode end, while for the reduction reaction, the hydrogen ions present in the plant sap gain electrons at the copper electrode at the cathode end. The flow of electrons through the circuit is responsible for the production of electrical energy.

The hydrogen evolution reaction is the common pathway mentioned for the metal electrode plant/fruit battery systems; however, considering the open air conditions, the reduction of oxygen ($O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$) at the copper cathode is also a probable reaction path.

6.1 Electrode Reaction Model

$$Zn \rightarrow Zn^{2+} + 2e^- \text{ (Anode, oxidation)} \tag{1}$$

$$2H^+ + 2e^- \rightarrow H_2 \text{ (Cathode, reduction)} \tag{2}$$

6.2 Voltage–Biomass Relationship

The open-circuit voltage was found to scale with the number of series-connected leaf cells rather than with electrolyte volume on its own. Since each 25 g increment in total biomass corresponded to one additional leaf cell wired in series, the voltage response is better modeled as:

$$V(N) = N \cdot V_{cell} \tag{3}$$

where V is the open-circuit voltage, N is the number of series-connected leaf-electrode units (ranging from 2 to 8 in this study), and V_{cell} is the average voltage contributed by each individual cell (≈ 0.54 V in this study). Because leaf mass was scaled proportionally with N (approximately 25 g per added unit), an equivalent empirical relationship in terms of biomass also holds:

$$V(m) = k \cdot m \tag{4}$$

where m is the leaf mass and $k \approx 0.0217$ V/g. However, this mass-based form should be read as a proxy for the underlying series-cell effect rather than evidence that electrolyte volume itself drives the voltage increase. The near-flat current observed across configurations (5.1–6.5 μA, Table 3) supports this interpretation: a genuine increase in electrolyte volume within a single cell would typically raise current as well as voltage, whereas series-connected cells are expected to add voltage while current remains limited by the highest single-cell internal resistance.

6.3 Power Output Estimation

$$P = V \times I \tag{5}$$

where P is power delivered to the load, V is measured voltage, and I is measured current, used to characterize the system's usable output at each biomass configuration.

7. Electrical Output Regulation Mechanism

In contrast to systems with active automated control, the output of the novel bio-electrochemical cell is controlled passively through physical and biological regulation processes. The moisture level directly controls the ionic conductivity, such that fresh leaves with more sap always generate greater voltage levels. The electrode size controls the rate of electron exchange in the anode/cathode reaction, while internal resistance, resulting from the cellular structure of the leaf tissue, controls the ability to maintain voltage levels under a load. The drying or decay of the leaf tissue results in less mobility of ions, thereby creating the need to define a useful lifetime of the cell, which can be increased by replacing the tissue periodically or integrating storage elements.

8. Results and Analysis

The performance of the proposed system was assessed by measuring open-circuit voltage, current, and power for seven leaf mass/series-cell configurations.

Table 3: Leaf Biomass and Generated Electrical Output

S.No.	Leaf Mass (g)	OCV (V)	Current (μA)	Power (μW)
1	50	1.09	5.1	5.56
2	75	1.63	5.3	8.64
3	100	2.17	5.6	12.15
4	125	2.72	5.8	15.78
5	150	3.26	6.0	19.56
6	175	3.80	6.2	23.56
7	200	4.34	6.5	28.21

The current was relatively constant (5.1 μA to 6.5 μA) through all seven configurations, which is expected for a serial cell connection, where voltages add up but currents are limited by the maximum internal resistance of any one individual cell. The results do not conform to those predicted in an electrolyte/mass scaling model, where higher volume should lead to increased current.

Fig. 2. Voltage generation in 100 g of leaves

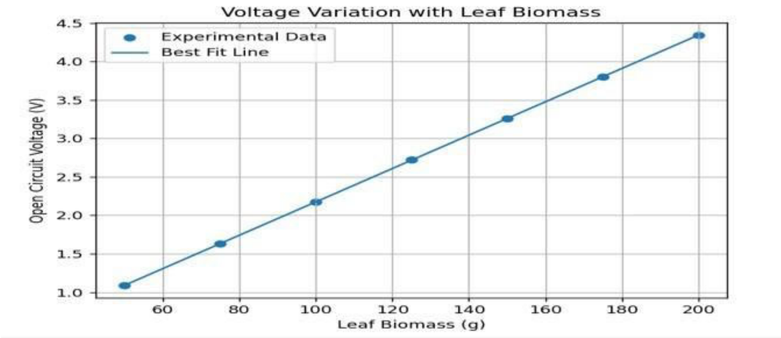

Fig. 3. Voltage variation with respect to mass of leaves used

The voltage increased almost linearly with leaf mass/series-cell count, as expected from the proportional model in Section 6.2. The current was in the microampere range during the entire test, confirming the system as a low-power bio-battery with high internal impedance. Correspondingly, the power output scaled accordingly, reaching the maximum of 28.21 μW at the 200 g configuration.

9. Environmental Impact

The proposed leaf-based bioelectric system contributes to environmental sustainability by converting otherwise discarded organic biomass to a usable micro-power source. There is no need for cultivation and chemical processing or the environmentally costly material extraction of conventional batteries. The electrolytic medium consists of biodegradable plant material so the system produces no lasting electronic waste except for the recyclable metal electrodes. This approach provides the circularity of maximising the resources of fallen leaves for practical use before their natural decomposition in line with broader green energy and sustainable waste-toenergy goals.

10. Scalability and Deployment

The proposed system is modular, thus suitable for use in diverse low power applications like environmental sensor networks, agricultural monitoring stations, and educational demonstration units. Due to the omnipresence of the relevant biomass (fallen leaves) and the renewability every day, the system can be scaled up by simply increasing the number of series or parallel connected leaf cells for particular voltage or current requirements. The system is amenable to decentralised, community level or institutional deployment with minimal investment in infrastructure due to the low-cost hardware configuration (electrodes, wiring and basic measurement equipment).

11. Conclusion

The results of this study have shown that fresh fallen leaf tissue, in combination with a zinccopper electrode system, is a natural bioelectric generator. The technique provides a green, renewable, low power energy source, causing no damage to the environment of the source plant, and using otherwise wasted biomass. The results confirm an almost linear relationship between leaf biomass / series-cell configuration and voltage output with power in the tens of microwatt range. In future work we will disentangle the specific contribution of intact living tissue versus dissolved ionic content, develop improved electrode materials, reduce internal resistance, and include energy storage components. The system shows great promise for use in stand-alone IoT devices, agricultural monitoring systems, and environmental biosensing applications.

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