Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 8, 607-623
2025
Publisher: Learning Gate
DOI: 10.55214/2576-8484.v9i8.9392

Plants as a possible green energy source in future: Opportunities and challenges

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Abstract: By embedding electrode pairs into trees and plants and employing electrochemical processes, it is possible to harvest electrical energy. This energy is environmentally friendly, autonomous, and available 24/7 regardless of weather conditions. This paper discusses the effects of various external and environmental factors on the energy harvested from plants. It also explores the challenges associated with utilizing plants as batteries. It has been observed that acid trees and succulent plants are rich sources of electrical energy. The shape, size, quality, material, placement of electrodes, and the number of electrode pairs are important factors in determining the amount of energy harvested, in addition to external and environmental influences. Furthermore, it has been noted that the electrical energy output from plants can be increased through series combinations of multiple plants. Heterogeneous series connections of different plant types produce larger energy outputs than homogeneous connections. Fresh leaves generate higher potential than damaged leaves due to increased dielectric properties. The lower electrical capacity of plants is attributed to higher impedance, which varies with frequency. Lower frequencies result in reduced current compared to higher frequencies due to reactance variations. Soil temperature and humidity are also significant factors that should be considered during energy harvesting. To optimize the energy harvested from plants for use as a future battery, all external and environmental factors must be optimized, along with increasing series connections. Electronic devices or sensors placed in remote or inaccessible areas can be powered effectively by this energy source. The main challenges in using plants as batteries include their low current output and the stability of the harvested energy.
Keywords: *Electrochemical process, Electrodes, Green energy, IoT, Living plants, Photosynthesis.*

1. Introduction

The Internet of Things (IoT) is a new emerging technology in which electronic devices/sensors communicate through internet to collect and share the data for making collaborative decisions to accomplish the tasks remotely in an optimal manner without much interference of human being [1-3]. IoT devices have enhanced sensing, computing, and communication capabilities that allow them to communicate, sense, or interact with their internal state or external environment. IoT systems are the next revolutionary concept in transforming the internet into a fully integrated network, enabling harmonious interaction between societies, individuals, and intelligent systems. During early phase of IoT development, energy was not a serious threat due to limited number of connected devices which were typically powered by Li-ion batteries [4, 5]. The use of Li-ion batteries or any chemical batteries are not only dangerous for environments but also needs to be regularly replaced or recharged, which may be very difficult, dangerous, or even impossible in remote or inaccessible locations. The regular

History: Received: 3 June 2025; Revised: 22 July 2025; Accepted: 25 July 2025; Published: 11 August 2025
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replacement or charging of the batteries can impose additional costs and complexity. As the IoT continues to evolve at an accelerated pace, development, and effective implementation of an appropriate method for energy autonomy in each IoT system is need of the hour [6, 7]. To operate the IoT system in an energy autonomous, maintenance-free manner with infinite lifetime. it needs to be powered from renewable energy sources [8] for operation, communication, and data processing instead of conventional battery. Demand of renewable energy is not only increasing in powering IoT based devices but also required for smart sustainable farming [9-12] because IoT plays a crucial role in sustainable agriculture by enabling real-time data collection and analysis, leading to more efficient resource management, improved crop health, and enhanced decision-making. This technology helps farmers to make informed decisions about irrigation, fertilization, and pest control, ultimately reducing waste, minimizing environmental impact, and maximizing yields. Renewable energy is a path for sustainable future which is generated from inexhaustible assets, for example, wind, rain, tides, waves, geothermal etc [13, 14]. The development of renewable energy sources is required to meet the global energy demand by reducing reliance on fossil fuels and minimizing greenhouse gas emissions which has been identified as one of the key societal challenges of modern time [15]. The renewable energy can improve the quality of human life, enhance people's health, and do less damage to the environment. Due to these reasons, green IoT technology attracted attention of the researchers across the globe [16-18]. Green IoT related to the reduction of energy consumption of IoT devices which achieves a sustainable environment for IoT systems. In general, energy saving can be achieved by improving the energy efficiency of devices and the use of energy-efficient monitoring and management systems. The sun is the most important source used to produce photovoltaic energy. Photovoltaic energy can be produced with the help of solar energy which is converted into electricity with the aid of solar photovoltaic panels. Solar energy (photovoltaics) is the fastest growing technology in terms of global annual and cumulative installed capacity. This source is an alternative to the conventional energy sources that supply power for remote communities because it is abundant in nature and considered as one of the cleanest energy sources with mature technology [19, 20]. Still there are many challenges associated with use of solar energy which limit us from scaling up [21, 22]. Some of these challenges include lower efficiency, higher installation and manufacturing cost and its availability during day and night as well as cloudy/rainy session [23-25]. In summer the sun shines brightest and longest during daytime whereas in winter the situation is entirely different.

Recently scientific explorations showed that plants may become a potential source of bioenergy which is not only renewable but also sustainable and cost effective in terms of maintenance and resources [26-28]. Plants are called autotrophs because they can use energy from light to make their own food. In the presence of light and chlorophyl, water, and carbon di-oxide (CO_2) are chemically combined in leaf of plant to make glucose, and this process is known as photosynthesis whereas in respiration process glucose molecules are broken down in presence of oxygen to liberate electrons [29, 30]. These two processes induce the flow of electrons inside the plants which can be captured by pair of electrodes. By embedding electrodes into the plants/trees and employing an electrochemistry process, the chemical energy can be converted into electrical energy via an oxidization-reduction reaction [31-33] process. Another way for extracting electrical energy from plant is due to mechanical movement of the plants in presence of air where any vibration and motion of the plants will be converted into electrical energy using electrostatic, piezoelectric or electromagnetic transducer. Bio electrochemical system is another method of harvesting energy from living plants where it extracts the energy by the anaerobic oxidation of rhizodeposits at the roots of plants using plant microbial fuel cell (PMFC). This source of energy is autonomous due to its availability. Placement of electronic devices or sensors for monitoring and data logging in remote areas such as forests can be powered by taking energy from the living plants around that area. The plant continues produces electrical energy all the time (24x7), both at night and during the day, while plants are still alive irrespective of the weather conditions.

The objective of the research paper is to the study the performance of the trees/plants as a source of electrical energy. We studied the environmental effects like hot wind, temperature, water droplet and dust on electrical energy harvested from plants. We have earlier observed that the leaf of Aloe vera and Sansevieria plants gets damaged due to insertion of electrode [31, 32]. This damage is due to reaction between electrode and gel of the aloe vera plant. The amount of damage is more in Aloe vera plants compared to Sansevieria plant. The damage of leaf poses a serious question on the survival of the plants. In this research paper we have used nail shaped electrode to avoid the damage of leaf. The stress in the leaf severely reduces the harvested potential due to dielectric property of the damaged leaf. Experimental results reflect that plants produce lower current (of order of μA) which is not enough to run moderate wattage gadgets. We have connected plants either in series or parallel to boost the harvested energy from plants. The stack effect of plants in terms of harvested potential is more dominant when heterogeneous plants are connected in series than the homogeneous plants connection. To optimize the harvested energy for useful purpose it is required to consider the quality and type of electrode pairs, separation between electrodes, number of electrode pairs used and quality of the leaf. It is also required to optimize the separation between electrode pair, environmental conditions and external factors to harvest maximum electrical energy from these sources. Although these energy sources are abundant in nature and useful for sustainable growth of cities and villages but to make them practical use as Plant base cell is real challenge. These challenges must be addressed to realize the reality of the concept. This paper also discusses in detail about the challenges associated with the realization of plant base cell (PBC) in future.

The paper is organized as follows. In Section II, the experimental setup and its detail have been presented. Section III discusses the experimental results in detail whereas section IV explains the challenges of harvesting electrical energy from plants/trees whereas section V concludes the paper.

2. Experimental Setup

Various experiments were performed on a variety of plants and trees to harvest electrical energy. These experiments are conducted both indoors and outdoors conditions, with varying results depending on the plant species, environment, and electrode materials. To use plants as a possible renewable power supply in future, we have conducted experiments under different environmental and external conditions. We have analyzed the challenges for meeting sustainable energy needs from the plant and use them as battery/or cell in future to replace hazardous chemical batteries. We have chosen plants ranging from succulent (these plants could store water in their leaves, stems and roots giving them fleshy or swollen appearance) to non-succulent (these plants have no water storage capacity) species which are easily available in tropical desert climate. A simple experimental setup for harvesting electrical energy from plants is shown in Figure 1(a). A digital multimeter was used to capture the voltage and current through the plants. The type and shape of the electrodes are major factors which affect the harvested electrical energy and hence it must be chosen carefully based on higher positive standard electrode potential and negative standard electrode potential. We have conducted experiments with two different shapes of the Cu-Al pair as shown in Figure 1(b). Copper (Cu) and aluminium (Al) are frequently chosen as electrode pairs in electrochemical applications due to their distinct electrochemical properties and potential. Aluminium is more reactive and readily oxidizes, making it suitable as the anode (negative electrode) whereas copper is less reactive and can be reduced at the cathode (positive electrode). The quality of electrode is another matrix for measuring the performance of electrical energy. During experiment process we have used sand paper to clean the respective electrodes frequently to avoid any dendrite accumulation.

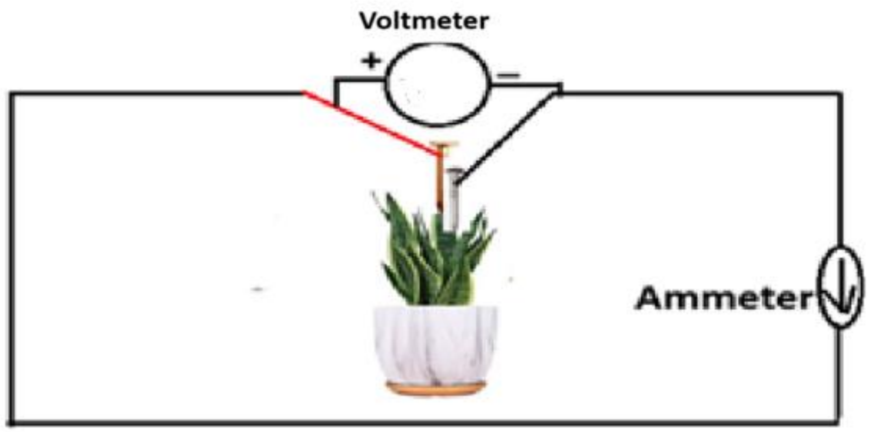

Figure 1.
(a): Experimental setup.

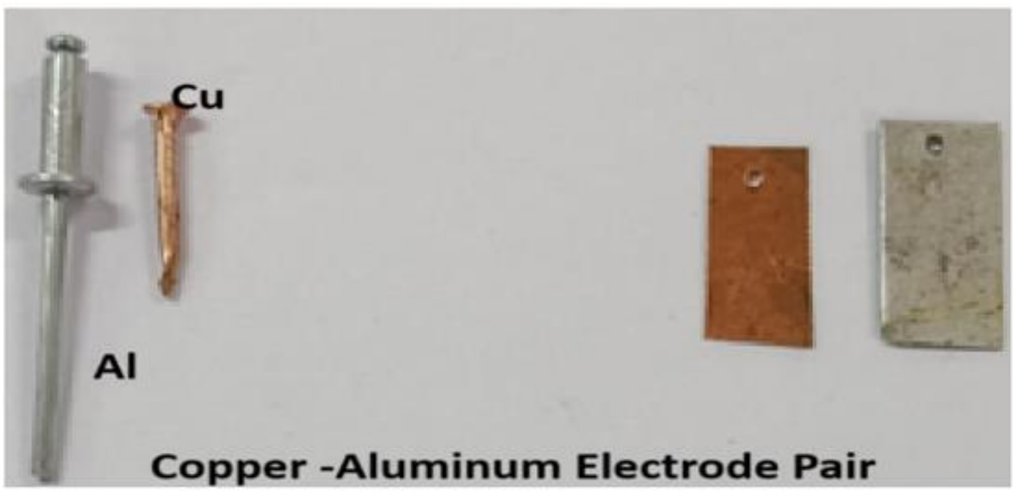

Figure 1.
(b): Shape of electrode pair.

The main concern related to treat plant or tree as a possible Plant base battery (PBB) in future is its lower conductivity. The lower current capacity is due to high electrical impedance of the cell membrane, which acts as an insulating layer. In Aloe vera leaf, the membrane lipids, a key component of the cell membrane, enable the plant to store electrical charge and acts as an insulator to prevent a strong current flow through the leaf. The impedance of the aloe vera leaf is related to the electrical properties of the leaf tissues and their ability to conduct current at different frequencies. Study related to the variation of leaf impedance with frequency is crucial for understanding plant health and water status because impedance, a measure of electrical resistance and reactance, is influenced by factors like cellular water content and membrane structure. This frequency-dependent impedance profile also provides valuable information about the ion concentrations, and other physiological aspects. The dependence of impedance on frequency can be explained with the help of the electrical equivalent model of an Aloe vera leaf as shown in Figure 2(a) [34]. The whole model is divided into three parts, namely, outside membrane, membrane and within membrane. This model represents the leaf's electrical properties, including its resistance to current flow (R), its ability to store electrical energy i.e. its parasitic capacitance behaviour (C), and its internal voltage generation (V). The cell membrane, which acts as an insulator between the intercellular and extracellular fluids, contributes to the capacitive effect. Resistance Rin represents the resistance of fluid within the cells, R_o represents the resistance in the fluid outside the cells, R_i represents the resistance within the fluid surrounding the cells whereas C represents the capacitance in the respective area of leaf. To experimentally observe the variation of impedance with frequency, we have performed experiment on Aloe vera leaf with the setup as shown in Figure 2(b). Here we have taken a pulse of 3 V for performing experiment because pulsed electric fields (PEF) allow for a non-destructive and relatively quick analysis of the plant's physiological state.

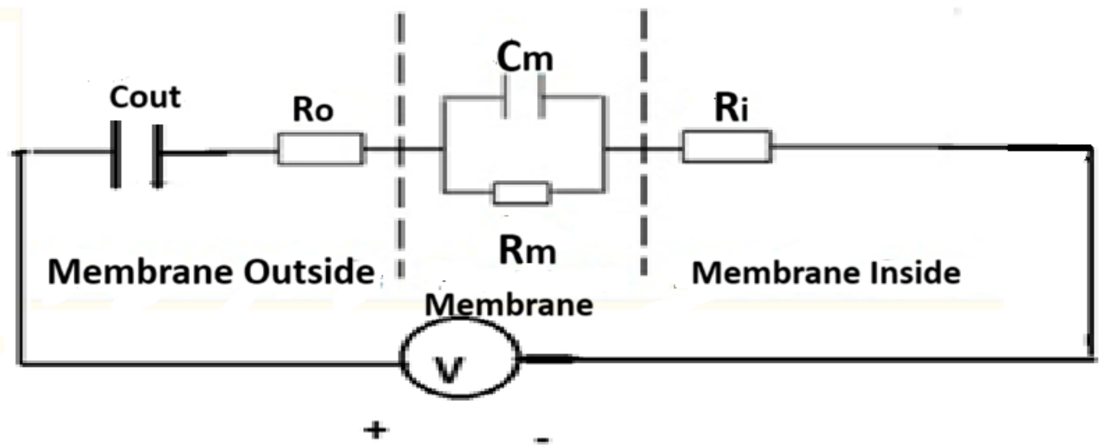

Figure 2.
(a): Electrical equivalent model of Aloe vera plant

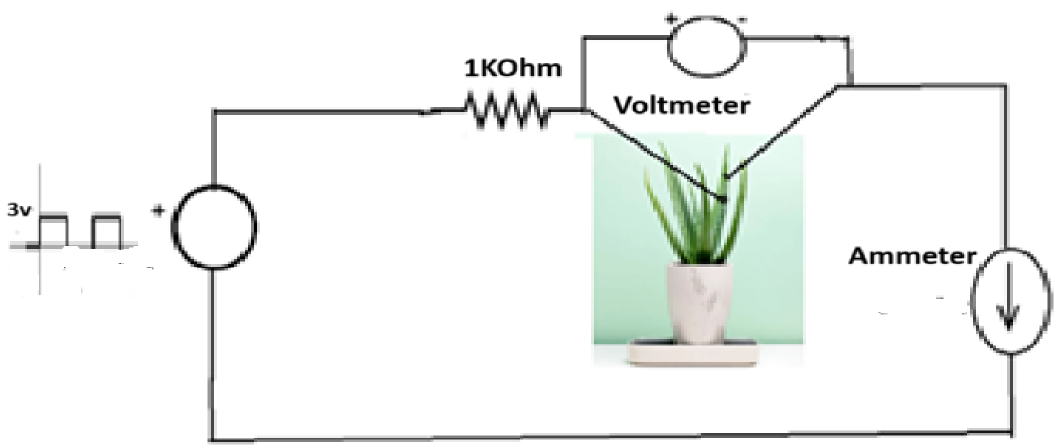

Figure 2.
(b): Experimental setup.

3. Result and Discussion

We have conducted extensive research on electrical energy generated from plants ranging from succulent to non-succulent as well as on various trees including acidic tree. Among all available trees, we observed that Phyllanthus emblica (Indian name amala tree) is the best source of electrical energy and produces potential order of 1.10 V due to acidic nature. Acidic trees are good source of electrical energy compared to non-acidic trees because of their ability to create an electrical potential through the movement of charged particles (ions). Similarly in plants, we observed that Aloe vera and sansevieria are favourable in terms of electrical potential. In this paper, we have chosen succulent plants for further investigation.

As discussed earlier for conducting the experiment we have chosen two shapes of electrode pairs. Our experiment shows that the nail type of electrode pair results in larger potential than the rectangular shaped pair ($V_{shrap\ edge}$=1.026 V, $V_{non-sharp\ edge}$=0.915V). The pointed or sharp edges can concentrate the electric field, potentially leading to higher field strengths which needs to be harnessed effectively. It is also observed that the position of electrode pairs and number of used electrode pairs are important factors that affect the harvested potential severely. Microorganisms around the plant root zone produces lot of bacterial activity which releases electrons. These electrons can be captured with electrodes placed around tree roots to harvest electrical energy. The generation of electrical energy continues if plants alive, but we do not observe any improvement in the harvested potential when one electrode is placed near root or in the soil and other on the leaf. This may be due to increased impedance. The quality of the leaf must also be considered while performing the experiment to harvest energy. We have conducted experiment on two leaves; one is severely damaged whereas other was moderate damaged. Due to severe damage of the aloe vera leaf the harvested potential falls from 1.026 V to 0.673 V whereas moderate damage leaf results in 0.845 V. The degradation of the harvested no load potential is due to increased dielectric properties of the dead tissues. Increased dielectric property will make the leaf more insulator and restrict the current flow.

It is experimentally observed that single tree or plant is not able to deliver larger potential or current which is not enough to power up any electronic devices. Therefore, to further improve the harvested potential, we have taken stack of trees and plants. We have connected two plants/trees in series for two cases, case 1: taking same type of plants/trees and case II: different type of plants/trees. This stack effect we termed as Internet of Plant (IoP). Two important observations were obtained, 1. no appreciable change in voltage/current is observed when two same types of plants/trees are connected in series, 2. Connection of heterogeneous plants/trees produces larger energy compared to homogeneous connection. Connecting two heterogenous plants (one Aloe vera and other Sansevieria) in series results in 1.145 V which further increase to 1.452 V as shown in Figure 3(a). The harvested no load voltage stabilizes at 1.452 V. We have increased the number of electrode pairs on same heterogenous series connection and observed the no load voltage increases to 2.363 V and reach to maximum of 2.533 V (Figure 3(a)). This increase is due to more number of series connection.

Figure 3.
(a): Heterogeneous plants connected in series.

We conducted the experiments on variety of the cactus plants as shown in Figure 3(b). These plants were grown in our university nursery. The average harvested potential from cactus plant is approximately 0.9 V. This potential is produced due to chemical reaction between the cactus and metal electrodes which is facilitated by citric acid present in the cactus. This citric acid acts like electrolyte solution which facilitates the flow of ions between the anode and cathode, enabling the electrical current to flow. We also conducted the experiment with heterogenous connection of cactus plants as shown in Figure 3(c). When two nearby heterogenous plants were connected in series, we get 1.765 V. Although, this no-load potential is larger than standard 1.5 V, which is required to run any electronic gadgets, but we were unable to power up medium or high wattage electronic devices/and gadgets. The main reason for this is due to poor current capacity even at higher potential.

Figure 3.
(b): Harvested potential from different cactus.

Figure 3.
(c): Series connection of two different cactus plants.

Figures 4(a) and 4(b) show the variation of impedance and current flow through the leaf at lower and higher frequencies. At lower frequency (≤5 KHz) capacitive reactance dominates which results in increase in the effective impedance of the leaf due to series connection of R and C (Figure 2(a)). The increased impedance of leaf at lower frequency results in lower current. This lower current at low frequency travels through the outer connective tissues. A peculiar observation is that although the effective impedance reduces as frequency increases from 5 KHz to 10 KHz but still current falls slightly. This can be explained that in this frequency range the current cannot penetrate deep into the cell layer and falls less rapidly than the earlier case (Figure 4(b)). At very high frequency (≥50 KHz) the overall impedance of the leaf reduces due to parallel connection of R and C. Now current penetrate entire leaf and results in larger current (Figure 4(b)). Since the harvested current from plants and trees are of order of μA and hence we are able to run only those sensors/devices which consumes μWatt energy as shown in Figure 4(c). This study confirms that very low power (μW) consuming devices can be easily powered by harvested energy from plants or trees in future. Parasitic capacitance in an Aloe vera leaf can reduce the harvested potential, leading to a decrease in the overall energy output due to leaf's internal structure. We have observed that this effect is more pronounced with larger leaf widths compared to smaller leaf width due to decrease in the volume of the conducting medium between electrodes over time. In future it is required to carry out a detail analysis of leaf anatomy to enhance the current capacity.

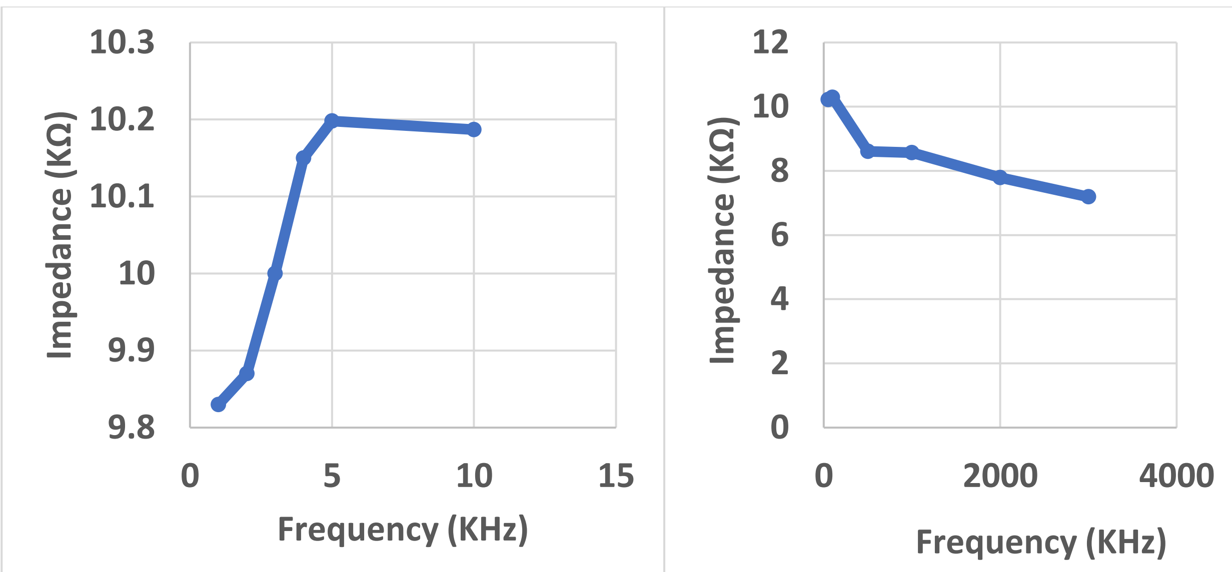

Figure 4.
(a): Variation of Impedance with frequencies.

Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 8: 607-623, 2025
DOI: 10.55214/2576-8484.v9i8.9392

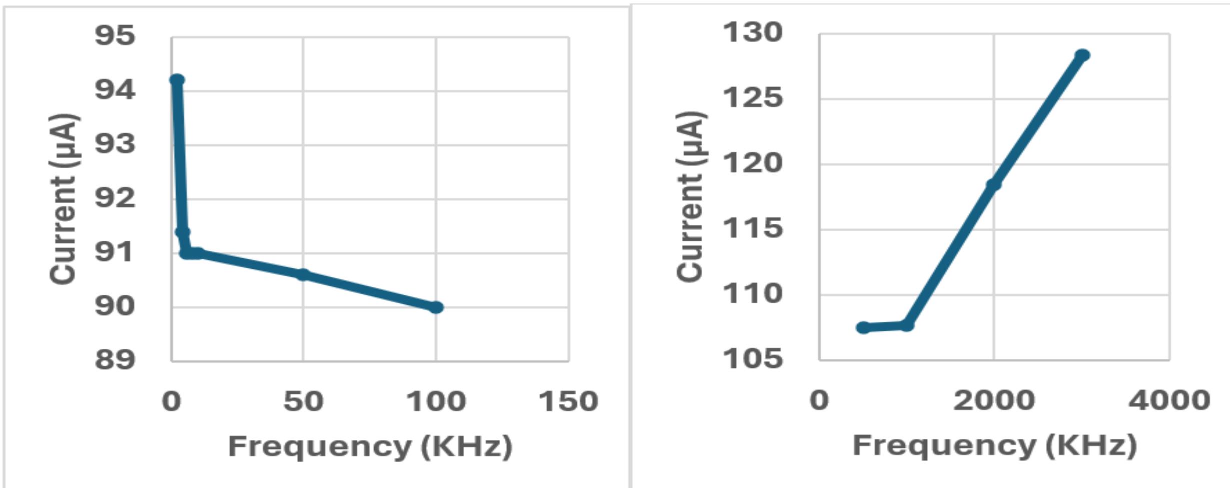

Figure 4.
(b): Variation of harvested current from Aloe vera plant with frequency.

Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 8: 607-623, 2025
DOI: 10.55214/2576-8484.v9i8.9392

Figure 4.
(c): Application of harvested potential from plant/trees to power up sensor

The effect of temperature on the harvested potential from Aloe vera and Sansevieria plants has been studied for two situations
Situation 1. blowing hot air using blower and
Situation 2. Putting the plants in oven.

The experimental results are shown in Figure 5. In the presence of hot air, the harvested potential from Aloe vera leaf first increase and then remain constant whereas change in harvested potential from Sansevieria leaf is almost negligible. In hot air, the water content of a plant decreases due to increased transpiration and potential damage to plant cells from heat stress. Additionally, high temperatures can lead to cellular damage, including protein denaturation and enzyme inactivation, further impacting the plant's ability to maintain its water potential. At lower and moderate temperatures, it may be possible that the photosynthesis activity in plant increases whereas at higher temperature there may be negative effect on photosynthesis action. A slight increase in photosynthesis may release more number of electrons/ions which can ultimately increase the current. These results also show that these two plants can survive even at higher temperature. At T=5⁰C, harvested potential from Aloe vera leaf is 0.818 V compared to 0.909 V from Sansevieria leaf because at lower temperatures, Sansevieria plant (Snake Plant) generally exhibits more photosynthesis action compared to Aloe vera.

We also interested to see how the presence of water droplet on leaf can affect the harvested energy from plants. For this purpose, we have created situation like rain and observed that the presence of water droplet on leaf increases the harvested potential of Aloe vera leaf to 0.945 V because water droplet on aloe vera leaf can improve plant-water ratio and improves the photosynthesis action which results in larger potential whereas potential from Sansevieria leaf falls from 0.920 V to 0.915 V because of decrease of CO_2 uptake through stomata which reduces photosynthesis in Sansevieria plant. Dust accumulation on plant leaves significantly impacts photosynthesis by reducing the amount of light reaching chlorophyll, affecting stomatal conductance, and potentially harming the leaf's overall health. The presence of dust particles on the leaf results in lower potential irrespective of plants due to increased impedance as well reduced photosynthesis process.

Understanding the moisture condition of soil is crucial for assessing the harvested potential of living plants because it directly impacts overall photosynthesis activity in the plants. Therefore, to understand the impact of moisture condition of soil on the harvested electrical energy from plants, we have performed experiment in outdoor conditions. Experimentally we observed that soil condition (wet or dry) affects the harvested potential. Dry soil increases the impedance and reduces the harvested potential whereas excessively wet soil creates stress in the plants which also results in decrease in harvested potential.

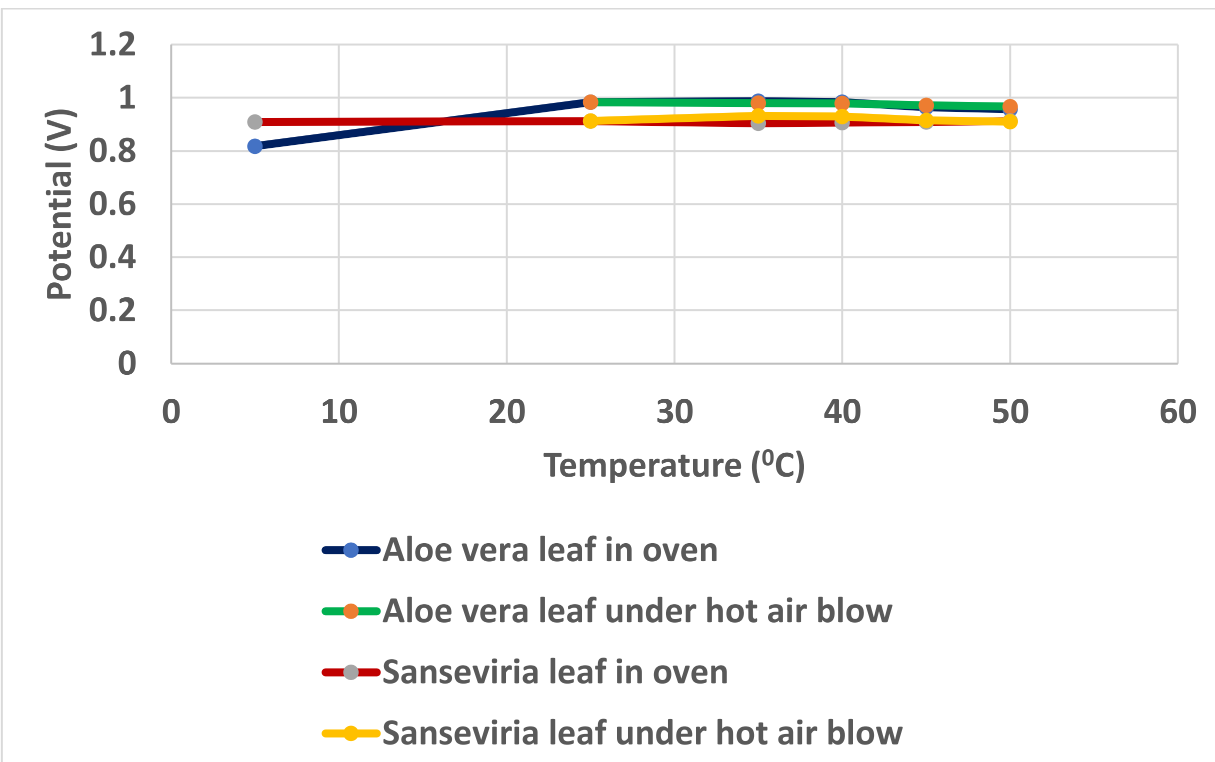

Figure 5.
Harvested potential in presence of water droplet on leaf.

Plant electrical signals, provides valuable insights into plant responses to stimuli, are often weak and prone to noise. This makes noise analysis crucial for accurately interpreting the electrical behaviour of plant. We have studied the effect of noise on the harvested electrical signal of Sansevieria leaf. During experiment, we have observed that when electrode pair is on the same leaf, we did not observe any noise present in the harvested potential but as soon as electrode pair is placed on different leaves, small noise is introduced in the harvested potential (Figure 6). This may be due to mismatch in impedance of the leaf. Noise reduction is important to isolate the plant's signal from unwanted disturbances which can be achieved by using electronic filter circuit.

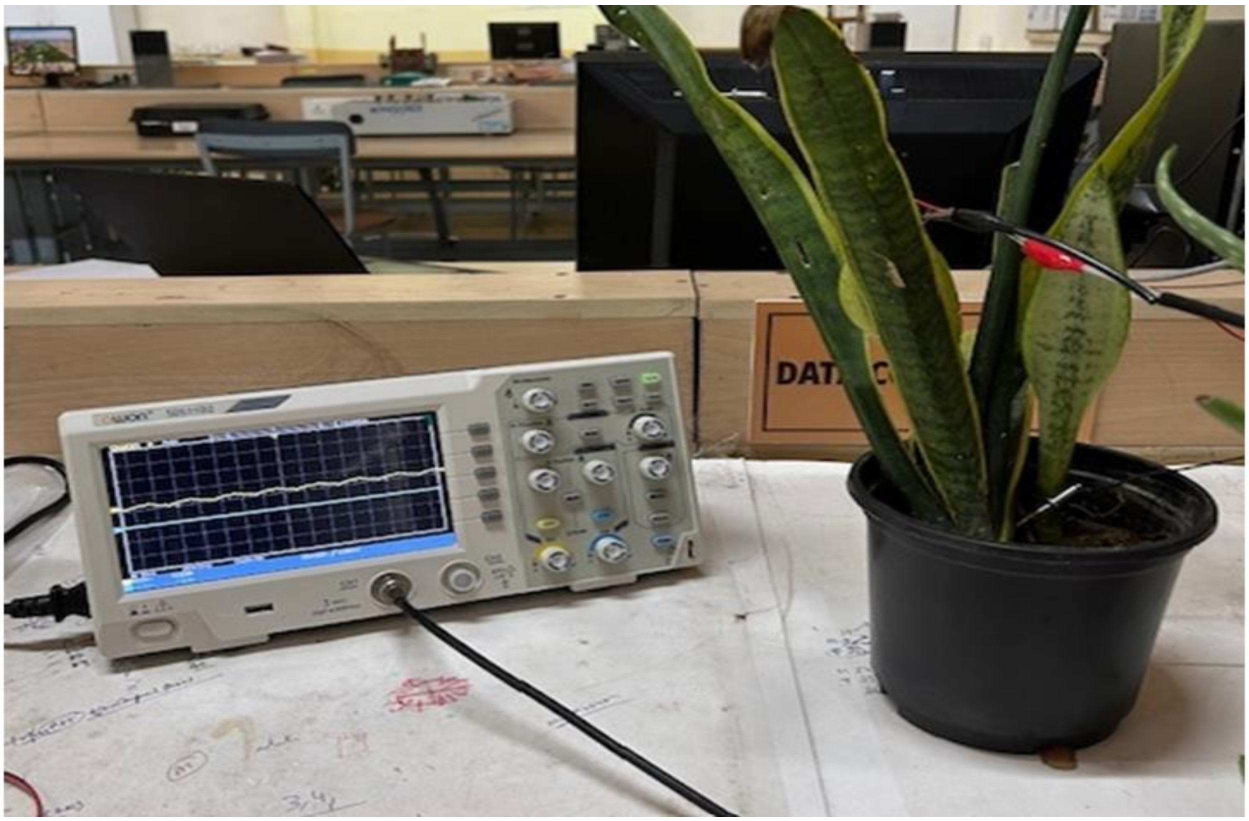

Figure 6.
Experiment to study noise effect.

4. Challenges

Harvesting electrical energy from plants faces significant challenges, including the need for high current efficiency, long-term stability, and scalability for practical applications. The main challenge associated with plants and trees, using them as a possible source of electrical energy in the future, is their lower current capacity. To address this problem, we have connected plants/or trees in series or parallel either taking homogeneous or heterogeneous types. In our study we observed that series or parallel connection either on same leaf or different leaves do not add the voltage or current as per circuit law due to mismatch in electrical impedance of the leaves. We have connected two homogeneous trees in series which are separated by 3-4 feet and observed that total harvested potential is not equal to sum of individual harvested potential but always closer to the larger individual potential. Also, series or parallel connection of two plants do not result in appreciable current improvement. These observations only confirms that the plants or trees generate lower current due to higher impedance.

ISSN: 2576-8484
Vol. 9, No. 8: 607-623, 2025
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Another challenge we faced is related to the stability of electrical energy. There is an appreciable variation in the harvested potential and current with time due to natural variability of plant activity and environmental factors which impact electrical energy generation and makes it difficult to achieve consistent and stable power output. This challenge imposes a serious concern to use plant as a possible power supply in future. This issue can be addressed by storing the harvested energy first into super capacitor instead of directly connecting the load.

The choice of electrode material and design/shape can significantly affect the voltage and current generated. Therefore, choice of suitable electrode materials that are biocompatible, efficient, and durable is an ongoing challenge. Also, optimizing electrode placement and configuration to maximize harvested energy is another big challenge in future for conceptualizing this concept into reality as battery.

Integrating plant-based energy harvesting systems with efficient and reliable energy storage solutions is another challenge for ensuring a continuous and stable power supply. Although, the current capacity of a leaf can be achieved by optimizing the environmental and internal structure simultaneously so that its photosynthetic efficiency can be increased but it cannot work alone. In future, by connecting more heterogenous plants together in series connection may increase the current capacity. The lower current capacity challenge can also be addressed by designing electronic circuit. This circuit is known as power management circuit in which first we have to store the harvested energy directly in input super capacitor and later boost the current at required level. This electronic circuit can be turned into a biohybrid energy storage device which will also stabilize the harvested energy with time.

A deeper understanding of plant biochemistry and the processes that generate electrical potential is another important issue and challenge which must be addressed appropriately. The plant health, its survival and maintain ecosystems after inserting the electrodes is important and serious challenge. Addressing the potential impact is one of the important tasks.

5. Conclusion

Unlike traditional energy sources, electricity generated from plants is renewable and eco-friendly which contributes to a sustainable future by allowing carbon-free energy, and cost-effective for remote areas. Acidic trees could play a valuable role in the green energy generation due to the potential difference in pH. This difference can create a current when a pair of electrodes is embedded in the tree and connected to an external circuit.

Factors like sap content and environmental parameters can influence the output power. Similarly, plants like Aloe vera, Sansevieria and Cactus are favourable to- act like plant base cell (PBC) in future. Like solar, wind, and other renewable sources, electricity from trees may be one day become part of an innovative approach to achieve carbon neutrality and eco-friendly environment. This energy will be cost effective and helpful in sustainable development of rural areas in terms of smart farming and power supply to their household devices and lightning bulb.

Plants produce very low voltage which can be boost to usable level by using power converters. Plant's photosynthesis activity is influenced by various factors, including sunlight, temperature, and moisture.

These fluctuations cause the harvested voltage and current to vary significantly, making it necessary to design reliable and consistent energy harvesting systems. It is important to find the suitable electrode materials that are biocompatible, efficient, and durable for optimizing the harvested energy. Electrode placement and number of electrode pairs must be taken into consideration to maximize the harvested energy. Environmental factors like temperature, humidity, and light availability play an important role in deciding the amount of generated electrical energy from trees and plants and these factors must be optimized for harvesting optimal energy.

The main limitation of plants/trees to use them as a battery source in future is their lower current capacity due to higher impedance. The current in the plants or trees can be increased through a combination of environmental factors, such as light, temperature, water, and manipulation of leaf anatomy and physiology which can help in reducing the impedance of the leaf. The impedance of the leaf also varies with frequency which reflects the health of the leaf and water content.

The series and parallel combination of heterogeneous trees or plants results in larger electric energy compared to homogeneous trees/plants.

This combination is termed as Internet-of-Plant (IoP). If this approach is successfully implemented, it could meet some basic electricity needs in small cities and remote rural areas where conventional power sources are often unavailable. In forests and densely populated plant areas where thousands of trees thrive, the total amount of electricity that could be generated from these trees might be enough to satisfy minimal energy requirements of surrounding communities.

To make it reality it is required to develop an electronic system to store the harvested energy first and then boost it to required current level so that it can be used as a plant-base cell (PBC) in future for sustainable growth.

Harvesting electricity from plants on a large scale is challenge due to the lower energy output per plant. To harvest appreciable energy, it needs to connect many trees in series which sometime impossible in the city. Therefore, to realize the plant as electrical energy source in we have to develop electronic systems, known as power management system, that can store the electrical energy to run the electronic devices and gadgets efficiently.

The cost of the system must be calculated by considering electrode types, power converters, and monitoring equipment. The developed circuit must be cost effective for practical applications as a battery to make sustainable growth basically for rural people and to fulfil the requirement of power.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Acknowledgement:

The authors are thankful to NIIT University-Neemarana for providing financial support under NIIT UNIVERSITY IGNITION GRANT (NUIG) scheme.

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