Green Signals:Analyzing Plant Bio potential Signals and their Interplay with Soil Moisture and Frequency components

DISSERTATION

Submitted in partial fulfillment
of the requirements for the Bachelor's degree

by

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DISSERTATION

St. Xavier's College, Mumbai

For the Bachelor's Degree
IN **PHYSICS**

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Table 1

Acknowledgement

We express our deepest gratitude to God for providing us with strength, guidance, and inspiration throughout this journey.

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Abstract

This dissertation investigates the bio potential signals within the plant and its relationship with environmental factors.

We employed a simple device using ECG electrode to capture signals (waveform) of different plants.The study focused on the influence of soil moisture (environmental factor chosen for study) of these signals, aiming to establish a correlation between these two variables and a predictive model.
Furthermore, we explored soil conductivity from the data received for particular plant and impact of varying soil moisture. To study the relationship of soil moisture to the bio potential values, an electrical circuit model was proposed, providing a theoretical framework for understanding the underlying electrical processes within plant-soil system.
Finally, a Fourier transform analysis was conducted on the captured bio potential signals to identify their frequency components. This analysis revealed the dominant frequencies present within the the signals, offering insights into the plant's communication dynamics.

This project serves as a robust foundation for future research, with our setup readily accommodating diverse experimental variations.

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Chapter 1

Introduction

Plants utilise electrical signals to communicate and respond to external vibrations, which is an extensive area of research. In the 1900s, Indian scientist Sir Jagadis Chandra Bose was the first to study the effect of microwaves on the membrane potential of plant tissues. He conducted pioneering experiments to demonstrate the presence of electrical signals in plants and invented the Crescograph to detect very slow responses to electric stimuli from the plants.

Today, many researchers use bio electric sensors to measure and monitor the electrical impulses in plants. The communication and environmental response mechanisms in plants are driven by bio electrical signaling, a fascinating process that utilizes weak electrical potentials generated by ion gradients across cell membranes. Unlike the robust action potentials in animals, plant bio electrical signals are subtle and triggered by various stimuli, including touch, wounding, and abiotic cues such as light intensity, pH changes, temperature fluctuations, and electromagnetic fields. These stimuli disrupt the ionic distribution within plant cells, leading to localized potential differences that trigger physiological responses.

Studying plant electro physiology enables the development of biosensors to monitor environmental conditions affecting plant electrical activity. This field helps detect pollutant and pesticide impacts, track climate change effects, and understand factors influencing crop yields.

This is a very extensive area of research that not many people or students are familiar with. A series of questions compels researchers to study plant electrical signals. Can these electrical signals be precisely controlled? What physiological information does the signal carry, and how can it be deciphered?
This dissertation delves into the application of bio electrical monitoring as a novel tool for assessing plant health. By capturing and analyzing electrical signals, we aim to establish a deeper understanding of plant physiology and responses to environmental stimuli. This knowledge can be leveraged to develop innovative strategies for optimizing crop health and yield on a large scale.

Chapter 2

Literature Review

Background:
The theoretical understanding of this project will include to understand what these parameters are in biological terms that is understanding what all processes contribute or are the causes for bio potential signals and all other underlying factors and considerations.

2.1 Bioelectrical Potential in Plants

Bio potential signals can be broadly classified into three categories:

- Action potentials: These are rapid, all-or-nothing signals that travel long distances. They are similar to the nerve impulses in animals.
- Variation potentials (VPs): These are slower, graded signals that are generated in response to damage or stress.
- System potentials (SPs): These are steady-state voltages that reflect the overall electrical activity of a plant cell or tissue.

Using this information, let us understand what exactly we deal with when we say bio potential in plants.

Plants utilize electrical signals called action potentials for communication, involving temporary shifts in voltage across cell membranes. Normally, the cell interior is negatively charged compared to the exterior (resting state). When stimulated, membrane channels open, causing rapid voltage increase (depolarization), followed by positive ion outflow and return to resting state (repolarization). Briefly, voltage may dip below resting state (hyperpolarization) before normalization.

These signals, also termed bio electric potentials, represent voltages generated within plant tissues in response to environmental factors and physiological processes. Monitoring them helps assess a plant's health and responsiveness to its environment.

Causes of these bio electric potentials.-

1. Ion flow: Selective channels in cell membranes control ion movement, creating electrical imbalances.
2. pH changes: Acidity levels within the cell affect ion flow, impacting electrical signals.
3. Plant hormones: These chemicals regulate plant responses to stress and environment, influencing bio electric activity.
4. External factors: Temperature, humidity, and soil conditions all affect ion movement and bio electric responses.

2.2 Soil Moisture

As mentioned above that the bio potential signals depend on or arise from environmental factors, we chose soil moisture as a factor due to the following reasons:
Soil moisture plays a crucial role in influencing the bio electric potential in plants, particularly because it affects water uptake, osmotic balance, and various physiological processes. Here's how soil moisture levels can impact bio electric potentials.

1. Water Uptake and Ions: Soil moisture directly affects water and nutrient uptake by plant roots. This, in turn, impacts:
    - Ion Concentration: Changes in moisture levels alter the concentration of ions available in the soil solution, affecting ion exchange and transport within plant cells.
    - Cell Turgor Pressure: Adequate moisture maintains cell turgor (pressure against the cell wall), crucial for cell function and bio electric responses.
2. Stomatal Regulation: When soil moisture is low, plants close stomata (leaf

pores) to conserve water. This closure affects ion transport and bio electric signals by limiting water and ion movement.

3. Stress Response: Water shortage triggers various stress responses in plants, including changes in gene expression and ion transport, all of which can impact bio electric potentials.

4. Electrochemical Gradients: Water and ion availability influences the electrical gradients across cell membranes, which in turn, affect bio electric potentials through ion movement and membrane potential.

2.3 Electrical Conductivity in Plants

Conductivity is a measure of electric current transmission through a substance, facilitated by ions, carriers with positive or negative charges. More charges imply more ions available for conduction, thus conductivity increases with ion abundance. Measured in millisiemens/cm, conductivity directly correlates with the number of ions present. Ion conduction generates bioelectric potential in plants.

2.4 Electrodes used

There are many types of electrodes which are used for capturing bio potential signals such as, internal electrodes, electrodes array, micro electrodes and surface electrodes.

The electrodes we used in this experiment is surface electrodes. Advantages of using this is that it is capable of capturing low and weak signals and can easily be standardized and also require minimal set up and hence are user friendly. They are generally used for humans and animals. Here we are exploring the use of this electrodes for plants as they are non invasive , hence can easily be attached to plant parts without causing damage.

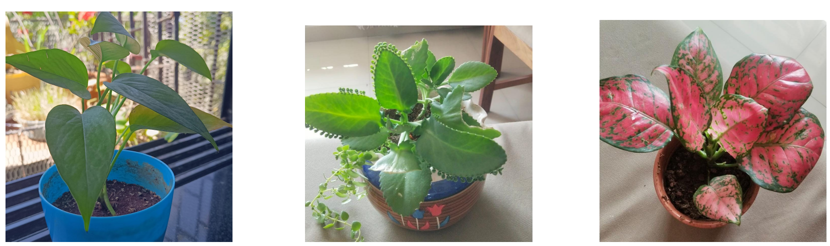
Thus, through referencing and researching terms such as bio potential, soil moisture, and surface electrodes, we have developed a cost-effective model for accurately measuring bio electric signals from plants.

Chapter 3

Experimental Details

3.1 Method

3.1.1 Plants used



(a) Plant A **(b)** Plant B **(c)** Plant C

Figure 3.1: Plant Used

1. Devil's Ivy (Money Plant) (A):
   Scientific name - Epipremnum Aureum, Family – Araceae
   The plant requires moderate water in a semi-shade location. It exhibits a fast growth rate. It often grows in terrestrial habitats/ tropical or subtropical climate.

2. Devil's Backbone (Kalanchoe)(B):
   Scientific name – Kalanchoe Brasiliensis, Family – Crassulaceae
   The plant requires fresh to moist soil in a semi-shade location. The perennials reach heights of 40-60 centimeters. The plant often grows in Brazilian forests.

3. Aglaonema (C):
   Scientific name- Aglaonema siam aurora, Family – Arum
   The plant grows to a typical height of 50 centimeters preferably in a tropical or subtropical climate. It requires a shady location and moist well-drained soil. It often grows in South-East Asia.

3.1.2 Apparatus Used

Arduino Board, Soil Moisture sensor, Bio potential sensor, jumper wires, Arduino IDE software.

1. Induino X Board: Induino is an electronic prototyping board. Jumper wires are used to connect / disconnect input pins. The device operates at 5 V and is powered via an USB connected to the computer.

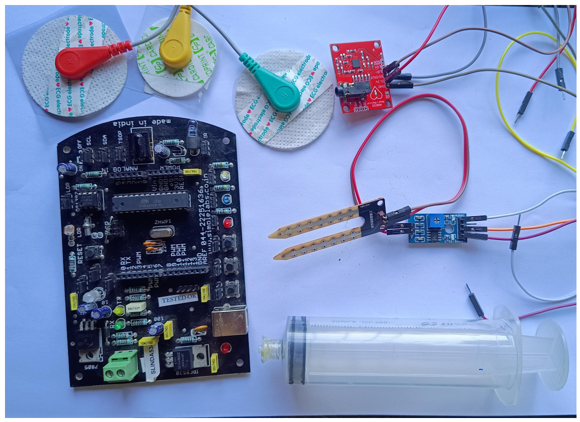


Figure 3.2: Apparatus

2. Soil Moisture Sensor: The operating voltage is 3.3-5 V. The two probes on the sensor act as variable resistors. The sensor uses capacitance to measure the water content of soil (by measuring the dielectric permittivity of the soil). The output from the sensor is an analog Voltage Value between 0-5 V.

3. Bio potential Sensor: The operating voltage is 3.3 V. AD8232 is an integrated signal conditioning block for ECG and other bio potential measurement applications.

3.1.3 Parameters

In this experiment, we have considered soil moisture level. We have assumed ideal conditions for external parameters like sunlight, humidity, temperature.

3.2 Procedure

3.2.1 Soil Moisture

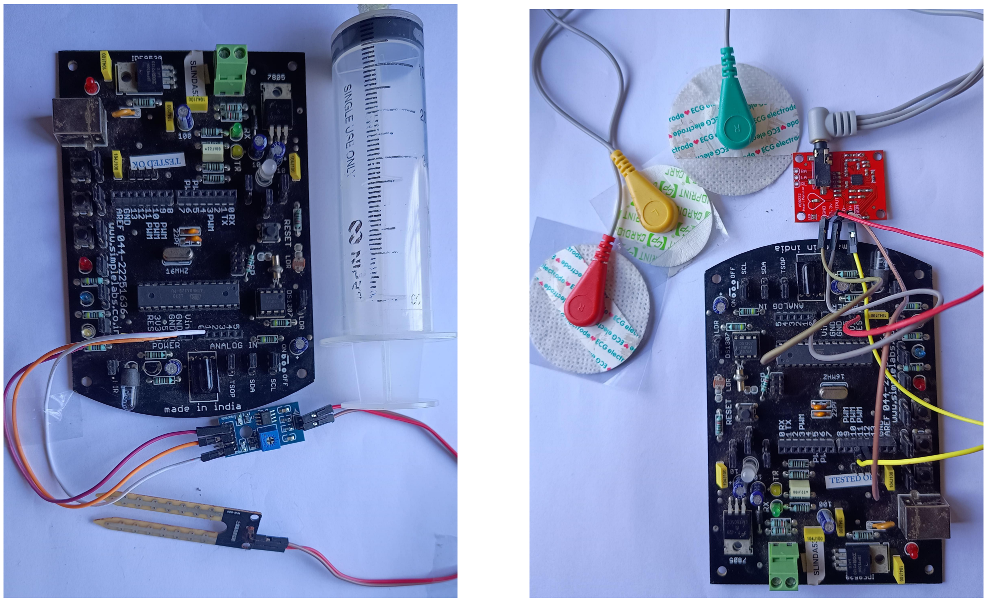
- Connect the circuit diagram.
- Write the code in Arduino IDE to measure the moisture level of the soil.
- Insert the sensor deep into the soil in the pot.
- Run the code and get the analog output from the IDE.
- The analog output obtained will be the soil moisture level.
- Add 5ml water. Wait for 5 minutes and take the reading again.

3.2.2 Bio-potential

- Connect the electrodes at a proper place on the leaves.
- Connect the Circuit diagram.
- After the soil moisture reading, take the bio-potential reading.
- Input the code in IDE software.
- Run the code.
- Note down the output in the excel sheet.
- Repeat the previous steps(while adding more water). Take 4 more readings.

Output of analogRead() is proportional to the voltage applied to the pin. The voltage range of 0 to 5 volts is divided into 1024. Soil moisture output is converted to percentage value and Potential value is converted to corresponding voltage value. Soil Moisture high and low values:

- Dry Value- 223
- Wet value- 160



(a) Soil Moisture Circuit **(b)** Bio-potential Circuit

Figure 3.3: Connections to sensors

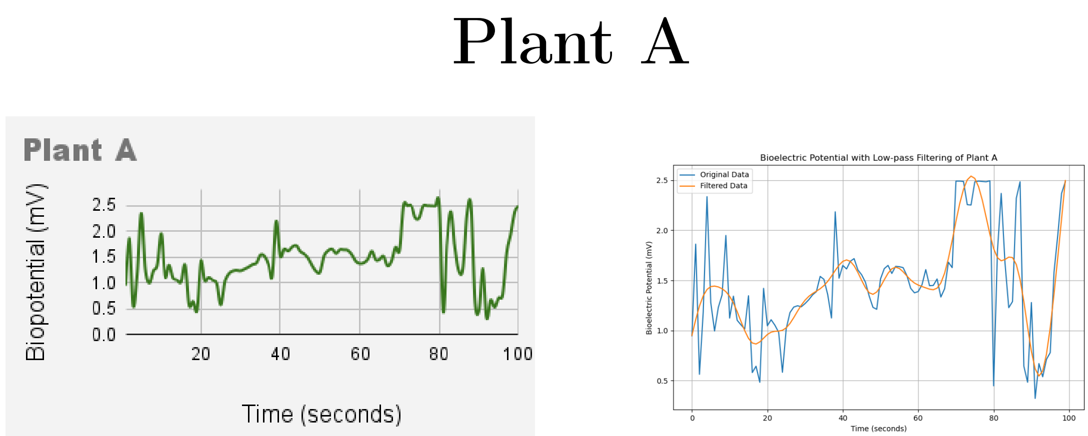
(a) ECG electrode set up **(b)** Soil moisture sensor set up

Figure 3.4: Set up

Chapter 4

Results and Discussions

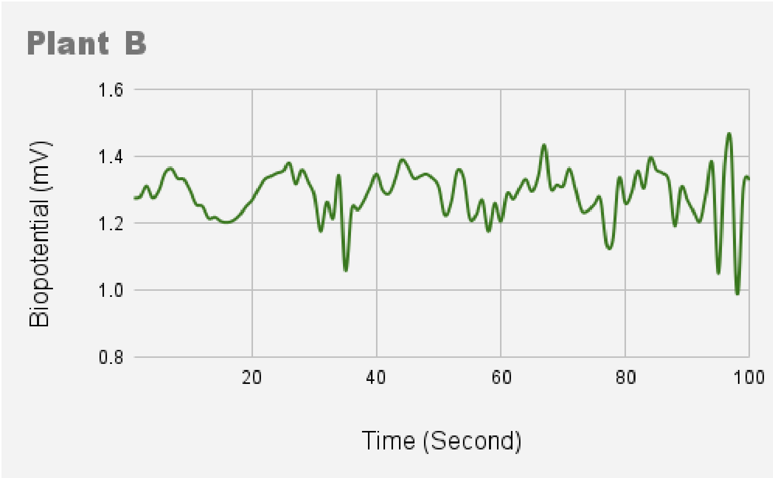
4.1 Data



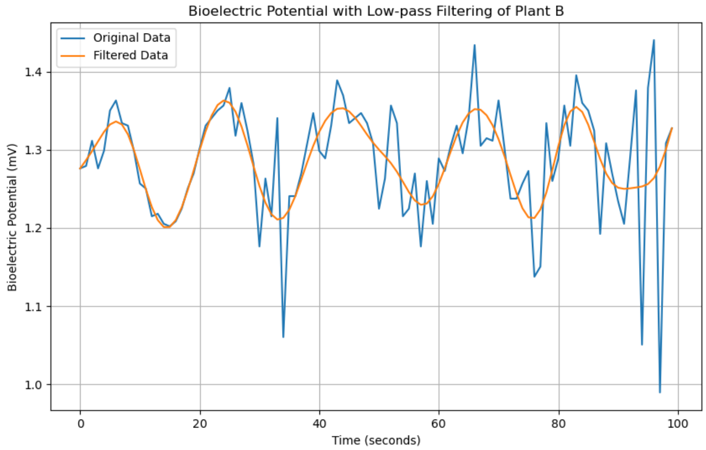
(a) Observed waveform **(b)** Filtered waveform

Figure 4.1: Waveform of signal from plant A

Plant B



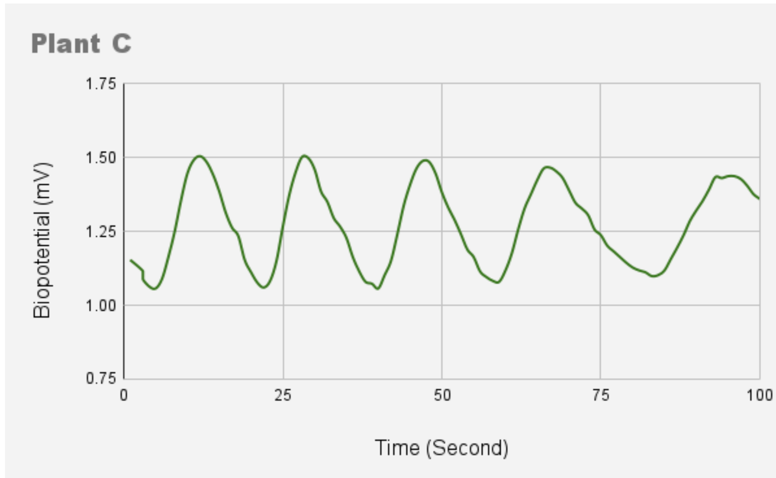
(a) Observed waveform



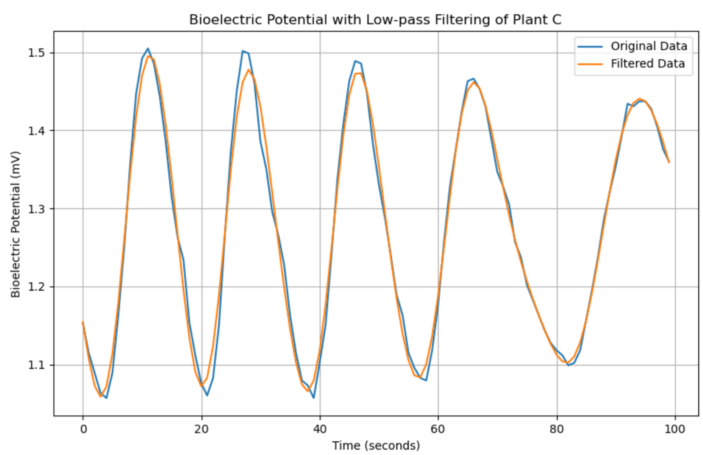
(b) Filtered waveform

Figure 4.2: Waveform of signal from plant B

Plant C



(a) Observed waveform



(b) Filtered waveform

Figure 4.3: Waveform of signal from plant C

4.2 Analysis

4.2.1 Data Analysis

For Plant A:

Sr No.	Soil Moisture(%)	Potential(mV)
1	33.33	1.4275
2	36.50	1.4265
3	47.61	1.4109
4	60.31	1.3825
5	61.90	1.3765

Table 4.1: Plant A readings

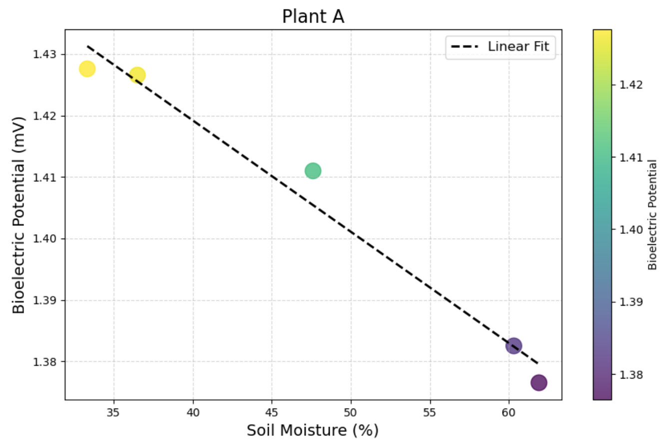


Figure 4.4: Varying soil moisture(plant A)

It can be observed from the data and graph observed:
Slope: -0.0018126, *Intercept: 1.491709*

For Plant B:

Sr No.	Soil Moisture(%)	Potential(mV)
1	58.73	1.318
2	61.9	1.3132
3	65.07	1.2411
4	68.25	1.3938

Table 4.2: Plant B readings

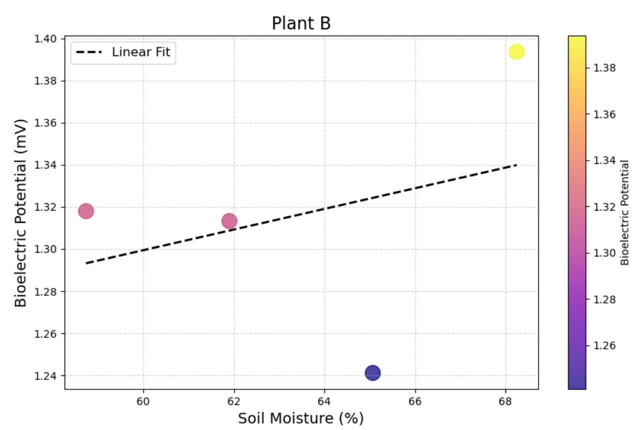


Figure 4.5: Varying soil moisture(plant B)

It can be observed from the data and graph observed:
Slope: 0.0049026, *Intercept: 1.005289*

Plant C

Sr No.	Soil Moisture(%)	Potential(mV)
1	30.158	1.2471
2	47.61	1.2568
3	55.55	1.2793
4	55.55	1.2858
5	61.9	1.2632

Table 4.3: Plant C readings

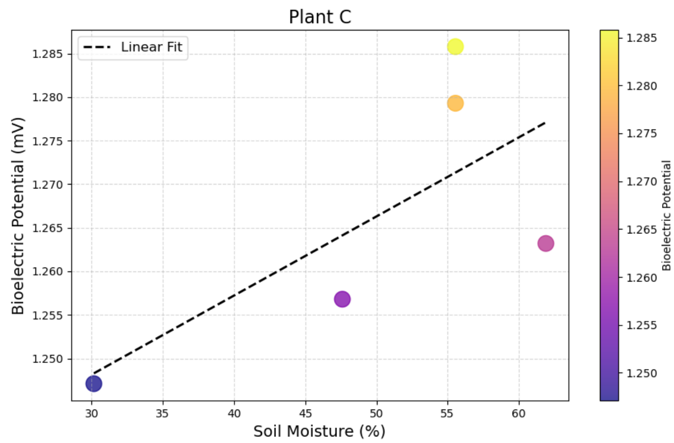


Figure 4.6: Varying soil moisture(plant C)

It can be observed from the data and graph observed:
Slope: *0.00090794*, Intercept: *1.220903*

Performing data analysis on the observed data, we have written a code on python that find polynomial regression of the best fit line of each plant based on the values of soil moisture and bio-potential signals.
Mathematical equations found for each family of plants:

Mathematical model for Plant 1:

$$Bioelectric\_Potential = -0.04 \times Soil\_Moisture + 1.49 \tag{4.1}$$

Mathematical model for Plant 2:

$$Bioelectric\_Potential = 0.09 \times Soil\_Moisture + 1.03 \tag{4.2}$$

Mathematical model for Plant 3:

$$Bioelectric\_Potential = 0.02 \times Soil\_Moisture + 1.22 \tag{4.3}$$

Assuming Conductivity constant= 5 and Moisture Constant= 6, we are finding conductivity of soil using the below formula:

$$conductivity = conductivity\_constant \times \frac{bioelectrical\_signal}{soil\_moisture} \times moisture\_constant \tag{4.4}$$

Using the Predictive model and conductivity formulae the following values have been calculated and given below:

Plant A:

Sr. No.	Soil Moisture(mV)	Measured Potential(mV)	Predicted Potential(mV)	Conductivity (mS/cm)	Error(%)
1	1.66	1.427	1.4236	25.78	0.238
2	1.82	1.4265	1.4127	23.513	3.23
3	2.38	1.4109	1.3948	17.784	1.14
4	3.01	1.3825	1.3696	13.779	0.933
5	3.09	1.3765	13664	13.364	0.733

Table 4.4: Estimated soil conductivity of Plant A with changing Soil Moisture

Plant B:

Sr. No.	Soil Moisture(mV)	Measured Potential(mV)	Predicted Potential(mV)	Conductivity (mS/cm)	Error(%)
1	58.73	1.318	1.372	13.494	4.09
2	61.9	1.3132	1.366	12.747	4.02
3	65.07	1.2411	1.36	11.446	9.58
4	68.25	1.3938	1.3536	12.228	2.88

Table 4.5: Estimated soil conductivity of Plant B with changing Soil Moisture

Plant C:

Sr. No.	Soil Moisture(mV)	Measured Potential(mV)	Predicted Potential(mV)	Conductivity (mS/cm)	Error(%)
1	1.507	1.2471	1.429	24.826	14.58
2	2.38	1.2568	1.3948	15.842	10.98
3	2.77	1.2793	1.3792	13.855	7.80
4	2.77	1.2858	1.3792	13.925	7.26
5	3.09	1.2632	1.3664	12.264	8.16

Table 4.6: Estimated soil conductivity of Plant C with changing Soil Moisture

4.2.2 Signal Analysis

Fourier transform is performed to the obtained signals to identify Frequency components and dominant frequency in that particular plant. It is observed that **Plant A** has **10 hetrz** as its Dominant frequency while **Plant B** and **Plant C** has **50 hertz** frequency as dominant from the figure 4.7.

Dominant Frequencies for Varying soil moisture for different plants is calculated as below:

Plant A:

Sr. No.	Soil Moisture (%)	Measured Potential (mV)	Peak Frequency (Hz)
1	33.33	1.4275	35.11
2	36.5	1.4265	16.09
3	47.61	1.4109	44.44
4	60.31	1.3825	21.3
5	61.9	1.3765	45.01

Table 4.7: Estimated Dominant Frequency of Plant A for varying soil moisture

Plant B:

Sr. No.	Soil Moisture (%)	Measured Potential (mV)	Peak Frequency (Hz)
1	58.73	1.318	27.77
2	61.9	1.31328	10.75
3	65.07	1.2411	13.15
4	68.07	1.3938	42.22

Table 4.8: Estimated Dominant Frequency of Plant B for varying soil moisture

Plant C:

Sr. No.	Soil Moisture (%)	Measured Potential (mV)	Peak Frequency (Hz)
1	30.158	1.2471	24.39
2	47.61	1.2568	23.07
3	55.55	1.2793	84.61
4	55.55	1.2858	38.46
5	61.9	1.2632	53.84

Table 4.9: Estimated Dominant Frequency of Plant C for varying soil moisture

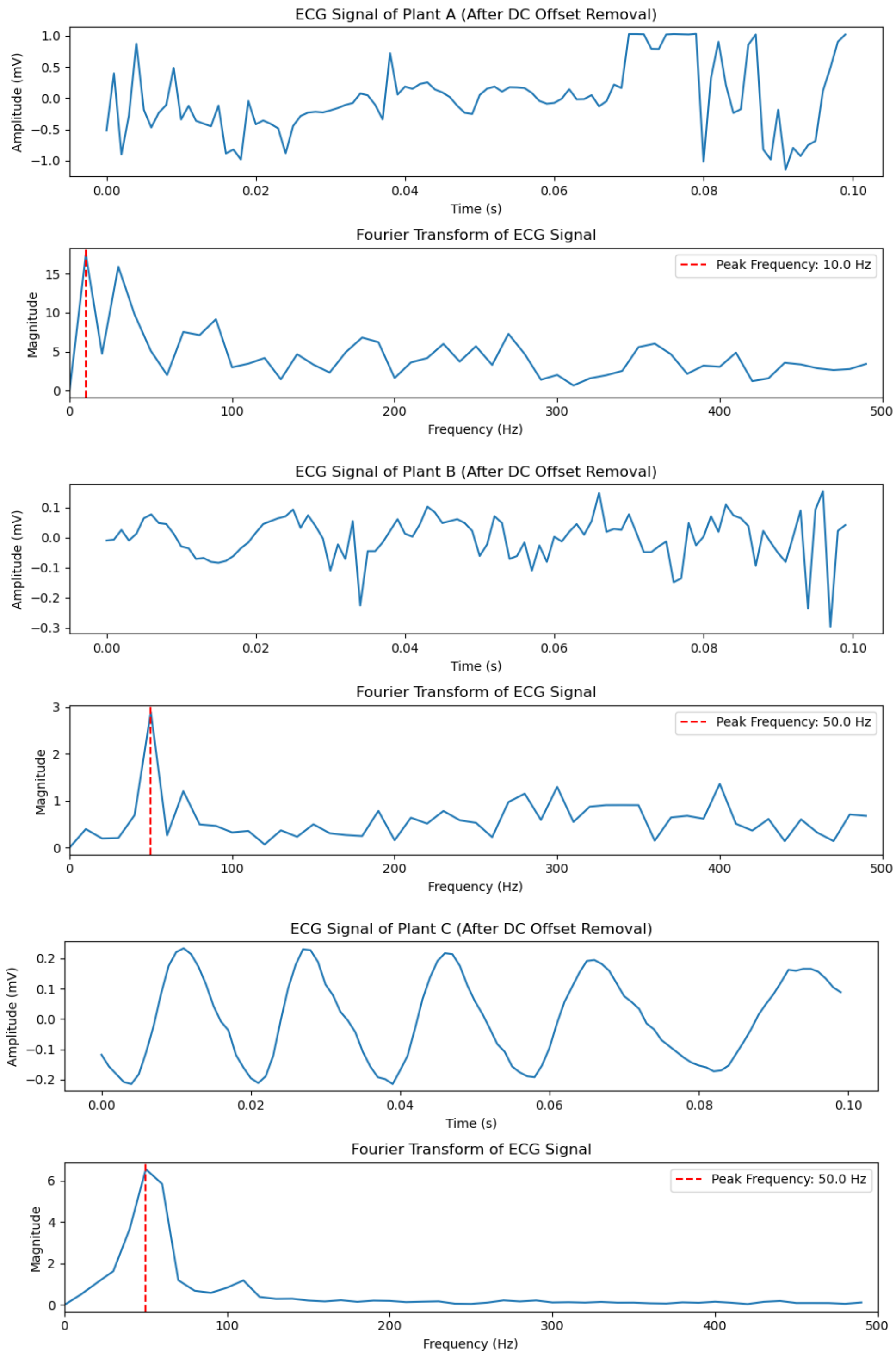


Figure 4.7: Fourier Analysis

4.3 Results

4.3.1 For Data Analysis:

- Different plants have varying response to increasing soil moisture, resulting in negative or positive correlation.
- The rate of change of potential with respect to soil moisture is given by the slope value obtained for each plant.
- The intercept of the graph shows the value of potential when the soil moisture is O or completely dry.
- Higher the soil moisture, better is the conductivity in soil.
- The average soil conductivity for Plant A is 18.84 mS/cm, for plant B is 12.47 mS/cm, for Plant C is 16.42 mS/cm.
- From the error analysis it can be observed that our predictive model is similar to the actual model, although it is less accurate for plant C whose error percentages range from 7.26% to 14.58%.

4.3.2 For Signal Analysis:

- It has been seen that plants do emit certain frequencies of values between 0-100 hertz.
- These frequencies does not have a set value but changes with different plants.
- It has been observed that dominant frequencies of each plant doesn't show any relationship with varying soil moisture.

4.4 Discussion

4.4.1 For Data Analysis:

- Plant cell membranes act like batteries, with a higher concentration of potassium ions inside compared to outside.
- Increased soil moisture makes more ions available for roots to absorb. Ions naturally move from high to low concentration (diffusion). This creates a

current flowing outwards, initially causing the bio potential to become more negative (inside becomes even more negative relative to outside).

- Electrostatic forces eventually balance the flow, establishing a new stable bio potential.This is because the negative charge building up inside the cell repels further outward movement of K+.
- The response can be positive or negative depending on the plant:
    1. Certain plants have ion channels that open or close in response to moisture changes. When water becomes more available, these channels might allow an influx of positively charged ions (like calcium, Ca2+), leading to a less negative or even a positive bio potential shift.
    2. Increased water uptake often leads to higher metabolic activity in the plant. This can result in increased activity of cellular pumps, further pushing K+ into the cell, ultimately leading to a more negative bio potential despite the initial diffusion-driven decrease.

Electrical circuit modelling:

- Lets us understand the above phenomena using a simple equivalent electrical circuit. Defining parameters as follows:
  1. Voltage source (Emf): Represents the plant's bio potential,under controlled conditions.
  2. Soil moisture dependent voltage source (Emfsm): The additional voltage source represents the influence of soil moisture on the plant's internal bio potential generation mechanisms.
  3. Soil moisture dependent resistor (Rm): Represents the resistance of the soil, decreasing with increasing moisture content.
- Imagine the plant bio potential (Emf) and plant tissue resistance (not explicitly shown in this model) acting as a single unit (let's call it "plant unit").
- As soil moisture increases, the conductivity of soil increases, Rm decreases (reciprocal of conductivity) which allows larger voltage drop across plant unit (since current is proportional to voltage drop and resistance).The voltage of Emfsm can be positive or negative depending on the plant species. Two phenomena of increase and decrease in bio potential can explained as:

    1. For first case (increase in bio potential), the Emfsm value is positive. Thus overall effect of this voltage on voltage source is less and my circuit

turns into a simple model where the larger voltage drop (mentioned above) accounts for higher measured bio potential.

2. Similarly for the case where bio potential decreases with increase soil moisture, the Emfsm value is negative which counteracts the effect of lower Rm. Hence net effect is the decrease in bio potential.

- It is important to note that these models are simplified representations, and the actual biological processes are likely more complex. However, the model provided a valuable framework for interpreting the observed relationships.

4.4.2 For Signal Analysis:

- From the results we can infer that the frequency component of the particular plant doesn't show any general relation with varying soil moisture. Hence multiple factors affect this frequencies like environmental factors and factors affecting growth inside the plant.
- This is because plant doesn't really generate these frequencies but they are the results of vibrations caused in the interior of a particular plant.
- Different tissues inside the plant has different frequency responses and plants react to various external stimuli hence changing the frequency components.

Chapter 5

Conclusion

Our device successfully captured electrical signals from various plants. By analyzing this data, we discovered a connection between a plant's bio potential (electrical activity) and its soil moisture levels. We developed a mathematical model to predict this relationship and a corresponding electrical model for theoretical explanation.

Additionally, analysis of the signals revealed frequency components that can be used to investigate physiological changes within the plants.

Overall, our findings support the idea that plant bio potential is influenced by multiple factors, not just soil moisture. The beauty of this model lies in its ability to be adapted to account for variations in other environmental factors as well.

This cost-effective approach provides a strong incentive for further exploration of plant biophysics and bio acoustics. By observing and analyzing external signals and frequencies, we can gain a deeper understanding of these phenomena through the lens of physics.

Chapter 6

Applications and future scope

- Built a device to capture the bio potential variations occurring within the tissues that can be used to monitor the plant's electrophysiological characteristics, providing insights into health and stress levels. It also allows to identify plant health problems, enabling fast treatments to minimize crop losses and maximize yields.
- By analyzing the frequency components and identifying patterns and trends of the biopotential signal, the model can potentially predict changes in the plant's health or response to environmental factors like soil moisture variations.
- Considering additional variables allows for correlation between bioelectrical potentials and other environmental factors like soil nutrient levels, temperature, humidity, and light intensity. And also provides insights into plant physiology and environmental interactions. This further facilitates on the research of sustainable agriculture practices.
- It also has various future research scopes such as studying how plants communicate with each other involving different frequencies.
- Understanding how plants communicate may lead to the development of methods to improve their capacity for adaptation to stressors or even promote beneficial interactions between plant species.
- Integrating machine learning techniques with biopotential data analysis can allow for real time monitoring and identification of complex patterns that are not apparent with traditional methods.

Appendix A

Code for Arduino IDE - Soil Moisture

```
int sensor_pin= A0;

void setup()
{
  Serial.begin(9600);
  pinMode(sensor_pin, INPUT);
}

void loop()
{
  int sensor_data= analogRead(sensor_pin);
  Serial.println(sensor_data);
}
```

Appendix B

Code for Arduino IDE- Bio-potential readings

```
void setup() {
// initialize the serial communication:
Serial.begin(9600);
pinMode(10, INPUT); // Setup for leads off detection LO +
pinMode(11, INPUT); // Setup for leads off detection LO -
}
void loop() {
if((digitalRead(10) == 1)||(digitalRead(11) == 1)){
Serial.println('!');}
else{
// send the value of analog input 0:
Serial.println(analogRead(A0));}
//Wait for a bit to keep serial data from saturating
delay(1000);}
Random:
int Volt=0;
int Value=0;

void setup(){
  Serial.begin(9600);}
void loop() {
  Volt= random(0,6);
```

Appendix C

The circuit diagram to take the readings of bio-potential signals from plants using AD8232.

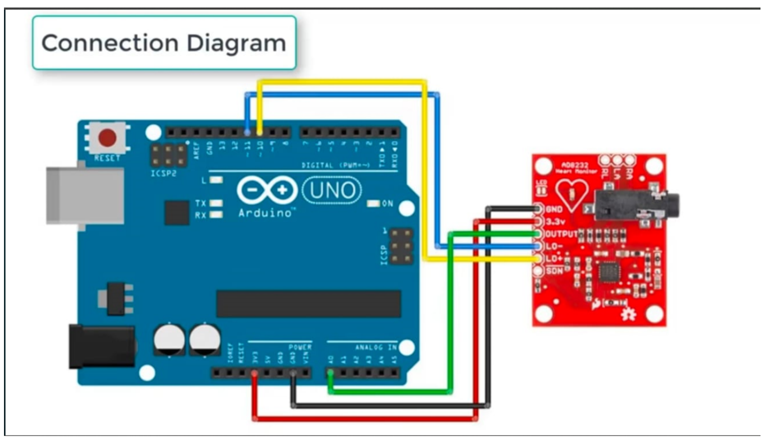


Figure 6.1: ECG electrode circuit diagram

Image taken from "Rahman, M. O., Shamrat, F. M. J. M., Kashem, M. A., Akter, M. F., Chakraborty, S., Ahmed, M., & Mustary, S. (2022, August 1). Internet of things based electrocardiogram monitoring system using machine learning algorithm. International Journal of Power Electronics and Drive Systems. https://doi.org/10.11591/ijece.v12i4.pp3739-3751".

Appendix D

The circuit diagram for soil moisture sensor.

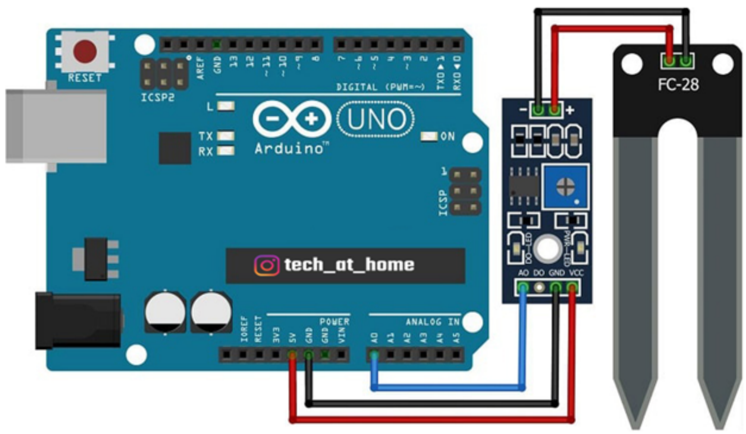


Figure 6.2: Soil Moisture sensor circuit diagram

Image taken from "D. (2022, October 15). Soil Moisture Sensor &8211; How to use with Arduino. DIY Engineers. https://www.diyengineers.com/2021/02/04/how-to-use-a-soil-moisture-sensor-with-arduino/".

Appendix E

All the data collected can be accessed through the QR code given.

Figure 6.3: QR Code for Data compiled

Bibliography

[1] Chaparro-Cárdenas, Silvia L., et al. ‘Plant Electrophysiology: Bibliometric Analysis, Methods and Applications in the Monitoring of Plant-Environment Interactions’. DYNA, vol. 88, no. 218, pp. 212–23, 2021. Avaiable URL: www.redalyc.org, https://www.redalyc.org/journal/496/49671325026/html/.

[2] K, Chaitra, et al. ‘THE SYNTHESIS OF BIO-ACOUSTICS USING PLANTS’. IJARCCE, vol. 12, no, 4, Apr. 2023. Available URL: https://doi.org/10.17148/IJARCCE.2023.124168.

[3] Lee, Jonny, and Paco Calvo. ‘The Potential of Plant Action Potentials’. Synthese, vol. 202, no. , p. 176. Springer Link, 6, Nov. 2023. Available URL: https://doi.org/10.1007/s11229-023-04398-7

[4] Radcliffe, David Elliott, and Jiri Simunek. Soil Physics with HYDRUS: Modeling and Applications. CRC Press/Taylor Francis, 2010.

[5] ‘Suggestions for Contributors to the Soil Science Society of America Journal’. Soil Science Society of America Journal, vol. 60, no. 1, Jan. 1996. Available URL: https://doi.org/10.2136/sssaj1996.03615995006000010002x

[6] The Ultimate Guide to Testing Electrical Conductivity of Soil. Available URL: https://blog.hannainst.com/soil

[7] K. S. Leifler, "Fast electrical signals mapped in plants with new technology." Available URL: https://liu.se/en/news-item/fast-electrical-signals-mapped-in-plants-with-new-bioelectronic-technology.

[8] A. G. Volkov, Plant Electrophysiology. Oakwood College, 7000 Adventist Boulevard, Huntsville, AL 35896, USA: Springer. Available URL: https://www.esalq.usp.br/lepse/imgs/conteudo.thumb/Plant-Electrophysiology-Theory-and-Methods.pdf

[9] J. Canales, C. Henriquez-Valencia, and S. Brauchi, "The Integration of Electrical Signals Originating in the Root of Vascular Plants," Front Plant Sci, vol. 8, p. 2173, Jan. 2018, doi: 10.3389/fpls.2017.02173. Available URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5767606/.

[10] H. P. K, "Arduino Based IoT Garden Monitoring System," Engineers Garage. Available URL: https://www.engineersgarage.com/arduino-based-iot-garden-monitoring-system/.

[11] J. D. Bronzino, Ed., The biomedical engineering handbook, 2nd ed. in The electrical engineering handbook series. Boca Raton, FL: CRC Press, 2000.

[12] "Simple Labs' Induino User Guide: InduinoX - An Overview," Simple Labs' Induino User Guide. Available:

https://induino.blogspot.com/2011/11/induinox-overview.html.

[13] R. Newman, “Wholesale and Retail Prices,” The Economic Journal, vol. 7, no. 27, p. 346, Sep. 1897, doi: 10.2307/2957118. Available: https://www.jstor.org/stable/10.2307/2957118?origin=crossref.

[14] Neuman, M. R. “Biopotential Electrodes.”The Biomedical Engineering Handbook: Second Edition.Ed. Joseph D. BronzinoBoca Raton: CRC Press LLC, 2000