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Analysis of Plant Conductivity and Resistance as Indirect Indicators of Nutrient Content Using Relaxation Oscillators

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ABSTRACT

Real-time monitoring of plant nutrient status is essential for optimizing fertilization in precision agriculture. This study evaluated electrical conductivity and resistance as indirect indicators of nitrogen (N), phosphorus (P), and potassium (K) nutrient content in avocado plants (Persea americana) using a low-cost resistive sensor system. The system features a relaxation oscillator circuit integrated with an Arduino Uno microcontroller to convert plant resistance into frequency signals, with an AC-based method implemented to mitigate DC polarization effects in biological tissues. A 14-day comparative experiment was conducted using two avocado plants: Plant A, which received NPK 16-16-16 fertilizer daily, and Plant B, an unfertilized control. Data were collected via stainless steel electrodes inserted into the plant stems. Results demonstrated that NPK fertilization consistently increased plant conductivity and decreased electrical resistance in Plant A (average: 20,841.72 Ω), while Plant B maintained comparatively higher and more stable resistance values (average: 24,309.24 Ω) throughout the observation period. The sensor system also detected physiological stress symptoms in Plant A from Day 11 onward, corroborated by visual observations of fertilizer toxicity. These results confirm that electrical resistance serves as a reliable indirect indicator of relative nutrient levels, offering a practical, economical, and non-destructive approach for real-time plant monitoring in precision agriculture.

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INTRODUCTION

Precision agriculture has emerged as a transformative paradigm in modern farming, aiming to maximize resource efficiency while minimizing environmental impact. One of the major challenges in this field is the real-time monitoring of plant nutrient status to optimize fertilizer application and reduce resource waste [1][2]. Excessive fertilizer use not only increases production costs but also poses significant environmental risks, including soil degradation, groundwater contamination, and greenhouse gas emissions. Conversely, nutrient deficiency leads to stunted growth, leaf chlorosis, reduced yield, and even plant death [3]. These consequences underscore the urgent need for a monitoring approach capable of providing timely information on plant nutrient conditions to support more precise and sustainable fertilization management.

Conventional laboratory-based soil and plant tissue analyses generally provide accurate results; however, these methods are often time-consuming, expensive, and impractical for rapid field-level decision-making [4]. Furthermore, most existing sensing approaches focus on measuring nutrient content in the soil medium rather than directly within plant tissue, limiting the ability to capture real-time physiological responses of the plant itself [5]. Visual observation by farmers remains the most common field method, yet visible symptoms of nutrient stress typically appear only after significant physiological damage has already occurred. Therefore, the development of a low-cost, non-destructive, and real-time sensing method capable of detecting nutrient-related changes directly within plant tissue represents a critical and underexplored research direction.

One promising approach involves utilizing the electrical properties of plant tissues. Biological tissues possess electrical conductivity influenced by the concentration of ions within cellular fluids, which is closely related to essential macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) [6,7]. Variations in nutrient uptake can alter ion density and water content within plant tissues, leading to measurable changes in electrical resistance and impedance [8,9]. Based on this principle, it is hypothesized that electrical resistance measurements of plant stems may serve as indirect indicators for evaluating nutrient conditions in plants. If this relationship can be confirmed experimentally, it would provide a physiological basis for developing real-time, in-situ nutrient monitoring that directly reflects the plant's internal ionic state.

However, electrical resistance measurements using direct current (DC) frequently suffer from electrode polarization effects that reduce measurement accuracy and stability [16].

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This polarization arises from ion accumulation at the electrode–tissue interface, causing the recorded resistance to drift unpredictably over time. To overcome this limitation, alternating current (AC)-based techniques and frequency-conversion methods using relaxation oscillator circuits have been proposed as more reliable alternatives [11,12]. The relaxation oscillator generates a non-sinusoidal waveform whose frequency is inversely proportional to the resistance of the measured medium. This AC-based approach effectively mitigates polarization artifacts, enabling more stable and repeatable measurements in biological materials. Previous studies have applied similar oscillator-based sensing for wood moisture measurement [16] and impedance-based plant monitoring [5], demonstrating the feasibility of frequency-conversion as a proxy for biological resistance. However, its application for detecting nutrient-driven resistance changes directly in the plant stem remains insufficiently explored.

In addition, the integration of resistive sensors with microcontroller-based systems has enabled the development of low-cost, portable, and continuous plant monitoring platforms [11,12]. These systems support automated agricultural management and data-driven farming practices, which are essential components of smart agriculture [13].

This study aims to evaluate electrical conductivity and resistance as indirect indicators of nitrogen (N), phosphorus (P), and potassium (K) nutrient content in avocado plants (Persea americana) using a resistive sensor system based on a relaxation oscillator circuit. Specifically, it analyzes the correlation between electrical resistance characteristics measured directly on plant stems and different fertilization levels over a 14-day observation period. The proposed approach is expected to contribute to the development of non-destructive, real-time monitoring methods for precision agriculture, particularly by addressing the gap between soil-based electrical measurements and direct in-plant nutrient assessment.

MATERIALS AND METHODS

Experimental Design

This study employed a comparative research design to evaluate the effect of NPK 16-16-16 fertilization on the electrical resistance and conductivity of avocado plant (*Persea americana*) stems. Two plants with uniform physical characteristics were observed simultaneously over a 14-day period: Plant A served as the experimental subject receiving NPK 16-16-16 fertilizer, while Plant B served as the unfertilized control receiving only water. This side-by-side comparative approach was selected to isolate the effect of nutrient enrichment on the plant's electrical properties while maintaining identical environmental conditions for both subjects. As illustrated in Figure 1, both plants were connected to the same resistive sensing system to ensure measurement consistency throughout the observation period.

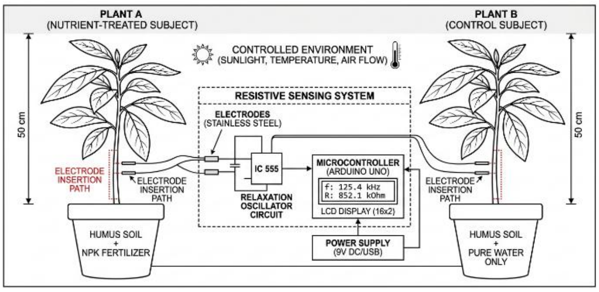

Figure 1 Schematic of the comparative experimental setup between the nutrient-treated subject (Plant A) and the control subject (Plant B) integrated with the resistive sensing system.

Plant Subjects and Experimental Setup

The research utilized two avocado plants (*Persea americana*) of the Alligator variety as biological subjects, selected for their uniform physical characteristics, including a height of approximately 70 cm and a stem diameter of 15 mm. Plant A served as the experimental subject receiving daily applications of NPK 16-16-16 fertilizer solution, while Plant B served as the control subject receiving only water without additional nutrients.

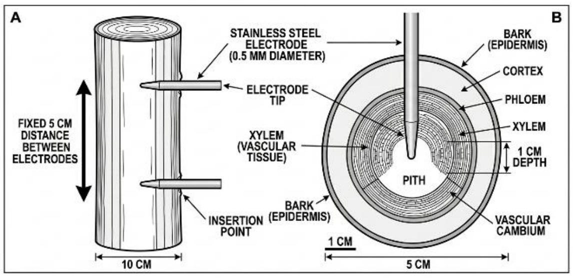

Figure 2 Detailed view of electrode insertion into the Persea americana stem, showing the fixed 20 mm inter-electrode distance, 10 mm insertion depth, and 5 cm height from soil surface.

To maintain experimental integrity, both subjects were placed in an identical environment with consistent sunlight exposure and ambient temperature throughout the observation period. The growth medium consisted of humus soil in identical containers. Stainless steel electrodes (0.5 mm diameter) were inserted into the main stem of each plant at a height of 5 cm from the soil surface, to a depth of 10 mm, with a fixed inter-electrode distance of 20 mm, as shown in Figure 2. Stainless steel was specifically selected for its anti-corrosive properties and high conductivity, which are essential for maintaining signal integrity and preventing chemical reactions at the insertion points [16]. The standardized electrode placement was maintained consistently across all measurement days to ensure comparable data acquisition.

Materials and Equipment

The electronic sensing unit was built around a relaxation oscillator circuit, as shown in Figure 3. The core component is a TL071CP operational amplifier (Op-Amp) configured as a Schmitt trigger, which generates a non-sinusoidal oscillating waveform. The oscillation frequency is determined by the RC time constant, where the plant's internal resistance (Rplant) acts as the variable timing component. The circuit uses a 12.34 nF mylar capacitor; two 100 kΩ feedback resistors that set the switching threshold at 50% of supply voltage; a 10 kΩ/20 kΩ voltage divider to scale the output signal within the safe operating range of the microcontroller; a 1N4148 diode to eliminate the negative half of the output waveform and protect the microcontroller input; and two 9V batteries in series providing a bipolar supply (±9V) required by the Op-Amp [16].

Data processing and system control were managed by an Arduino Uno microcontroller (ATmega328P), which measured the incoming frequency from the oscillator and derived resistance values in real time using Equation (6). A 16×2 LCD displayed frequency readings locally. During initial setup, a calibrated digital oscilloscope validated the circuit's frequency output against known resistance values (resistors with verified resistance) to confirm measurement accuracy.

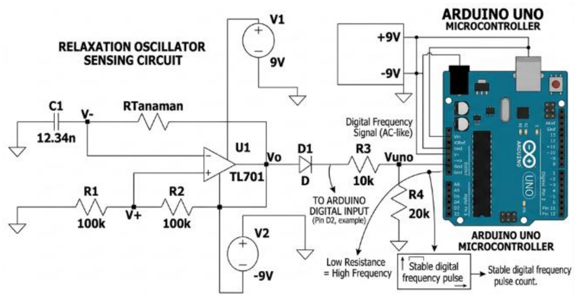

Figure 3 Complete hardware integration, showing the interface between the sensing circuit and the Arduino Uno microcontroller

System Design (Hardware)

The relaxation oscillator circuit converts the biological impedance of the plant stem into a digital frequency signal. The use of AC-based excitation was specifically chosen to mitigate the electrode polarization effects that are commonly observed in DC resistance measurements of biological tissues [16]. In DC measurements, ion accumulation at the electrode–tissue interface causes unstable and drifting resistance readings; AC excitation prevents this accumulation, resulting in more stable and repeatable measurements [16].

In the relaxation oscillator circuit, the plant resistance (Rplant) acts as the primary timing component for the charging and discharging of capacitor C. The output frequency (f) is inversely related to Rplant according to the following equation derived from the circuit's switching behavior:

$$R_{plant} = \frac{1}{2 f C_1 \ln(3)} \quad (1)$$

where C_1 = 12.34 nF. This inverse relationship means that an increase in plant conductivity (due to higher ionic concentration from nutrient uptake) produces a measurable increase in output frequency, which the Arduino Uno microcontroller reads and converts to a resistance value in real time.

Data Acquisition Procedure

The data acquisition process systematically observed the electrical resistance response of both plants throughout the 14-day comparative observation. Prior to the main collection phase, a system stability test was conducted for 15 minutes to verify that the measurement system had reached a steady-state condition and to characterize any initial transient drift [12]. Once stability was confirmed, the main observation commenced.

During the first three days (Days 1–3), both plants received only water, establishing a baseline electrical profile under identical conditions. From Day 4 onward, Plant A received NPK 16-16-16 fertilizer daily, while Plant B continued to receive only water. Frequency and resistance data were recorded daily at a consistent time each day to minimize the influence of circadian variation [13]. The Arduino Uno processed the digital signals by calculating the HIGH and LOW durations of the oscillator output pulse to determine frequency in Hertz (Hz), which was then converted to resistance in Ohms (Ω) using Equation (6). Periodic visual observations were documented photographically to provide biological validation for the electrical fluctuations recorded by the sensor.

Data Analysis

The collected daily datasets were subjected to comparative descriptive analysis. The resistance and frequency trends of Plant A (fertilized) and Plant B (control) were plotted against time across the 14-day observation period. To ensure data reliability, a 5-second averaging interval was applied by the Arduino program during each daily measurement session, reducing the effect of momentary sensor instability or environmental noise. All data processing and visualization were conducted using Origin software.

RESULT AND DISCUSSION

Device Stability Testing

A stability test was conducted prior to the main observation to verify that the measurement system produces consistent readings and minimizes unwanted deviation during operation. Measurements

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were recorded continuously for 15 minutes under constant environmental conditions to characterize any initial transient drift before the system reached steady state [12]. The results are presented in Figure 4.

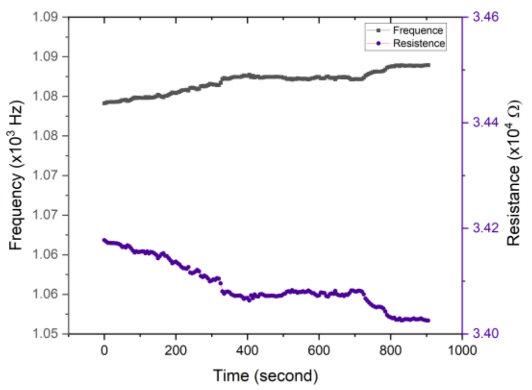

Figure 4. Graph of plant resistance and frequence changes over 15 minutes

Based on the data in Figure 4, the initial resistance value was recorded at 34,177.53 Ω and gradually decreased to 34,025.55 Ω by the end of the 15-minute period. The total shift amounted to 152.29 Ω, representing approximately 0.446% of the initial value — a drift magnitude considered acceptable for biological tissue measurements [16]. The change followed a linear downward trend (R^2 = 0.8723), indicating long-term stability without significant noise spikes. Small fluctuations observed within each measurement segment are attributable to external factors such as circuit noise, power supply stability, or minor variations in electrode contact quality [11]. These results confirm that the system is sufficiently stable for extended daily observation. All subsequent daily measurements were taken after allowing the system to stabilize for at least 15 minutes following electrode connection.

Frequency Response to NPK Fertilization (14-Day Observation)

Over the 14-day observation period, the measurement system detected a clear difference in frequency response between Plant A (treated with NPK 16-16-16 fertilizer) and Plant B (unfertilized control). Plant A exhibited a higher overall average frequency of 1,913.61 Hz compared to 1,644.96 Hz for Plant B, indicating that NPK fertilization consistently increased the ionic conductivity of the plant tissue. The dynamic changes in these frequency values over the two-week observation period are further illustrated in Figure 5.

Both samples exhibited a sharp frequency decline during Days 1–3, interpreted as an acclimation phase during which the plant tissue adapts to the inserted electrodes and the sensor system reaches biological equilibrium [13]. This initial transient behavior has been similarly observed in studies employing impedance-based plant sensing, where the first few measurement days show higher variability before stabilization [5]. Following this phase, Plant A demonstrated an increasing frequency trend from Day 4 through Day

10, reflecting progressive ion accumulation in the vascular tissue as NPK nutrients were absorbed. Plant B, lacking nutrient supplementation, maintained comparatively lower and more variable frequencies throughout.

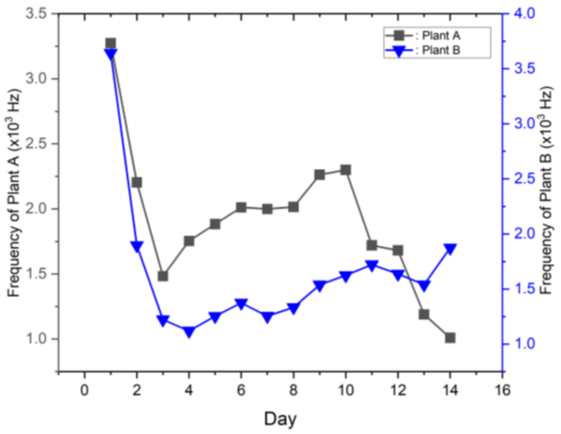

Figure 5. Frequency comparison between Plant A and Plant B

A notable behavioral shift occurred from Day 11 onward, where Plant A's frequency dropped sharply from 2,300.24 Hz on Day 10 to 1,720.66 Hz on Day 11 (as shown in Figure 5), corresponding to a resistance increase from 16,033.83 Ω to 21,434.60 Ω on the same days (see Figure 7). This abrupt shift is consistent with physiological stress associated with fertilizer overdose; wherein excessive ionic concentration disrupts cellular membrane integrity and reduces tissue conductivity [6,7]. The relatively large standard deviations — 546.31 Hz for Plant A and 624.51 Hz for Plant B — reflect the influence of environmental variability and internal plant dynamics on electrical readings.

Physical Plant Observations

To provide biological validation for the electronic data, visual observations were conducted daily and documented photographically throughout the 14-day period. The most significant visual difference between the two plants was recorded on Day 11, coinciding with the sharp electrical shift detected by the sensor system on the same day, as shown in Figure 6.

Physical Plant Observations

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(a) (b)

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Figure 6. Condition of plants on Day 11: (a) Plant A showing scorched leaf edges and yellowing consistent with fertilizer toxicity; (b) Plant B maintaining healthy deep green leaves.

As shown in Figure 6(a), Plant A (fertilized with NPK 16-16-16) began exhibiting clear symptoms consistent with fertilizer toxicity: leaf edges appeared scorched, with a distinct yellowish-brown discoloration. These symptoms are characteristic of excessive ionic concentration drawing water out of cells through osmotic imbalance, a condition commonly referred to as fertilizer burn [8]. This physical deterioration is directly consistent with the simultaneous resistance increase detected by the sensor on Day 11, providing mutual validation between the electronic measurements and biological observations.

In contrast, Figure 6(b) shows that Plant B maintained a healthy appearance with deep green leaves throughout the entire observation period. The absence of external nutrient input prevented ionic overload, maintaining stable tissue electrical properties and healthy physiology. These complementary observations confirm that the resistive sensor system is sensitive to the internal physiological state of the plant, and that the recorded electrical fluctuations represent genuine biological responses to nutrient intervention rather than measurement artifacts.

Resistance Analysis and Inverse Relationship with Frequency

The 14-day measurement results confirm the inverse relationship between ionic nutrient concentration and electrical resistance throughout the observation period. Plant A (with NPK fertilization) maintained a lower average resistance of 20,841.72 Ω compared to Plant B (without fertilizer), which averaged 24,309.24 Ω — a difference of approximately 3,467 Ω, representing a 14.3% reduction in average stem resistance attributable to NPK-driven ionic enrichment. The daily resistance values for both plants are presented in Figure 7.

The resistance trend across the observation period can be divided into three distinct phases. During Days 1–3 (acclimation phase), both plants showed high and declining resistance values as the electrode–tissue interface stabilized. During Days 4–10 (active nutrient absorption phase), Plant A consistently showed lower and more stable resistance than Plant B, with a minimum of 16,033.83 Ω on Day 10 compared to Plant B's 22,716.67 Ω on the same day — a difference of 6,682.84 Ω. This pattern confirms that NPK 16-16-16 fertilization increases the concentration of free electrolyte ions — including potassium (K^+), phosphate (PO_4^{3-}), and nitrogen compounds (NO_3^-, NH_4^+) — within the plant's vascular system, enhancing electrical conductivity and reducing resistance [6,7]. During Days 11–14 (stress phase), Plant A's resistance rose sharply, reaching 36,520.83 Ω on Day 14, exceeding Plant B's value of 19,684.81 Ω on the same day, consistent with fertilizer toxicity and cellular damage reducing ionic mobility within the tissue [8].

These findings are consistent with those of Bodale et al. (2021), who reported that higher nutrient uptake in tomato plants was associated with measurable increases in electrical conductivity across different phenological stages, supporting the use of electrical parameters as indirect indicators of plant nutrient status [4]. Similarly, Zhang and Wienhold (2002) demonstrated a positive correlation between soil ionic content (N, P, K) [17] and electrical conductivity, with resistance decreasing as ion concentration increased — a relationship that the present study extends to direct stem tissue measurement in avocado plants [18,19]. While direct comparison of absolute resistance values between studies is limited by differences in plant species, electrode configuration, and measurement frequency, the directional consistency of these findings strengthens confidence in the observed relationship.

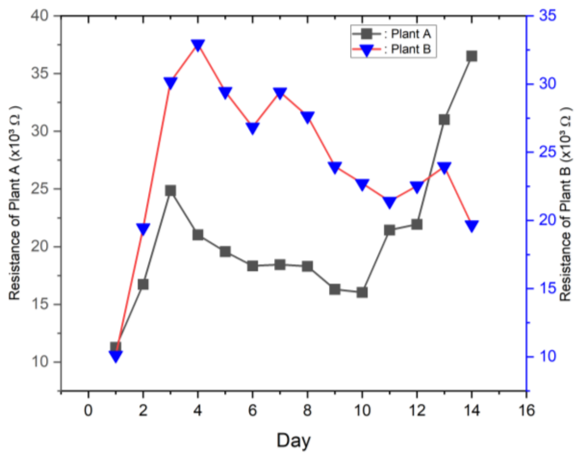

Figure 7. Graph of daily resistance value comparison.

Factors Influencing Sensor Readings

While the resistive sensor system demonstrated sensitivity to nutrient-driven changes, several external and internal factors must be considered when interpreting the data. Water content was identified as the most dominant confounding variable alongside ionic nutrient concentration in determining the electrical conductivity and resistance of plant tissue [14,22,23]. Because water acts as the primary solvent for ionic transport within plant vascular systems, variations in tissue hydration can significantly alter resistance values even when fertilizer dosage remains constant [14].

Several additional factors also influence sensor readings. Plant species and age affect the baseline electrical properties of stem tissue, as older or

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lignified stems generally exhibit higher resistance due to reduced cellular water content and vascular activity [7]. Electrode placement consistency is critical in resistive-based systems, since even minor variations in insertion depth or inter-electrode distance alter the conduction pathway through the tissue and produce different resistance readings [11,16]. The quality of electrode–tissue contact and the condition of the stem surface at the insertion point also affect signal stability [20,21].

Due to these confounding variables, the resistance values recorded in this study are more accurately understood as a composite indicator of both nutrient status and tissue water content, rather than as an absolute measure of a specific nutrient concentration. This interpretation is consistent with findings from broader electrical conductivity research in agricultural systems, where EC measurements are recognized as integrative indicators requiring site-specific calibration for quantitative nutrient estimation [24,25]

Potential and Limitations of the Monitoring System

The resistive sensor system developed in this study offers several practical advantages. The combination of a relaxation oscillator and Arduino Uno provides a low-cost, portable, and real-time measurement platform that does not require destructive sampling of plant tissue [11,15]. The system's ability to consistently differentiate between fertilized and unfertilized plants across 14 days of observation demonstrates sufficient sensitivity for comparative monitoring applications in precision agriculture [1,2].

However, several limitations should be acknowledged. First, the study was conducted on only two individual plants of a single species (*Persea americana*), which limits the generalizability of the findings. Second, no independent chemical validation of actual N, P, and K concentrations in the plant tissue was performed alongside the electrical measurements. While the observed resistance trends are directionally consistent with expected ionic behavior and with published literature [4,17], direct quantitative validation against laboratory-based nutrient analysis (such as atomic absorption spectroscopy or colorimetric assay) would be necessary to establish a calibration relationship between resistance values and specific nutrient concentrations. Third, the confounding influence of tissue water content on resistance readings could not be fully isolated in the current experimental design.

Future studies should address these limitations by: (1) expanding the number of plant replicates to improve statistical robustness; (2) incorporating simultaneous laboratory-based nutrient analysis to validate and calibrate the electrical measurements; (3) integrating a separate moisture sensor to decouple the contributions of water content and ionic concentration to the resistance signal; and (4) testing the system across multiple plant species and fertilizer types to assess broader applicability.

CONCLUSION

This study evaluated electrical conductivity and resistance as indirect indicators of nitrogen (N), phosphorus (P), and potassium (K) nutrient content in avocado plants (Persea americana) using a resistive sensor system based on a relaxation oscillator circuit integrated with an Arduino Uno microcontroller. The system converts plant stem resistance into frequency-modulated signals via an AC-based measurement approach, effectively mitigating the electrode polarization effects that limit conventional DC methods.

The 14-day comparative observation between Plant A (fertilized with NPK 16-16-16 daily) and Plant B (unfertilized control) produced three key findings. First, NPK fertilization consistently reduced the electrical resistance of Plant A relative to Plant B throughout the active nutrient absorption phase (Days 4–10), with Plant A averaging 20,841.72 Ω compared to 24,309.24 Ω for Plant B — a difference of approximately 14.3%. Second, the inverse relationship between ionic nutrient concentration and electrical resistance was confirmed: higher NPK input increased ion density in the plant's vascular tissue, enhancing conductivity and reducing resistance in a pattern consistent with established electrical conductivity principles in biological media [4,17]. Third, the sensor system demonstrated sensitivity not only to nutritional enrichment but also to physiological stress: the sharp resistance increase in Plant A from Day 11 onward coincided with visible symptoms of fertilizer toxicity, providing mutual validation between electronic data and biological observations.

These results confirm that electrical resistance measured directly on plant stems can serve as a reliable indirect indicator of relative nutrient levels under controlled comparative conditions. The proposed approach offers a practical, economical, and non-destructive alternative for real-time plant monitoring

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that does not require laboratory-based chemical analysis for comparative assessment.

Nevertheless, several limitations must be acknowledged. The experiment involved only two individual plants of a single species and variety, limiting statistical robustness and generalizability. No independent chemical validation of actual N, P, and K concentrations was performed alongside the electrical measurements, preventing quantitative calibration of the resistance–nutrient relationship. Additionally, the confounding influence of tissue water content on resistance readings could not be fully isolated.

Future research should address these limitations by: (1) increasing the number of plant replicates and testing across multiple species and growth stages; (2) incorporating simultaneous laboratory-based nutrient analysis to establish a quantitative calibration between resistance values and specific nutrient concentrations; (3) integrating a complementary moisture sensor to decouple the contributions of water content and ionic concentration to the resistance signal; and (4) developing IoT-based connectivity to enable remote real-time monitoring for broader precision agriculture applications.

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