Developing a Low-Cost Arduino-Based Colorimetric Soil Tester for Precise Nutrient Analysis

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Abstract

Macronutrients such as Nitrogen (N), Phosphorus (P), and Potassium (K) are essential for plant growth and development, contributing to root formation, stem strength, and overall plant vitality, particularly in young plants. However, the availability of these macronutrients in the environment can be unpredictable and excess amounts can lead to nutrient runoff, causing problems such as eutrophication in the surrounding water bodies. As a result, utilizing a fast and effective soil tester becomes vital, ensuring precise readings, especially given the dynamic changes in soil conditions in natural areas, thereby aiding in the optimization of growth conditions.

Precise fertilization based on accurate soil testing is crucial to mitigate nutrient runoff. Several soil testing methods and tools targeting the fundamental macronutrients (Nitrogen, Phosphorus, and Potassium - NPK) have been introduced, but most encompass laboratory environments and require a certain amount of time and budget. Additionally, a few recently introduced portable commercial electric current sensors, when utilized, return "estimated" values, by referring to pH-based equations, without providing true levels for each macronutrient (NPK). Along with macronutrient concentrations, ensuring the survivability of plants requires precise testing of the soil's pH level.

Traditional laboratory soil testing methods require abundant time, making them impractical for real-time field applications. To address this, a fast, portable, reliable and efficient soil nutrient testing solution is required—a "pop-and-go" method that allows for immediate assessment. Therefore, the goal of this project is to develop a portable soil testing device that rapidly, yet accurately measures the soil's macronutrient levels and pH, and displays the required nutrient concentrations and pH level to obtain optimal soil condition.

LITERATURE REVIEW

Soil nutrient monitoring is very important in modern farming. It helps crops get the right amount of fertilizers while reducing waste and environmental harm. Traditional soil testing in laboratories is accurate but can be expensive and slow. Because of this, there is a growing need for fast and portable soil testing technologies. This review looks at recent developments in soil nutrient detection, focusing on electrochemical probes, colorimetric digital testers, and spectral sensors, and how they are used in precision agriculture.

Electrochemical Probes: A Promising but Inaccurate Method

Electrochemical probes are used to measure soil nutrients by detecting ion levels through chemical reactions. These probes require calibration using special reference solutions to give correct results. At first, this method seemed promising because it allows real-time testing. However, after studying research papers and conducting our own experiments, we found major problems with accuracy. The readings changed too much due to factors like soil moisture and temperature. Because of these issues, we could not get reliable results using this method.

Colorimetric Digital Testers: The Fastest Option

Colorimetric digital testers are one of the quickest ways to test soil nutrients. These testers work by adding a chemical to the soil, which causes a color change. The color is then analyzed to determine the amount of nutrients in the soil. This method is fast and easy to use, so we based our research on the manual process behind these testers. However, while they provide quick results, they may not always be accurate, especially when testing different types of soil.

Spectral Sensors: A More Advanced Approach

Because of the limitations of electrochemical probes and colorimetric testers, we decided to focus on spectral sensors. These sensors work by analyzing how light interacts with the soil. Unlike other methods, they do not require chemicals or direct contact with the soil solution. In our research, we tested the AS3741 spectral sensor and used it to improve the accuracy of colorimetric digital testing. By combining spectral sensing with color-based analysis, we aimed to create a better system for real-time soil monitoring, which could help improve autonomous farming technology.

LACK OF KNOWLEDGE/TECHNIQUE

To find a suitable solution, we initially tested NPK prong testers, which are widely used for their convenience. The Soil NPK Sensor, Soil Nutrient Intelligent Fertilizer Detector Garden Lawn NPK Tester Meter was examined due to its practicality in field conditions. However, these sensors provide NPK readings in moles per liter, and their accuracy was questionable.

To verify their effectiveness, we conducted a controlled test in a chemistry lab, preparing a solution with a known molar concentration and comparing it with the sensor's readings. The results showed that the sensor's measurements were inconsistent, likely due to an unknown calibration method using solution conductivity, making it unreliable for precise soil testing.

On the other hand, the AS7341 sensor is highly sensitive to surrounding light, and during testing, it consistently provided inconsistent readings. To address this, we decided to design a 3D-printed enclosure to maintain constant light conditions and surroundings, ensuring more accurate readings.

PROPOSED STUDY

The study aims to develop a **calibration method** that provides a reasonably accurate prediction of macronutrient concentrations in soil. By establishing a standardized calibration approach, we seek to create a quick and reliable testing method that can be integrated into the robot for real-time soil assessment. This will enable faster decision-making and improve the success rate of infant plant plantations by ensuring optimal nutrient availability from the start.

METHODS

SAMPLE PREPARATION

Each test used 10 grams of soil as the standard sample size.

Water Preparation: Distilled water with a pH of 7.0 was used for all dilutions to ensure consistency and eliminate external contamination.

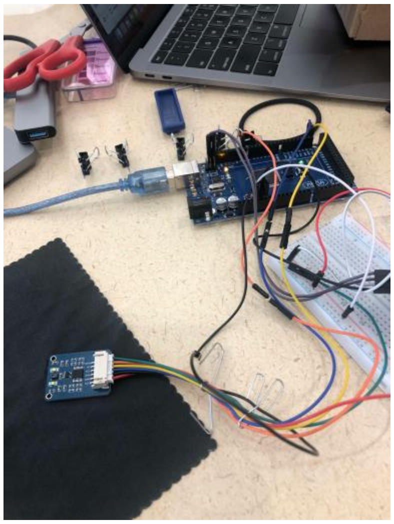
Dilution Ratios: Different soil-to-water ratios were tested to evaluate nutrient concentration readings:

- Potassium (K): Ratios of 1:2.5, 1:5, and 1:20 were tested.
- Phosphorus (P): Ratios of 1:10, 1:20, and 1:50 were evaluated.

EXPERIMENTAL TOOLS

The primary tools used for the study included:

1. **Rapidest Digital Soil Test Kit** and **Luster Leaf Rapidest Soil Test Kit**: These kits provided nutrient concentration readings in parts per million (ppm), offering a baseline for soil nutrient analysis.



2. **Arduino with AS7341 Spectral Sensor**: An Arduino microcontroller was used to integrate the AS7341 spectral sensor, which measures light reflectance to estimate soil macronutrient concentrations. This setup allowed for a more customizable and precise testing solution, enabling the detection of nutrient levels through spectral data.

3. **3D-printed Enclosure**

Was used to shield the Arduino sensor from external light, ensuring enhanced accuracy for color detection in the solution.

PROCEDURE

1. Mixing: Soil samples were mixed with distilled water at the designated ratios.
2. Wait Time:
   - For potassium and phosphorus tests: A waiting period of 10 minutes was observed after mixing for nutrient dissolution.
   - For pH testing: Readings were taken after 2 minutes and 5 minutes to monitor stability.
3. Tester Calibration: The NPK tester was compared against the known calibration solution to determine its accuracy for soil nutrient analysis.
4. Readings and Interpretation: Nutrient concentrations were recorded in ppm and classify categories of Adequate, Deficient, Depleted, or Surplus.

Data Table for Nutrient Concentration of Soil Sample

Table 1. Potassium (P) Solution

Soil Mass(g)	Water Volume(mL)	Ratio	Potassium Expected (ppm)	Category
10	25	1:2.5	400	Adequate
10	50	1:5	200	Deficient
10	200	1:20	50	Depleted

Table 2. Phosphorus (P) Solution

Soil Mass(g)	Water Volume(mL)	PH (After 2 minutes)	PH (After 5 minutes)	Ratio	Potassium Expected (ppm)	Category
10	100	7.5	7.5	1:2.5	400	Adequate
10	200	6.5	7.5	1:5	200	Deficient
10	500	6.0	7.0	1:20	50	Depleted

RESULT AND CONCLUSION

In this experiment, we utilized the AS7341 spectral sensor to predict soil macronutrient concentration levels by analyzing the blue color intensity of a soil solution. The soil sample was first soaked in a solution, allowing nutrients to dissolve and create a measurable color change. The AS7341 sensor then scanned the solution to obtain an average color intensity reading, which was used to determine the actual concentration category of soil nutrients.

Table 1. Phosphorus (K) Actual Concentration & Count of Blue Color

Actual Concentration	Surplus (100 ppm)	Sufficient (50 ppm)	Adequate (20 ppm)	Deficient (10 ppm)	Depleted (5 ppm)
Actual Average count of blue color based on the concentration (avgBlue)	avgBlue <= 1188	avgBlue <= 1510 && avgBlue >= 1188	avgBlue <= 1719 && avgBlue >= 1510	avgBlue <= 1871 && avgBlue >= 1719	avgBlue >= 1871 && avgBlue <= 2300

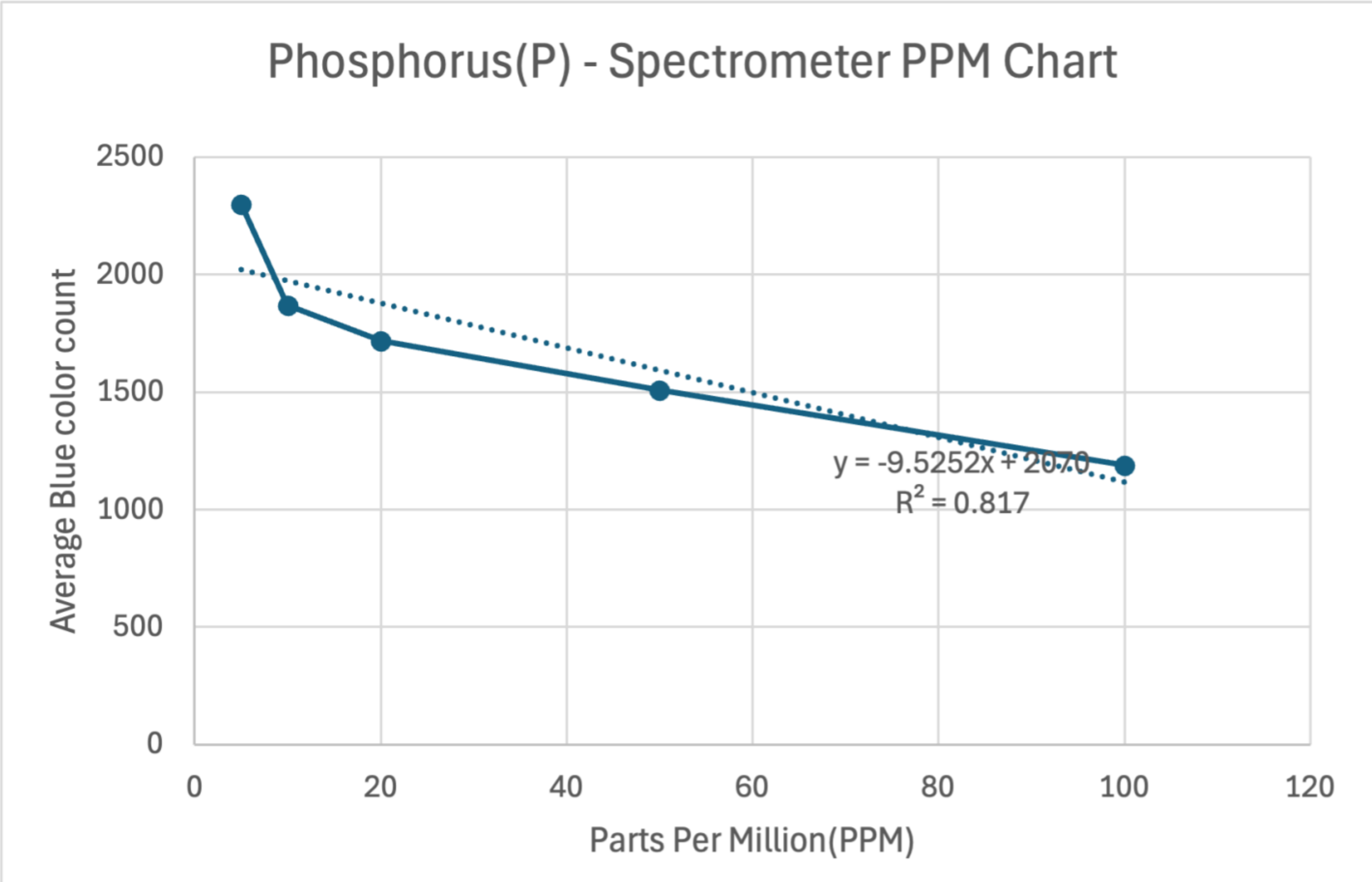
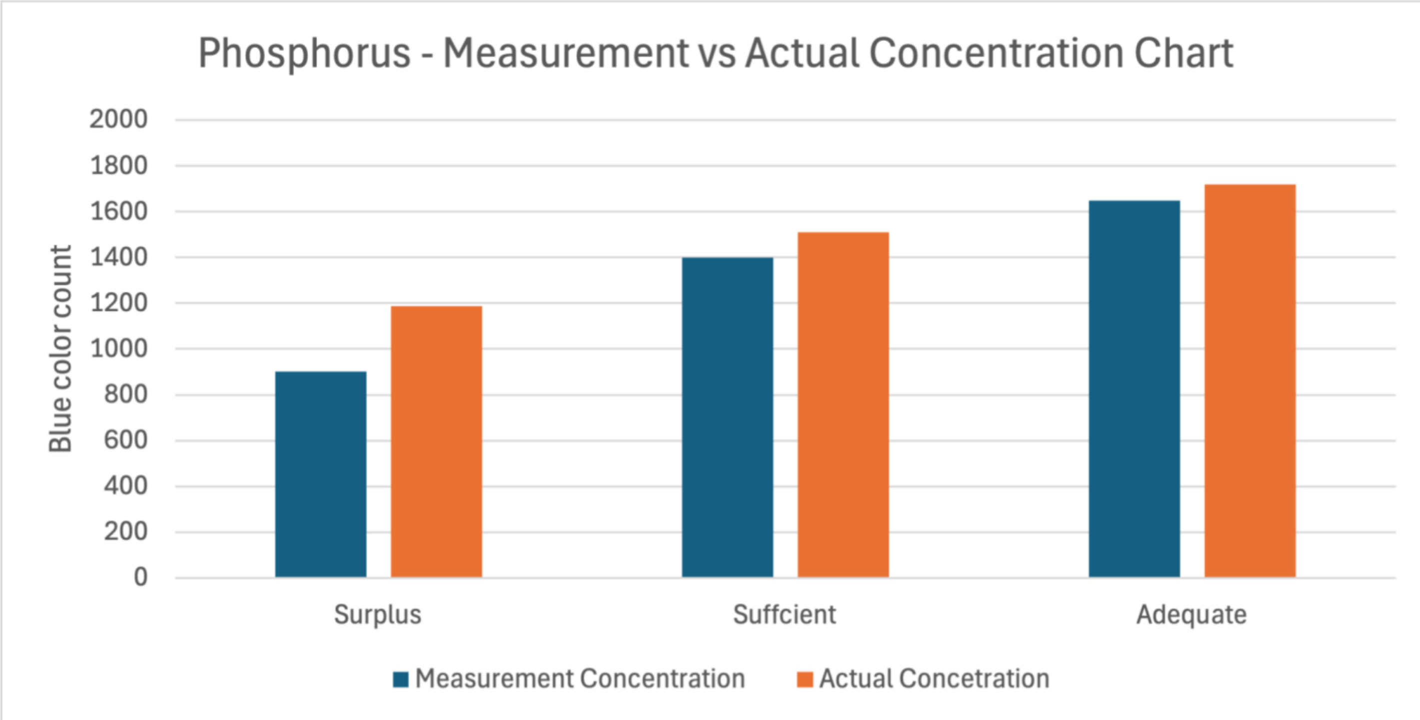


Table 2. Actual Concentration vs Measurement Concentration of Phosphorus

Actual Concentration	Measurement Concentration	Average Count of blue color based on the Arduino Sensors Measurements (avgBlue)
Surplus	Surplus	avgBlue ~= 900
Sufficient	Sufficient	avgBlue ~= 1400
Adequate	Adequate	avgBlue ~=1650


Phosphorus - Measurement vs Actual Concentration Chart
Blue color count
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Surplus
Suffcient
Adequate
Measurement Concentration
Actual Concetration

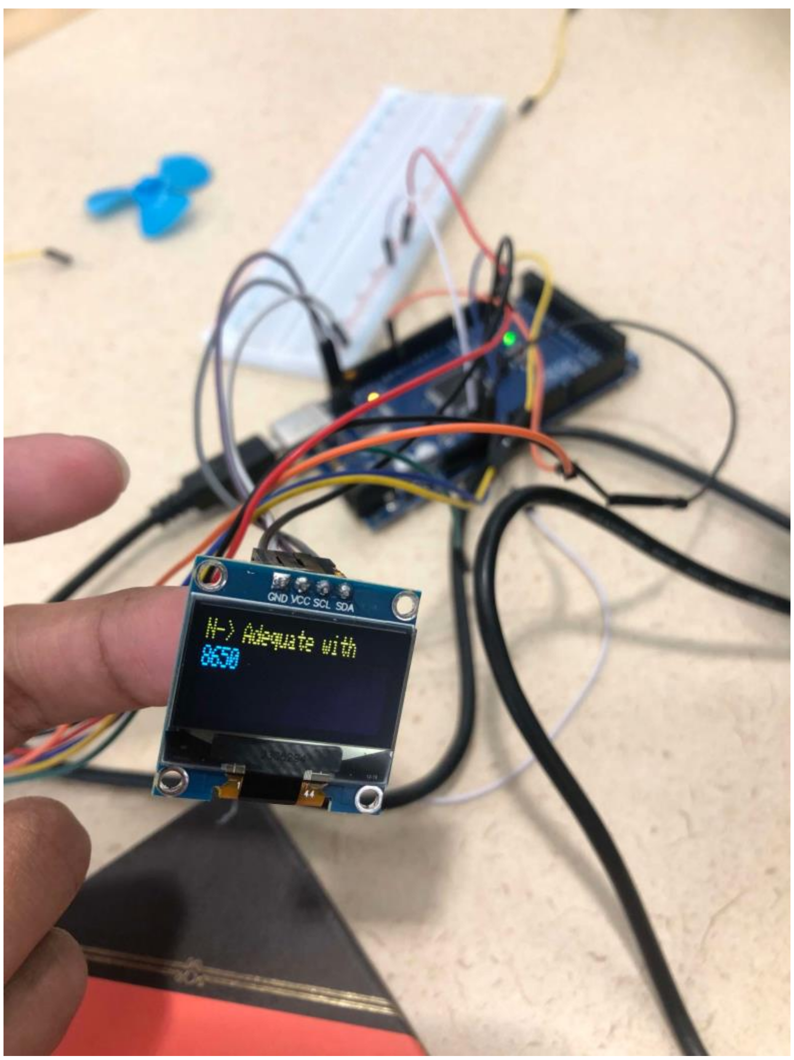
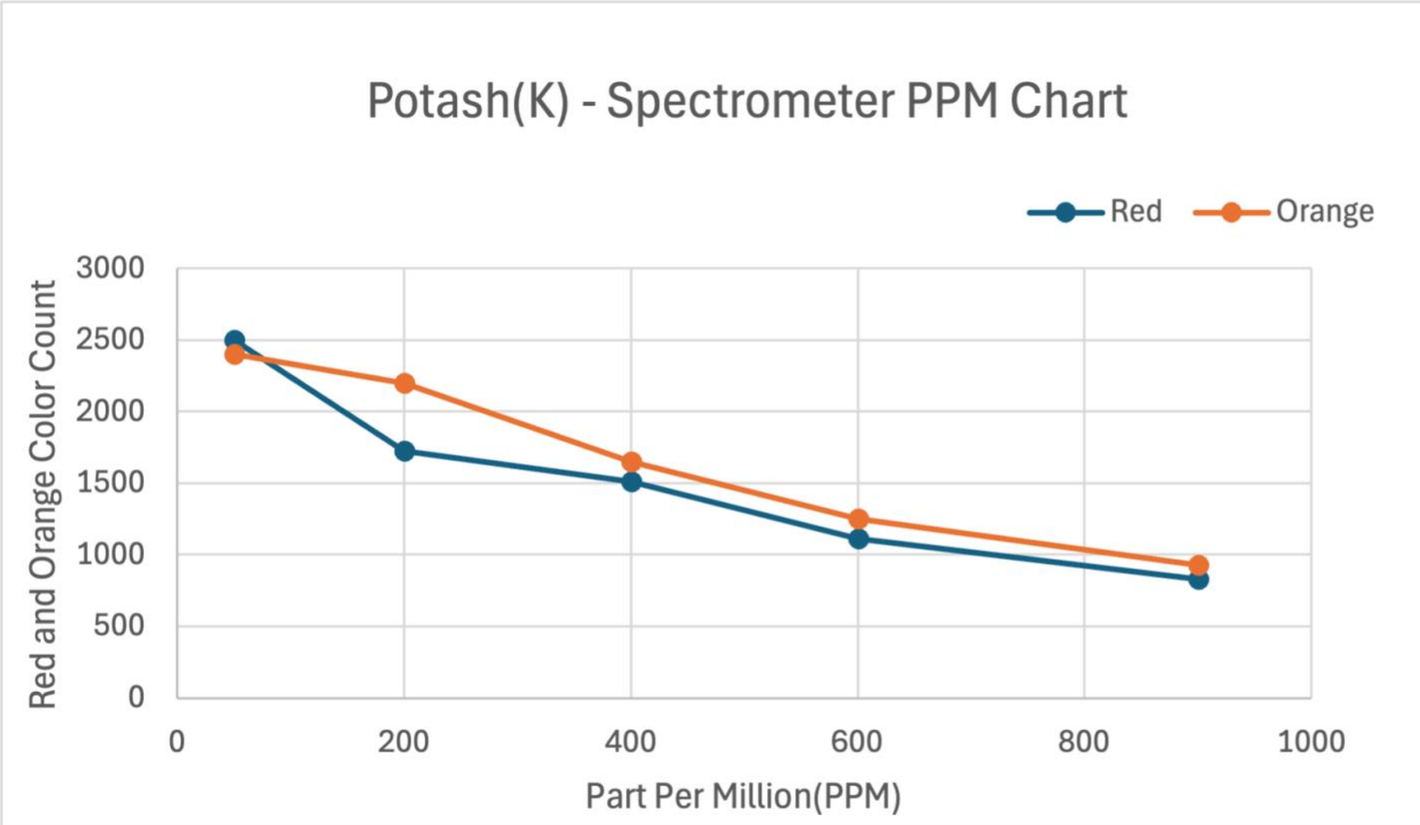

GND VCC SCL SDA
N-> Adequate with
8650

Table 1. Potassium (K) Results

Actual Concentration	Surplus (900 ppm)	Sufficient (600 ppm)	Adequate (400 ppm)	Deficient (200 ppm)	Depleted (50 ppm)
Actual Average Counts of red color based on the concentration (avgRed)	avgRed <= 829	avgRed <= 1110 && avgRed >= 829	avgRed <= 1510 && avgRed >= 1110	avgRed <= 1725 && avgRed >= 1510	avgRed <= 2500
Actual Average Counts of orange color based on the concentration (avgRed)	avgOrange<= 929	avgOrange <= 1250 && avgOrange>= 929	avgOrange <= 1650 && avgOrange >= 1250	avgOrange<= 2200 && avgOrange >= 1650	avgOrange <= 2200



DISCUSSION

Our setup successfully predicted the concentrations of nitrogen, phosphorus and potassium in five categories: surplus, sufficient, adequate, deficient, depleted. The AS7341 sensor's results are calibrated using reference color panels, ensuring accurate spectral measurements. This demonstrates a viable and effective calibration method for obtaining reasonably accurate predictions of macronutrient concentrations in soil. By providing reliable results, our approach contributes to the development of accessible and efficient tools for soil nutrient analysis.

The application of the AS7341 sensor involves a simple yet effective process: soil is soaked in a tube, and the solution is treated with a concentration tester to produce a color change. This tube is then placed into a 3D-printed enclosure designed to minimize external light interference, ensuring consistent and accurate readings. The AS7341 sensor scans the solution and displays the results on an LCD screen, providing immediate feedback on nutrient concentrations.

This mechanism has significant potential for integration into a variety of agricultural technologies. For example, the AS7341 sensor can be incorporated into a robotic automated system for large-scale soil analysis. Such a system could autonomously collect soil samples, process them, and analyze macronutrient levels in real-time. This would allow for precision agriculture applications, such as optimizing fertilizer use, identifying nutrient deficiencies, and improving crop yield efficiency. Additionally, the portability and reliability of this system make it suitable for smallholder farmers or researchers conducting on-site soil testing in remote locations.

CONCLUSION

This study successfully developed an effective system for detecting soil macronutrient concentrations, particularly phosphorus and potassium. By utilizing the AS7341 spectral sensor in a controlled environment with a 3D-printed enclosure, we minimized external light interference, leading to consistent and accurate readings. The system's ability to classify soil nutrient levels into categories such as surplus, sufficient, and adequate validates its practicality for field applications.

This research contributes to the advancement of rapid, real-time soil testing solutions, providing a portable, low-cost, and efficient alternative to traditional laboratory methods. The successful integration of this system into agricultural technology enhances precision farming, allowing for better nutrient management and optimized crop growth.

FUTURE WORK

Building on these findings, future research will focus on:

1. Expanding Sensor Capabilities – Incorporating additional spectral analysis to measure other essential macronutrients such as nitrogen (N) for a more comprehensive soil assessment.
2. Automating Soil Analysis – Integrating the AS7341-based system into a robotic platform that can autonomously collect and analyze soil samples in real time.
3. Machine Learning Implementation – Developing AI-based calibration models to improve the system's accuracy by recognizing complex soil compositions and environmental factors.
4. Field Deployment & Validation – Conducting large-scale field tests in various soil conditions to validate the system's performance outside controlled laboratory settings.
5. Wireless Connectivity – Implementing IoT (Internet of Things) technology to allow remote monitoring and real-time data analysis via cloud platforms.

Ultimately, these advancements aim to enhance agricultural automation, specifically for infant plant plantation robots, which require precise nutrient assessments for optimal growth.

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Furthermore, we acknowledge the manufacturers and suppliers of the AS7341 spectral sensor for providing the necessary tools to develop and refine our system. Finally, we recognize the importance of agricultural innovation and hope that this research contributes to the advancement of sustainable and technology-driven farming practices.

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