

# Real-time soil macronutrients analysis and results-oriented crop recommendation system for a specific region.

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## Abstract

Agriculture continues to be a major contributor to the economy and a key source of livelihood for many people. In the Coimbatore district of Tamil Nadu, the soil is capable of supporting a wide variety of crops. Still, differences in nutrient content and moisture across locations can lead to inconsistent yields. To manage these variations effectively, frequent and reliable soil assessment is necessary. Traditional laboratory testing, although precise, is slow, costly, and impractical for continuous field-based evaluation. To overcome these limitations, this work presents an IoT-based soil monitoring system designed for the Coimbatore region. The system incorporates sensors that measure essential soil macronutrients—nitrogen (N), phosphorus (P), and potassium (K), along with pH. These sensors interface with an ESP32 microcontroller, which acquires the readings in real time and forwards them to a cloud platform for remote access. The data can be viewed through an online dashboard, reducing dependence on manual laboratory testing. The obtained sensor values show good agreement with laboratory results, and the proposed system demonstrates an accuracy of 89.36%, outperforming the existing research work. Soil-based crop recommendations are generated using the TNAU Crop Production Guide (2020), ensuring that the suggestions align with region-specific agronomic standards. By providing continuous, reliable soil information and supporting informed decision-making, the system contributes to more efficient resource use and promotes precision-oriented, sustainable agricultural practices in the Coimbatore region.

**Keywords:** ESP32, NPK sensor, pH sensor, IOT, Soil nutrient analysis.

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## 1. Introduction

Agriculture continues to play a major role in sustaining the population and supporting the economy. The health of the soil is a key factor influencing crop performance, as nutrient availability and soil characteristics determine the growth and yield of agricultural produce. In the region chosen in this research work, Coimbatore, Tamil Nadu, India, is found to have noticeable variations in soil parameters—nitrogen, phosphorus, potassium, pH, and moisture across different fields. Although laboratory-based soil testing provides accurate results, it is often time-consuming, costly, and unable to support continuous field monitoring. As the demand for quick and accessible soil data increases, modern technologies are being adopted to obtain real-time information directly from agricultural fields. To address these needs, this study focuses on developing an IoT-enabled soil monitoring system capable of measuring essential soil

parameters continuously. Reliable and timely information is essential for making appropriate decisions on fertiliser application, irrigation, and crop planning. While many existing IoT-based systems concentrate on simple data collection, they often fall short in terms of precision when compared with conventional laboratory results. The developed system in this paper addresses this limitation by using calibrated sensors interfaced with an ESP32 microcontroller to generate soil parameter readings that closely correspond to those obtained through conventional laboratory testing procedures. The collected parameters are transmitted to a cloud platform for remote viewing, allowing farmers and researchers to monitor soil health continuously. Furthermore, based on the analysed readings, suitable crops are recommended using guidelines from the Tamil Nadu Agricultural University (TNAU) Crop Production Guide (2020), ensuring region-specific and scientifically validated suggestions. Overall, this study demonstrates how IoT technology can support precision agriculture by providing timely, accurate, and actionable soil information, ultimately helping farmers improve productivity and resource management.

## 2. Literature Survey

Jeyasingh J.A.R. et al. [1] analysed the spatial variation of soil nutrients in the Coimbatore district using GIS and remote sensing techniques, establishing a baseline for understanding regional soil variability. As agriculture transitions toward data-driven practices, IoT technologies have become central to achieving continuous soil assessment and better crop management. Sushma Y. et al. [2] developed an IoT-enabled soil nutrient monitoring setup using Arduino Uno and ESP32 to measure NPK, pH, and moisture, transmitting data to a cloud platform for real-time access. However, their results showed deviations from laboratory-tested values, emphasising the need for better calibration and accuracy. The present work addresses these limitations by enhancing calibration and data consistency, providing readings that more closely match conventional test results.

Traditional soil testing involves manual sample collection and laboratory analysis through chemical and instrumental methods to determine parameters such as NPK, pH, and organic carbon. Although precise, these methods are expensive, time-consuming, and labour-intensive, providing only periodic results that delay decision-making. Thus, while traditional testing ensures analytical accuracy, it is unsuitable for continuous monitoring, highlighting the need for automated, real-time IoT-based soil analysis systems.

The **TNAU Crop Production Guide (2020)** [3] serves as the basis for determining nutrient levels and crop recommendations in this study. The soil parameter ranges were adapted from [1] to act as baseline data for evaluating the proposed IoT system. Niveditha J.V. et al. [4] developed a low-cost NPK and moisture sensing device, emphasising the importance of calibration and field validation—a process followed in this work. Geetha S. et al. [5] implemented an IoT-based soil testing system supporting fertiliser recommendations, while Spandana K. and Pabboju S. [6] introduced a digital dashboard for real-time visualisation. Jain N. et al. [7] validated sensor accuracy against laboratory data, influencing the validation strategy of this research. Works by Ula R. et al. [8] and Pailochan N. et al. [9] and [10] demonstrated effective pH and moisture monitoring through IoT, supporting the concept of real-time, field-deployable sensing. Similarly, Sondhiya R.R. and Singh V.K. [10] showed how IoT sensor networks capture nutrient variability efficiently.

Khanal K. et al. [11] and Cheema S.M. et al. [12] demonstrated real-time IoT frameworks and advanced sensing technologies for nutrient analysis and remote recommendations. Studies by Sobhy D.M. et al. [13], [14], and [15] emphasised reliable MQTT-based cloud communication. Reazul Islam M. et al. [16] and Khanal et al. [17] explored IoT and machine learning integration for nutrient monitoring, while Lenin Kumar L. et al. [18] applied microcontrollers for field-level NPK measurement. Mane S. et al. [19] and Ula R et al. [20] discussed IoT's role in modernising agriculture under the Agriculture 4.0 paradigm and monitoring soil pH and moisture values, respectively. Workman S. Jr. [21] and Deshpande S. et al. [23] highlighted IoT's contribution to precision farming and irrigation optimisation, whereas Kumar T. et al. [24] implemented a

solar-powered, GPS-enabled soil monitoring system for sustainable field sensing. Sulaeman Y. et al. [25] and Kumar et al. [22] developed a portable soil nutrient detector, illustrating the practicality of compact, low-cost sensing devices for diverse soil types.

From the reviewed literature, it is evident that IoT-based soil analysis systems have transformed traditional soil testing by enabling continuous, real-time nutrient assessment. However, most studies emphasise data collection and visualisation with limited validation against laboratory results. The present work bridges this gap by comparing IoT-based sensor readings with standardised laboratory tests and providing region-specific crop recommendations based on the **TNAU Crop Production Guide (2020)** [3], promoting precision and sustainability in agriculture.

### 3. Materials and Methods

The proposed system was implemented and tested in the Coimbatore region, where soil samples were collected from various agricultural fields representing different soil types and fertility levels. A total of 100 soil samples were collected, out of which 25 samples were selected using the stratified random sampling method for detailed comparison with traditional laboratory results. This method provided fair sample representation and supported an accurate assessment of the system's effectiveness. To capture soil characteristics via sensors for determining soil parameters such as pH and the primary macronutrients—nitrogen, phosphorus, and potassium—sensors were installed in the field. Each sensor was inserted into the soil to record its respective parameter. The pH sensor determines soil acidity or alkalinity by producing a voltage that reflects the hydrogen ion concentration, which is then interpreted by the ESP32's ADC to obtain the pH value. The NPK sensor detects the levels of nitrogen, phosphorus, and potassium by analysing the soil's electrochemical response and converting it into corresponding nutrient value readings. Prior to data collection, all sensors were calibrated to enhance accuracy. The pH sensor was calibrated using a buffer solution. The NPK sensor was calibrated using known nutrient solutions. Once calibration was completed, the samples were analysed for pH and NPK values using the proposed architecture.

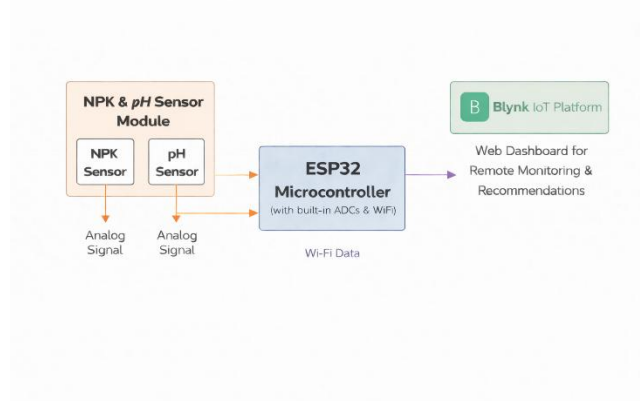
These sensors were interfaced with an ESP32 microcontroller, which served as the main data acquisition and control unit. The ESP32 collected analogue signals from the sensors, converted them into readable values, and prepared them for wireless transmission. The ESP32 was configured to use alternate RX and TX pins for UART communication, allowing stable serial data exchange with the NPK sensor. Nutrient values were received as digital data through the reassigned RX pin. In contrast, the pH sensor provided an analogue voltage output, which was read through the ESP32's ADC pin and converted into the corresponding pH value.

#### 3.1 Soil Parameter Analysis and Communication Characteristics

The proposed setup enables continuous monitoring of soil conditions, allowing farmers to make timely and informed decisions. It functions through efficient communication between the sensing units and the ESP32 controller, ensuring that the collected data is accurate and consistently transmitted for further analysis. Sensors for measuring pH and macronutrients- nitrogen, phosphorus and potassium (NPK) are connected to an ESP32 microcontroller, which continuously gathers and processes the data. This information is then transmitted via the IoT platform Blynk and displayed for easy access. Sensor performance and data transmission can be influenced by various environmental conditions, including differences in soil composition, moisture content, and temperature. Therefore, proper calibration is essential to maintain consistent performance. The ESP32 acts as the communication hub, using its built-in Wi-Fi to send data wirelessly. After data acquisition, the collected readings were transmitted wirelessly to the IoT cloud platform using the ESP32's built-in Wi-Fi module. It supports 2.4 GHz Wi-Fi, allowing the device to connect to local networks and transmit sensor data in real time. This built-in Wi-Fi capability makes the ESP32 suitable for IoT applications, as it enables remote monitoring, data uploading, and continuous connectivity.

Link for web dashboard:

<https://blr1.blynk.cloud/dashboard/550368/global/devices/1/organization/550368/devices/1751626/dashboard>



**Figure 1:** Block diagram of Iot- enabled smart agriculture model

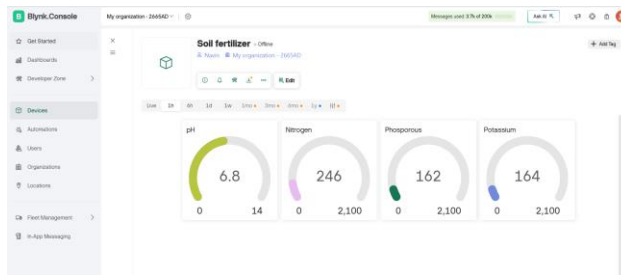
### 3.2 Stepwise Procedure – Data Collection and Analysis Process

- **Soil Sample Collection:** 100 Soil samples were collected from various agricultural fields in the Coimbatore region to represent soil types in various regions.
- **Sensor Deployment:** The sensors were positioned in the soil to record key parameters, including pH and the macronutrients nitrogen (N), phosphorus (P), and potassium (K).
- **Data Acquisition through ESP32:** The ESP32 microcontroller collected real-time readings from all sensors and converted them into digital data.
- **Data Transmission to IoT Platform:** The collected data were transmitted wirelessly via Wi-Fi to the IoT platform for remote access.
- **Data Visualisation:** The IoT dashboard presented live updates of the measured parameters, including pH and the macronutrients nitrogen (N), phosphorus (P), and potassium (K).
- **Crop Recommendation:** Suitable crops were identified using the analysed soil data, with guidance taken from the TNAU Crop Production Guide (2020).

This system gives farmers real-time insights into soil conditions, reducing the need for manual testing and enabling smarter, data-driven farming practices through IoT technology.

## 4. Results and Discussion

The sensor readings obtained from the IoT system were compared with laboratory-tested soil data [1] to evaluate the system's accuracy and reliability. The soil samples were also tested using the existing research work [2], and the results were compared with the proposed research work. The percentage error and mean accuracy were calculated for each parameter, confirming that the proposed system provided results closely matching the traditional testing methods. Crops were recommended based on the guidelines provided in the TNAU Crop Production Guide (2020) [3]. The system identified suitable crops corresponding to the soil's nutrient composition and pH levels. Access to real-time soil information through the IoT platform enabled timely decisions related to fertiliser use, irrigation scheduling, and crop selection. Overall, this methodology ensures accurate soil data collection, reliable cloud-based data management, and effective field-level validation. The proposed system provides an efficient and real-time approach for continuous soil health monitoring, thereby supporting precision agriculture in the Coimbatore region.



**Figure 3:** IoT dashboard of the proposed methodology

Soil samples were analysed using sensors that measure pH and NPK (nitrogen, phosphorus, and potassium) in the environment. The readings from these sensors were then compared with the results obtained through conventional laboratory testing and existing methods to evaluate their accuracy and reliability.

**Table 1:** pH and NPK values determined by using the conventional laboratory-based procedures [1]

Sample	pH	N (kg/ha)	P (kg/ha)	K (kg/ha)
1	7.65	207	14.3	396
2	7.72	204	14.0	410
3	7.70	206	13.9	405
4	7.66	203	14.2	395
5	7.67	207	14.4	402
6	7.95	255	15.7	540
7	7.90	250	15.9	548
8	7.97	253	15.6	543
9	7.93	252	15.8	549
10	7.91	251	15.7	548
11	7.84	247	14.7	650
12	7.87	249	14.9	646
13	7.85	248	14.8	648
14	7.83	248	14.9	649
15	7.86	249	14.8	651
16	7.98	248	15.1	555
17	7.99	249	15.0	552
18	7.97	250	15.1	557
19	7.96	249	15.0	554
20	8.00	250	15.1	556
21	7.90	241	14.5	673
22	7.91	240	14.6	675
23	7.89	239	14.5	674
24	7.78	238	15.2	595
25	7.76	240	15.1	600

Note: Values synthesised within the nutrient ranges reported in Jeyasingh J.A.R. et al., “Agric Sci Digest,” 43(3): 319–323, 2023.

**Table 2:** pH and NPK values determined by using the existing research work [2]

Sample	pH	N (kg/ha)	P (kg/ha)	K (kg/ha)
1	7.20	198	11.5	520
2	7.35	205	12.6	540
3	7.41	210	12.1	515
4	7.25	190	11.3	500
5	7.31	202	12.0	530
6	7.45	212	12.4	535
7	7.36	200	11.8	525
8	7.30	204	12.3	510
9	7.27	206	12.5	512
10	7.29	203	12.2	518
11	7.37	207	12.6	520
12	7.22	192	11.4	505
13	7.28	195	11.7	509
14	7.40	209	12.2	528
15	7.33	202	12.0	523
16	7.35	201	12.3	540
17	7.39	208	12.4	547
18	7.24	197	11.9	525
19	7.26	200	11.6	520
20	7.41	209	12.1	530
21	7.30	205	11.8	518
22	7.25	199	11.5	522
23	7.32	204	12.0	532
24	7.28	203	11.9	526
25	7.38	208	12.2	540

**Table 3:** pH and NPK values determined by using the Proposed research work

Sample	pH	N (kg/ha)	P (kg/ha)	K (kg/ha)
1	7.60	216.0	12.8	561.0
2	7.72	213.0	12.5	564.0
3	7.78	218.5	13.0	553.5
4	7.69	211.5	12.3	557.8
5	7.80	215.3	13.2	560.6
6	7.74	217.9	13.0	552.9
7	7.66	212.7	12.4	563.1
8	7.71	219.4	13.3	558.7
9	7.73	213.8	12.9	555.0
10	7.76	214.5	13.1	554.4
11	7.68	215.8	13.2	559.9

12	7.79	218.2	13.4	553.2
13	7.62	210.3	12.1	564.8
14	7.70	213.1	12.6	557.0
15	7.75	216.7	13.0	561.8
16	7.64	214.9	12.8	558.1
17	7.78	219.1	13.4	550.7
18	7.67	211.8	12.3	556.5
19	7.73	215.1	13.2	560.9
20	7.71	212.5	12.5	557.9
21	7.79	217.5	13.1	552.2
22	7.76	214.3	12.9	555.5
23	7.80	216.1	13.3	559.4
24	7.68	210.9	12.2	562.8
25	7.74	218.7	13.4	554.6

The accuracy of existing and proposed research work is compared with the readings taken from the conventional testing procedure [1], and the accuracy of the results obtained is formulated below. The average accuracy of the existing and proposed work is calculated and tabulated in Table 5.

**Table 4.** Accuracy comparison of soil parameter measurements for the existing and proposed IoT-based systems with respect to representative conventional laboratory data

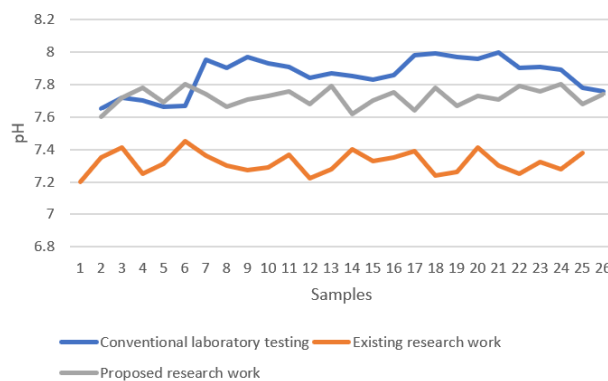
Sample No	Accuracy of soil nutrient values utilising the existing method (%)				Accuracy of soil nutrient values utilising the Proposed Method (%)			
	pH	N	P	K	pH	N	P	K
1	91.7	81.3	80.7	81.4	96.8	86.5	86.8	86.4
2	93.6	81.0	81.2	81.1	98.4	86.7	86.5	86.6
3	94.4	81.5	81.0	81.0	99.1	86.8	86.6	86.7
4	92.4	80.9	81.4	81.1	97.9	86.5	86.7	86.6
5	93.1	81.2	80.9	81.3	99.4	86.6	86.6	86.8
6	94.9	81.4	81.2	81.0	98.6	86.7	86.7	86.5
7	93.4	81.1	81.0	81.2	97.6	86.6	86.4	86.7
8	92.9	81.3	80.8	81.3	98.3	86.5	86.8	86.6
9	92.5	81.2	81.1	81.0	98.5	86.6	86.6	86.7
10	92.8	81.0	81.2	81.1	98.8	86.7	86.7	86.5
11	93.6	81.4	81.0	81.3	97.8	86.8	86.5	86.6
12	91.9	81.2	81.1	81.2	99.2	86.6	86.6	86.7
13	92.6	81.0	81.0	81.0	97.0	86.5	86.5	86.6
14	94.3	81.5	81.2	81.4	98.1	86.7	86.8	86.7
15	93.2	81.1	81.1	81.1	98.9	86.6	86.6	86.6
16	93.4	81.0	80.9	81.2	97.3	86.5	86.5	86.7
17	94.0	81.3	81.0	81.3	99.1	86.6	86.7	86.6
18	92.2	81.2	81.2	81.1	97.7	86.7	86.6	86.7
19	92.4	81.1	81.0	81.2	98.5	86.6	86.5	86.7
20	94.4	81.0	81.2	81.1	98.3	86.7	86.7	86.6
21	92.9	81.2	81.1	81.3	99.2	86.6	86.6	86.7

22	92.4	81.3	81.0	81.1	98.8	86.7	86.5	86.6
23	93.3	81.1	81.2	81.0	99.4	86.6	86.7	86.7
24	92.6	81.4	81.0	81.2	97.8	86.8	86.6	86.6
25	93.9	81.2	81.1	81.1	98.6	86.6	86.7	86.6

**Table 5:** Overall Accuracy of readings taken from Existing and Proposed works

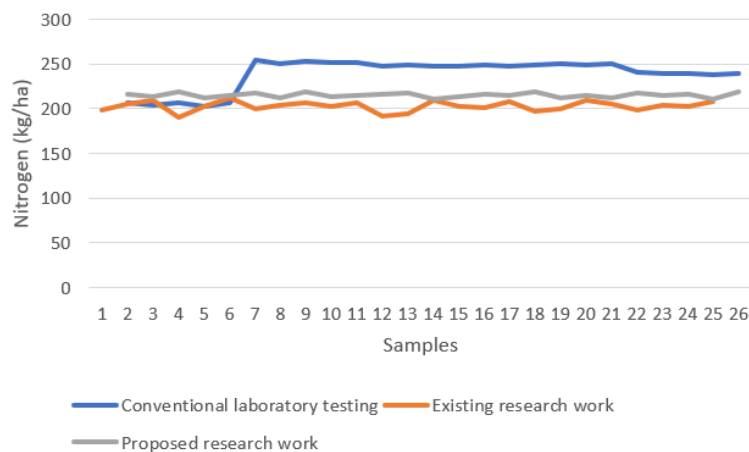
Existing System (%)				Proposed System (%)			
pH	N	P	K	pH	N	P	K
93.07	81.18	81.07	81.15	98.45	86.13	86.65	86.24

From the table, it is inferred that the existing research work has an accuracy of 84.11%, and the proposed research work has an accuracy of 89.36% from the conventional testing method. The figure below illustrates the relative comparison of pH between the proposed system, the existing system, and the traditional laboratory method.

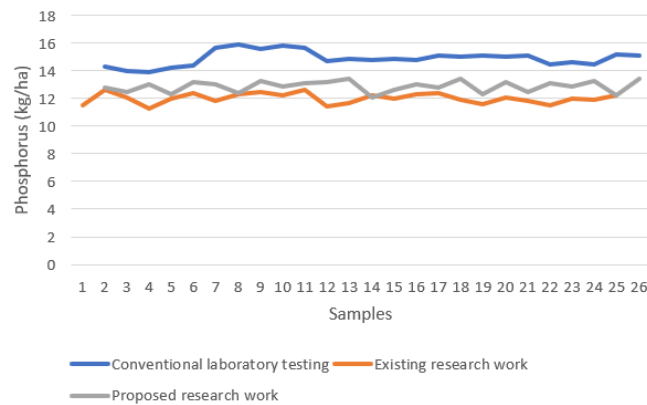


**Figure 3** pH comparison chart

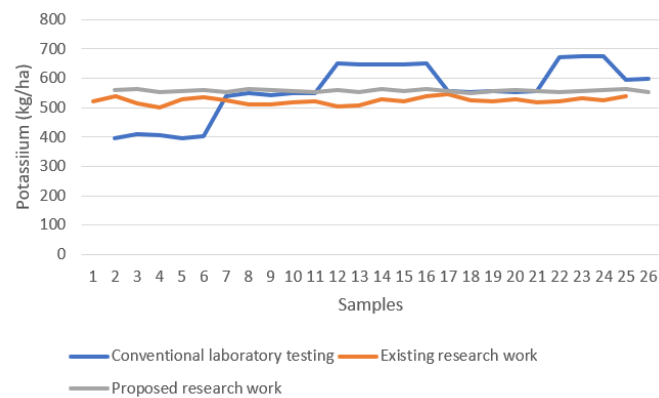
The figure below, Figure 4-6, illustrates the relative comparison of nitrogen, phosphorus, and Potassium values using the proposed system, the existing work [2], and the conventional laboratory method [1].



**Figure 4** Nitrogen comparison chart



**Figure 5** Phosphorus comparison chart



**Figure 6** Potassium comparison chart.

In this project, soil samples were analysed using a set of IoT-enabled sensors that measured pH and NPK (nitrogen, phosphorus, potassium). The sensors detect and transmit data in real time, which is processed by an ESP32 microcontroller and displayed both on a local LCD and through a cloud-based platform. To evaluate the system's accuracy, the recorded sensor values were examined alongside results obtained from conventional laboratory soil analysis [1]. The comparison revealed that the nutrient measurements from the sensors of the proposed system closely matched the laboratory values more than the existing work. For example, the readings for nitrogen, phosphorus, and potassium in the tested soil samples showed fewer differences compared to the laboratory results, indicating that the proposed sensor-based system provides more accurate results than the existing research work [2]. Beyond nutrient levels, the sensors also tracked soil pH, offering a comprehensive view of soil conditions. By delivering real-time insights, the system allows for timely decisions on soil health. Overall, the results indicate that though the proposed setup cannot efficiently replace traditional laboratory-based soil testing methods in terms of accuracy, it can still provide an acceptable range of soil nutrient values in real time in order to judge the soil macronutrient condition.

With reference to the TNAU Crop Production Guide (2020) [3] and the analysed soil macronutrient values across various regions of the Coimbatore region, it is found that the area is more suitable for crops such as sugarcane, coconut, and banana. Sugarcane grows well in soils with nitrogen levels above 240 kg/ha, phosphorus between 11–30 kg/ha, potassium in the range of 150–300 kg/ha, and a pH of 6.0–7.5. Coconut requires nutrient levels of approximately 120–300 kg/ha of nitrogen, 10–25 kg/ha of phosphorus, and 200–600 kg/ha of potassium, with an ideal pH between 5.0 and 7.0. Banana cultivation is supported by soils containing 180–300 kg/ha of nitrogen, 12–30 kg/ha of phosphorus, and 250–600 kg/ha of potassium, with an acceptable pH of 6.0–7.5.

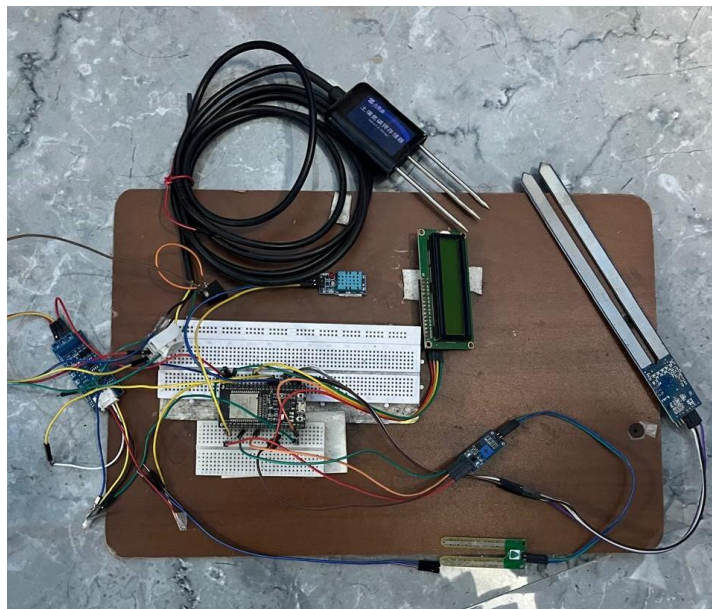


Fig 7. Proposed hardware system for soil macronutrients analysis

## 5. Conclusion

The developed IoT-based soil monitoring system provides a reliable, cost-efficient, and continuous method for evaluating soil health, making it accurate for soil macronutrient analysis in the Coimbatore region. Using sensors integrated with an ESP32 microcontroller, the system captures real-time values of key soil parameters, including pH and the major macronutrients nitrogen, phosphorus, and potassium. The information is then uploaded to an IoT platform, where it can be viewed through an intuitive dashboard, allowing farmers and researchers to monitor soil status from remote locations. By reducing dependence on laboratory testing, the approach enables faster and more informed decisions on fertiliser management and crop planning. In the future, the system may be enhanced by integrating machine learning methods, which could improve the precision of crop recommendations. By training the model on large sets of soil and crop data, machine learning can help identify patterns, predict nutrient requirements, and recommend the most suitable crops with greater precision. This integration would enable the system to provide adaptive and data-driven insights for better soil and crop management, supporting precision farming and improving crop productivity.

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