Intelligent Soil Nutrient Monitoring using Antenna-Enabled Advanced Sensor Technologies for Enhancing Crop Yield and Agricultural Productivity.

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Abstract: Sensing technologies play a vital role in achieving sustainable agricultural production through precision agriculture. This study presents an overview of key sensing methodologies used for monitoring soil nutrients, with a focus on recent advancements in sensor devices reported in the literature. A prototype system was developed using an AS73211 colour sensor integrated with a NodeMCU microcontroller to detect soil macronutrients. Two different soil samples were analyzed to evaluate the system's performance. Experimental results revealed that the concentrations of Nitrogen, Phosphorus, and Potassium exceeded their respective threshold wavelength ranges of 445–485 nm**,** 505–565 nm, and 625–685 nm in both samples. The findings demonstrate the effectiveness of the proposed sensing approach in identifying nutrient levels. Overall, the developed method is practical, reliable, and well-suited for real-time soil monitoring, supporting efficient fertilizer management and sustainable farming practices.
Keywords: NPK, soil sensor, NODE MCU.

I. Introduction

Precision agriculture is an advanced farming approach that uses technology and data-driven techniques to optimize agricultural practices. It involves the use of GPS, sensors, drones, and data analytics to monitor crop conditions, soil health, and environmental factors in real time. By enabling site-specific management, precision agriculture helps improve crop yields, reduce resource wastage, and enhance sustainability. This method supports informed decision-making, ensuring efficient and environmentally friendly farming. Agriculture plays a vital role in India's economy, and soil fertility is one of the key factors influencing crop productivity. The availability of essential macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), along with micronutrients including zinc, iron, boron, manganese, and copper, directly affects plant growth and yield. Imbalances in these nutrients can lead to reduced crop performance and poor soil health. To address this challenge, Wireless Sensor Network (WSN)-based precision agriculture systems are employed for continuous monitoring of soil nutrient status and environmental conditions.

Electronic soil sensors deployed across agricultural fields measure nutrient concentrations, moisture content, pH, and other critical parameters in real time. The collected data is transmitted wirelessly to a central monitoring system for analysis and decision-making. This approach enables site-specific nutrient management and optimized fertilizer application based on actual soil requirements. Consequently, it reduces excessive fertilizer usage, minimizes environmental pollution, and improves resource utilization. Real-time nutrient monitoring also supports sustainable agricultural practices and enhances crop productivity. Therefore, integrating WSN technology with soil nutrient sensing provides an efficient solution for modern precision farming.

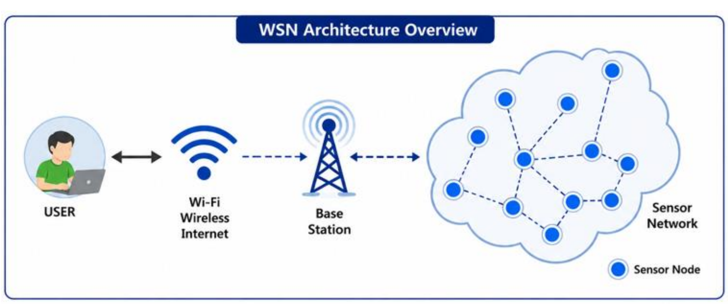


Figure-1.1: Layout of a multi-node wireless sensor network system.

Figure 1.1 illustrates a Wireless Sensor Network (WSN) architecture in which NPK sensor nodes are strategically deployed across an agricultural field to monitor soil nutrient levels in real time. The sensor nodes communicate through a wireless network and transmit the collected data to a central gateway node for aggregation and analysis. This architecture enables comprehensive nutrient mapping and supports informed decision-making for precision agriculture applications.

Wireless Sensor Networks (WSNs) comprise multiple distributed sensor nodes that monitor environmental and soil parameters such as moisture, temperature, humidity, and nutrient levels in real time. Each sensor node consists of sensing elements, a microcontroller, a wireless transceiver, and a power source for data acquisition and communication. The collected data is transmitted wirelessly to a gateway or cloud platform for storage, processing, and analysis. WSNs provide a cost-effective and energy-efficient solution for monitoring large agricultural fields and other remote environments. In precision agriculture, WSNs support intelligent decision-making by enabling continuous monitoring of soil conditions, optimizing resource utilization, and improving crop productivity.

The main Objective is to recognize several micro nutrients and macro-nutrients such as commercial nitrogen (N), phosphorous (P) and potassium (K) fertilizers present in the soil by organizing electronic sensors in a different locations in the crop field. Using wireless sensor technology the data is collected, monitored and transmitted to the server for better yield of the crop.

II. Architecture Diagram

1. Wireless Sensor Network

The goal of this work is to develop an innovative agricultural crop monitoring system using a Wireless Sensor Network (WSN) to enhance crop productivity and accurately detect key macronutrients in the soil. The system is designed to deploy electronic sensors at various points across the field to monitor the presence and concentration of essential nutrients specifically Nitrogen (N), Phosphorus (P), and Potassium (K). These sensors continuously measure soil nutrient levels and transmit the data wirelessly to a central server. This real-time information is then made accessible to farmers, allowing them to understand the chemical condition of their soil and apply fertilizers accordingly for optimal crop health. By enabling timely and precise nutrient management, the system supports more efficient use of commercial N, P, and K fertilizers, which have historically played a major role in boosting agricultural yields. The below figure-2.1 shows that Architecture of Wireless Sensor Network for Agricultural Monitoring.

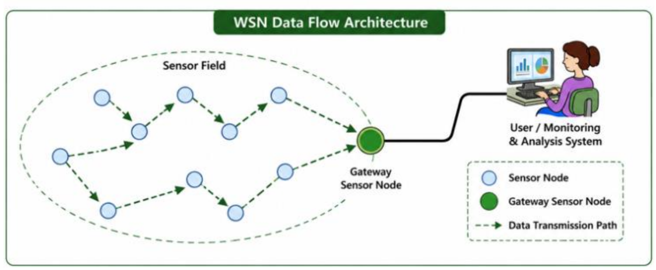


Figure-2.1: Wireless Sensor Network Architecture Monitoring.

However, excessive use of these fertilizers (NPK) has been cited as a source of contamination of surface and groundwater. There are different stages in crop growing and each step requires different nutrient levels. The farmer has to spend a lot of time in nursing the field area. There are various techniques available to measure and monitor soil nutrients level hence farmers can improve the crop production. Insufficient nutrient levels can unhelpfully affect crop production while excess nutrient levels will either have a similar effect or simply be wasted.

The sensor nodes will collect data in the range of different soil macro-nutrients using electronic sensor and transmit to the database server through the Wireless Sensor Networks (WSN). The chemical level of the soil is monitored by the sensors and data is transmitted over the wireless channel to the farmer's system through which he can timely get the knowledge of chemical level in the soil in his field and accordingly he can apply fertilizers to his farm. [17]

2. WSN Framework

The proposed Wireless Sensor Network (WSN) architecture for smart agriculture comprises sensor nodes, a gateway, and a data processing unit. Sensor nodes are deployed across the agricultural field to continuously monitor soil conditions, environmental parameters, and crop health. Each node integrates sensors for measuring variables such as temperature, humidity, and soil moisture, a microcontroller for data acquisition and processing, a wireless transceiver for communication, and a power source, typically batteries or energy-harvesting devices. The collected data are transmitted to a gateway, which serves as an intermediary between the sensor nodes and the external network. The gateway forwards the aggregated data to a centralized server or cloud platform, where it is stored, processed, and analyzed using advanced analytical tools and machine learning algorithms.

This enables real-time monitoring, predictive analytics, and informed decision-making for efficient agricultural management.

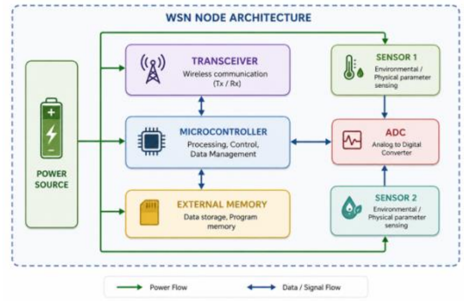


Figure-2.2: Wireless Sensor Network-node-architecture.

3. Communication Protocols

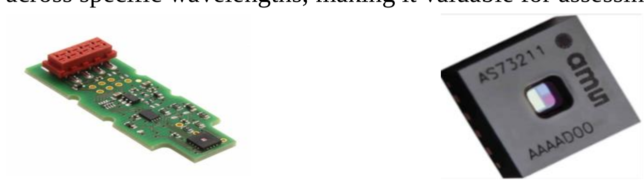
The communication layer of the Wireless Sensor Network (WSN) framework is responsible for the reliable and efficient transmission of data between sensor nodes and the gateway. It employs routing protocols, such as topology-aware routing algorithms, to determine optimal communication paths based on network structure, thereby improving data delivery efficiency and reducing energy consumption. The framework supports various wireless communication technologies, including Zigbee, LoRa, and Wi-Fi, selected according to application-specific requirements such as communication range, power efficiency, bandwidth, and data transmission rate. These protocols ensure seamless connectivity and facilitate the timely transfer of sensor data for further processing and analysis.

III. Sensor Selection for N, P, and K Monitoring.

The AS73211 color sensor is an advanced optical sensor used for monitoring important soil macronutrients such as Nitrogen (N), Phosphorus (P), and Potassium (K)**.** It is capable of accurately measuring light and color variations reflected from soil samples, which are related to nutrient concentrations. The AS73211 can be easily interfaced with a NodeMCU microcontroller for real-time data collection, processing, and wireless transmission, making it an effective solution for smart soil nutrient monitoring in precision agriculture.

1. Overview of AS73211 Sensor

The AS73211 sensor is a low-power color sensor equipped with multiple photodiodes and an analog-to-digital converter (ADC). It can capture light intensity across specific wavelengths, making it valuable for assessing soil nutrient levels.



(a) **(b)**

Figure-3.1: (a) AS73211 Color sensor Board (b) Photodiode array of XYZ true color sensor

Figure 3.1(a) shows the AS73211 color sensor board, which is a low-power and highly sensitive spectral sensor used for measuring light intensity and color. **Figure 3.1(b)** illustrates the photodiode array of the XYZ true color sensor integrated within the AS73211. The sensor contains optical filters and a built-in analog-to-digital converter (ADC) that help capture and process light information accurately across different wavelength bands. It measures light through three channels (X, Y, and Z), allowing precise detection of specific spectral characteristics. In precision agriculture, the AS73211 sensor can be used to analyze spectral reflectance from soil and plants, helping to assess nutrient levels, monitor crop health, and support effective agricultural management decisions.

2. Overview of ESP8266 Node MCU.

The ESP8266 Node MCU is an open-source microcontroller board that integrates Wi-Fi connectivity, making it highly suitable for Internet of Things (IoT) applications. Based on the ESP8266 Wi-Fi SoC developed by Espressif Systems, the Node MCU board includes built-in GPIO pins, UART, SPI, I2C, and ADC interfaces, allowing it to interact with various sensors and actuators.

3. Overview of ESP8266 Node MCU 16×2 LCD Interface

To connect a 16x2 LCD display with the ESP8266 Node MCU while conserving GPIO pins and avoiding the use of I2C, a strategic approach involves the utilization of a serial-to-parallel shift register IC, specifically the 74HC595. This integrated circuit facilitates the expansion of GPIO lines, enabling efficient interfacing with the LCD while requiring only three pins on the ESP8266.

The LCD denoting 16 characters per line across two lines, employs a 5x7 pixel matrix for each character. It comprises two crucial registers: the Command Register and the Data Register. The Command Register executes predefined tasks instructed to the LCD, such as initialization, screen clearing, cursor positioning, and display control. On the other hand, the Data Register stores the ASCII values representing the characters intended for display on the LCD.

IV. Experimental Methodology.

1. Soil Nutrient Detection Using Optical Wavelength Mapping

This section explores a non-invasive method for detecting soil nutrients through optical wavelength mapping**.** By analyzing the reflectance and absorption characteristics of soil under specific light wavelengths, essential nutrient concentrations—such as nitrogen, phosphorus, and potassium—can be estimated. The technique leverages spectral data captured through optical sensors or spectrometers for real-time nutrient assessment. This approach enhances precision agriculture by enabling efficient and timely fertilizer management based on actual soil conditions.

2. Absorption Wavelengths for Nitrogen, Phosphorus, Potassium

Figur-4.1 depicts a combined optical transducer with NODE MCU for detecting NPK in the soil. The light source was measured by the microcontroller (NODE MCU) in a transmission system. In addition, it served as a data collecting system for light detecting systems and offered control features for the display. In our current system, an AS73211 chip with low power and low integration is employed as the optical transducer. Three channels create a continuous or triggered measurement by converting light signals from photodiodes to a digital output. The photodiodes transform the incoming light into a photo current, which is then converted to digital data by a later current-to-digital converter. Using an external resistor, an internal reference generator supplies all essential references for the A/D conversion and the photodiodes.

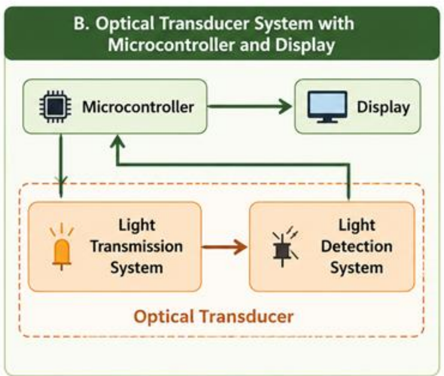


Figure-4.1: Block-diagram-of-integrated-optical-transducer-with-microcontroller.

Three 16-bit registers hold the A/D conversion's output and may be accessed through the I2C interface. The input pin SYN can be utilized for the measurement's externally driven start or start and stop. The state of the conversion is shown in the output, READY.

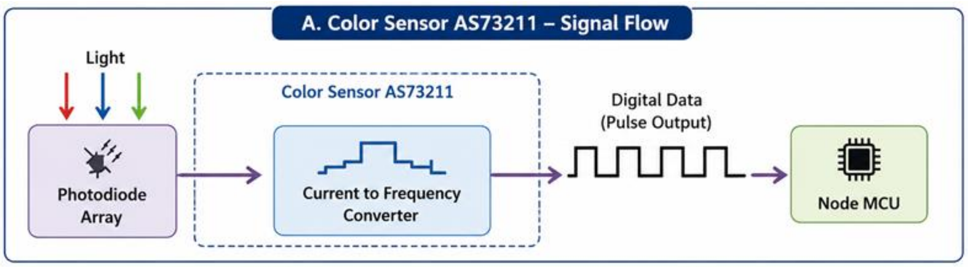


Figure-4.2: Functional Block Diagram for working of color sensor and Node MCU

The AS73211 is ideal as an optical converter for three distinct wave lengths due to its great versatility. Figure-4.2 illustrates the employment of a color sensor for the detection of nutrition levels in soil. This sensor functions by emitting white light onto a soil sample and evaluating the intensity of the reflected light using the AS73211 chip integrated within the sensor. To regulate the light intensity reaching the soil sample, the Node MCU microcontroller is utilized. Additionally, the Node MCU facilitates the storage of nutrition values in a data repository via the ESP8266 Wi-Fi module and exhibits the results on an LCD display

The color sensor operates by harnessing the wavelengths of three distinct colors like Red, Green, and Blue, each correlated with the levels of Nitrogen, Phosphorus, and Potassium in the soil. By comparing the absorption wavelengths of the sample to standard values, the sensor determines the concentration of nutrients present. Light reflected from the soil is captured by a photodiode, while the soil itself receives light emitted from a light-transmitting source. This process enables the sensor to assess nutrient levels accurately and provide valuable insights for agricultural management.

Node MCU (Microcontroller) is an open-source LUA based firmware developed for the ESP8266 WIFI chip. Node MCU firmware comes with the ESP8266 Development board/kit i.e. Node MCU Development board. Since Node MCU is an open-source platform, its hardware design is open for edit/modify/build. Node MCU Dev Kit/board consist of ESP8266 WIFI enabled chip.

The **ESP8266** is a low-cost Wi-Fi chip developed by Espresso Systems with TCP/IP protocol. Node MCU Dev Kit has **Arduino like** Analog (i.e. A0) and Digital (D0-D8) pins on its board. Table-1 provides a visual representation of the various wavelengths involved in the process.

3. LED Light Reflection and Soil Response Calibration

LED light reflection and soil response calibration are crucial concepts in the context of using optical sensors in agricultural applications, particularly for measuring soil nutrient levels. These processes play a vital role in determining the nutrient content of soil, which can ultimately inform better agricultural practices and enhance crop productivity.

Table-4.1: Illustrate different wavelengths.

Nutrient	Absorption wavelength(nm)	Color	Standard Wavelength(nm)
Nitrogen(N)	445-485	Blue (Z)	450-495
Phosphorous(P)	505-565	Green (Y)	495-570
Potassium(K)	625-685	Red (X)	635-700

The Table-4.1 represents the absorption characteristics of three essential soil nutrients—Nitrogen (N), Phosphorus (P), and Potassium (K)—based on their respective optical properties. Each nutrient is associated with a specific absorption wavelength range in the visible spectrum:

1. **Nitrogen (N)** primarily absorbs light in the blue region, with an absorption wavelength range between 445 and 485 nm. This corresponds to a blue color zone, and its standard detection wavelength generally lies between 450 and 495 nm.
2. **Phosphorus (P)** shows peak absorption in the green region, with a typical range of 505 to 565 nm. The standard wavelength for detecting phosphorus falls within 495 to 570 nm, which also aligns with the green spectral zone.
3. **Potassium (K)** absorbs light in the red region of the spectrum, ranging from 625 to 685 nm. Its standard detection range is slightly broader, extending from 635 to 700 nm, matching the red color band.

V. Experimental Setup and Calibration

The experimental setup involved integrating nutrient-specific optical sensors to detect N, P, and K levels based on their absorption wavelengths. Each sensor was calibrated using standard solutions of known concentrations to ensure accurate readings. A controlled light source and wavelength filters were used to isolate specific spectral bands. Calibration curves were plotted to correlate absorbance values with nutrient concentrations.

1. Schematic Design of the Optical Sensor System

The Figure-4.3 represents provides a visual representation of the schematic layout employed in the experimental setup designed to measure soil nutrients. The intricate details of the setup can be observed in Figure 4.3, specifically illustrating the arrangement of the soil measuring apparatus. In this setup, the AS73211 chip and LED were meticulously (exactly) positioned in a parallel configuration to facilitate accurate measurements.

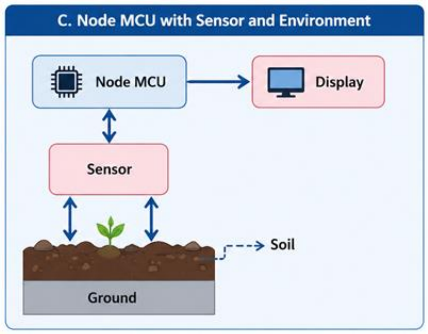


Figure-4.3: Schematic diagram for measuring nutrient in soil sample

The primary function of the chip sensor is to detect light, which is achieved by capturing the reflected light emitted from the LED and subsequently directed towards the reflector.

2. Soil Sample Description and Measurement Protocols

Table-4.2: Soil Characteristics of different samples.

Sample	Soil Characteristics
1	Dry and sandy
2	Grassy and damp

$$\begin{pmatrix} X_{sensor} \\ Y_{sensor} \\ Z_{sensor} \end{pmatrix} = K.\begin{pmatrix} adcX \\ adcY \\ adcZ \end{pmatrix} \rightarrow \quad \textbf{(1)}$$

X_{sensor}, Y_{sensor} and Z_{sensor} in equation (1) are corrected sensor values in ADS73211 chips that determines the colour. adcX, adcY and adcZ are different absorbed readings of the photodiodes of the sensor. The NODE MCU established a set of predefined limit values that were employed to compare the measured wavelengths for each nutrient to. This voltage levels—High, Mid, and Low—were used to categorize the degrees of nutrient shortage in the soil.

VI. Results and Discussion

Figure.-6.1 depicts the sensor module's reactions to LED illumination for various lengths of the path. To find the ideal route length between 1.0 and 6.0 cm, all of these replies will be compared. Hence as a result of the ADS73211 chip's sensitivity, as illustrated in Figure-6.1 the received light was greatly dispersed at both shorter and longer distances. Thus, a 5 cm optimal route length between the sensor chip and soil sample was selected founded on the analytical results.

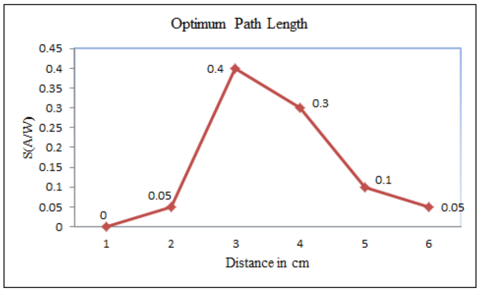


Figure-6.1: Determination of optimum path length.

Soil Sample	Nutrient	Wavelength (nm)	Absorbance
Sample 1	Nitrogen (N)	470	0.78
	Phosphorus (P)	530	0.85
	Potassium (K)	670	0.68
Sample 2	Nitrogen (N)	460	0.82
	Phosphorus (P)	540	0.81
	Potassium (K)	660	0.73

Table-6.1: Absorbance Readings for NPK Nutrients in Soil Samples

The Table-6.1 highlights the absorbance measurements of Nitrogen, Phosphorus, and Potassium for two soil samples, using wavelengths that fall within each nutrient's ideal detection range. In Soil Sample 1, Phosphorus recorded the highest absorbance value (0.85), suggesting a greater concentration compared to Nitrogen and Potassium, with Potassium showing the lowest. For Soil Sample 2, Nitrogen had the strongest absorbance (0.82), indicating it was more abundant in that sample. These absorbance values help estimate how much of each nutrient is present in the soil.

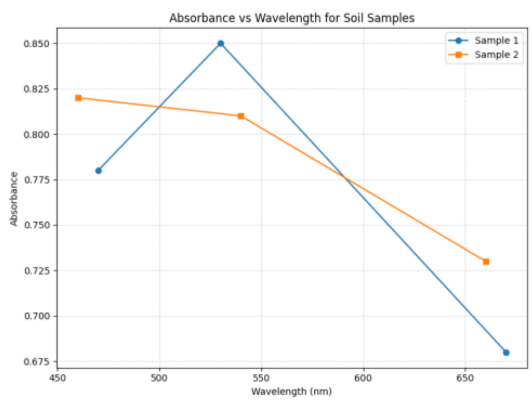


Figure-6.2: Absorbance Vs Wavelength for soil Samples.

The provided figure-6.2 illustrates the absorbance spectra of two soil samples across varying wavelengths in the visible region. The x-axis represents the wavelength (in nanometers, nm), ranging from 450 nm to 650 nm, while the y-axis denotes absorbance, indicating how much light is absorbed by the soil samples at each wavelength.

The absorbance characteristics of the two soil samples across the visible wavelength range reveal distinct optical behaviors. Sample 1, represented by the blue line with circular markers, demonstrates a prominent absorbance peak at approximately 530 nm, where the absorbance reaches its maximum value of around 0.85. On either side of this peak, the absorbance declines sharply—dropping to about 0.78 at 470 nm and further decreasing to roughly 0.68 at 660 nm. This pattern indicates that Sample 1 exhibits strong light absorption near 530 nm, likely due to the presence of particular chemical constituents or organic matter that interact significantly with light at this wavelength.

In contrast, Sample 2, shown by the orange line with square markers, displays a more gradual and consistent decline in absorbance across the same wavelength range. Starting with a relatively high absorbance value of approximately 0.82 at 470 nm, the absorbance slightly decreases to about 0.81 at 540 nm, followed by a further reduction to approximately 0.73 at 660 nm. This smoother curve suggests that Sample 2 has more uniform optical properties, indicating less variability in its composition compared to Sample 1. The comparative analysis highlights the potential of using absorbance spectra to differentiate soil samples based on their chemical and organic content.

The threshold wavelengths of NPK content in the soil are illustrated as shown in Table-5. The obtained wavelengths of NPK presence in soil samples 1 and 2 are displayed as bar graphs in figure.-6.2. According to the value above the 485 nm threshold wavelength, soil sample 2 has the maximum quantity of nitrogen.

Nitrogen is present in sufficient amounts in Sample 1. Phosphorous is present in sufficient amounts in both samples 1 and 2. Whereas sample 2 has an acceptable quantity of potassium, sample 1 has low potassium content. As a result, it is simple to compute the NPK soil concentration in each sample when just a specific nutrient is applied to the sample.

Table-6.2: Bandwidth of wavelengths for NPK soil

Nutrient	Wavelengths in nm
Nitrogen	445-485
Phosphorous	505-565
Potassium	625-685

The figure-6.3 (bar graph) compares the absorbed wavelengths corresponding to the presence of Nitrogen (N), Phosphorus (P), and Potassium (K) in two different soil samples like Sample 1 and Sample 2**.** The x-axis lists the three essential macronutrients, while the y-axis represents the absorbed wavelengths in nanometers (nm)**.**

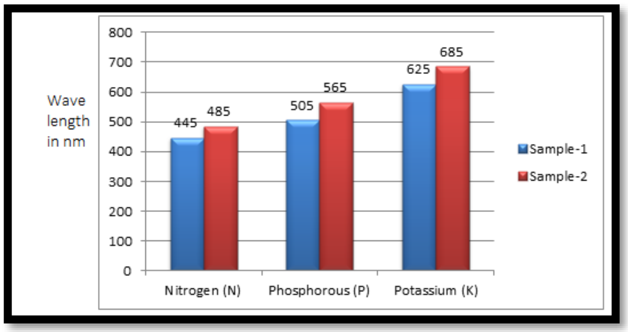


Figure-6.3: Absorbed Wavelengths of NPK in Soil Sample 1 and Sample 2

1. For Nitrogen (N), Sample 1 exhibits absorption at 445 nm, whereas Sample 2 shows a slightly higher wavelength of 485 nm. This shift suggests a potential difference in the chemical bonding or environmental conditions affecting nitrogen content between the two samples.
2. In the case of Phosphorus (P), the absorption in Sample 1 occurs at 505 nm, while Sample 2 absorbs light at 565 nm. The higher absorption wavelength in Sample 2 may indicate a variation in phosphate compounds or soil pH influencing phosphorus detection.
3. For Potassium (K), Sample 1 absorbs at 625 nm, while Sample 2 shows absorption at 685 nm. The significant increase in wavelength for Sample 2 could be attributed to changes in potassium mineral forms or their interaction with other soil components.

CONCLUSION

The results of this study demonstrate that the integration of the AS73211 color sensor with the Node MCU platform provides an effective and cost-efficient approach for estimating soil nutrient levels, particularly nitrogen (N) and potassium (K). The proposed system enables farmers to assess soil fertility with greater accuracy and at a significantly lower cost compared to conventional soil testing methods. By measuring the light absorption characteristics of soil samples using LED-based color sensing technology, the system can estimate and visualize the concentrations of nitrogen, phosphorus, and potassium (NPK) present in the soil. This information supports informed fertilizer management, helps prevent excessive fertilizer application, and promotes sustainable agricultural practices. Consequently, the developed solution offers a practical tool for improving soil health monitoring and enhancing crop productivity through data-driven decision-making.

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