Experimental study of NPK Compound Fertilizers in Hydrophobic Fertilizers using UV Spectroscopy and Light Absorption Technique

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Abstract. This study introduces a cost-effective optical process to measure the nitrogen (N), phosphorus (P), and potassium (K) in fertilizers that are hydrophobic nutrients using UV spectroscopy and light-absorption techniques. A microcontroller, wavelength-specific light-emitting diodes (LEDs), and a TCS3200 color sensor were combined to estimate the nutrient concentrations using Beer-Lambert law modeling. The calibration of standard solutions such as nitrate nitrogen, phosphate, and potassium oxide shows linear responses with good correlation of concentration (R^2 is N-0.96, P-0.97, K-0.95). The maximum absorption peaks at discrete LED wavelengths were experimentally verified with a laboratory UV spectrometer. The findings indicate that the suggested system is a rapidly portable, non-destructive method for measuring fertilizer concentration in soil and can be used in precision agriculture.

Keywords: Beer–Lambert Law, Hydrophobic Fertilizer, NPK Sensor, NPK Detection, Soil Nutrients, TCS3200 Color Sensor.

1 Introduction

The original compound fertilizers, such as nitrogen (N), phosphorus (P), and potassium (K), are vital nutrients for plant growth and affect vegetative growth, root formation, and water balance [1-3]. A proper balance of these nutrients in soil is important for obtaining maximum crop productivity and minimum environmental impact. Nevertheless, traditional laboratory tests for analyzing nutrients in fertilizers and soils are time-consuming and require specialized equipment, which limits their use in the field.

Optical sensing techniques, especially ultraviolet-visible (UV–Vis) spectroscopy, have emerged as a reliable alternative technique in quantifying nutrients because of their wavelength-specific absorption properties [4], [6]. These methods allow quick and nondestructive determination of the concentrations of nutrients by using absorbance-based modelling by applying the principle of Beer-Lambert law.

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Hydrophobic fertilizers, which have controlled-release coatings to control nutrient dissolution and minimize nutrient losses to leaching, pose further difficulties for analysis due to changes in optical and scattering characteristics. Most of the current optical sensing research is conducted on soil samples rather than coated compound fertilizers. Precision agriculture requires real-time nutrient-sensing devices that are portable enough to serve as a foundation for fertilization plans based on findings from various reported research data [10]. The present study fulfills this requirement by designing and testing a portable optical sensing system to measure the concentration of NPK in hydrophobic compound fertilizers using wavelength-selective LEDs, RGB-based sensors, and UV spectrometric validation.

2 Literature Review

2.1 Methods based on UV-Vis Spectroscopy

UV-Vis spectroscopy has been widely applied for nutrient quantification due to the wavelength-specific absorption behavior of nitrogen, phosphorus, and potassium compounds [4], [7]. A spectrophotometric approach toward smart nutrient deployment demonstrated reliable absorbance-based nutrient detection using spectrophotometry.

2.2 Portable LED-Based optical sensors

Portable optical systems integrating LEDs and photodetectors have enabled real-time soil nutrient monitoring [8], [9]. Detection of nitrogen, phosphorus, and potassium (NPK) nutrients of soil using optical transducers reported microcontroller-based optical transducers for soil analysis.

2.3 Systems based on colorimetric and RGB

Color sensors such as TCS3200 have been applied for nutrient classification [10], the study presents a miniaturized chip-based colorimeter that enables compact and effective colorimetric analysis of NPK nutrients.

However, most studies focus on soil samples rather than hydrophobic compound fertilizers. The optical behavior of coated fertilizers introduces additional scattering and absorption effects. This study contributes by integrating RGB-based sensing with UV validation specifically for hydrophobic NPK formulations.

Despite significant advancements in optical nutrient sensing, limited studies address hydrophobic fertilizer formulations and their validation against laboratory-grade UV spectrometers. This study aims to develop and experimentally confirm a compact LED-based optical system for exact quantification of NPK in hydrophobic fertilizers.

3 Methodology

3.1 System Overview

The proposed system estimates soil macronutrient concentration (nitrogen, phosphorus, and potassium) using an optical absorption technique. Specific wavelength light-emitting diodes (LEDs) corresponding to the absorption bands of N, P, and K are sequentially illuminated through the sample. A TCS3200 color sensor measures the resulting light intensity, which is correlated with nutrient concentration using calibration-based mathematical modeling.

3.2 Optical Absorption Principle

The optical detection principle is based on the Beer–Lambert law, which establishes a logarithmic relationship between absorbance and analyte concentration and is widely used in spectroscopic nutrient analysis [4], [6]. The detection principle is based on the Beer–Lambert law, which relates light absorbance to analyte concentration. Absorbance A is expressed by equation (1).

$$A = \log_{10} \frac{I_0}{I} \quad (1)$$

Where:
I = incident light intensity
I_0 = transmitted or reflected intensity
Since the TCS3200 sensor provides frequency output proportional to intensity is as shown by equation (2).

$$A = log_{10} \frac{f_0}{f} \quad (2)$$

Where:
f = reference frequency (distilled water)
f_0 = sample frequency

3.3 Selecting Wavelength and Sensor Configuration

The selection of blue, green, and red LEDs was guided by previously reported absorption bands of nitrogen, phosphorus, and potassium, ensuring selective optical interaction with each nutrient [9], [6]. The corresponding color filters of the TCS3200 sensor were activated to measure frequency output for each nutrient selectively.

3.4 Calibration Procedure

The calibration curves showed strong linearity with R^2 values of 0.96 (Nitrogen), 0.97 (Phosphorus), and 0.95 (Potassium), confirming the suitability of the Beer–Lambert model within the tested concentration range.

The standard nitrate nitrogen, phosphate, and potassium oxide solutions were used for analysis. The linear regression is expressed by equation (3).

$$C = mA + c \quad (3)$$

Where; C is concentration (mg), A is Absorbance, m is slope and c is intercept

3.5 Nutrient Concentration Estimation

The calibration results lead to the equations for the nutrient concentrations for three basic samples and are computed as equations (4), (5), and (6) respectively.

$$N = m_N \log_{10}(\frac{f_{0B}}{f_B}) + C_N \quad (4)$$

$$P = m_P \log_{10}(\frac{f_{0G}}{f_G}) + C_P \quad (5)$$

$$K = m_K \log_{10}(\frac{f_{0R}}{f_R}) + C_K \ (6) \quad (6)$$

Where $f_{0B}, f_{0G}\ and\ f_{0R}$ are the reference frequencies for the blue, green, and red channel lights, and $f_B, f_G\ and\ f_R$ are the sample frequencies respectively.

3.6 Soil Sample Analysis

The soil samples were added with distilled water in a constant proportion to create a homogenous suspension. The optical measurements were carried out under regulated illumination. The resulting sensor frequencies are hence derived. These frequencies are then formulated into calibration equations to decide the approximate values of each nutrient concentration in mg.

3.7 Data Processing and Output

Optical transducer systems have been developed based on microcontrollers to test nutrients. The Arduino platform is used as it is flexible, cheap, and easy to integrate [9], [10]. The output frequency of the TCS3200 sensor was analyzed using a microcontroller-based embedded board, as illustrated in figure 1. The calculated nutrient values were tabulated and recorded for analysis. The multiple readings were averaged to optimize the results.

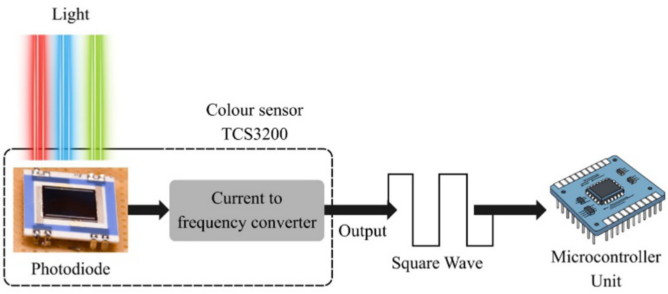

Fig. 1. Block diagram of the TCS3200 color sensor interfacing system. Incident light is converted by the photodiode array into a frequency-based square-wave signal proportional to color intensity. The output is processed by a microcontroller for real-time color detection and analysis.

4 Hardware Implementation

4.1 System Design Concept

An optical transducer is the core sensing system and is interfaced with a microcontroller unit to detect nutrients from the specified sample placed between the light source and the detector, as illustrated in figure 2. The light transmission system emits optical radiation that interacts with the specific sample placed in the sample chamber. The detection system captures and converts the optical signal into a proportional electrical signal. A central processing unit would be a microcontroller device which will control the sequence of emission of the light sources and data acquisition of the detector. It works out the concentrations of the nitrate nitrogen (N), phosphorus (P), and potassium oxide (K) based on the calibrated absorption models using raw electrical signals. The display unit is then made to render the results which are interpreted by the user. The system can be fed with either a 9V or 12V DC independent power supply to provide a field-use portable system.

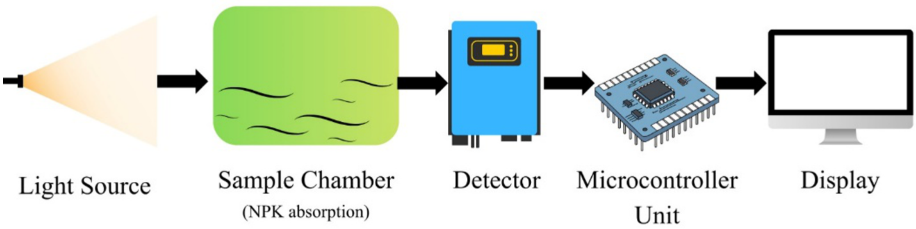

Fig. 2. Block diagram of the proposed experimental system for NPK fertilizer analysis. A controlled light source passes through the sample chamber, and the transmitted signal is detected, processed by a microcontroller, and displayed. The setup enables rapid and reliable nutrient quantification through optical absorption measurement.

4.2 System Design Schematic

The schematic circuit diagram of the TCS3200 color sensor, as shown in figure 3, describes the construction of the optical sensing circuit.

The system comprises an LED, a photodiode sensor package, an Arduino microcontroller, and a display. The LED lights fall on the specific sample that is placed on a reflective surface. The surface ensures that light not absorbed is reflected and detected by the photodiode. The interaction of incident light with the specific sample leads to typical absorption; the intensity of the remaining reflected light is deviated from the incident light when it interacts with the target analyte concentration. This reflected light intensity is measured by the photodiode module to produce an analog voltage signal. The Arduino analog-to-digital converter (ADC) converts the photodetector output into discrete voltage levels. The microcontroller runs an algorithm to calibrate the voltage readings to the corresponding levels of nutrient (N, P, K) with the known calibration curves. The measured data is then presented in a format that is readable by the user. The proposed system is applicable for field deployment due to its low cost and portability.

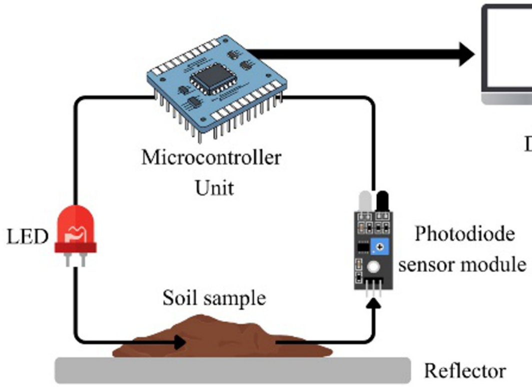

Fig. 3. Schematic diagram of the TCS3200 color sensor–based soil analysis system. An LED illuminates the soil sample, and the reflected light is captured by the photodiode module, processed by the microcontroller, and displayed. The configuration enables real-time optical characterization of soil properties.

4.3 Hardware Implementation and Operational Methodology

The developed hardware system was designed to ensure the accurate optical measurement of soil nutrient content. A confined, light-shielded optical chamber (black box) was created to avoid being disturbed by ambient and infrared radiation. The samples of soil are placed on a plain mirror that can also serve as a reflective base on which the samples are to be measured. One of the greatest design innovations of this system is that it has a totally closed black optical chamber, which is really very effective in reducing ambient light effects and increasing the repeatability of measurement.

4.4 Principle and Configuration of Optical Sensing

The system utilizes three narrow-band LEDs with blue, green, and red colors for the detection of nitrogen (N), phosphorus (P), and potassium (K), respectively. Table 1 summarizes the specifications of the LED used.

The incident wave from the light source falls on the sample placed on a reflective surface such as a mirror. The sample absorbs a small amount of incident light for a specific wavelength for a respective sample and reflects the remaining light. This is reflected and then detected by the photodetector, and the photodetector converts this reflection in the form of a voltage range as the output. The sensor used then provides this information in the form of frequency. The microcontroller reads this signal and digitizes it by using the inbuilt analog-to-digital converter (ADC). The processed values are then converted to the concentration of the nutrient.

Table 1. Selection of LED emission wavelengths based on characteristic absorption bands of nitrogen (N), phosphorus (P), and potassium (K) for optimized optical nutrient detection.

Nutrients	Absorption Band (nm)	LED Colour	LED Wavelength (nm)
Nitrogen (N)	438–490	Blue	460–485
Phosphorus (P)	528–579	Green	500–574
Potassium (K)	605–650	Red	635–660

4.5 NPK Measurement Procedure

System flow represents the systematic experimental method of analyzing NPK fertilizers in hydrophobic compound fertilizers using a UV spectrometer and light absorption technique as shown in figure 4.

This starts with the thorough preparation of the sample of hydrophobic fertilizer as well as a reference (distilled water) sample such that they are all in liquid form, which is the requirement for both systems. The samples are placed into a UV spectrometer test chamber and exposed to UV lights. The incident light effectively attenuates on the molecular constituents of the sample, resulting in wavelength-specific absorption. This absorption is controlled by chemical characteristics of the sample. As a result, it gives the peak wavelength at which maximum absorption takes place. The different samples of N, P, and K have been tested with the quantity of 5 ml to 25 ml in a step of 5 ml and the peak wavelength of absorption for each sample.

For the proposed optical detection technique, the same set of samples have been used and tested with the same iterations. When the light interacts with each sample, optical absorption takes place. This absorption of wavelength for a specific nutrient change is based on the chemical properties of the sample under test. And the remaining waves are reflected due to the mirror present beneath the sample. This reflected light signal is then collected by a photodetector and transformed into a waveform analogous to frequency. This data is processed by the Arduino board to interpret the absorption of wavelengths, which are then modeled as a result of the concentration of the NPK fertilizer.

Table 2 shows a consolidated hardware list used in setting up the proposed experimental setup.

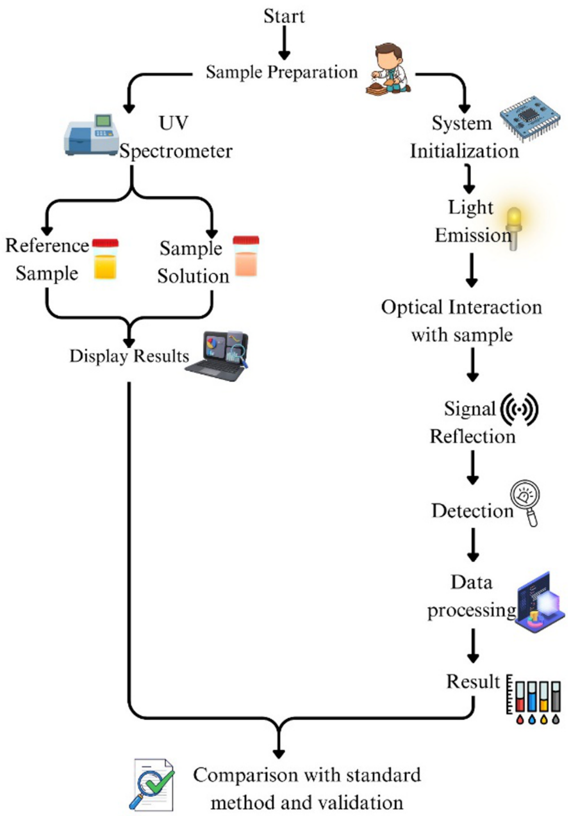

Fig. 4. Flow diagram of the nutrient detection and validation process, including sample preparation, optical sensing, signal processing, and result generation. The outcomes are validated against standard UV-spectrometer measurements.

Table 2. Consolidated hardware configuration and specifications of the developed TCS3200-based optical sensing system for NPK nutrient detection.

Component	Specification	Purpose
Blue LED	460–485 nm	Nitrogen detection
Green LED	500–574 nm	Phosphorus detection
Red LED	635–660 nm	Potassium detection
TCS3200	RGB Colour Sensor	Intensity measurement
Arduino UNO	ATmega328P	Signal processing
LCD	16×2	Output display
Power Supply	9–12V DC	Portable operation
Optical Chamber	Black enclosure	Ambient light isolation

5 Results

The experimental outputs of the optical NPK sensing system are as shown in table 3. Every measurement was performed 5 times. Nutrient standard deviation was between 2.1 mg and 4.5 mg, which means that the repeatability was satisfactory. The distilled water non-zero values are due to baseline sensor values and noise in the photodetectors. These values were also subtracted during the normalization process so that adequate computation could be achieved on the absorbance calculations.

Table 3. Experimentally measured concentrations of nitrogen (N), phosphorus (P), and potassium (K) (mg) for different test samples using the developed optical sensing system.

Sample Description	N (mg)	P (mg)	K (mg)
Distilled Water	11.4	13.3	16.1
Nitrate Solution	**82.8**	21.5	37.3
Phosphate Solution	36.2	**79.9**	19.5
Potassium Solution	25.8	31.6	**101.9**
Soil + Water	103.5	92.4	105.3

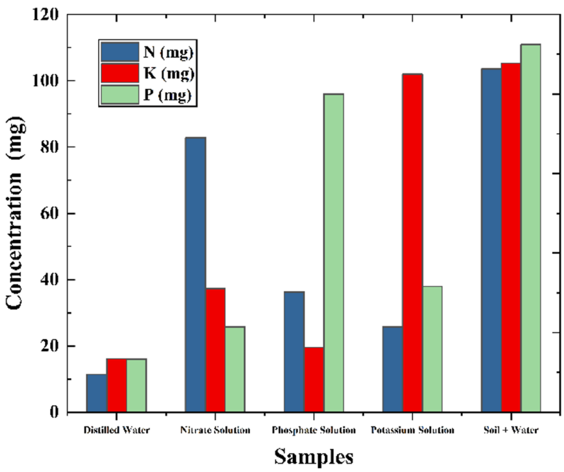

Fig. 5. Measured nitrogen (N), phosphorus (P), and potassium (K) concentrations (mg) for different samples using the developed TCS3200-based sensing system. The results show distinct nutrient variation across samples, consistent with calibration and UV–spectrometer validation.

As shown in figure 5, the bar graph represents the concentration of the various samples. Distilled water has an insignificant level of nutrients, which is used to reference it. The concentration of the individual nutrients in the solution of nitrate nitrogen, phosphate, and potassium oxide is predominant, proving the evident selectivity and correct differentiation between N, P, and K. The soil-water sample is characterized by relatively high concentrations of all three macronutrients, which can be attributed to the extrusion of mixed nutrients in the conditions of real soil. The obtained findings validate the quality of the suggested approach in the separation and determination of specific macronutrients in soil. The analysis of results was performed by analyzing the average, minimum, and maximum values of overall results across different samples.

5.1 Interpretation of Results (TCS3200 Colour Sensor-Based NPK Detection)

The results were analyzed to determine the average, minimum, and maximum overall results over multiple times. Nutrient analysis was conducted by using the TCS3200 color sensor, which measures the change of color intensity in relation to the nitrogen (N), phosphorus (P), and potassium (K) concentration in the various samples. The neutral response of the sensor was determined by distilled water, which demonstrated insignificant levels of nutrients. The concentrations of these nutrients were selectively increased, indicating the capacity of the sensor to distinguish each of the NPK components in the sensor depending on their unique color percentage absorption. All three nutrients were found in the soil-water extract in relatively higher amounts, which implies the adoption of the system as useful regarding the analysis of the actual samples of the environment rather than laboratory data. The correlation between absorbance and concentration was tested with the known standard solutions, and it was observed that the proposed method could be used in the assessment of soil nutrients, though it is likely that some deviation could be due to conditions of illumination and sensitivity of the sensor.

5.2 Calibration Characteristics

Linear regression analysis came up with Phosphorus (0.97), Nitrogen (0.96), and Potassium (0.94) coefficients of determination (R2) [15]. These findings verify that there are very high linear dependences of absorbance and concentration of nutrients in the proposed sensing system that can be utilized to test the Beer-Lambert law.

6 Validation with UV-Spectrometer

The phenomenon of experimental results was confirmed with the help of a UV spectrometer, one of the common laboratory methods that are used to verify the properties of nutrient absorption in the samples of soil and fertilizer [4], [7]. The NPK solutions were used to determine the maximum absorption by a UV spectrometer.
The principle of colorimetry is proven by the observed correlation between the intensity of reflected color and concentration of nutrient according to the earlier works on soil nutrient sensing [10], [11].

By using three standard solutions, used in hydrophobic farming. As the UV light of different wavelengths was passed through the sample, the extent to which maximum

absorption takes place at a particular wavelength. It is observed that the highest absorption takes place at a wavelength to which the selected nutrient reacts.
Figure 6 illustrates that the maximum absorption takes place at a wavelength of 450 nm, which indicates the wavelength of maximum absorption of the nitrate nitrogen standard solution.

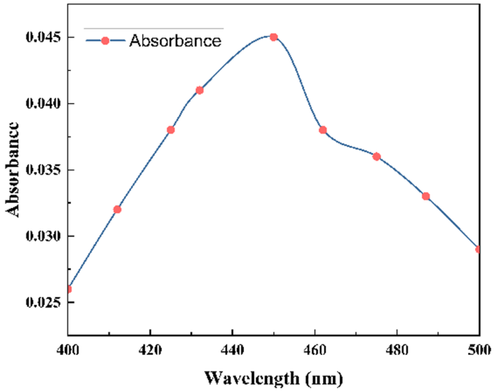

Fig. 6. UV-visible absorbance spectrum of nitrate nitrogen solution showing the characteristic maximum absorption peak in the 440–450 nm wavelength range. The identified λ_max was used for calibration and validation of nitrate concentration measurements in the developed sensing system.

The wavelength of maximum absorption of the phosphate solution is found to be at 560 nm. This is represented in figure 7.

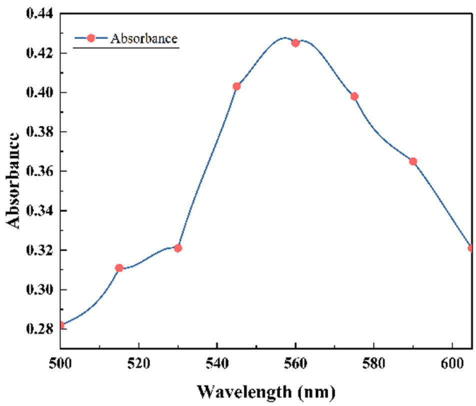

Fig. 7. UV-visible absorbance spectrum of phosphate solution indicating the characteristic maximum absorption peak around 550–560 nm. The identified λ_max was employed for calibration and validation of phosphorus concentration in the developed sensing system.

Figure 8 represents this and indicates the maximum absorption at a wavelength of 627 nm for the potassium oxide solution.

The maximum absorption wavelengths obtained using the analytical results are then compared with the absorption that takes place using proposed technique values to check out the consistency and accuracy.

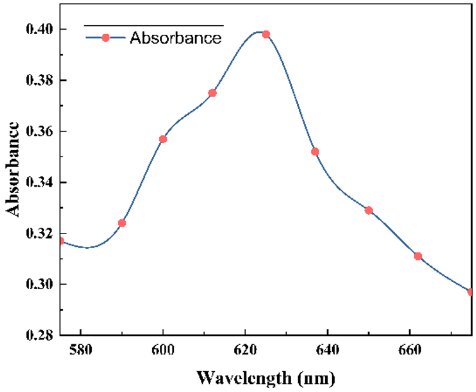

Fig. 8. UV–visible absorbance spectrum of potassium solution showing the maximum absorption peak near 620–630 nm, used for calibration and validation of potassium concentration in the developed sensing system.

7 Conclusion

This study illustrates a handheld optical sensing system for the measurement of NPK in hydrophobic fertilizers that have R2 values of more than 0.94. Modelling and repeatability are improved by the enclosed optical chamber and calibration-based modelling. The system is cost-effective and field-deployable and provides an alternative to a laboratory UV spectrometer. The proposed system measures nutrients in rapid response and has an application in precision agriculture.

The future research will be on the enhancement of robustness by developing better calibration models, machine learning-based compensation, and a larger UV-NIR spectral analysis [13], [14], and the integration of IoT to provide real-time, field-scale nutrient monitoring.

Author's Contribution

Rahul Chavhan conceived the idea, formulated the research objectives, and supervised the project. Nandkishor Kinhekar and Ajayshree Watkar developed the experimental setup, performed data acquisition, and conducted the analysis. Arpit Rawankar assisted in validation, result interpretation, and visualization. All contributing authors are involved in writing, reviewing, and approving the final manuscript.

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