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An IoT-based soil analysis system using optical sensors and multivariate regression

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Abstract: Food is the primary requirement for the survival of any living being on this planet. The rapid increment in the population is a major concern for adequate food production due to the depletion of agricultural land, which has turned into housing societies. However, agriculture is India's main business and primary income source for the farmers. The agricultural crop yield mainly depends upon the physical parameters of the soil, such as micronutrients and pH values. The main constraint in monitoring these parameters is the location of land at the far remote places and it takes enough time to test these parameters following the lab test process. The real-time analysis of all the parameters remained a big challenge for the farm owner, so the soil fertility level could not be sustained at the optimum level during most of the crop production cycle. This ultimately results in the average level of crop production and becomes a matter of chance since the soil fertility and other parameters barely suit the crop type under cultivation. This paper mainly focuses on developing an Internet of Things (IoT) based digital method to measure the availability of soil macronutrients and their pH using a color optical sensor TCS3200 and transmit those parameters to a long distance in case of unavailability of any telecommunication network. The paper also describes the deployment of Long Range (LoRa) units interfaced with ESP8266 for long-distance communication and uploading the entire information over the cloud platform, which will be displayed over the mobile using an API. The average accuracy of the proposed method in determining the soil macronutrients was 0.969 for phosphorus, 0.953 for nitrogen, 0.961 for potassium, and 0.921 for Soil pH.

Introduction

The plant nutrient management at the optimum level is done by performing soil tests at regular intervals. To determine the appropriate amount of fertilizers required for cultivation, these soil tests can be performed by following a standard procedure that can be done manually or using a system based on variable rate technology (VRT) (Faber et al., 2007). The primary requirement for determining the current availability of the micronutrients in the soil is to perform a soil analysis test. The conventional methods were used to estimate the presence of the micronutrients available in the soil. As per the requirements of these nutrients by the crop, the addition of the deficient nutrients or the decision to neutralize the effect of excess nutrients can be easily taken to avoid any hindrance in the crop growth under cultivation. The major nutrients required for the crop are Nitrogen, Phosphorous, and Potassium (NPK). The crop develops protein, synthesis chlorophyll, and performs photosynthesis with adequate nitrogen. The deficiency of nitrogen may also cause a reduction in the consumption of other micronutrients (Wei et al., 2020).

Moreover, for the sufficient growth of the root of a plant, phosphorus is involved. Inadequacy of phosphorus implies confined root growth, hence leading to the undergrowth of plants, and potassium is used to convey photosynthesis assimilates and enzyme initiation. Its

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inadequacy implies irregularity in the entire process (Mandal et al., 2021).

Although the above composts play a significant role in the defensive development of crops and, at last, in the higher capacity of production and soil fruitfulness. Yet, persistently uniform use of composts above the threshold level enhances the expense of production as well as raises a major ecological threat concerning groundwater and soil contagion (Wittry and Mallarino, 2004; Kim et al., 2008; Tung et al., 2009; Zhu et al., 2021; Kashyap and Kumar, 2021). Mineral levels that are above the cut-off don't further enhance the development of the plant. Above the critical threshold, phosphorus and nitrogen levels can prompt exorbitant plant and algal development in water that can deteriorate drinking water, angling and causing a blood disorder called methemoglobinemia: cardiovascular illness, lung sickness, anemia and different metabolic issues in the consumer of those crops grown with excessive use of fertilizers (ATSDR, 2013; Lu et al., 2022). High potassium can prompt an unevenness of base immersion levels and high solvent salts. In people, it gives rise to kidney sickness or different circumstances, for example, coronary illness, coronary artery sickness, adrenal deficiency, diabetes, and hypertension (WHO, 2003; Fan et al., 2022). Thusly, it required that ranchers should consistently do spatially arranged soil investigations for macronutrients to be aware of the compost adequacy or deficiency. But regrettably, for a lot of soil tests, the expense of soil examination for NPK in the research center isn't reasonable for most of the ranchers. Likewise, the lab strategies take much time to examine macronutrients relying on the number of soil tests, while field situations can be changed with time.

The difficulties encountered by the farmers motivated us to introduce the Internet of Things (IoT) based framework. IoT empowers us to use technologies, work in a team, establish communication, give information in real-time from sensors remotely for processing, and provide more important data for effective decision-making capabilities of the system (Akhter and Sofi, 2022). It is decisively an evolving technology in application sectors such as medical care, security, factory, horticulture, etc. Incorporating an IoT-based system requires knowledge of the research sector with the hardware and potential outcomes associated with the internet for controlling the various connected devices in the IoT architecture (Zamora-Izquierdo et al., 2019). IoT is more similar to the physical world associated with the web, communication, and sharing information to one another that are smart gadgets. It is certainly not a novel thought yet it is popular for execution due to new development in hardware (Sowmya et al., 2021). With sensor networks, IoT gives another gadget to interact and analyze real-time information in the physical environment (Dagar et al., 2018) with a decision-making cycle and automation contagion (Ahmed et al., 2021; Sivakumar et al., 2022). The farmer adopting conventional agriculture encounters many issues of contagion (Lee et al., 2013), which can be easily rectified with IoT and permit us to anticipate, observe, and manage all the farming produce. The agriculture is the main source of income and nurturing the gigantic population of India (Tuli et al., 2014). Approximately, 50% population has actually acquired agriculture as a profession in India.

Utilizing the idea of IoT, a system is suggested that acquires PA (precision agriculture) to conquer such disadvantages and to wirelessly observe soil nutrients (Ahmed et al., 2017). Acknowledge the amount of nutrients in the soil is fundamental to guarantee the ideal use of composts. The sensors are coordinated with Arduino uno board and the qualities measured from sensors are sent to the cloud and shown in the application. The developed IoT-based software system has the intelligence to measure the quantity of nutrients using an optical sensor, which can help improve the soil quality and ensure the crop's rapid growth. This research proposes an IoT-based system using an optical sensor to determine the soil pH and the soil nutrient constituents as shown in Figure 1. By adopting this mechanism, the farmer can analyze the data by himself instantly on the field. The results can be obtained on the mobile app using a pair of long-range (LoRa) transmitter systems linked

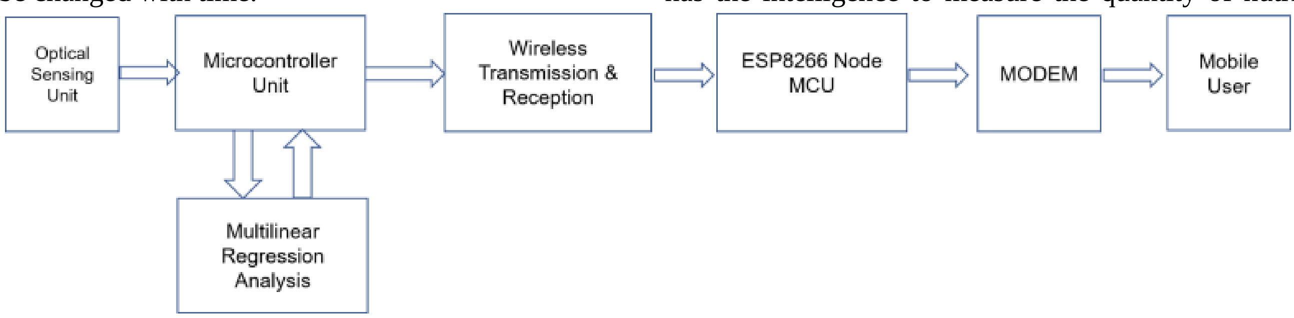

Figure 1. Block diagram of the developed system

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with ESP8266/NodeMCU for providing internet connectivity. The system can also help the farmer maintain database records for further reference. The development of this system requires prior knowledge of IoT and the color sensor used for the rapid testing of soil samples.

Related Works

All the factors primarily impact soil productivity and temporal and spatial variability in harvest. Soil-forming variables, such as parent material, environment, geography, and time, are intrinsic factors. While field management exercises and maintenance processes are extrinsic factors (Sun et al., 2003). Normally soil characteristic changes with time and space. The dispersal of soil nutrients is usually influenced by natural circumstances that play a significant part in horticulture (Atreya et al., 2008). Plant, perspective, and analysis are the land characteristics that collectively control the characteristics of soil and help in the growth of plants. At any place, fields, and areas inside the field and, surprisingly, in hardly any millimeter space, soil parameters change (Bouma and Finke, 1993).

Integrating spatial and temporal information is essential to accomplish higher proficiencies in nutrient utilization. A PC-based system may extraordinarily enhance this situation to eliminate these kinds of issues. By monitoring the important data, clients can go with informed financial and agronomic choices. To evaluate soil nutrient dissemination, NN (Neural Networks), fuzzy logic systems, geo statics, and regression tree have been utilized (Zhang et al., 2007). To understand nutrient elements inside fields, the distribution of these methods is extremely valuable. We want to evaluate the genuine quantity of nutrients in the soil to determine the right quantity of nutrients to be given and to pick the right crop to increase production in the same land (Gliessman, 1985; Staben et al., 2003). The generally used method for estimating soil nutrients depends on using color-developing compounds (Hue et al., 2000; Laboski et al., 2006). Chemical compounds are industrially accessible as soil analyzers. With the help of a nutrient color chart, color developed by chemical compounds of solutions of nutrients separated from soil can be evaluated. Hence, the quantity of nutrients available in the soil continuously changes because of the researcher's analysis, and accomplishing a quantitative analysis is complex. A spectrophotometer is applied to examine developed color in solutions to evaluate an exact measurement (Reisenauer, 1978). However, this became costly and complex. Thusly, it is important for researchers to find a solution to replace techniques based on a spectrophotometer and color chart based on cost-effectiveness (Potdar et al., 2021).

Materials and Methods

The main objective of this research was to develop an economically cheap optical technique that could give helpful data on soil fertility to enhance the easy approach to improve the conventional methods and introduce the technology in it. Thus, in such a manner, the target of this work was:

a) To introduce the technology to practically examine and create a connection between soil micronutrients and reflectance spectra by sensory approach.

b) Depending on this connection, we expected to get a novel spectral signature and numerical models for every target nutrient classified by a microcontroller.

c) Also, in view of these models, then enhance the optical sensor method for observing and evaluating soil nutrients accessible to a mobile user from any remote location.

To accomplish these targets, the steps to be followed are displayed in Figure 2.

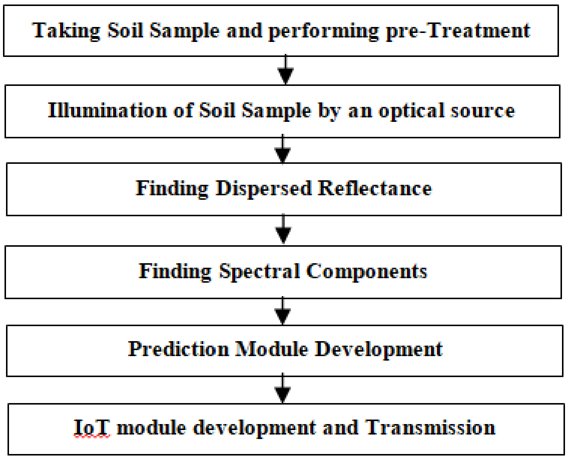

Figure 2. Steps for Module Design

A compact soil macronutrient analyzer is created by working with an embedded board and an optical sensor. The prototype comprises three sections:

a) The development of an enclosed chamber to position the sample accurately to detect the sample characteristics.

b) The optical color sensor consists of the light-emitting diode and an array of a photodiode working as a detector.

c) Sample analyzer using Arduino uno, LoRa transmitter & Receiver, and ESP8266 for further uploading of information over the cloud.

Preparation of the test solution

To verify the result obtained from the developed model. The soil samples are collected from three different fields and tested in the lab following a standard procedure. The results are then noted for verification purposes. To determine the soil's nutritional composition using the apparatus designed specifically for this experiment, the soil samples are first converted into a liquid solution by adding one portion of the soil sample and five portions of distilled water and stirring it for about two to three minutes. The motive of mixing the soil in water is to dissolve the available macronutrient in water. Now, keep the prepared solution aside for about 20 minutes and wait for the precipitation of the remaining soil contents in water. As the water sample gets cleared, the liquid is separated into a clean container. Now, the extracted water solution is poured into four different test tubes (approx. 15-20 ml in each), and the reactive reagents supplied from any rapid soil test kit is used to mixed with the liquid and shaken for about a few minutes as directed by the supplier's instruction. This rapid test kit consists of four different reagents for preparing the soil solution to identify the presence of NPK macronutrient composition in the soil. These reagents available in the kit measure the nitrate-nitrogen (NO_3), phosphorous (P_2O_5), potassium (K_2O), and lastly, a solution to predict the PH value. For preparing a colored spectral solution, one can use a required chemical and follow the further step as discussed further. All the prepared solution will have their own distinguished colors. But, the prediction of the exact value is difficult to obtain from the naked eye. However, the system developed in this research has the capability to identify the true range of values with minimum probability of error to determine the available macronutrients in the soil.

Proposed System Model

The proposed system developed in this research, as shown below in Figure 3 employs TCS3200 optical sensors integrated with Arduino uno microcontroller.

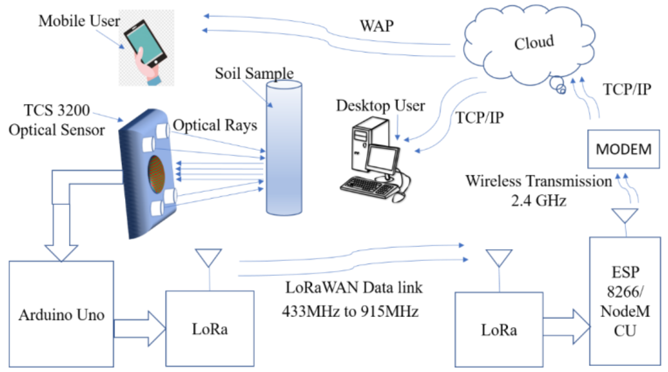

Figure 3. Proposed System Model

The values obtained from the sensors are digitally converted and then analyzed by the ATMega328 microcontroller installed on the Arduino board. After analysis, this microcontroller produces the nutrient value, which is further transmitted between a pair of LoRa units separated by a long distance. The LoRa transmitter-receiver unit is used to communicate up to the range of 15 kilometers in a rural area, without requiring any communication network. LoRaWAN works in the frequency range of 433 MHz to 915 MHz. The operating frequency of LoRa units can be chosen as per the country's telecommunication guidelines. The receiver LoRa unit is interfaced with ESP8266/NodeMCU further to upload the information over the cloud through a modem using TCP/IP. The soil macronutrient value can also be received over the Laptop/Desktop or mobile phone using a dedicated application designed for this specific purpose and used by the farmer.

Sensor Calibration and Determination of R, G, and B color components equivalent to soil macronutrient value

The prepared test solution described above will have its own distinguished color. Hence, the TCS3200 optical sensor used in the proposed system model can identify the color in the visible spectrum range by converting light into its corresponding frequency, as shown in Figure 4.

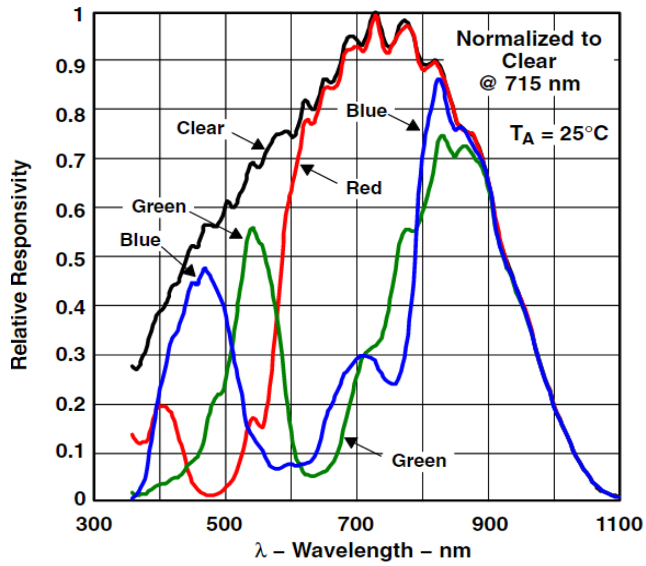

Figure 4. Photodiode spectral responsivity [TCS3200 Datasheet - Texas Advanced Optoelectronic Solutions]

The test sample collected in the test tube is placed in the enclosed cylindrical container one by one. The optical sensor is mounted on the inner wall of this cylindrical container. The optical sensor has four white LEDs. Thus, the illumination of the collected sample inside the test tube by white light reflects the bright light of the same wavelength of the corresponding color and the array of the photodiodes available in the TCS3200 optical sensor detects it. Now, the received light by the photodiode is converted into the frequency of the corresponding color.

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Table 1. Soil Macronutrient Abundance or Deficiency (Reisenauer, 1978)

Macronutrients (mg/kg)	Low	Medium	High	Soil Classification	pH Value
NO_3-N (Nitrate Nitrogen)	<25	25-60	>60	**Strongly Acidic**	<5
P_2O_5 (Olsen Phosphorous)	<6	6-10	>10	**Acidic**	5.5 – 6.5
K_2O (exchangeable Potassium)	<50	50-80	>80	**Neutral**	6.5 – 7.5
				Alkaline	>7.5

The sensor output is obtained into the equivalent R, G, and B (red, green, blue) component values by programming Arduino Uno. The sensor is calibrated first by illuminating the standard color samples (Red, Green, and Blue) and the empty test tube. The equivalent R, G, and B values are checked in the output of the program for every standard color sample. Later, the evaluation of the macronutrient was done on a spectrophotometer and color chart depending on evaluation in the lab, and afterward, the same soil samples were examined with the help of our prototyped technique to calibrate the system, and obscured soil tests were examined autonomously with an optical sensor and spectrophotometer. For calibration, several sample values were tested in the lab and examined by the designed prototype to verify the results. Finally, the designed system performance was compared. For validation purposes, the analytical laboratory has listed the ideal range of the soil macronutrient abundance or deficiency and PH based soil classification (Reisenauer, 1978) as listed in table 1.

Mathematical Model for Macronutrients Value Prediction

The relationship between the available macronutrients in the sample solution and its reflected light beam is derived. The multilinear regression analysis is used to obtain the best-fitted curve. For optimization, the sample values of the reflected rays of the lab-tested samples are plotted on the graph and their equivalent R, G, and B component values are considered the ideal source of data sets since it matches the laboratory results with maximum accuracy (Faber et al., 2007). On the basis of the noted accuracy of the characteristic curve for the lab-tested results and the R, G, and B component values of the reflected rays of the number of distinct samples. The mathematical relation was established with the measurement of the coefficient of determination i.e., R^2, and which is close to one for best fitting.

The plot of each macronutrient's color test data set shows a linear relationship with its lab-tested nutrient value. Hence, the multiple linear regression model is identified as the best suitable method to establish a mathematical relation between R, G, B and macronutrient value. The relation is derived as

$$y_{NPK,\ Ph} = \beta_0 + \beta_1 r - \beta_2 g - \beta_3 b + \varepsilon \quad \text{.............}\mathbf{(1)}$$

Where β is the column vector of parameters, y is the Ph and nutrient values, ε is the scalar called an error term. The β is estimated using the ordinary least square estimator as:

$$\hat{\beta} = (rgb^T rgb)^{-1} rgb^T y_{NPK,\ Ph} \quad \text{...............}\mathbf{(2)}$$

The value of y is estimated by

$$\hat{y}_{NPK,\ Ph} = rgb^T \hat{\beta} \quad \text{...........................}\mathbf{(3)}$$

And the error term ε is estimated as

$$\hat{\varepsilon} = y_{NPK,\ Ph} - rgb^T \hat{\beta} \quad \text{.........................}\mathbf{(4)}$$

The regression analysis evaluates the best curve fitting if the value of R^2 lies between zero and one. Where R^2 is the ratio of the sum of the square value of the difference of the true value of the nutrient and the mean of the true value to the total sum of the square of the difference of the estimated value of the nutrient and the mean of the true value.

Results and Discussions

The soil solution obtained, as mentioned above, is placed in the developed prototype, as shown in Figure 5. The optical sensor converted the reflected light into the frequency and the R, G, and B component values are displayed on the serial monitor of the laptop screen, as shown in Figure 5.

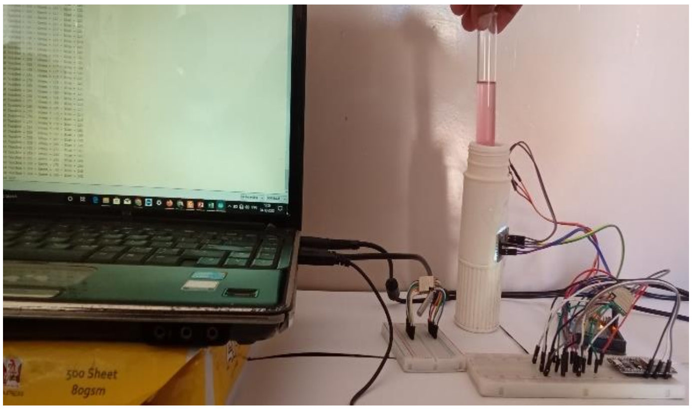

Figure 5. Experimental setup

The test was repeated for the 6 soil samples collected from the different regions near Lucknow city, located in India. This test has generated the various R, G, and B values and the mathematical relation yields the equivalent value of each soil macronutrient as listed in Table 2.

Table 2. Soil Macronutrient Composition and Soil pH

Soil Macronutrients	Soil Sample-1			Soil Sample-2		
	LAB Test Readings	Model Reading	Status	LAB Test Readings	Model Reading	Status
NO_3-N	61.01	64.03	High	53.06	52.01	Medium
P_2O_5	11.48	11.13	High	9.61	10.30	High
K_2O	96.40	92.70	High	68.06	70.86	Medium
pH	8.04	8.19	Alkaline	7.36	8.14	Alkaline
Soil Macronutrients	Soil Sample-3			Soil Sample-4		
	LAB Test Readings	Model Reading	Status	LAB Test Readings	Model Reading	Status
NO_3-N	46.15	48.99	Medium	33.32	35.66	Medium
P_2O_5	7.04	6.99	Medium	6.16	5.75	Low
K_2O	49.86	53.05	Medium	39.92	43.72	Low
pH	7.04	7.60	Alkaline	6.44	7.34	Neutral
Soil Macronutrients	Soil Sample-5			Soil Sample-6		
	LAB Test Readings	Model Reading	Status	LAB Test Readings	Model Reading	Status
NO_3-N	25.21	22.23	Low	26.41	24.2	Low
P_2O_5	5.64	5.21	Low	4.75	5.08	Low
K_2O	32.21	30.21	Very Low	38.19	41.43	Low
pH	5.89	5.82	Acidic	6.71	7.44	Neutral

***All Macronutrient values are in mg/kg**
**** NO_3-N, P_2O_5, K_2O are Nitrate-Nitrogen, Olsen-Phosphorus and exchangeable potassium**

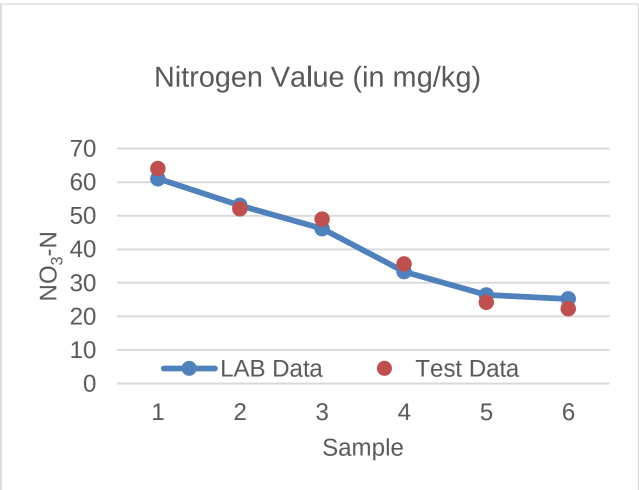

Figure 6 (a). Nitrate Nitrogen

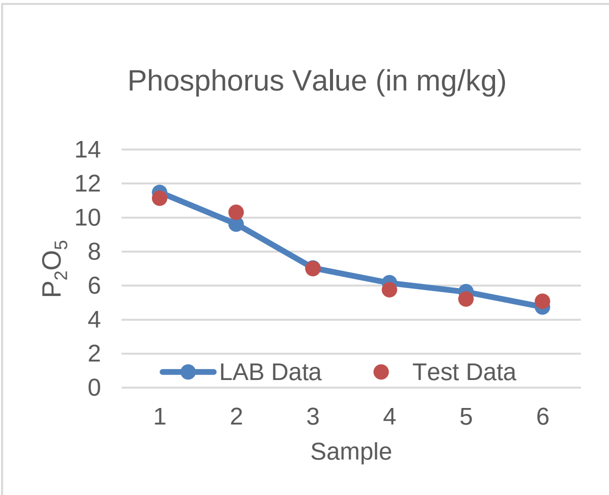

Figure 6(b). Olsen Phosphorus

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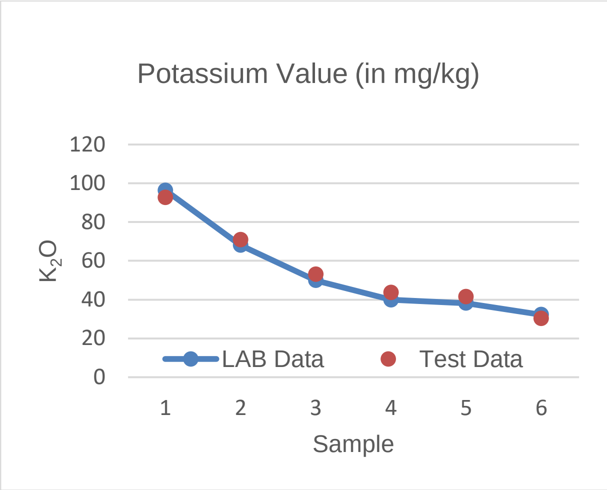

Figure 6 (c). Exchangeable Potassium

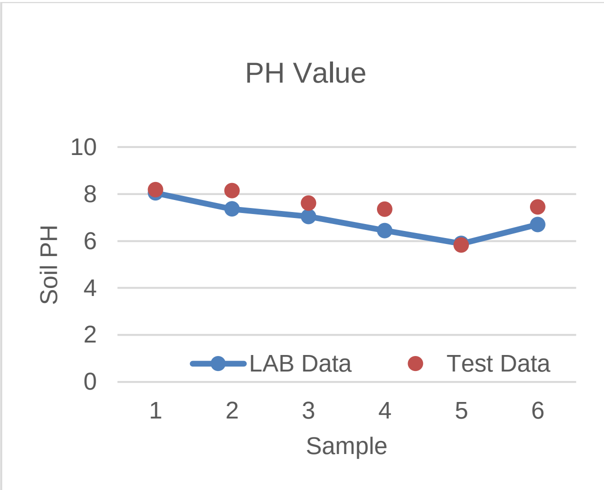

Figure 6(d). Soil pH

The equations determined by doing regression analysis are given below for evaluating the three basic macronutrients and the pH value from the R, G, and B color components detected by the optical sensor.

The equation for evaluating nitrogen by MLR method

$$y_{Nitrogen} = 34.48351 + 0.4023r - 0.28316g - 0.20888b \quad \textbf{(5)}$$

The equation for evaluating phosphorus by MLR

$$y_{Phosphorus} = 10.81449 - 0.01366r - 0..5954g + 0.04589b \quad \textbf{(6)}$$

The equation for evaluating potassium by MLR

$$y_{Potassium} = 110.8833 - 0.1523r - 0.38059g - 0.004b \quad \textbf{(7)}$$

The equation for evaluating pH by MLR

$$y_{PH} = 9.650052 - 0.01492r - 0.01524g + 0.005041b \quad \textbf{(8)}$$

Where;

$y_{Nitrogen}$: calculated nitrogen value in mg/kg

$y_{Phosphorus}$: calculated phosphorus value in mg/kg

$y_{Potassium}$: calculated potassium value in mg/kg

y_{pH} : calculated pH value in mg/kg

LoRa further transmits the evaluated values to the LoRa receiver separated by a distance of 1 km. The data is successfully received and further uploaded to the cloud server using ESP8266 and the received data is clearly visible on the web page having a defined domain name server.

The evaluated values for each soil macronutrient from the developed model show satisfactory results compared with the tested value in the lab, as shown in Table 2. The estimated phosphorus value was the best fitted with maximum accuracy, as shown in Figure 6(b). In estimating nitrogen and phosphorus values, good accuracy is achieved and can be seen in Figures 6(a) and 6(c), respectively. However, more variation in estimating pH value from the true is reported as shown in Figure 6(d). The coefficient of determination and standard error (ε) for estimating the value of nitrate-nitrogen, Olsen phosphorus, exchangeable potassium, and soil pH are 0.9416, 0.9517, 0.9166, 0.7514, and 3.57, 0.5417, 5.04, 1.10 respectively. The values are close to the best approximation as per the multilinear regression model. Thus, the developed model works well in estimating all the soil macronutrients accurately and precisely.

Conclusion

An IoT-based soil macronutrient identification system proposed in the research is successfully developed and shows satisfactory results. The unknown samples were collected from various regions near Lucknow, which were tested in the lab and the developed system verifies the results. The developed system produces the R, G, and B component values as the output from the color sensor, which is converted into the equivalent value of the macronutrient which was tested in the lab. The values are evaluated for nitrate-nitrogen (NO_3-N), Olsen phosphorus (P_2O_5), exchangeable potassium (K_2O), and soil pH based on the equations developed in this paper. The Arduino Uno board uses the equations to convert the R, G, and B component values into the equivalent macronutrient value using a program. The obtained values were transmitted to the cloud by the pair of LoRa units interfaced with ESP8266. The results are approaching the true value with an error rate of 1% to 2% of milligrams per gram of each macronutrient. The proposed framework is very useful for farmers to monitor their soil macronutrient value at regular intervals without delay. This system also helps the farmer maintain the records for further reference and determine felicitous crops to be cultivated. The results can also be used for predicting crop yields based on the available macronutrients. In future, the work will be extended to determine the availability of the micronutrients without using any rapid test kit. The future work can also include the development of a mobile app for estimating all the soil nutrients by capturing and analyzing the soil image.

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Conflict of Interest

The authors declare no conflict of interest.

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