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Remote Analysis of Soil Macronutrients Using Optical Sensor for Precision Agriculture

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Abstract: Continuous cropping without adequate measurement and provisioning of soil nutrient may endanger the sustainability of agriculture. Soil nutrient measurement is greatly required for proper plant growth and effective fertilization. Existing methods of soil testing generally use visual comparison of soil solution colour with the colour-chart and this makes it subjective and error prone and time consuming whereas the spectrophotometer is very expensive and none of the approach suitable for remote analysis of soil macronutrients. On the other hand, the optical sensor could sensitively detect the soil solution colour changes thereby detecting soil nutrients in the sample without delay and subjective error. In this work, a compact optical sensor based on photometric detection of soil nutrients using high precision Photo Diode (PD) and Light Emitting Diode (LED) was developed. Real-time optical sensor using PIC microcontroller was integrated to a remote data collection server for the ease of acquisition and post-processing. The wavelength of LEDs is chosen to fit the absorption band of chemical reagents whose colour develops by reaction with soil nutrients. The sensor was used to detect three soil macronutrients: ammonia nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), available phosphorus oxide (P_2O_5) from colour changes caused by addition of chemical reagent in a transparent plastic cell (5.5 mm path length). The resolution of 0.1-20 mg/100g was used as standard solution. The fifteen test samples were taken from different farmlands and ten soil samples were used to calibrate the optical sensor comparing with the result obtained by a colour chart laboratory judgement. The calibration factors obtained were then used to evaluate five unknown soil samples and the results were finally compared with laboratory results, and designed system showed good level of agreement with the laboratory results.

Keywords: Soil nutrient; macronutrients; ammonia nitrogen; nitrate nitrogen; phosphorus; LED.

1. Introduction

Precision agriculture (PA) can be defined as-the improvement of crop performance and environmental quality by applying technologies and agronomic principles for managing spatial and temporal variability associated with all aspects of agricultural production. PA focuses to the optimization of the field level management. It aims to solve problems that can be categorized into

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3 groups: Crop science, Environmental protection, and Economics. PA helps in dissemination of gathered information to the farmers, mostly living in rural areas that can be applied in their crop production methodologies and the policy makers to plan long-term priorities [1]. PA based geospatial technologies, such as global positioning system, geographical information system, remote sensing, geo-statistics and variable rate applications can be used for obtaining efficient nutrient management in crop fields [2]. Production of a crop depends on the interaction between the soil and plant properties. Maximization of crop production is reflected by the biological, chemical and physical condition of the soil. Root absorbs required amount of nutrients and water from the soil where biochemical reactions take place. Plants rate of nutrient absorption depends on the minerals available in the soil. Insufficient supply of any necessary nutrients causes the production of crop to degrade. Although the requirement of a particular nutrient is determined by the plant growing in the soil, some of the nutrients are necessary for almost all the plants in great amount known as Macro moles or Macronutrients [3]. Root environment of the plant can be changed by supplying nutrients outside the soil which is commonly known as fertilization. However, proper distribution of fertilizer is necessary for the proper crop production. Over and under fertilization can greatly reduce the production. To optimize fertilizer use efficiency by overcoming the problem of over and under fertilization, variable rate fertilizer application, one of the basic tenets of PA has been shown in [4]. This technology is mainly used for increasing the crop production and crop quality as well as to reduce resource wastage and promote stewardship of the environment. Traditional fertilization system in Bangladesh relies on farmer's experience in cultivation and weather condition. This type of manual fertilization without proper justification of soil condition is error prone. Moreover, soil environment control is also necessary for preventing ground water pollution.

Soil productivity, spatial and temporal variability in crop is mainly influenced by both intrinsic and extrinsic factors. In intrinsic factor, soil forming factors such as parent material, climate, topography and time are mainly included. In extrinsic factors, farm management practices and maintenance operations are mainly included [5]. Generally the soil property varies a lot with respect to space and time. The distribution of soil nutrients is mainly affected by natural condition, which plays a major role in the agriculture system [6]. The variability in soils mainly depends on natural conditions. Slope, aspect and evaluation are the landscape attributes, which significantly control the soil properties and in turn plant growth [7]. On any scale including areas, fields and regions within the field and even in few millimetre spacing, soil variation can largely occur [8]. For achieving higher efficiency in nutrient usage, spatial and temporal data, which are an integrated approach, is necessary. For removing these types of problem, a computer based system can greatly improve this condition. Users can make informed agronomic and economic decisions, by observing the relevant information. To analyse soil nutrient distribution, geo-statistics, neural networks, regression trees and fuzzy logic systems have been used recently [9]. For understanding nutrient dynamics within crop fields, the deployment of these techniques is very useful. To get the correct amount of nutrients to be provided and to choose the right crop for multiple cropping in the same land, we need to measure the actual amount of nutrients present in the soil [10, 11]. The most common method used for soil nutrient measurement is based on usage of colour-developing chemicals [12, 13]. A method using colour-developing chemicals for soil nutrients is also useful and commonly used by farm workers. The chemical reagents are commercially available as a soil analyser. Solutions of nutrients extracted from a soil, whose colour is developed by chemical reagents, are estimated by a subjective judgment with the colour charts for the nutrients. Thus, the value of soil nutrients content is always fluctuating due to the tester's judgment and it is difficult to achieve a quantitative analysis. To execute a precise measurement, a spectrophotometer can be

applied to investigate the colour developed in solutions. The system with the spectrophotometer, however, becomes complicated and expensive [14]. Therefore, an optometric solution replacing spectrophotometer and colour-chart based approach while keeping the price least become very important for agri-researcher.

To get round the problems, a simple and low cost optical sensor using Light Emitting Diodes (LEDs) is developed to evaluate the colour of solutions made by the soil analyser. In this paper, we have reported an optical soil macronutrients analysing system which is capable of remotely logging data to computer server for further analysis. The system designed with Photo Diode (PD), three Light LEDs as light source, PIC Microcontroller and GPRS modem. Light rays form LEDs were passed through the soil solution prepared by the chemical reaction of reagents with soil nutrients where degree of presence of any nutrient is represented by the deepness of the colour of the prepared soil solutions. PD senses the light beams and depending on the intensity of the transmitted beam quantity of the nutrients is analysed for that solution. Nutrient solutions were made from soil samples from different farmlands and soil nutrient solutions were prepared in the laboratory. Analysis of nutrient was carried out on standard spectrophotometer and colour-chart based analysis in the laboratory first and then same soil solution was analysed using our proto-typed system to calibrate the system and unknown soil samples were evaluated independently with the optical sensor and spectrophotometer, and finally the performance of the designed system was compared.

2. Nutrient solution preparation

Nutrient solutions were prepared for measuring three components of the soil: Phosphorus (P), Ammonium Nitrogen (NH_4-N) and Nitrate Nitrogen (NO_3-N). Preparation of solutions for each of these components is described here separately.

- Phosphorus (P): Solution of phosphorus was prepared using Olsen's Method [15]. At first, 5.00 g soil was weighted into a dry 100ml plastic bottle with a screw cap. Then 100 ml 0.5 M $NaHCO_3$ was added to it and kept at 25°C. Then the bottle was shaken by an orbital shaker for exactly 30 minutes before being filtrated by a dry filter. The colour of the prepared solution and the amount of P is greatly dependent on the shaking time. Therefore, the shaking time must be observed strictly and filtering must be done without delay.
- Ammonium Nitrogen (NH_4-N): 0.5-1.0 g soil sample was weighted into a 250 ml Erlenmeyer flask, then 100 ml distilled water was taken into the flask and shaken for 1 hour. After that, the solution was taken into a volumetric flask and rinsed several times with distilled water. The solution was then filtered into a dry flask. 4 drops of methyl red-methylene blue indicator solution was added to the content in the flask and was titrated with 0.05 NaOH until the colour changed from violet to green.
- Nitrate Nitrogen (NO_3-N): NO_3 formed a coloured nitro-compound with salicylic acid and the intensity of the colour varied with the amount of NO_3 present in reaction. Firstly, the 0.5-1.0 g soil sample was taken into an Erlenmeyer flask. Then 100ml distilled water was added and shaken for 1 hour. The solution was transferred to a volumetric flask and mixed with distilled water. Then the solution was filtrated into a dry flask or beaker. 2.0 ml of filtrate was then put into an Erlenmeyer flask by a pipette. 8.0 ml salicylic acid - H_2SO_4 mixture was added to the Erlenmeyer flask and cooled at room temperature. Finally, 100 ml 2M NaOH was added to the Erlenmeyer flask and rinsed several times to get the colour solution.

3. Sensor selection

Absorption spectra of colour-developed standard solutions with various contents were investigated using a spectrophotometer to decide the wavelength of LED for the sensor. Three soil

nutrients were used for the analysis using a commercially available soil analyser. The absorbance of each colour-developed solution in a fused silica cell with a path length of 10 mm was measured over the wavelength range from 350 nm to 1000 nm. The absorbance ***A*** is obtained shown in equation (1)

$$A = log_{10}(\boldsymbol{I}_{in}/\boldsymbol{I}_{out}) \qquad (1)$$

where $\boldsymbol{I}_{in}$ is the incident light intensity and $\boldsymbol{I}_{out}$ is the intensity after passing through the cell. The absorption spectra for the colour-developed solutions at room temperature are shown in Figure 1.

The phosphorus (P_2O_5) solution has a relatively broad absorption band between 700 nm and 900 nm in Figure 1(A). The absorption spectrum for ammonia nitrogen (NH_4-N) with several contents is shown in Figure 1(B) with an absorption peak at 650 nm. The nitrate nitrogen (NO_3-N) absorption peak appears at 540 nm as shown in Figure 1(C).

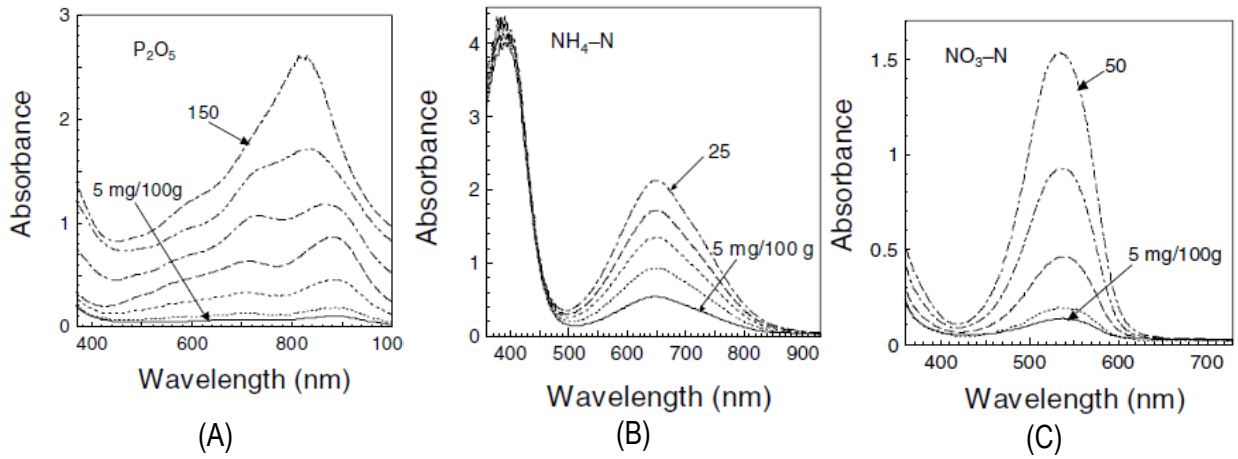

Figure 1. Absorption spectra of colour-developed standard solutions with various contents of soil nutrients: (A) P_2O_5, (B) NH_4–N and (C) NO_3–N [16]

LEDs are highly suitable as a light source of the sensor because they cover a wide wavelength range from ultraviolet to infrared, are low-cost have long lifetime and small size, etc. Therefore, it is easily possible to find a matching LED wavelength to the absorption band of the macronutrients. The wavelength of LED is chosen to fit the absorption peak of colour-developed standard solutions as shown in Figure 1. The three LEDs used for the sensor are surface mountable-type LEDs (Stanley Electric) of green (UR1105W), red (HUG1105W) and infrared (DN1102W). The emission spectra of the LEDs are measured by an optical spectrum analyser and shown in Figure 2. The centre wavelengths of the LEDs are 524 nm, 632 nm and 849 nm, respectively. The bandwidths for the LEDs are of the order of 17–26 nm (full width at a half maximum).]

4. Sensor configuration

Figure 3 shows the block representation of the developed sensor. The light source consists of three LEDs of green (G), red (R) and infrared (IR). The top surface of each LED package is glued to one end of a 100 mm long plastic optical fibre (POF) with a diameter of 1.0 mm. The light emitted from the LED is coupled into the glued POF. The other ends of three POFs are bundled in order to minimize the difference of emitting area from each POF. The light from the POF is transmitted into a transparent plastic cell having a size of 13 × 14 mm^2 and 5.5 mm in path length (L), and

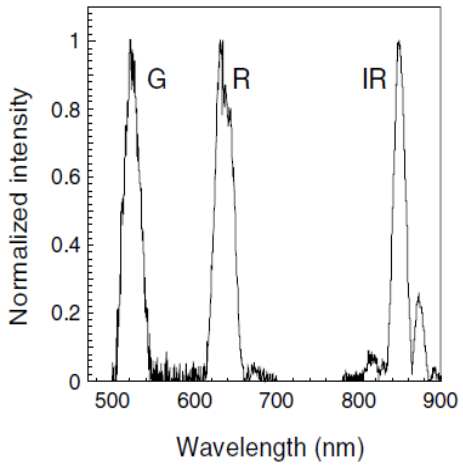

Figure 2. Emission spectra of light emitting diodes of the sensor: Green (G), Red (R) and Infrared (IR) LED [16]

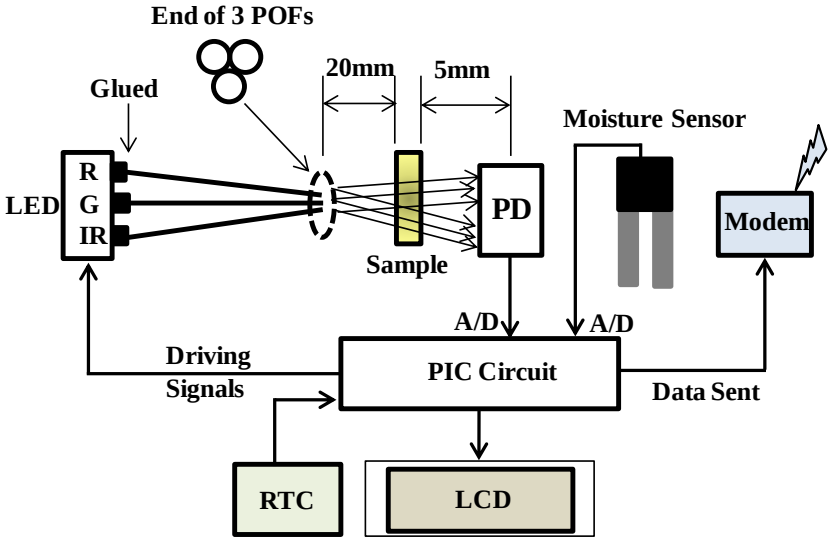

Figure 3. Configuration of the optical sensor

then detected by a silicon photodiode (Hamamatsu Photonics S1337-1010) having a detecting area of 10 × 10 mm^2. The beam diameter at the photodiode surface is 9.0 mm. The photodiode output is sent to a Peripheral Interface Controller (PIC) circuit via an internal 10 bit analogue-to-digital (A/D) converter. The system also includes a simple moisture sensor which can be used to detect soil moisture and enable researchers to remotely monitor the soil moisture level. The sensor has a built-in potentiometer to control its sensitivity.

The PIC circuit mainly composing a PIC16F877A IC (Microchip Technology) was integrated with LEDs, PD, Moisture sensor, Real Time Clock (RTC) DS1307 (Maxim Integrated) and Wavecom Fastrack Supreme 10 GPRS modem (Sierra Wireless). PIC16F877A IC is quite faster (200 nanosecond instruction execution) yet easy to program, provides with the necessary resource for driving signal for LEDs and sensing intensity signal from PD and executes data processing and communication among the other components.PIC16F877A features 256 bytes of EEPROM data memory, 2 Comparators, 8 channels of 10-bit A/D converter, 2 capture/compare/PWM functions, Synchronous Serial Port which can be configured as either 3-wire Serial Peripheral Interface (SPI)

or the 2-wire Inter-Integrated Circuit (I^2C) bus and a Universal Asynchronous Receiver Transmitter (USART). An RS-232C controller (MAX232, Texas Instrumentation) was used as the level converter between the RS-232 interface of GPRS modem and USART of PIC16F877A.The GPRS modem was used to send the recorded intensity contribution from the PD to the remote data server where data from different fields are stored and analysed. A 4×16-character LCD display was used as local user-interface for the operator (researcher or farmer) to indicate the work sequence of the system and also to display the A/D reading for different LED's locally. Lithium ion battery backed RTC circuit was designed using DS1307 IC to allow the system to send data with time-stamp to the data server for real-time processing. Figure 4 shows the photograph of the designed and developed system with each important component was labelled for clarification.

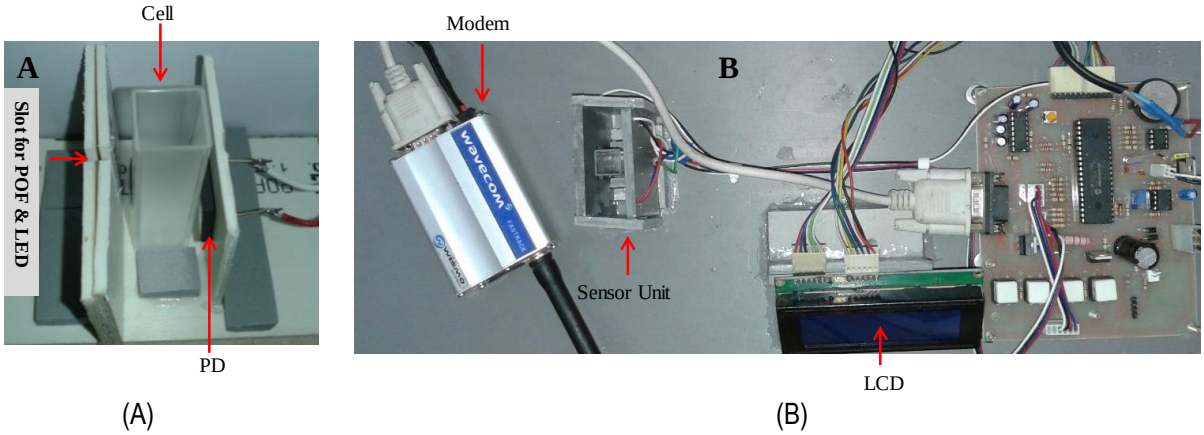

Figure 4. Snap-shot of the developed optical sensor unit (**A**) and complete system (**B**)

5. Experimental study

In the measurement, each set of the three LEDs (Green, Red and Infra-Red) are sequentially operated each for 0.5 s ON/OFF period and repeated for 10 cycles. It has been noticed that the A/D values for each nutrient solution fluctuate slightly over different samples. Therefore, ten A/D values for each nutrient solution for each LED were recorded and averaged to produce representative A/D value (nutrient sensor data). LED light intensity measured in a PD after absorbed due to the nutrient solution were recorded first for empty solution (reference solution) and then soil nutrient solution. Calculating the difference between these A/D value of reference and nutrient measurements, soil nutrient contribution from sensor was obtained. This difference quantity will be referred as "difference in A/D value" in rest of the paper. Soil samples were irrigated with different amount of water to test the performance of moisture sensor, then the sensor was dipped into the bucket of soil sample and ten A/D values were recorded for each soil sample to avoid variability and averaged to get more stable moisture sensor data to map it into moisture level (in standard Cbar unit of moisture). It was found that A/D values have to be scaled one-eighth (1/8) to get the moisture level comparing with standard moisture meter.

5.1. Sensor Calibration

Fifteen sets of soil samples were collected from fifteen farmlands with different soil properties of Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Bangladesh randomly with the expectation of having different macronutrient contents. Sensor data were recorded and their contributory nutrient values were calculated using the method described above

for fifteen different soil samples among which ten soil samples were used for calibrating the sensor and remaining five soil samples were used for evaluation of the designed system. These fifteen soil samples were also characterized in the chemical laboratory to measure the soil nutrient contents. Table 1 shows the first ten soil nutrient measured in the laboratory which were used as reference to calibrate the optical sensor.

Table 1. Macronutrient lab values for ten soil samples

P_2O_5 (ppm or mg/Kg)	NH_3-N (mg/100g)	NH_4-N (mg/100g)
14.3	0.89	0.43
40.2	1.43	0.48
33.9	0.28	0.64
64.6	0.43	0.55
54.7	0.64	0.62
77.9	0.68	0.61
82.6	1.24	0.72
118.2	0.26	0.77
25.9	0.63	0.63
68.5	1.45	0.81

For plotting and further data processing, the digitized photodiode output (A/D value) (the intensity contribution of the LED after absorption in the nutrient solution) was displayed to the local LCD and also sent to the data server with the timestamp via transport control protocol (TCP) socket using GPRS modem.

It is very important to define a data frame in the transmission system so that in the server-end data can be easily extracted with the correct timestamp. In this experiment, the following data frame format has been used shown in Table 2.

Table 2. Format of data frame

Field ID	;	*Date*	;	*Time*	;	*Avg P Value*	;	*Avg NH_3-N Value*	;	*Avg NH_4-N Value*	;	*Moisture Value*	;

A TCP connection between the field researcher and remote server was created using pre-configured access point name (APN) information, and data frame was then transmitted over the TCP connection. After the completion of data transmission, the TCP connection is closed, which ensures reliable and secured low-cost data transmission.

Figure 5 shows the difference between the A/D value of reference and nutrient measurements which is equivalent to nutrient contribution for three different LEDs while applied in P_2O_5 (A), NH_3-N (B) and NH_4-N (C) macronutrients solution respectively. Comparing the difference A/D values observed in P_2O_5 macronutrient solution for R, G and IR LEDs, it is apparent that the IR light has been most significantly absorbed by the soil solution. If this findings is compared with Figure 1(A) and Figure 2 information where it has been shown that the highest absorbance of P_2O_5 is observed between 800-900 nm wavelengths and interestingly IR radiation wavelength lies in the same wavelength range. Therefore, it can be summarized that difference A/D measurement recorded for IR LED is related to the quantity of P_2O_5 macronutrient present at that particular soil solution. Similarly, Green light was absorbed by the NH_3-N nutrient solution in highest quantity and the emission spectra of Green LED shows that highest absorption between 500-600 nm (Figure 2). This matches with the absorption spectra of NH_3-N soil nutrient shown in Figure 1(C) and the

difference A/D measurement of Green LED is therefore related to the quantitative measurement of NH_3-N nutrient in soil solution. Finally, Red LED response in Figure 5 (C) represents the quantity of NH_4-N in soil solution and this can be verified from Figure 1 (B) and Figure 2 where emission peak (600-700 nm) of Red light is observed at the highest absorption region of NH_4-N spectra.

The laboratory measurements (shown in Table 1) and its scaled version, matched with the representative LED response (Figure 5), were shown for P_2O_5, NH_3-N and NH_4-N respectively in the Figure 6 (A), (B) and (C) respectively. From Figure 5 it is clear that the IR, Green and Red LED responses are vital for calibrating the designed sensor response for quantative measurement of soil macronutrients P_2O_5, NH_3-N and NH_4-N respectively. To quantify the relationship between the representative LED response shown by the difference in A/D value and the laboratory measurements of macronutrients, these data were linear fitted to each other (shown in Figure 6) for ten soil samples. It was observed that there is a linear relation between the LED response and the laboratory measurements. Linear fitting of these two data showed that it is possible to link the difference A/D value with laboratory measurements. It is found that the difference in A/D value is nothing but a scaled version of the laboratory measurements. Figure 6 also showed how the scaling factor different soil macronutrients were calculated and it was found that the laboratory measurements need to be multiplied by scaling factor 2.75, 29 and 37.5 for P_2O_5, NH_3-N and NH_4-N respectively to get a scaled version (shown in Figure 7 light ash colour) of the laboratory measurements. Figure 7 clearly depicts that scaling the lab macronutrient values by the above-mentioned factors in-line those close to what we have recorded in the LED response (i.e., difference in A/D value). Therefore, these calibration factors can be used for future reference to measure the nutrient content from any unknown soil samples with only optical analysis of the soil solution and there will be not need to check in laboratory.

To evaluate the above statement, five remaining soil samples have been used to evaluate the performance of the calibrated system. The nutrient contents were calculated using the optical sensor and downscaled using the calibration factor 2.75, 29 and 37.5 for P_2O_5, NH_3-N and NH_4-N respectively and compared with the laboratory measurements.

6. Results and Discussion

Figure 5 demonstrates the average response from PD for three LEDs (Green, IR & Red) for three different macronutrients for ten different soil samples used for optical sensor calibration. Figure 5(A) shows that strong absorption of IR spectra was observed for P_2O_5 macronutrient; whereas Figure 5B shows that the Green light is absorbed highest in NH_3-N macronutrient solution. Red light is absorbed most in NH_4-N macronutrient solution. These results were compared with laboratory measurements to get the calibration factor using Figure 6. Figure 7 shows the calibration of optical sensor based system with the standard laboratory measures. Laboratory measures were scaled (P_2O_5 - 2.75, NH_3N – 29 and NH_4N – 37.5 times) to match with the PD output of different representative LEDs. It was found that different LEDs' contribution; IR LED for phosphorus (P_2O_5), Green LED for nitrate nitrogen (NH_3-N) and Red LED for ammonia nitrogen (NH_4-N), respectively closely matches with the laboratory results for different macronutrients. This calibration outcome has been used for characterizing the remaining five unknown soil sample solutions out of the fifteen soil samples. The moisture data recorded from different soil samples were compared with the standard moisture recorder showed very good level of similarity.

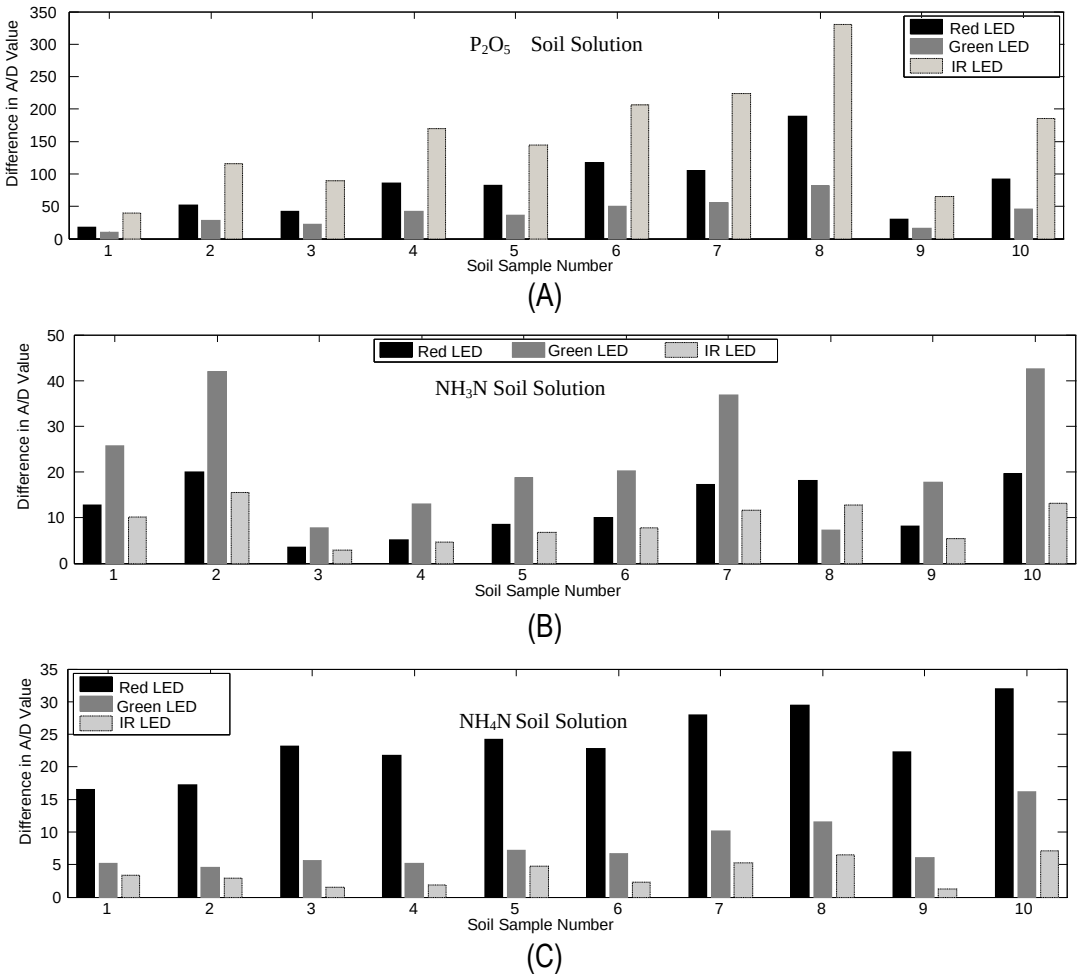

Figure 5. Contributory A/D values for the macronutrient P_2O_5 (**A**), NH_3-N (**B**) and NH_4-N (**C**) for three different LEDs in ten different soil samples. Unit less difference between the A/D value for reference solution and nutrient solution is shown in y-axis

The average response of representative LED recorded using PD for five soil samples (not used for calibration) is shown in Table 2, and the nutrient quantity was calculated based on the calibration factor obtained while calibrating the optical sensor. Consequently, the optical sensor data is compared with the standard laboratory analysis, which showed a good degree of agreement and percentage of error was calculated for different soil samples and nutrients. However, further investigation of more soil samples is necessary to verify the accuracy and adaptability of the optical sensor. In addition, the results of the samples have to be compared with corresponding results by another high-resolution soil analyser or soil-analysing method in the future work.

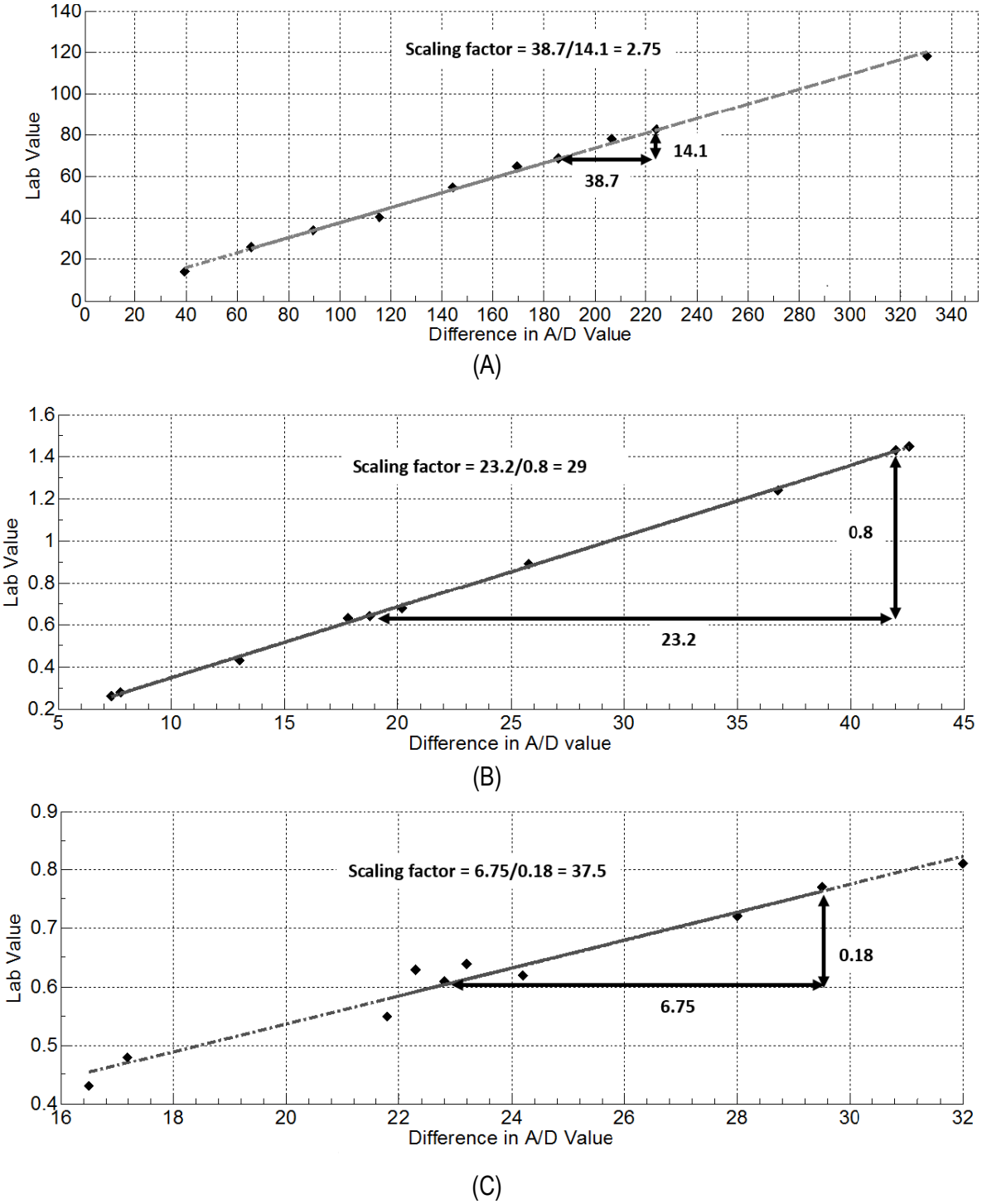

Figure 6. Linear fitting of difference in A/D value with lab value shown for macronutrient (**A**) P_2O_5, (**B**) NH_3-N and (**C**) NH_4-N. Note: the calculation of scaling factor for each macronutrient is also shown

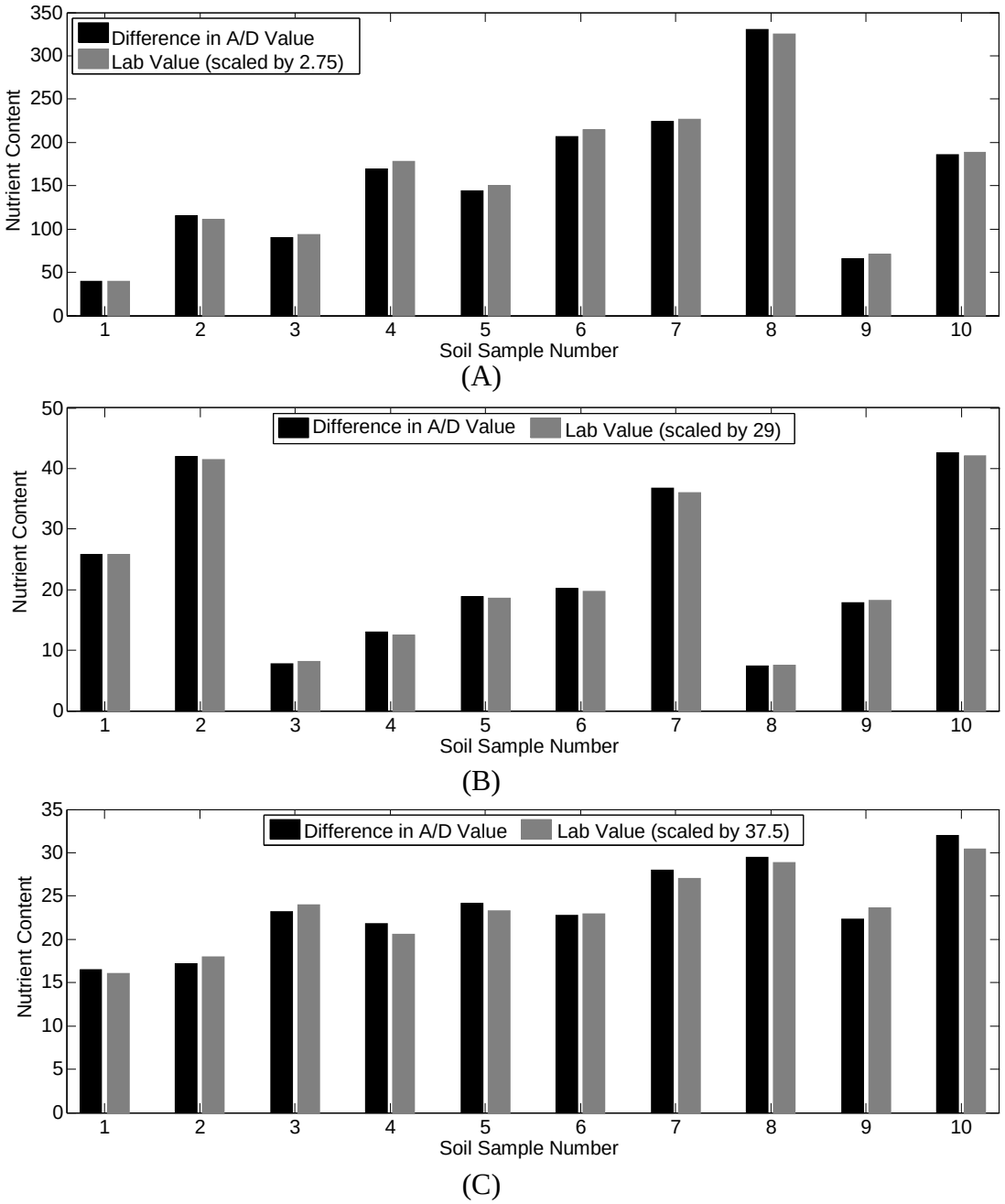

Figure 7. Comparison between measured value and scaled lab value of macronutrient P_2O_5 (**A**), NH_3-N (**B**) and NH_4-N (**C**) with matching LED response. Note: the y-axis shows unit less difference in A/D value as shown in Figure 5 and also scaled version of lab value of nutrient mg/Kg (P_2O_5) and mg/100g (NH_3-N or NH_4-N)

Table 2. Calculation of macronutrient for five unknown soil samples and comparison with laboratory results

IR LED (P_2O_5)	Green LED (NH_3-N)	Red LED (NH_4-N)	P_2O_5 (ppm or mg/kg) Sensor/Lab/ % Error (+/-)	NH_3-N (mg/100g) Sensor/Lab/ % Error (+/-)	NH_4-N (mg/100g) Sensor/Lab/% Error (+/-)
98	16	18	35.7/36.2/1.4%	0.55/0.54/-1.9%	0.48/0.51/5.9%
175	45	29	63.6/64.9/2%	1.55/1.61/3.7%	0.77/0.82/6.1%
159	13	30	57.7/55.8/-3.4%	0.45/0.49/8.2%	0.8/0.75/-6.7%
215	8	10	78.3/78.9/0.8%	0.275/0.28/1.8%	0.26/0.27/3.7%
234	24	20	85.2/84.3/-1.1%	0.83/0.87/4.6%	0.53/0.58/8.6%

7. Conclusion

A simple optical sensor based on optical analysis of soil nutrients using three LED light sources was constructed and its' sensing characteristics were investigated experimentally and compared the results with the existing standard spectrophotometer and colour-chart based analysis. In the colour-chart analysis, the soil solution colours were compared visually with the colour-chart and this makes it subjective and error prone whereas the spectrophotometer results more precise however not suitable for remote analysis of soil macronutrients. Conversely, the optical sensor could sensitively detect the colour changes caused by the chemical reaction between soil nutrients in the sample and colour developing reagents. The resolution achieved was as small as 1.0-2.0 mg/100 g for available phosphorus oxide (P_2O_5), nitrate nitrogen (NO_3-N) and ammonia nitrogen (NH_4-N) for the standard solutions of soil nutrients. However, the system was modelled to analyse only three macronutrients, and in future, we are expecting to design a system having wider spectral range to cover more soil macronutrients. In addition, solution based system makes the optical sensor lab-dependent and non-portable, which in future, will be improved.

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