An Optical Soil Sensor for NPK Nutrient Detection in Smart Cities

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***Abstract*—An optical absorbance-based sensor designed to measure the concentration of vital Nitrogen (N), Phosphorus (P) and Potassium (K) nutrients in urban soil was developed. This device was characterized and tested in nine diverse green spaces around New York City's Morningside Heights neighborhood, including street-tree pits and park spaces. The results show that the sensor can detect at minimum, a 1.4% change in nutrient concentration. Additionally, it was shown that the sensor can operate in various ambient light settings (indoor and outdoor) after calibration. A study of NYC's green spaces shows that, on average, soil in street-tree pits that supports plant life has 54% more N, 34% more P, and 37% more K than park spaces, respectively. This new sensor technology will enable more detailed monitoring of soil nutrient conditions and thus help promote healthy green spaces in large urban environments.**

Keywords—Optical transducer; NPK soil; Photodiode, Urban soil

I. INTRODUCTION

Urban green spaces such as street tree pits and parks are important to a city's ecosystem. Green space also promotes different physical activities, psychological well-being, and improves the public health of urban residents. Numerous studies have shown that these areas of vegetation have a positive impact on both the air quality and the physical and mental health of the city's population [1]. Improving the quality and quantity of urban plants typically involves appropriate and adequate addition of three elements to the underlying urban soil: Nitrogen (N), Phosphorus (P) and Potassium (K). Nitrogen improves the growth of plant leaves and vegetation, Phosphorus serves to promote the growth of plant roots and stems, and Potassium encourages plant flowering and fruiting [2-3]. Thus, an NPK sensor, that can accurately measure the concentration of these elements can play a fundamental role in dynamically monitoring the overall health of the urban soil with the goal of promoting healthy urban greenspaces. Previously, researchers have developed several types of NPK sensors utilizing various methods including electrical conductivity, electrochemical sensing, and the measurement of optical reflections [4]. The work highlighted in this paper utilizes a novel, optical NPK measurement technique specifically verified and tested in urban soils located in the Morningside Heights neighborhood of New York City.

Previous work in urban smart city sensors [5] has established a low-cost, low-power beacon for monitoring and evaluating factors that influence soil health, including light, humidity, temperature, and pressure. Since the NPK level is another important factor for determining soil health, this paper focuses on measuring soil NPK levels using an optical transducer. The principle of the optical NPK sensor is based on the interaction between the incident light and the soil surface properties [4]. Different concentrations of NPK in soil leads to different amounts of RGB light absorption. Thus, the measured transmitted light detected by the photodiode is directly related to the NPK concentration levels in the tested soil. The optical transducer is low-cost and is fabricated on a small form-factor printed circuit board (PCB). It transmits its sensor data via Bluetooth Low Energy (BLE), a common wireless communication network in smart city applications. This BLE platform can be integrated with other sensors and buried into the soil for real time NPK level detection. The optical sensor has some major advantages over other techniques, such as a high sensitivity and a wide dynamic range. However, the optical sensors are susceptible to interference from the surrounding environment.

In the designed optical sensor, a combination of LEDs act as a programmable light source to transmit light to the soil. A photodiode is then used as a detector to receive the reflected light [2]. The utilized wavelength range spans from 400 nm to 1000 nm, this is based on the soil absorbance level [6]. N is strongly absorbed between the wavelengths of 450 nm to 540 nm. Similarly, P and K have peak absorption wavelengths of 800nm-970nm and 620nm, respectively [2]. In this work, we developed a sensor platform utilizing LEDs and photodiodes matched to the specific absorption spectrum of each nutrient. The optical interface connects to an Analog-to-Digital Converter (ADC) and is transmitted serially to a NINA-B306 Bluetooth module over an I^2C connection.

This paper is organized as follows. Section II introduces detection methods and the experimental set-up for sensor testing. Section III describes and discusses the testing results, while conclusions are provided in Section IV.

II. METHODOLOGY

A. Setup Overview

The system overview for the integrated NPK detection system is shown in Fig. 1. The optical transducer system contains the light transmission and detection system. The optical transducer is then connected to the Analog-to-Digital (ADC) device to convert the analog sensor signals to digital signals. Finally, the ADC communicates with the NINA-B306 via I_2C to display the detection results wirelessly.

The light transmission system is shown in the left part of Fig. 1 and is comprised of three red, green, and blue LEDs. The three LEDs in the light transmission system emit light with wavelengths within the absorption range of N, P and K nutrients in soil. Nitrogen has an absorption wavelength

between 438-490 nm, so a blue LED was chosen (460-485 nm) for Nitrogen's light transmission. Phosphorus has an absorption wavelength between 528-579 nm, so a green (500-574 nm) LED was used for light transmission. Finally, Potassium has an absorption wavelength of 605-650 nm, so a red (635-660 nm) LED was utilized for its light transmission [2]. A control mechanism that allows independent detection of the three different nutrients was also designed. For instance, when the blue LED turns on, the corresponding N photodiode also turns on, however, the green LED, red LED, P photodiode, and K photodiode remain in the off mode. Therefore, each of the N, P and K nutrients can be detected individually.

After light is absorbed by the soil, some light is transmitted and the intensity of the transmitted light is measured by the photodiodes, with the intensities of the collected light indicating the NPK levels. The right part of Fig. 1. shows the light detection system connect to the ADC.

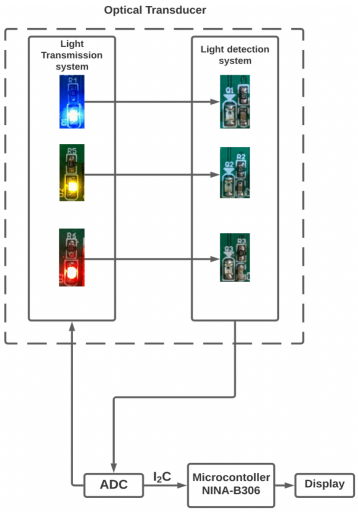

Fig. 1. Overview setup of integrated NPK detection system

The voltage signals were collected by an ADS1015 12-bit ADC. Additionally, a NINA-B306 was used as the sensor's microcontroller. As the system has 12-bit precision, so the full voltage value of 3.3 V was received. The ADC is the value collected inside of the MCU, then the Vadc = ADC/4096×3.3V.

B. *Sample Testing Procedures*

We applied our NPK detection system to test three types of soil in the laboratory. Fig. 2(a) shows the color difference among highly N, P and K-rich soil, respectively. For the soil sample preparation, we obtained three identical Sphagnum Peat Moss soil samples from a vendor, and added 150g N crystals (RAW brand) to one sample, 150g P crystals (RAW brand) to the second sample, and 150g K crystals (RAW brand) to the last sample; finally, 50g water was added to all samples and the soil was mixed. For the RAW brand N/P/K crystals, the N is derived from Ammonium Sulfate, the P is derived from Monoammonium Phosphate, and K is derived from Potassium Sulfate. Since the colors of these three soil samples were different, the optical method was deemed suitable for NPK detection. Fig. 2. (b) illustrates the experimental setup for detecting the NPK content. The position of the PCB board was fixed in place in order to optimize the path length between the transducer and the soil sample and to stabilize the detection process.

C. *Data Analysis Method*

To determine the concentration of each nutrient, the Beer-Lambert Law equation was applied. Using this law, a linear relationship between the absorbance and the concentration of the absorbing species was assumed [7]. The equation of the absorbance is shown in Equation (1), where A stands for absorbance, I_t is the intensity of the transmitted light, and I_0 is the intensity of the incident light.

$$A = -log\frac{I_t}{I_0} = log\frac{I_0}{I_t} \qquad (1)$$

Based on the absorbance calculated from (1), the nutrient concentration could be calculated using the equation shown in (2), where c is the concentration of the nutrient (mol/L), A is the absorbance calculated from (1), ε is the molar absorption coefficient, a quantity that signifies how strongly the sample is absorbed at a particular wavelength [7], and l is the path length between soil and the receiver. The molar absorption coefficient depends on the different wavelength of the light. Therefore, a nutrient higher concentration (C) leads to more absorbance (A), which means more light is absorbed in the soil rather than transmitted.

$$c = \frac{A}{\varepsilon l} \qquad (2)$$

(a)

(b)

Fig. 2. (a) Soil samples in high K, high P and high N (b) Experimental setup for lab measurements

III. Testing, Results and Discussion

In the test, the path length between the optical transducer and soil sample were fixed to 0.3cm. To validate the functionality of the NPK sensor system, two different measurements were taken. Firstly, a dynamic concentration was measured in a soil testbed. This allowed precise amounts of nutrients to be added to the base soil continuously. This was done to verify the minimum and maximum concentration of each nutrient the sensor could reliably detect. Lastly, the sensor was tested in the field and also with soil sampled from around the Morningside Heights neighborhood in New York. A variety of different types of soil were taken to represent the diverse green spaces found around the city.

Fig. 3. Dynamic NPK testbench setup

A. *Dynamic Testing*

The dynamic concentration testing was performed using the set up shown in Fig. 3. The experiment was designed to test the sensor's ability to measure small amounts of nutrient change in the soil. To perform this measurement, 0.5g N/P/K (RAW brand) was added to 35g Sphagnum Peat Moss soil for each testing period. During this time, the minimum nutrient concentration that the sensor could detect was 1-2g. This shows that the sensor can measure as little as 1g of added nutrients to the original soil testbench. To keep the concentration level trackable, 35g of water was added to the test soil initially to assist in dissolving the added nutrients uniformly. The total volume for the setup was kept at 0.5L. In the experiment, the N crystal was much coarser than the other two nutrients, thus it was initially finely crushed to dissolve into the soil more easily.

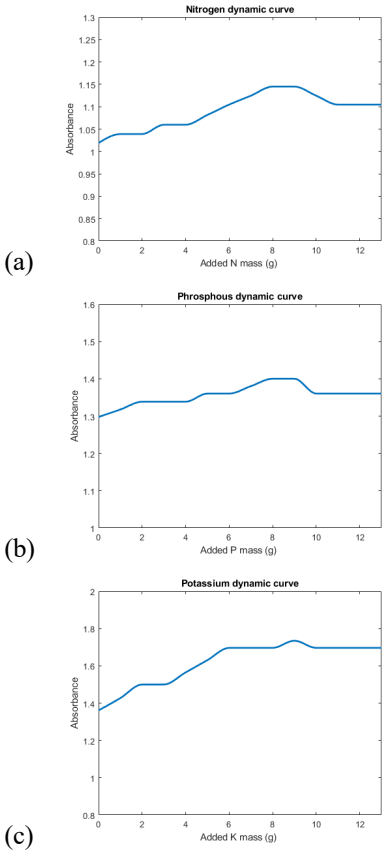

Fig. 4. Dynamic curves for adding NPK nutrients

Based on the methods introduced in Section II, Fig. 4. shows the results of the dynamic testing. The vertical axis stands for the absorbance that is calculated from Equation (1). The higher content concentration for one nutrient causes its photodiode to receive less light. From Beer's Law, the intensity of the transmitted light and the absorbance is reciprocally related. In Fig. 4, it is observed that the higher nutrient concentration has a higher absorbance. Such a trend is reasonable and agrees with Equation (1). The horizontal axis shown the mass of N/P/K nutrient crystals added to each testbench. During each test, only one nutrient was added dynamically while the other two nutrients were kept constant. This was done to isolate the changes in absorbance to the addition of a specific nutrient. Fig. 5. shows that each of the NPK's absorbance increased when adding 1g to 9g of additional nutrient. This corresponded to an increase in overall nutrient concentration based on Equation (2). However, each nutrient eventually reached a saturation point. After adding 10g of K, 8g of N, or 8g of P, respectively, the absorbance value decreased by 0.05 of absorbance value. At this point, continuing to add more nutrients did not continue to increase the absorbance and thus a saturation point was reached,

B. *Urban Soil Testing*

To verify the effectiveness of our sensor in urban soil, nine 150-gram samples were collected from various locations around NYC's Morningside Heights neighborhood. Fig. 5. shows examples of the different types of urban soils that were tested. To cover a large range of NYC's soil diversity, samples were taken from parks (Morningside and Central Park), tree pits without plantings, and tree pits with plantings (i.e. flowers and Shrubs). Fig. 5. (d) shows the experimental setup for each measurement. The nine locations of the testing urban soil are marked in the map shown in Fig. 6.

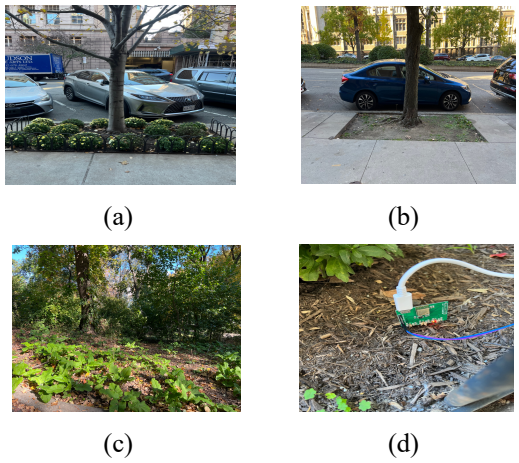

Fig. 5. (a) Urban street soil samples with foliage (b) Urban street soil samples without foliage (c) Soil Samples from Morningside Park (d) Experimental setup for outdoor measurements

All nine sample's NPK levels were tested outside at each location. In addition, four samples were collected and remeasured in the lab to ensure that the sensor readings were correctly calibrated. These four samples were taken from site 9, site 6, site 4 and site 7, as shown in Fig. 6 and Table II. The NPK results for both the lab and outdoor testing is shown in Table I. Since the optical environment in the lab and outdoor were different, which could lead to different results for the same sample in these two environments, the results from the field were normalized to the lab environment. As for the normalization process, lab data and outdoor data which were measured from the same soil samples were plotted against each other, then a linear curve was fitted through the data. The fitting result was used to correct all the outdoor measurements to the lab scale. This process was repeated for the N, P, and K separately since each of nutrients have a different normalization curve. Table I shows that the normalized outdoor NPK data and the lab NPK data measurements are around the same value. The absorbance was relatively consistent in the lab and in the outdoor environment, which proved the sensor's reliability in different light conditions/settings. In this way, we removed the effects of light level in the calculation of the NPK concentration.

TABLE I. URBAN SOIL SAMPLE RESULTS IN LAB AND OUTDOOR

Sample No.	Site No.	Absorbance					
		Nitrogen		*Phosphorus*		*Potassium*	
		Lab	*Out -door*	*Lab*	*Out -door*	*Lab*	*Out -door*
1	6	0.964	0.958	1.360	1.319	1.382	1.381
2	7	0.569	0.573	0.786	0.799	0.794	0.794
3	4	0.855	0.858	1.102	1.102	1.139	1.146
4	9	0.886	0.890	1.360	1.379	0.971	0.991

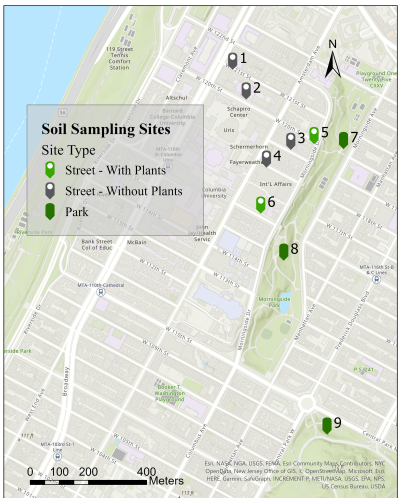

Fig. 6. Map for the locations that urban soil samples were collected

Table II shows the normalized outdoor testing results from the nine locations shown in Fig. 6. All the outdoor testing were performed in the daytime. Fig. 7. shows the histogram of the nine urban soil testing results. From both Table II and Fig. 7., the street-tree pit soil without plantings had a lower absorbance (and therefore nutrient concentration) for all the NPK nutrients than the street-tree pit soil with plantings. The street-tree pit soil samples with plants have higher NPK concentrations than the soil samples in park, which is possibly due to the street-tree pit soil with the plants being maintained by city workers, and thus being fertilized regularly, or the possibility that the tree pits are functioning as latrines for dogs and other animals. Conversely, NPK level in the green spaces in the two parks are closer to those in the natural environment, thus possibly there is no such fertilization at these sites.

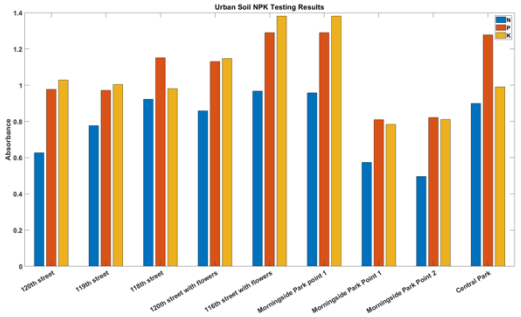

Fig. 7. Histogram of urban soil testing results measured from outside

TABLE II. URBAN SOIL NPK TESTING RESULTS

Type	No.	Location	Absorbance		
			Nitrogen	*Phosphorus*	*Potassium*
Tree pits without foliage	1	121st street	0.627	0.977	1.029
	2	120th street	0.777	0.972	1.004
	3	119th street	0.922	1.152	0.981
	4	118th street	0.858	1.102	1.146
Tree pits with foliage	5	120th street	0.968	1.290	1.381
	6	116th street	0.958	1.319	1.381
Park	7	Morningside Park point 1	0.573	0.799	0.794
	8	Morningside Park point 2	0.496	0.822	0.811
	9	Central Park	0.890	1.379	0.991

IV. CONCLUSION

In conclusion, an integrated optical sensor for NPK nutrient detection in soil was developed. The sensor was validated in both a laboratory-based urban testbed and in outdoor measurements across a diverse range of urban green spaces. Measurements show that readings from the device can be normalized, enabling the device to operate under diverse lighting conditions. The device is also capable of detecting very small traces of nutrient concentrations. Additionally, the work has shown that NYC tree pits with plant life show a significantly higher nutrient concentration than those without plants. Future goals for this project include adding a Bluetooth Low Energy wireless communication network to seamlessly collect soil health data in order to monitor urban soil health in real time.

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