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Portable internet of things-based soil nutrients monitoring for precision and efficient smart farming

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ABSTRACT

This paper describes the design and implementation of a portable internet of things (IoT)-based system for online monitoring of soil nutrients, specifically nitrogen (N), phosphorus (P), and potassium (K), to improve precision and efficiency in smart farming. The main goal is to use IoT technology to analyze soil conditions on-site and provide advice about fertilization and soil management. The system measures soil nutrient levels using field-based sensors, such as an NPK probe, and transmits data over a wireless sensor network. The research comprises a quantitative evaluation of the performance of the IoT system using various sensors. An analysis of variance (ANOVA) was used to compare the accuracy of the IoT device with industrial soil nutrient measurement equipment, demonstrating differences in P and K values but not in N values. This disparity points to certain areas where the accuracy of the P and K measurements in the IoT system should be improved. This IoT-based soil nutrient monitoring system highlights the potential of smart farming technology to boost agricultural output, optimize resource consumption, and support sustainable farming practices. The system's portability and online data availability provide farmers with exact soil condition information, allowing them to make more efficient and intelligent farming decisions.

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1. INTRODUCTION

Soil nutrients are an important factor for farming as they directly impact plant growth and yields [1]–[3]. These nutrients, including nitrogen (N), phosphorus (P), and potassium (K), are vital for various biochemical processes in plants. Especially N and P which are essential nutrients for plant growth, and they play a critical role in the soil-plant system [4], [5]. Although N and P are primarily found in the soil, their concentration varies depending on the type of soil, location, and environmental factors [6]. The growth and productivity of plants are influenced by the availability of certain nutrients in the soil. Determining the quality and quantity of these nutrients in the soil is an important requirement in precision agriculture, hence it is essential to detect N and P [4], [7]–[10]. It is essential to build sensors capable of measuring soil characteristics at the scale necessary for precise mapping of within-field variations [11]. To maximize agricultural production, precision agriculture uses a variety of technology, such as global positioning system (GPS) services, sensors, and big data [12]. The importance of soil factors such as temperature, moisture, water level, and conductivity are crucial to improving the quality and yield of the crop. Precision agriculture can be defined as "the application of modern information technologies to provide, process, and analyze multi-source data of high spatial and temporal resolution for decision making and operations in the management of crop production [13].

Although few have been used, internet of things (IoT) technologies has ushered in a new era of agricultural sensor networks. The bulk of research claims that a wireless sensor network gathers data and transmits it to a central server using wireless protocol [6]. The use of data analytics will assist farmers increase crop yields by utilizing the data gathered from sensors on agricultural fields [14]. IoT frameworks are used in conjunction with the IoT to make it simple to observe, handle, and interact with data and information [13], [15], [16]. There is a need for a wireless smart sensor architecture with multimodal data collecting capabilities. The solution comprises cloud and mobile computing-based data storage and display. The data collected by these sensors is transmitted to a cloud infrastructure, where it can be analyzed in real-time [4], [5], [10], [17]–[20]. This real-time monitoring allows farmers to make informed decisions regarding fertilization, watering, and overall soil management. The complexity of smart farming can be seen from the technology involved, i.e., sensing technologies, software application, communication systems, telematics and positioning technologies, hardware and software systems, and data analytics solutions [12]. IoT applications in smart farming also include farm vehicle tracking, livestock monitoring, storage monitoring and other farm options [14].

The objective of this study is to develop a wireless sensor system that can monitor soil conditions in real-time and determine when fertilizers should be applied to maximize productivity [4], [5]. In other words, the technology provides means for researchers and farmers to better manage crop inputs (e.g., reduce the quantity and rate of fertilizers without sacrificing food production) [16]. Knowledge about the spatial variability of soil nutrients is important for agricultural management practices and improving sustainable land use [11]. The agriculture industry stands to benefit significantly from IoT's use in soil parameter monitoring. The characteristics of IoT devices/sensors that make them suitable for agriculture are there: i) portability; ii) reliability; iii) memory; iv) durability; v) power and computational efficiency; and vi) coverage [21]. This technology has the potential to transform farming practices, increase farmers' incomes, and encourage sustainable agriculture by increasing production, reducing expenses, and offering real-time data [22]. Through remote sensing, smart agricultural systems minimize wastage, increase production, and allow management of a wider variety of resources [19], [23]–[25]. By utilizing IoT technologies and field-based sensors for continuous monitoring of soil nutrients, moisture levels, and other key parameters, farmers can make informed decisions regarding fertilization, watering, and overall soil management. This leads to optimized crop growth, reduced waste, and increased yield.

2. METHOD

2.1. Research strategy

The research is conducted by utilizing a quantitative approach, which is a way of looking for information that can be represented as numbers and used for analysis. The performance of the IoT system will be assessed quantitatively using data from a variety of sensors, including soil-probe nutrients sensor, pH sensor, humidity, and air temperature sensor. There are three types of sensors that are widely used in agriculture: physical property sensors, biosensors, and micro electro-mechanical sensors. According to application principles, electrical sensors include many types, such as capacitive, resistive, inductive, and eddy current [26]. An intelligent sensor node comprises three components namely: sense, compute, and communicate. The sensing component is responsible for capturing the real-world parameters such as moisture and temperature. The computational component preprocesses the captured parameter value and the communication component makes sure that the gateway sensor nodes are able to communicate with gateway nodes and can share the information among them [27]. The black box testing method will be used to test and compare the reading outcomes of each sensor, and the "JXBS-3001-SCPT-SC soil integrated sensor" will be used to aid in estimating the accuracy level of sensor readings with the root mean square error (RMSE) calculation.

For this portable IoT-based system, the necessary hardware includes: i) ESP32 microcontroller; ii) nitrogen, phosphate, and potassium (NPK) probe sensor; iii) long range (LoRA) SX1276; iv) organic light-emitting diode (OLED) LCD; and v) GPS module. The NPK Probe sensor doesn't need any chemicals to function. 5 separate needle probes are used to collect data on soil nutrients using this sensor. The sensor runs at a voltage range of 9 to 24 Volt DC and has an NPK measuring resolution of up to 1 mg/kg. It also incorporates a serial modbus communication mechanism. The system and device architecture are shown in the Figures 1 and 2.

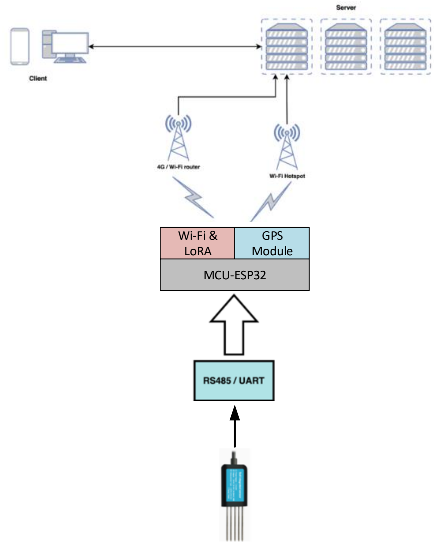

Figure 1. IoT-based soil nutrients monitoring system architecture

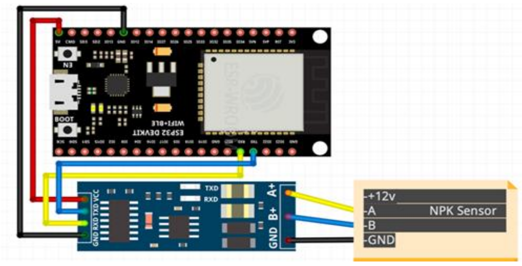

Figure 2. IoT-based soil nutrients monitoring device (wire notes: red: 5 volts; black: GND; blue: serial-Tx; yellow: serial-Rx)

2.2. Design of the portable IoT-based hardware

The device incorporates essential components, including the ESP32 microcontroller, OLED display, LoRa communication module, GPS unit, NPK sensor, and a power button. The ESP32 serves as the computational core, managing data processing and connectivity. An OLED display offers online data visualization for farmers. The LoRa module enables long-range data transmission, allowing remote field monitoring. With a GPS module, each measurement is accurately geotagged. A specialized NPK sensor measures crucial soil nutrients. The schematic and circuit board are shown in the Figures 3 and 4.

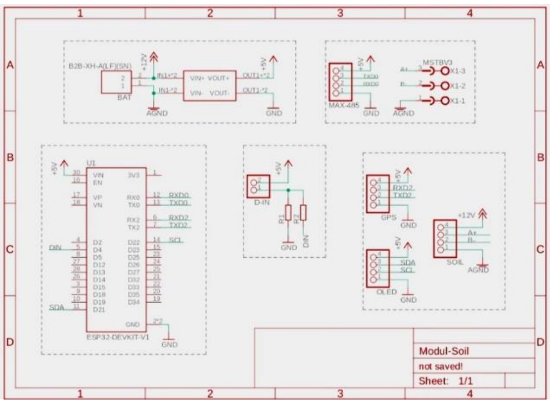

Figure 3. The schematic of portable IoT-based monitoring device

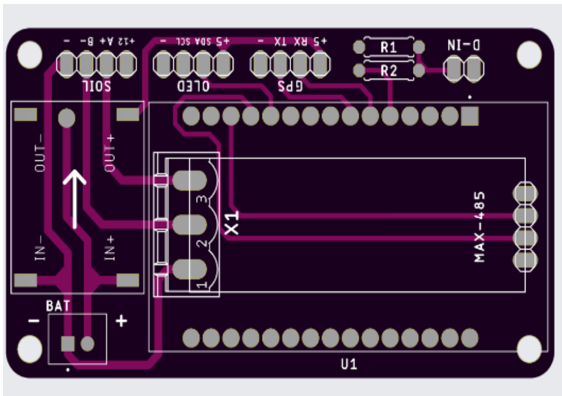

Figure 4. The circuit board design of portable IoT-based monitoring device

Upon activation, the NPK sensor conducts soil nutrient measurements. The ESP32 processes this data, while the GPS module records the precise location. Results are displayed on the OLED screen in a user-friendly format. The ESP32 securely transmits data to a cloud-based platform or designated server through the LoRA module. This facilitates online access to soil nutrient data via web or mobile applications. Such accessibility empowers farmers to make informed decisions about fertilization and crop management. The detailed about the pinout for ESP32 connection is shown in Table 1. Detailed information about the JXBS-3001-SCPT-SC is shown in Table 2. Table 3 presents the detailed soil 7-in-1 soil pH meter kit NPK EC conductivity temperature moisture PH multifunction sensor information utilized by the portable IoT-based soil nutrients system.

Table 1. Pinout connecting of ESP32 to the modules

No	Pinout ESP32	Modul name	Pinout module
1	GPIO 22	OLED display	SCL
2	GPIO 21		SDA
3	GPIO 2	LoRa module	DIO 0
4	GPIO 5		NSS
5	GPIO 14		Reset
6	GPIO 18		SCK
7	GPIO 19		MISO
8	GPIO 23		MOSI
9	TX2	GPS	RX
10	RX2		TX
11	TX0	RS-485/NPK	TXD
12	RX0		RXD
13	GPIO 4	Button	Button-GND

Table 2. Information about the JXBS-3001-SCPT-SC

No	Information	Value
1	Series	Agriculture soil sensor
2	Description	Portable soil NPK sensor
3	Theory	FDR
4	Output	12-24 vdc
5	Amplifier type	Standard
6	Operating temperature	-40 to +80
7	Resolution (bits)	1 mg/kg
8	Current-supply (max)	24 vdc
9	Output configuration	5 vdc
10	Humidity range	-40 to +80
11	Sensing range	0-1999 mg/kg
12	Acceleration range	1 s
13	Sensitivity (mV/g)	High
14	Sensitivity (LSB/(°/s))	High
15	Sensitivity (mV/°/s)	High and fast

Table 3. Soil 7-in-1 soil pH meter kit NPK EC

No	Information	Value
1	NPK detect range	0-1999 mg/kg
2	Accuracy	± 2% F.s
3	EC range	0-20000 us/cm
4	Humidity range	0-100%
5	Temperature range	-40 ℃ to 80 ℃
6	Response time	<10 s
7	Baud rate	2400/4800/9600

2.3. Data collecting

The data of soil nutrients was collected randomly from specified agriculture fields in a zig-zag pattern. The NPK probe sensor inserted 5 to 10 cm into the soil to determine the soil's NPK levels. The measurement of soil nutrients was conducted on the agricultural field around different villages in Wonogiri, Indonesia. For analysis, few samples tags marked as P1, P2, P3, through P24 which were collected from different locations having GPS coordinates of [-7.97918385, 110.946764], [-8.06634869, 110.879614], [-8.03665317, 110.879614] and [-8.0366279, 110.884316], respectively, as shown in the study area map in Figures 5 and 6.

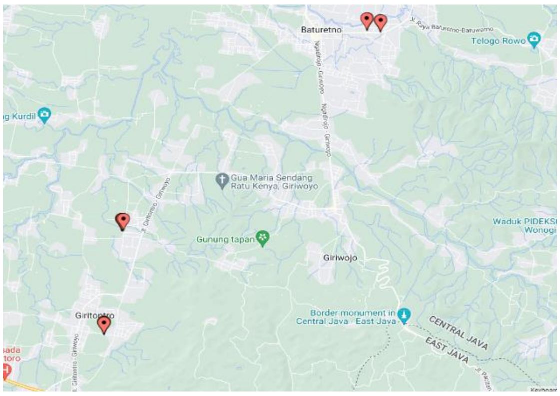

Figure 5. Map area of collected data

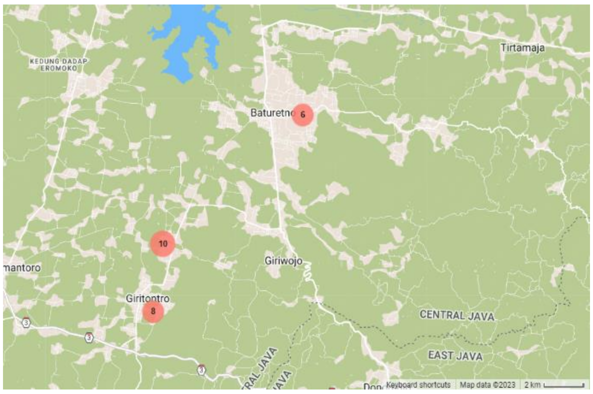

Figure 6. Number of data collected on each sample location

3. RESULTS AND DISCUSSION

The RMSE calculation will be used to test the accuracy of the results of reading the IoT system used, then analysis of variance (ANOVA) is performed to determine if there are any statistically significant differences in the NPK values between the portable IoT device and the JXBS-3001-SCPT-SC. ANOVA is a statistical method used to determine whether there are any statistically significant differences between the means of several independent groups. The general formula to determine statistical significance, F-statistic, is shown in (1) [28]. The accuracy of the portable IoTs-based soil nutrients device is conducted by comparing the device's value with JXBS-3001-SCPT-SC soil integrated sensor. Table 4 shows the comparison of the reading results by the devices.

$$F = \frac{variation\ between\ groups}{variation\ within\ groups} \quad (1)$$

Table 4. Validation of the IoTs-based soil nutrients

Sample no.	Portable IoT device reading (ppm)			JXBS-3001-SCPT-SC reading (ppm)		
	N	P	K	N	P	K
P1	145.0	146.3	203.3	188.6	262.2	517.8
P2	25.0	28.7	126.5	462.6	631.6	1235.4
P3	251.6	249.3	97	422	574.4	1201.6
P4	149.4	150.00	206.8	160.2	223.6	446.4
P5	128.8	130.20	181.6	145.2	196.8	396.4
P6	117.6	118.80	167.2	99.2	138.8	278
P7	146.3	148.33	206.3	152.4	207.8	417.8
P8	175.0	175.00	243.3	86.8	123	250.8
P9	113.8	111.8	162.0	86.2	120	239
P10	126.6	125.2	176.8	115.8	162.2	326.6
P11	59.00	75.5	191.7	134.8	188.8	382
P12	200.80	202.4	27.4	168.8	248.6	487.2
P13	158.3	162.6	230.3	115.8	161.8	329.6
P14	206.3	212.3	41.6	121.6	172.2	345.6
P15	133	131.5	184.5	151.2	213.6	433
P16	154.2	156.8	221.8	105.2	146.6	298.4
P17	123.75	125.25	176.75	107.8	151	304.4
P18	133.4	135.8	188.8	129.6	180.2	362
P19	171.6	170.4	233.6	171	242	480.6
P20	190.6	191.6	15.6	176.6	249	498.8
P21	171	170	240	138.2	187.6	388.6
P22	114.5	114.75	161.5	128.4	176.2	357.6
P23	72	71.5	97.5	75.2	104.8	213.8
P24	93.7	93.25	129.5	106.2	143.8	272.4

Table 5 presents the F-statistic and p-value for each element NPK, allowing a comparison of the statistical significance across these elements. The results indicate significant differences in the P and K values between the portable IoT device and the JXBS', but not in the N values. For the N, the F-statistic is 0.56 with a p-value of 0.457. This p-value is greater than the common alpha level of 0.05, indicating that there is no statistically significant difference in the N values between portable IoT device and the JXBS'. The

F-statistic for P is 7.42 with a p-value of 0.009. This p-value is less than 0.05, suggesting that there is a statistically significant difference in the P values between the two groups. Likewise, the F-statistic for K is 25.70 with a p-value of approximately 0.000007. This very low p-value indicates a statistically significant difference in the K values between portable IoT device and the JXBS'. The visual comparison of nutrients reading for portable IoT devices and JXBS' are shown in Figure 7.

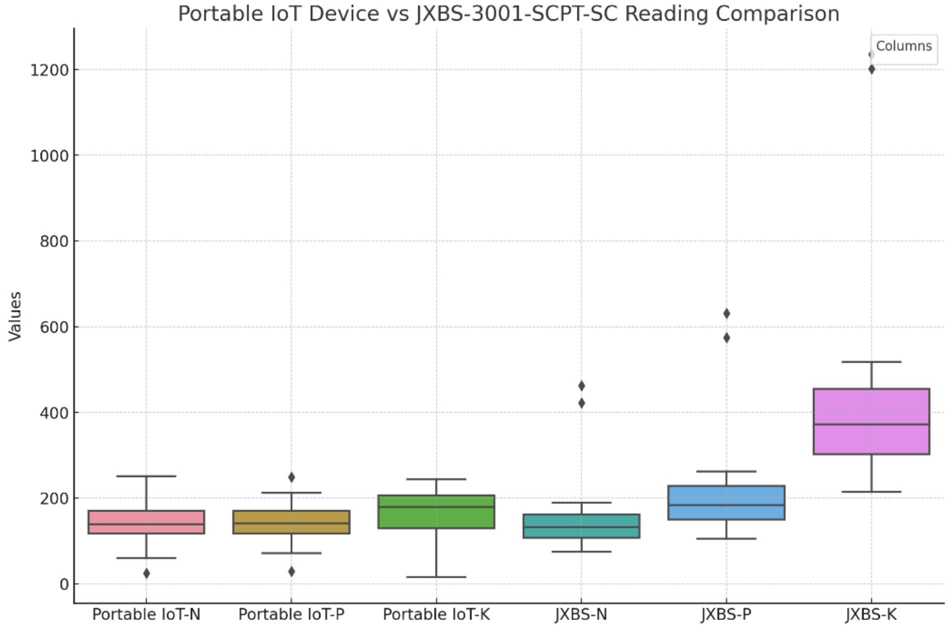

Figure 7. Comparison of nutrients for each device

Table 5. ANOVA analysis of N, P, and K

Element	F-Statistic	P-Value
N	0.56	0.4571
P	7.42	0.0091
K	25.70	0.000007

The differences shown by the ANOVA results indicate the need for further adjustments to the soil nutrient readings by the portable IoT device. However, the results of reading the N value shows that the device can take quite accurate readings. Further development is to improve the accuracy of device readings.

4. CONCLUSION

A portable device has been developed that integrates IoT technologies with soil nutrient monitoring to provide online and on-the-go analysis of soil conditions. This device utilizes field-based sensors to measure soil. In addition, the portable IoT-based soil nutrient monitoring device is equipped with a mobile application that enables farmers to easily access and interpret the collected data. The mobile app provides online updates on soil conditions, allowing farmers to monitor their crops even when they are on the go. This not only saves time and effort but also enhances the overall efficiency of farming operations. In addition to precise farming techniques and optimizing crop production. The IoT technologies provide online data and insights that enable farmers to monitor their soil conditions and make proactive decisions regarding fertilization and watering. This leads to more efficient resource utilization and improved crop yields. The ANOVA results suggest significant differences in the P and K values, but not in the N values between portable IoT devices and the JXBS'.

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