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Development of an IoT-Based Device for Real-Time Detection of Soil NPK Nutrient Content to Optimize Soybean Yields

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ABSTRACT

The optimal growth of soybean plants is critically dependent on the availability of essential nutrients in the soil, particularly nitrogen (N), phosphorus (P), and potassium (K). Plants achieve optimal growth when nutrient levels exceed deficiency thresholds. A significant challenge in soybean cultivation at the farmer level is the precise determination of fertilizer dosage and timing of application. This study presents an Internet of Things (IoT)-based device for the real-time detection of NPK nutrient content in soil, aimed at enhancing soybean yields. The device enables timely and accurate nutrient application, minimizing the soil's residual fertilizer risk, which can lead to environmental pollution and decreased land productivity. Field experiments were conducted to evaluate NPK fertilization methods on soybean crops in two distinct soil types, namely Vertisol and Entisol. The methodology involved comparing local farmers' fertilization practices with the recommendations derived from the NPK detection device. Results illustrated a significant increase in soybean yields when fertilization was performed according to the device's recommendations, yielding an increase from 1.2 to 1.79 t.ha^{-1} on Vertisol soil and from 1.75 to 2.57 t.ha^{-1} on Entisol soil.

Keywords: Fertilization optimization; Internet of Things (IoT); Nitrogen (N); Phosphorus (P); Potassium (K)

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INTRODUCTION

The Internet of Things (IoT) application is critical for improving land productivity in soybean cultivation. IoT technologies facilitate precision agriculture by enabling real-time monitoring and data collection, which can significantly enhance decision-making processes for farmers (Wolfert et al. 2017). According to data from the annual report of the Ministry of Agriculture, Republic of Indonesia (MARI 2019), soybean productivity at the national level experienced negative growth in 2018 (−4.62%) despite an 82.39% increase in production (Table 1). This paradox can be explained by the quality of the dry seed produced, which is a crucial indicator of productivity (MARI 2019). Furthermore, data from the Indonesian Central Bureau of Statistics (BPS-Statistics Indonesia) highlights a declining trend in soybean productivity from 2014 to 2018, pointing to systemic issues in cultivation practices and resource management (BPS-Statistics Indonesia 2019). If this trend continues, it could disrupt the supply of soybeans necessary to meet national demand for derivative products such as tofu, tempeh, and soy milk. To mitigate these challenges, the integration of IoT systems can optimize irrigation, soil health, and pest management, ultimately leading to enhanced productivity and sustainability in soybean farming (Dhanaraju et al. 2022).

Soil fertility management is a crucial aspect of crop production, particularly in soybean cultivation. Farmers can minimize excessive fertilizer residues by accurately identifying the nutrients in the soil, thereby reducing wastage and mitigating the risk of soil pollution. Excessive fertilizer residues can lead to soil degradation, resulting in decreased land productivity (Larson and Pierce 1994). Specifically, nitrogen fertilizer residues can contribute to soil acidification, as observed by (Perin et al. 2020), while phosphorus residues can form insoluble compounds, such as Fe-P and Al-P, leading to stable occluded-P compounds (Cahyono 2009). Furthermore, excessive potassium uptake, known as "luxury consumption," can occur when plants absorb more potassium than required without any yield improvement (Kaiser and Rosen 2018). In cases where soil deficiencies in nitrogen, phosphorus, or potassium occur, the Internet of Things (IoT)-based device provides accurate and timely recommendations for nutrient composition required in the soil.

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Table 1. National soybean productivity of Indonesia

	2014	2015	2016	2017	2018*	Growth Rate (2018 vs. 2017) (%)
Productivity (kg.ha^{-1})	15.51	15.68	14.90	15.14	1.44	−4.62
Production (ton)	954.997	963.183	859.653	538.728	982.598	82.39

Remarks: From the annual report of the Ministry of Agriculture, Republic of Indonesia (MARI 2019)

This ensures optimal soybean productivity and promotes healthy plant growth by supplying sufficient, balanced, and timely nutrient availability (Epstein and Bloom 2005). Soil nutrient status can be assessed based on crop yields and the yield percentage, which compares yields without specific fertilizers to yields with those fertilizers. Zhang (2006) categorizes soil micronutrient status based on relative yield as follows: extremely low (<50%), low (50-70%), moderate (75-95%), and high (>95%). The optimal fertilizer dosage for plants depends on soil micronutrient status, nutrient requirements, and fertilization efficiency. It is site-specific due to varied and often unbalanced nutrient availability in the soil (Parjono 2019). The required fertilizer amount is the difference between plant needs and available soil nutrients, adjusted for efficiency and conversion factors (Larson and Pierce 1994). While soil testing provides approximate nutrient levels, practical assessments classify soil status as low, medium, or high, allowing farmers to adopt targeted fertilizer application strategies.

MATERIALS AND METHODS

Assembly of the device

Measurement system. This system was designed to measure soil NPK levels based on electrical properties (Perdana et al. 2023). The physical variable measured was soil conductivity, determined using a sensor with two probes powered by a battery (Sayyad et al. 2024). This type of sensor falls under the category of modulated sensors, requiring external energy to drive the system (Swathi et al. 2023). When the battery can self-charge without manual intervention, the sensor is classified as having self-powering or self-driving capabilities, which are key characteristics of an intelligent sensor (Khairnar et al. 2016). Additionally, the system included moisture and pH sensors, providing valid readings under varying soil conditions (dry, normal, or wet). This adaptability highlights the sensor's self-adaptation ability. Sensors possessing either or both self-powering and self-adaptation features are considered intelligent sensors (Kumar et al. 2019).

Monitoring system. This system enabled the transmission of real-time soil NPK data remotely via IoT technology (Zambon et al. 2019). Communication was bidirectional, allowing the sensor to send NPK data to users and enabling users to send commands back to the sensor for adjustments or updates (Yan et al. 2016). These updates included conversion parameters or expert knowledge in the embedded database (Prabha et al. 2018). The real-time, bidirectional communication enhanced the system's capacity for expert updates and knowledge adaptation to specific soil conditions (Ojha et al. 2016), forming a crucial aspect of smart monitoring (Masrie et al. 2018).

Controlling system. Although this system did not autonomously intervene in fertilization or irrigation, it provided recommendations to farmers based on soil variables measured (NPK levels, moisture, and pH) (Patil and Kale 2016). These data supported a decision support system (DSS) embedded with expert knowledge (Pravin et al. 2018). The DSS generated precise recommendations on the quantity and timing of fertilizer applications (Ihsan and Aditya 2023). The smart system feature ensured that the recommendations were tailored to local conditions (Susanto and Nurcahyo 2020). The device includes the following components: i. Microcontroller to process sensor data and connect to the LoRa module; ii. LoRa RFM95 to transmit data to the database; iii. Battery Shield to store and regulate battery power; iv. Voltage Regulator to adjust voltage; v. NPK Sensor to detect soil Nitrogen, Phosphorus, and Potassium levels; vi. pH Sensor to measure soil pH; vii. Moisture Sensor to detect soil moisture levels; and viii. OLED Layer to display real-time data.

Testing on soybean crops

The effectiveness of the assembled NPK detection device was evaluated in soybean fields. The tests were conducted on two types of soils: Vertisol Kebak Kramat and Entisol Colomadu. Vertisol is characterized by its high clay content, whereas Entisol represents sandy soils. Each soil type was subjected to two treatments: (1) Control (P0): Fertilization using dosages recommended by local farmers and (2) Device Recommendation (P1): Fertilization based on the recommendations provided by the NPK detection device. The experiments were conducted in plots measuring 3 m x 4 m, with five replicates for each treatment. The fertilizer dosages applied for each soil type were P0 = Control (farmer's method): Urea: 100 kg.ha^{-1}; SP36: 150 kg,ha$^{-1;}$ and KCl: 150 kg.ha^{-1} (applied at planting). P1 = Device Recommendation: The recommended dosage of NPK fertilizer was determined by installing the device on the experimental plot in the field. NPK levels were measured at 10, 20, and 30 days after planting. Based on the recommended NPK fertilizer dosage obtained from the device, the soybean plants were subsequently fertilized following these recommendations. The soybeans were harvested 87 days after planting. The yield data underwent statistical analysis utilizing a *t*-test to assess the effectiveness of the treatments.

RESULTS AND DISCUSSIONS

Assembly of the NPK detection device

The operational mechanism of the NPK detection device is depicted in the diagrams in Figure 1 andFigure 2. Figure 1 illustrates the workflow of the NPK detection device for assessing soil nutrients, moisture, and pH levels. The process begins with the device's setup, followed by a calibration step to ensure that the initial readings are at zero value. Once the device is powered on and displays an initial reading of zero, the sensor is inserted into the soil to detect the nutrient content of nitrogen (N), phosphorus (P), potassium (K), pH, and moisture levels.

This detection utilizes the principle of resistance measurement, whereby the sensor is connected to a microcontroller equipped with an analog-to-digital converter (ADC) pin. The readings obtained are converted into digital values based on the voltage supplied to the device. Subsequently, the LED screen displays these readings in digital format, providing real-time information on soil characteristics.

Figure 2 illustrates the network topology of the NPK detection device. This device is equipped with multiple sensors, including those for nitrogen (N), phosphorus (P), potassium (K), and soil moisture. Using an internet connection, data transmission to Google Cloud Firebase is facilitated through Wi-Fi or LoRa sensors. All monitoring data are stored in a table within the Google Cloud Firebase database, and appropriate fertilization recommendations for the monitored soil are continuously generated by the NPK detection device.

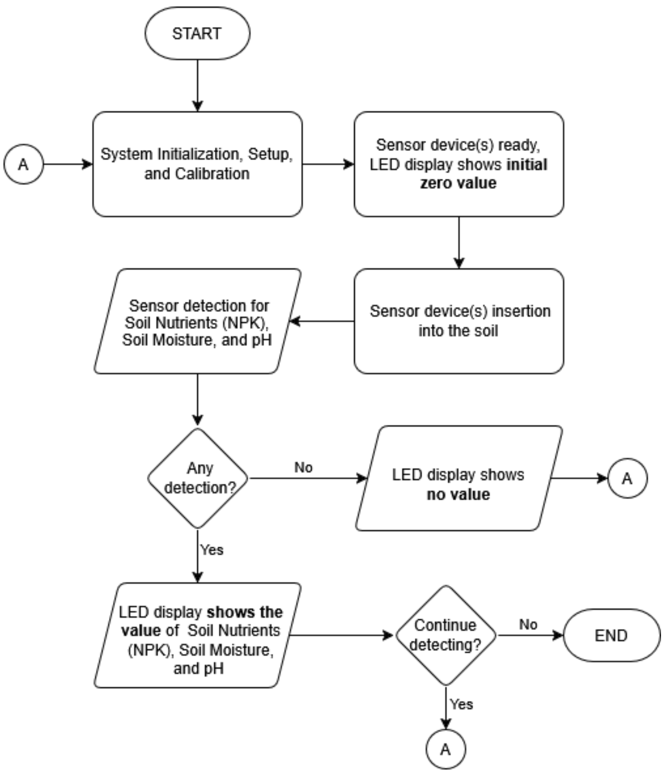

Figure 1. Operational workflow of the NPK detection device

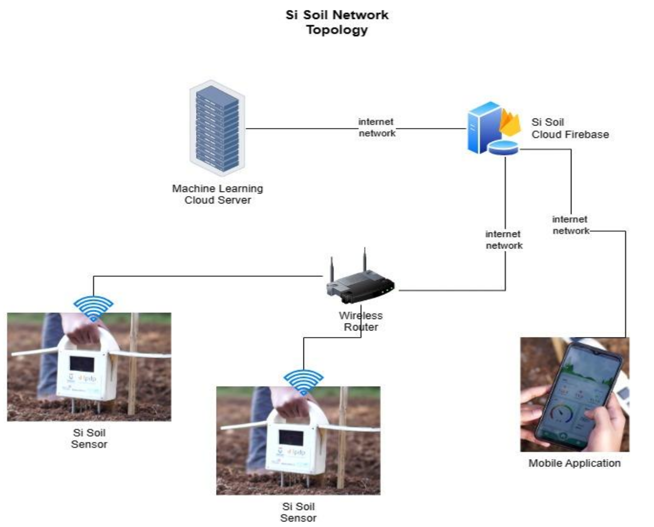

Figure 2. Network topology of the NPK detection system

In real-time, a mobile application can access the Firebase database via an internet connection, providing updates on the sensor readings for each NPK detection device and the recommended fertilizer dosages required (Chauhan and Gupta 2019).

Testing on soybean plants

Soil NPK on Vertisol and Entisol. Two soils, Vertisol and Entisol, used in the study, contained N, P, and K, as illustrated in Table 2. The data showed that total N in Entisol was higher compared to N in Vertisol. Both soils contained high levels of available P but low in exchangeable K.

Table 2. Results of laboratory analysis of N, P, and K levels in Vertisol and Entisol soils

Soil Properties	Analysis Methods	Vertisol	Entisol
pH	Electrode glass	7.20	5.76
C-Organic	Walkley & Black	1.85%	2.14%
Total N	Kjeldhal	0.15%	0.34%
Available P	Olsen	12.32 ppm	14.64 ppm
Exchangeable K	Extraction Am. Acetate 1 N pH 7.00	8.97 ppm	14,82 ppm

A study by Wahyunto et al. (2016) from the Indonesian Agency for Agricultural Research and Development (IAARD) found that fertile soil with adequate nitrogen (N), phosphorus (P), and potassium (K) is ideal for soybean cultivation. To achieve optimal soybean seed weight, the soil must contain total nitrogen levels ranging from 0.21 to 0.5%, with available phosphorus levels of at least 11 ppm and potassium levels of no less than 41 ppm.

Grain yield (t.ha⁻¹) on Vertisol. The soybean grain yield on Vertisol is presented in Table 3. The data in Table 3 indicate that all plots receiving fertilizer based on the recommendations from the NPK detection device produced higher grain weights than the control plots. The statistical analysis results, conducted using a t-test, are illustrated in Figure 3.

The t-test results for soybean grain weight per hectare indicate that the treatment using the NPK detection device significantly produced higher grain weights per hectare (α = 5%) than the control plots, which received the standard NPK dosage applied by local farmers.

Table 3. Soybean grain yield (t.ha-1) on Vertisol soi

Block	Treatments	
	Control	Device
1	1.50	1.87
2	1.62	2.10
3	1.37	1.62
4	1.50	1.75
5	1.12	1.62
Total	7.11	8.96
Mean	1.20	1.79

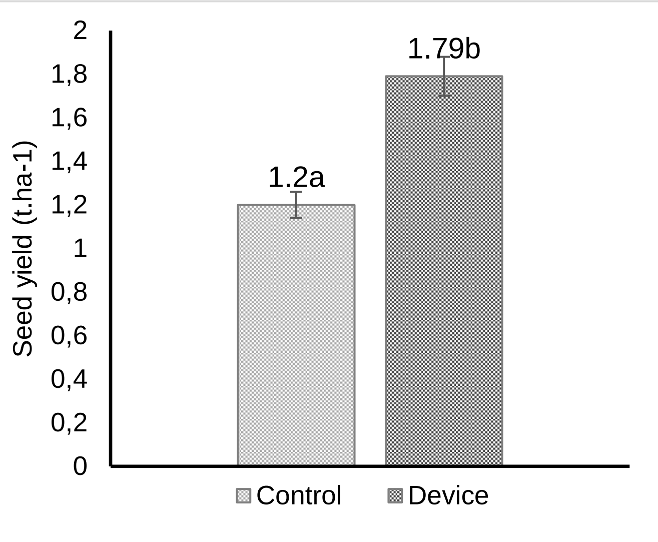

Figure 3. *T*-test results for soybean grain weight on Vertisol soil

The control plots utilized a common fertilizer application of 100 kg.ha^{-1} of urea, 150 kg.ha^{-1} of SP36, and 150 kg.ha^{-1} of KCl, with all fertilizers applied at the time of planting. In contrast, the dosage recommended by the NPK detection device was used in three stages as follows: First fertilization: Urea 34.16 kg.ha^{-1} + SP36 25.4 kg.ha^{-1} + KCl 60.6 kg.ha^{-1}, applied 10 days after planting; Second fertilization: Urea 33.8 kg.ha^{-1} + SP36 46.8 kg.ha^{-1} + KCl 26.5 kg.ha^{-1}, applied 20 days after planting; Third fertilization: Urea 24.2 kg.ha^{-1} + SP36 50.6 kg.ha^{-1} + KCl 21.2 kg.ha^{-1}, applied 30 days after planting.

Soybean grain yield (t.ha^{-1}) on Entisol Soil. The soybean grain yield on Entisol is presented in Table 4. The data in Table 4 demonstrate that all plots fertilized according to the recommendations of the NPK detection device resulted in higher grain weights than the control plots. The statistical analysis results using the t-test are shown in Figure 4.

Table 4. Soybean grain yield (t.ha-1) on Entisol soil

Block	Treatments	
	Control	Device
1	1.50	2.25
2	1.62	2.50
3	1.75	2.75
4	2.00	2.50
5	1.87	2.87
Total	8.76	12.87
Mean	1.75	2.57

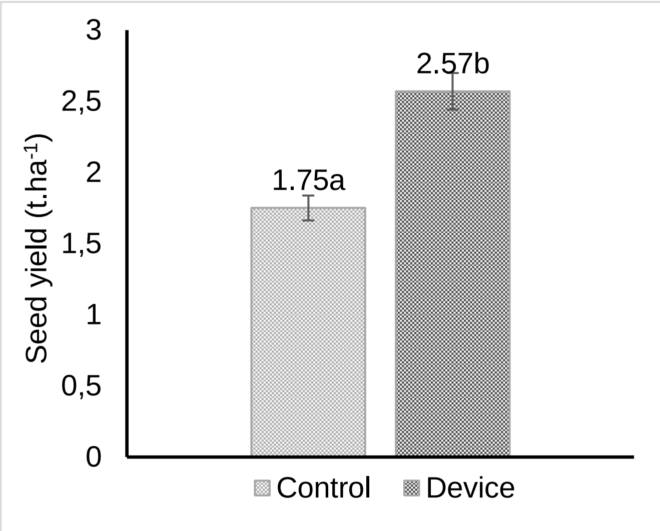

Figure 4. *T*-test results for soybean grain weight on Entisol soil

The results of the *t*-test analysis for soybean grain weight per hectare revealed that the treatment employing the NPK detection device significantly yielded higher grain weights per hectare (α = 5%) compared to the control plots, which received the standard NPK dosage commonly applied by local farmers. The control plots utilized a fertilizer application rate of 100 kg.ha^{-1} of urea, 150 kg.ha^{-1} of SP36, and 150 kg.ha^{-1} of KCl, with all fertilizers applied when planting. In contrast, the NPK detection device's recommended dosage was applied in three stages: First fertilization: Urea 35 kg.ha^{-1} + SP36 36.30 kg.ha^{-1} + KCl 26.5 kg.ha^{-1}, applied 10 days after planting; Second fertilization: Urea 32.5 kg.ha^{-1} + SP36 58.2 kg.ha^{-1} + KCl 39 kg.ha^{-1}, applied 20 days after planting; Third fertilization: Urea 20.5 kg.ha^{-1} + SP36 40.3 kg.ha^{-1} + KCl 25.5 kg.ha^{-1}, applied 30 days after planting.

The field experiments conducted in this study demonstrated that utilizing the NPK detection device resulted in a more effective and efficient NPK fertilization method for soybean plants in both Vertisol and Entisol soil types. On Vertisol, the total NPK fertilizer applied (Urea: 92.16 kg.ha^{-1}, SP36: 122.8 kg.ha^{-1}, KCl: 108.3 kg.ha^{-1}) resulted in soybean grain yields of 1.79 t.ha^{-1}, which represents a 49% increase compared to the control fertilization dosage. Similarly, on Entisol, the NPK fertilization dosage applied using the detection device (Urea: 88 kg.ha^{-1}, SP36: 128.5 kg.ha^{-1}, KCl: 110 kg.ha^{-1}) yielded 2.57 t.ha^{-1}, a 46% increase compared to the control treatment, which yielded only 1.75 t.ha^{-1}. This study concludes that real-time, plant-specific NPK fertilization recommendations can reduce fertilizer usage while achieving higher soybean grain yields.

The timing of nutrient provision is crucial for successful plant growth. Research has shown that the phosphorus (P) content in the soil is notably high shortly after fertilization but decreases steadily as the plant develops, with a significant decline in available P observed 30 days after planting (Yan et al. 2016). Previous studies have indicated that phosphorus fertilizer is most effective for annual crops when applied at intervals of 0, 15, and 30 days following planting (Cahyono and Hartati 2013). Furthermore, to optimize fertilization efficiency, it is essential to consider the appropriate dosage, type, timing, and placement of fertilizer (Johnston and Bruulsema 2014).

The method of fertilizer application significantly impacts nutrient uptake efficiencies, characterized as the proportion of nutrients absorbed by plants relative to the amount added. Effective fertilizer application strategies can enhance nutrient use efficiency, reduce waste, and promote sustainable agricultural practices.

CONCLUSIONS AND SUGGESTIONS

This study concludes that the NPK nutrient detection device can provide fertilization dosage recommendations based on real-time monitoring of NPK levels. In addition to recommending reduced NPK doses, the device increased soybean yields by 49% on Vertisol and 46% on Entisol, compared to yields obtained with conventional NPK doses applied by farmers.

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