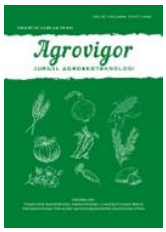
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Article

Soil Fertility and pH Measuring Tool for Paddy Soil Using Internet of Things Technology

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ABSTRACT

Agriculture is a vital sector that is a food security sector. However, agricultural productivity is still often hampered by the lack of monitoring of soil conditions, which results in inaccurate fertilizer application. The development of an Internet of Things-based fertility measuring tool is an innovative solution to overcome this problem. With the ability to provide accurate data on N, P, K and pH nutrient levels quickly, this tool allows farmers to fertilize precisely. The research method used is Research and Development which has stages of literature study, system design, web application development, calibration and testing: data analysis and improvement. Sandy soil samples L1, L3, and L4 nitrogen error 6–7%, phosphorus error 8–10%, potassium error 6–10%, and neutral soil pH slightly acidic error <5%. Clay soil samples L2, L6, L7, and L9, nitrogen and potassium content error 5–6% and 6–7%. Phosphorus error around 7%. Soil pH ranges from 3–5%, indicating slightly acidic conditions. Clay samples L5, L8, and L10 contain 5–10% nitrogen, 6–9% phosphorus, 6–8% potassium, and 3–5%. Therefore, the results of N, P, and K measurements on sandy, loamy, and clay soils should be interpreted with caution and confirmed through laboratory tests.

INTRODUCTION

Agriculture is a vital sector that not only supports national food security but also plays a significant role in global economic growth (Dariah et al., 2020). However, agricultural productivity often faces serious challenges, one of which is the improper management of soil fertility and acidity (pH). Soil that lacks essential nutrients or has an imbalanced pH level can hinder nutrient absorption by plants, ultimately leading to decreased crop yields (Purwanto & Arifin, 2019). Therefore, monitoring soil fertility and pH is a crucial aspect in supporting sustainable and efficient agriculture.

To date, the measurement of soil fertility—including nitrogen (N), phosphorus (P), and potassium (K) content—as well as soil pH is still largely carried out manually using conventional tools or through laboratory testing (Nurhidayati et al., 2022). These methods have several limitations, such as delays in obtaining results, high operational costs, and a lack of data accuracy and continuity. As a result, farmers often struggle to make timely and accurate decisions regarding fertilization and land management strategies (Putra & Suryani, 2021). The absence of real-time information becomes a major obstacle in the implementation of precision agriculture.

The development of Internet of Things technology offers an innovative solution to this issue through automated sensor-based monitoring systems. By utilizing soil sensors integrated with IoT technology, data on soil fertility and pH can be collected, transmitted, and analyzed in real time (Ray, 2017). This allows farmers to access accurate and up-to-date information, enabling them to take precise action in land management and fertilizer application. Therefore, the development of an IoT-based soil fertility and pH measurement tool for paddy fields is a strategic step toward realizing a more modern, efficient, and sustainable agricultural system.

MATERIALS AND METHODS

Soil Fertility

Soil fertility is defined as the soil's ability to optimally support plant growth, primarily through the availability of macronutrients (including N, P, K). The physical, chemical, and biological factors of soil also determine the level of fertility and can be influenced by management practices such as fertilization and the use of organic fertilizers (Sumarni, Rosliani, & Duriat, 2010). The NPK macronutrients include Nitrogen (N), which plays a role in the formation of proteins and chlorophyll, as well as supporting vegetative plant growth. Phosphorus (P) functions in root development, flowering, and fruit maturation. Potassium (K) aids in protein synthesis, and enhances plant resistance to diseases and drought (Rahman, Hasanuzzaman, & Hossain, 2020).

Internet of Things

The Internet of Things refers to any device or electronic equipment that can directly interact with users and is used for monitoring or controlling such devices via the Internet. The Internet of Things describes a system architecture integrated across sensors, software, networks, and appropriate interfaces that provide real-time awareness and integrate people, processes, and knowledge to gather intelligence for informed decision-making (Sumarudin et al., 2019).

ESP8266 Microcontroller

ESP8266 is a microcontroller module with Wi-Fi connectivity widely used in the development of Internet of Things (IoT) systems. ESP8266 is often integrated into platforms such as the Wemos D1 mini, which simplifies programming through the Arduino IDE and enables real-time remote control capabilities. Equipped with a processor, memory, and GPIO, the ESP8266 can function independently without an additional microcontroller. The ESP8266 features interfaces such as SPI, I2C, UART, and a 10-bit ADC, and it has 16 pins including both digital and analog pins (Putra & Utama, 2020)

NPK Sensor

An NPK sensor is a device used to measure the content of the three primary macronutrients in soil: nitrogen (N), phosphorus (P), and potassium (K). These elements are essential for plant growth and development. Monitoring NPK levels in the soil is crucial in agriculture to determine the appropriate fertilization needs in order to improve productivity and efficiency. NPK sensors operate based on the principle of electrical conductivity to detect nutrient ion concentrations in the soil. A commonly used method is electrochemical, where the sensor detects specific ions

based on the electrical voltage generated when the ions react at the electrode surface (Putra & Susanto, 2021).

Soil pH

Soil pH is a measure of the soil's acidity or alkalinity—the lower the value, the more acidic the soil; conversely, the higher the value, the more alkaline. The pH value affects the availability of nutrients and microbial activity in the soil. Average soil pH ranges from 3 to 10, with the ideal range for many crops being between 5.5 and 7.0. The impact of pH on soil fertility is significant: in acidic soils (low pH), toxic ions such as Al^{3+} and H^{+} increase, which can inhibit root growth and nutrient uptake. On the other hand, in alkaline soils (high pH), elements such as Fe, Mn, and Zn become less available due to being bound in insoluble forms (Wikipedia contributors, n.d.).

Soil Types

Soil types are one of the important media where nutrients are stored. Common soil types found in agricultural areas include clay, loam, and sandy paddy field soils. Sandy soil has coarse particles and small surface area, making it less capable of retaining water and nutrients. In contrast, clay soil has extremely fine particles (< 0.002 mm), high plasticity, cohesive nature, low permeability, and excellent water retention and cation exchange capacity. Meanwhile, loam is a balanced mixture of sand, silt, and clay, making it moderately porous and less compact than clay. Loam is often considered ideal for many plants due to its balanced characteristics (Hardiyatmo, 2002).

System Development Method

The research method used is the Research and Development (R&D) method, which is a systematic approach to producing innovative products through a series of validation and testing stages. In the context of IoT technology development, the R&D model generally refers to a framework that includes needs identification, prototype design, limited trials, revisions, and final product implementation (Sugiyono, 2019). This method is suitable for research on IoT-based soil fertility measurement tools because it combines scientific exploration (research) with engineering processes (development), ensuring that the resulting product meets criteria of usability, accuracy, and sustainability (Wijaya et al., 2022).

The R&D stages are as follows:

a. Literature Study: Includes needs analysis and literature review to support the research.
b. System Design: Selecting soil fertility and pH sensors, and the ESP8266 microcontroller.
c. Web Application Development: Creating an IoT interface for soil data processing and fertilization decision-making.
d. Calibration & Testing: Field-testing the tool, comparing soil test results with those from agricultural laboratory testing, followed by statistical validation against standard instruments to ensure data accuracy is accountable (e.g., correlation or error margin based on agricultural science standards).
e. Data Analysis & Refinement: Evaluating the tool's accuracy and its impact on agricultural productivity.

RESULTS AND DISCUSSION

Tool and Materials

The selected tools and components are tailored to meet the needs of a digital system for measuring soil fertility and pH in paddy fields, integrated with Internet of Things (IoT) technology. The selection of components such as the ESP8266, NPK and pH sensors, and data communication modules is intended to ensure the device can accurately measure, process, and transmit data in real-time. The complete list of tools and materials used can be seen in Table 1.)

Diagram Block

This subsection presents the block diagram of the developed soil fertility and pH measuring system for paddy fields using Internet of Things (IoT) technology. The block diagram provides an overview of the system's blocks tool, starting from data collection by the NPK and pH sensors, data processing by the ESP8266 microcontroller, to data transmission to a display and an online platform. The diagram also illustrates the integration between hardware and internet connectivity to support real-time data monitoring via a website or web-based application.

Schematic tool

This schematic diagram of the circuit used in the IoT-based soil fertility and pH measurement system for paddy fields. The schematic illustrates in detail the

connections between key components such as 18650 batteries, the ESP8266 module, NPK sensor, pH sensor, and LCD, all arranged on a breadboard. The purpose of this schematic is to provide a visual guide on the electrical and data pathways between components, thereby facilitating the assembly and testing processes of the device.

Flowchart system

This system workflow through a flowchart that illustrates the operational process of the IoT-based soil fertility and pH measuring device for paddy fields. The flowchart begins with the initial step of placing the device into the soil, followed by the sensor reading the fertility and pH values, and then checking the stability of the data. If the data is stable, the device will transmit it to a website, where the system will display and analyze it to generate agricultural action recommendations. This flowchart aims to provide a systematic understanding of the device's working stages in a logical and sequential manner.

Table 1. Tools and Materials

No	Tools Name	Qty
1	ESP8266	1
2	Sensor NPK	1
3	Sensor pH	1
4	LCD I2C	1
5	Modul Max485	1
6	Socket USB Female	2
7	Kabel Jumper Male	20
8	Baterai 18650	3
9	BMS 12V 3s	1
10	Modul Stepdown 5V	1
11	Box	1
12	Socket DC 5mm	1
13	Swicth On/Off	1
14	PCB berlubang	1
15	Pin Header (set)	5

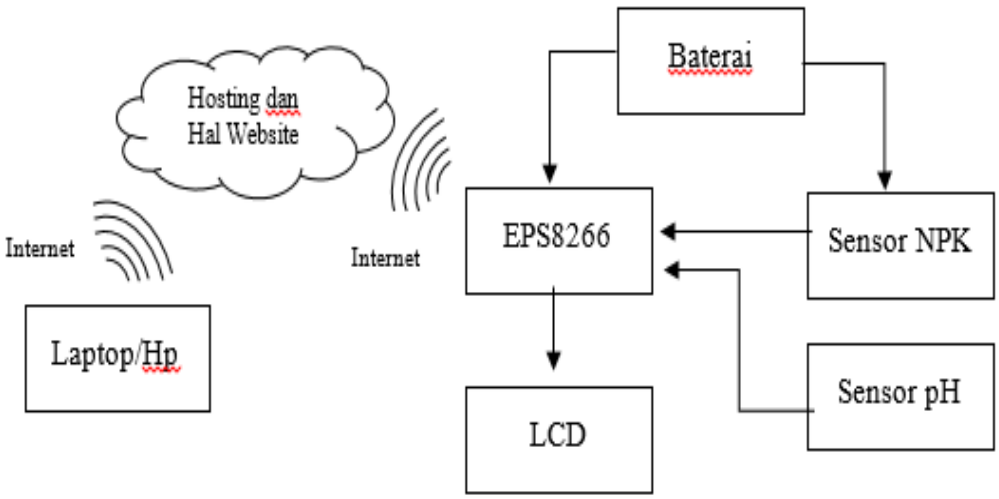


Figure 1. Diagram blocks tool

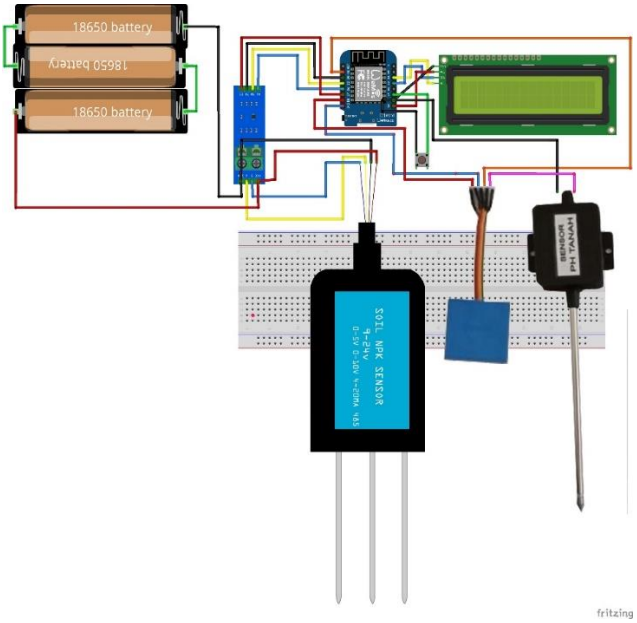


Figure 2. Schematic tools

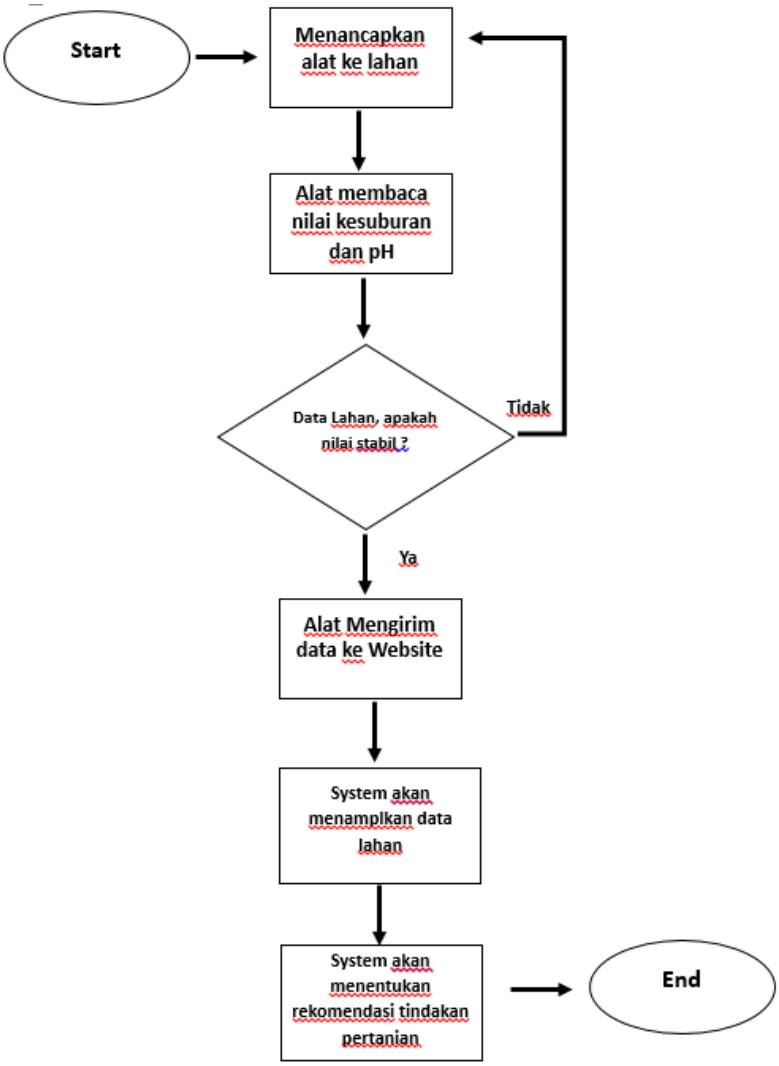


Figure 3. Flowchart system

Flowchart description from the diagram above

a. Start: Begin the process.
b. Insert the Device into the Soil: Insert and place the device into the soil area where fertility needs to be measured.
c. Device Reads Fertility Values: The NPK sensor (Nitrogen, Phosphorus, Potassium) reads the soil fertility parameters, and the pH sensor measures the soil's acidity or alkalinity level.
d. Is the Fertility Data Stable?: Wait until the device displays stable fertility data. If the data is not stable, repeat the process of inserting the device into the soil.
e. Device Sends Data to the Website: The data is transmitted via the IoT module (Wi-Fi) to the website database and stored.
f. System Displays Soil Data: Data is shown on the Web Dashboard (fertility and pH values). The system analyzes: fertility status (low/medium/high), and provides fertilizer recommendations based on NPK and pH values.
g. Agricultural Action Recommendation: The system suggests the appropriate type of fertilizer needed and pH adjustment (lime/sulfuric acid).
h. End: The process is completed.

Database Design

The database design used in the research to store soil fertility and pH measurement data. The purpose of this database design is to systematically organize and manage the data so it can be easily accessed, analyzed, and displayed in the system. The database table used is named npk_ph, consisting of several fields such as no, nitrogen, phosphorus, potassium, and ph. Each field has a specific data type and length according to its data category. The no field is used as the primary key to uniquely identify each data entry.

Design Web User Interface planning

This design presents the user interface design of the dashboard page for the web-based application that monitors soil NPK and pH values. The dashboard is designed to display real-time measurement data, including the levels of Nitrogen, Phosphorus, Potassium, and soil pH, shown in mg/kg and pH scale. It also features a fertilizer prediction button that enables the system to provide fertilization recommendations based on the displayed data. The interface is designed to be simple and informative to help users, especially farmers or agricultural advisors, easily understand the condition of the land accurately and quickly.

The Figure 4 shows the fertilization prediction page of an application for monitoring soil NPK and pH levels. This page displays the concentration of soil nutrients such as Nitrogen (N), Phosphorus (P), Potassium (K), and soil pH in mg/kg and pH scale. There is a "Fertilizer Prediction" button which, when clicked, displays the predicted fertilizer requirements based on the detected nutrient levels. The table below shows the recommended amounts of fertilizers for each element, such as Urea, KCL, SP-36, and Lime, in kg/ha

Soil Fertility Measuring Device Display

Front View

The Figure 5 shows the front view of the soil fertility measuring device. There is an LCD screen displaying information on nitrogen, phosphorus, potassium, and pH levels. The LCD shows nutrient values (NPK) in mg/kg.

Side View

The Figure 7 shows the side view of the measuring device. On the side, there is a 12V battery voltage display, a power on/off button to turn the device on, and a charging port for the battery.

Table 2. Table npk_ph

No	Field Name	Type	Length	Primary Key
1	no	int	5	Yes
2	nitrogen	int	4	
3	fosfor	int	4	
4	Kalium	Int	4	
5	ph	float	2.1	

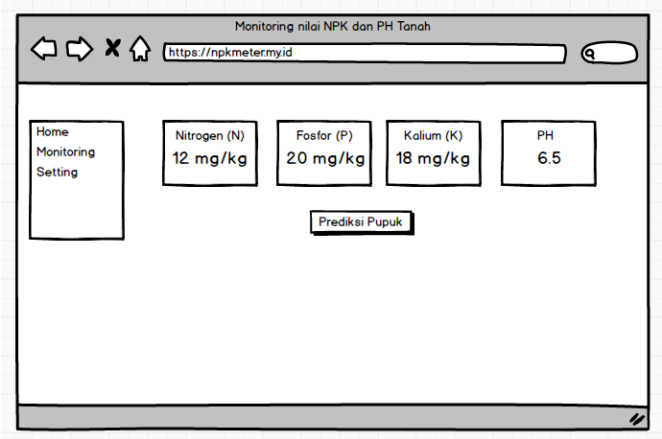


Figure 4. Dashboard page planning

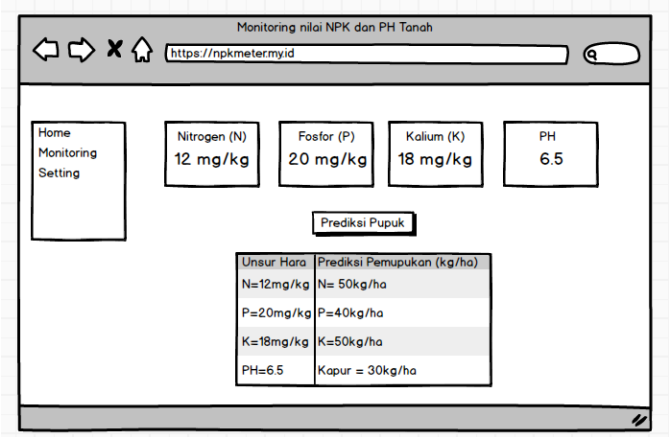


Figure 5. Fertilization Prediction Page planning.



Figure 6. Front view of the soil fertility measuring device.



Figure 7. Side view of the soil fertility measuring device.

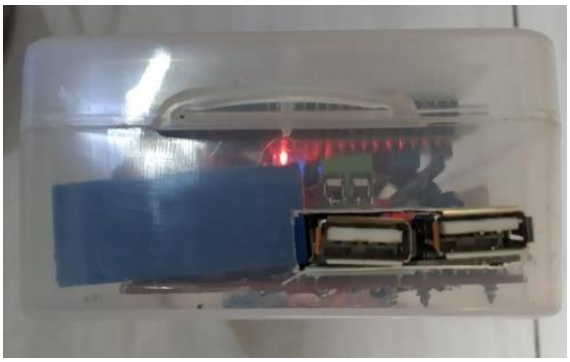


Figure 8. Top view of the soil fertility measuring device.



Figure 9. NPK and pH Sensors

Top View

The Figure 8 shows the top view of the soil fertility measuring device. On the top side, there are sockets to connect the NPK and pH sensors. The right socket is for the NPK sensor, and the left one is for the pH sensor.

NPK and pH Sensors

Figure 9 is the image of the NPK and pH sensors. Each sensor uses a socket connection to be easily plugged into the soil fertility measuring device, making it more practical.

Website Display of the Soil Fertility Monitoring System

Dashboard Page

The web page shown in the Figure 10 is an interface designed to provide real-time monitoring of soil NPK and pH levels, connected to a soil fertility measuring device. It also includes a fertilization recommendation menu based on nutrient and pH analysis. Information on nitrogen, phosphorus, potassium, and soil pH is visually displayed in colored boxes. Users can select the type of crop from a dropdown menu and input the land area in square meters to receive appropriate fertilization recommendations based on soil conditions. There is also

a “Show Recommendation” button that processes the data and displays fertilization suggestions. The navigation menu on the left includes options such as "Home", "Fertilizer Basics", and "Guidelines" to help users easily navigate the site.

Fertilizer Recommendation Page

The image below shows the fertilizer recommendation menu display. The recommended types of fertilizers are based on the fertility values previously displayed. Three types of fertilizers are recommended: Urea, SP-36, and KCL, along with the respective fertilizer amounts. These recommendations help farmers determine the correct fertilizer dosage to optimize plant growth and ensure efficient fertilizer use.

Literature review on ideal soil fertility values for rice plants

Soil fertility levels are crucial for plant growth. Soil fertility values (NPK and pH) need to be determined based on minimum or ideal standard values required for optimal crop development. Below is a dataset showing the minimum or ideal recommended values needed.



Figure 10. Dashboard page of the soil measuring application.



Figure 11. Fertilizer recommendation page.

Table 3. Recommended Ideal Soil Fertility Values for Rice Food Crops

No	Element	Ideal Requirement	Fertilizer Type	Nutrient Content (%)
1	Nitrogen	120-200 mg/kg	Urea	46% N
2	Fosfor	30-40 mg/kg	SP-36	36% P
3	Kalium	60-80 mg/kg	KCL	60% K
4	pH	5.5-6.5	Kapur	

Source: (BBSDLP, 2011), (BB Padi, 2019), (Dariah, Maftuah, & Agus, 2010), (Hidayanto, 2019), (BPPP, 2020)

The table above shows that if the nitrogen level is 120–200 mg/kg, phosphorus is 30–40 mg/kg, potassium is 60–80 mg/kg, and the pH is between 5,5 – 6,5 then the soil fertility level can be considered sufficient. If the nutrient and pH values are below those in the table, the soil fertility can be considered low.

Literature Review on Recommended Fertilizer Application Rates for Rice Crops

Proper fertilization is crucial to achieving optimal rice yields and maintaining soil fertility. The recommended amount of fertilizer for rice crops is generally based on soil nutrient analysis and the crop's specific needs. The following table presents the recommended fertilizer application rates for rice.

Initial Data Collection of Soil Nutrient Content in Various Locations

Soil, as a planting medium, plays a crucial role in plant growth. Soil fertility serves as an indicator of whether plants can grow optimally. The following is the initial data collected on soil fertility values from various locations. The table below presents the initial soil samples taken before fertilization and planting, and the samples have been tested in an agricultural laboratory.

From Table 5, it can be observed that soil fertility values in various locations are still not optimal. The obtained fertility levels do not yet meet the minimum requirements, indicating the importance of sufficient nutrients for optimal plant growth.

Data Collection Results on Soil Type for Each Sample Code

Agricultural land, particularly paddy fields, varies greatly in soil types across regions. Several types of soil have been collected through field observation and direct interviews with farmers. Soil type significantly affects nutrient retention and fertilizer absorption. The observed locations are influenced by environmental factors, such as proximity to rivers or surrounding trees, which contribute to soil formation.

Table 4. Recommended Fertilizer Application Rates for Rice Crops

No	Element	Fertilizer Type	Minimum Requirement	Maximum Requirement
1	Nitrogen	Urea	150 kg/ha	250 kg/ha
2	Fosfor	SP-36	50 kg/ha	100 kg/ha
3	Kalium	KCL	50 kg/ha	75 kg/ha
4	pH	Kapur		2000 kg/ha

Source: (BALITTANAH, 2012), (Gunawan et al., 2020, (Latif & Impron, 2023)



Figure 12. Soil Samples

Table 5. Initial Analysis Results of Soil Nutrient Content in the Research Area

No	Sample Code	Land Location	Nitrogen mg/kg	Phosphorus mg/kg	Potassium mg/kg	pH
1	L1	Ds. Plosogeneng	95	29	53	5.8
2	L2	Ds. Tambakberas	123	30	67	6.2
3	L3	Ds. Denanyar	98	29	54	6.0
4	L4	Ds. Kebontemu	97	23	52	6.4
5	L5	Ds. Tembelang	121	32	59	6.8
6	L6	Ds. Morosunggingan	117	33	60	6.5
7	L7	Ds. Turipinggir	123	34	61	6.0
8	L8	Ds. Megaluh	114	32	59	6.2
9	L9	Ds. Mayangan	124	34	67	6.4
10	L10	Ds. Jatipelem	117	28	64	6.1



Figure 13. Initial Data Collection of Soil Nutrient

Table 6. Observation Results of Soil Types

No.	Sample Code	Land Location	Soil Type
1	L1	Ds. Plosogeneng	sandy soil
2	L2	Ds. Tambakberas	clay loam
3	L3	Ds. Denanyar	sandy soil
4	L4	Ds. Kebontemu	sandy soil
5	L5	Ds. Tembelang	clay soil
6	L6	Ds. Morosunggingan	clay loam
7	L7	Ds. Turipinggir	clay loam
8	L8	Ds. Megaluh	clay soil
9	L9	Ds. Mayangan	clay loam
10	L10	Ds. Jatipelem	clay soil

Table 7. Comparison data of NPK and pH measurements between the device and laboratory results before fertilization

No	Sample Code	Lab N	Tool N	Eror %	Lab P	Tool P	Eror %	Lab K	Tool K	Eror %	Lab pH	Tool pH	Eror %
1	L1	95	101	+6	29	27	-7	53	57	+8	6.1	5.8	-4,9
2	L2	123	116	-6	30	32	+7	67	62	-7	6.0	6.2	+3,3
3	L3	98	105	+7	29	26	-10	54	58	+6	6.2	6.0	-3,2
4	L4	97	104	+7	23	25	+9	52	56	+10	6.1	6.4	+4,9
5	L5	121	109	-10	32	30	-6	59	62	+5	6.5	6.8	+4,6
6	L6	117	123	+5	33	31	-6	60	64	+7	6.2	6.5	+4,8
7	L7	123	129	+5	34	32	-6	61	65	+7	6.3	6.0	-4,8
8	L8	114	104	-9	32	29	-9	59	63	+7	6.5	6.2	-4,6
9	L9	124	130	+5	34	32	-6	67	62	-7	6.2	6.4	+3,2
10	L10	117	107	-9	28	30	+7	64	59	-8	5.9	6.1	+3,4

N, P, K Device: Values are generated by applying a random error variation in the range of ±5–10% relative to the laboratory values.
pH Device: Values are generated by applying a smaller random error variation in the range of ±0.2 to ±0.3.
Error %: Calculated using the formula: ((DeviceValue−LabValue)/LabValue)∗100
A plus sign (+) indicates that the device value is higher than the lab value (overestimate).
A minus sign (-) indicates that the device value is lower than the lab value (underestimate).

From the table above, it can be seen that the types of soil used for this research are sandy soil, clay loam, and clay. There are 3 locations with sandy soil, 4 with clay loam, and 3 with clay soil.

Comparison results of NPK and pH measurements between device and laboratory before fertilization

The table below presents a comparison between the measurement results of Nitrogen (N), Phosphorus (P), Potassium (K), and soil pH obtained using the soil fertility device and those obtained from laboratory analysis as a reference. This comparison aims to evaluate the accuracy and consistency of the device in detecting soil nutrient and pH levels. By analyzing the discrepancies and matches between the two methods, it can be assessed how reliable the device is as a field measurement alternative. The data in this table serve as an important foundation for further development and validation of the device to ensure effective and practical use in soil fertility monitoring.

CONCLUSION

Sandy soil samples from L1, L3, and L4 exhibit varying nutrient characteristics. The nitrogen content in these soils is considered low, but the soil fertility measuring device consistently gives readings about 6–7% higher than laboratory test results. Conversely, phosphorus levels range from low to moderate, with the device showing errors of approximately 8–10%. Potassium levels also show slightly higher readings, with a discrepancy of around 6–10%. The soil's acidity (pH) is neutral to slightly acidic, and in this case, the device shows excellent accuracy with an error margin below 5%. Overall, the soil fertility device should be used with caution on sandy soils, as it tends to overestimate N and K, and underestimate P, and results should ideally be confirmed through laboratory testing.

Clay loam soil, represented by samples L2, L6, L7, and L9, demonstrates a reasonably fertile profile. Nitrogen and potassium levels are adequate, and the fertility measuring device shows good accuracy for both elements, with nitrogen reading errors between 5–6%, and potassium errors between 6–7%. Phosphorus levels are moderate, but the device still tends to slightly underestimate, with a phosphorus reading error of around 7%. The pH value ranges between 3–5. Overall, this clay loam soil is highly suitable for cultivation.

Clay soil samples (L5, L8, L10) contain sufficient nitrogen and medium to high potassium levels. However, for this type of soil, the fertility measuring device exhibits an inconsistent reading pattern for N

and P, with significant error rates—approximately 5–10% for nitrogen and 6–9% for phosphorus. This suggests that clay texture may affect the device's ability to accurately read certain nutrients. On the other hand, the accuracy of the device in measuring potassium and pH remains acceptable in clay soils, with potassium error rates around 6–8% and pH around 3–5%. Therefore, the N, P, and K measurement results from the fertility device on clay soils should be interpreted carefully and preferably confirmed with laboratory analysis.

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AUTHORS CONTRIBUTIONS

SJ and UKNQ designed and planned the experiment. SJ and UKNQ collected data and performed data analysis. UKNQ interpreted the data. SJ prepared the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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