

DESIGN AND DEVELOPMENT OF AN IOT-BASED SOIL FERTILITY MONITORING SYSTEM USING A 7-IN-1 NPK SENSOR AND AI-BASED CROP PREDICTION MODEL

Joaquin Camilo Tololiu¹, Refgiufi Patria Avrianto²

Informatics Study Program, Universitas Pradita

E-mail: joaquin.camilo@student.pradita.ac.id¹, refgiufi.patria@pradita.ac.id²

Received: 24/05/2026 | Revised : 01/06/2026 | Accepted: 20/06/2026 | Published :03/07/2026

Abstract

Soil quality plays a crucial role in determining agricultural productivity, making accurate and continuous monitoring essential. This study focused on designing and developing a soil fertility monitoring system that delivers real-time information and predicts crop suitability. The system integrates sensor-based data collection with intelligent data processing techniques. Soil data were obtained using a multi-parameter sensor and then processed through stages of cleaning, normalization, and feature preparation. Multiple algorithms were trained to detect patterns in soil conditions and enhance prediction capabilities. The system architecture comprises data acquisition, transmission, storage, and visualization to support effective monitoring. A systematic development approach was employed, including preparation, implementation, and integration phases. The proposed system facilitates efficient soil data management and promotes precision agriculture through ongoing monitoring and predictive analysis of soil conditions.

Keywords: IoT-based Soil Monitoring, 7-in-1 NPK Sensor, Soil Fertility Analysis, AI-based Crop Prediction, Precision Agriculture.

INTRODUCTION

Soil is the most important element found on land because it plays a crucial role in sustaining plant life. Soil not only acts as a medium where plants grow, but also functions as an element that retains the water needed by plants. In addition, soil stores many essential nutrients required for plant growth. Physically, soil serves as a medium for root development, helping plants grow and obtain sufficient amounts of water and air. Plants grow well in soil because it provides everything they need, including water and air [1] The development of Internet of Things (IoT) technology has enabled continuous soil moisture level monitoring with the help of sensors [2]. One of the commonly used devices is the NPK sensor, which is utilized to measure the levels of Nitrogen (N), Phosphorus (P), and Potassium (K) in the soil. These three elements are the main factors determining soil fertility levels.

ESP32

ESP32 is a highly comprehensive System on Chip (SoC)-based microcontroller because it has been integrated with various peripherals, including WiFi 802.11 b/g/n wireless connectivity and Bluetooth version 4.2. Within a single chip, it already contains vital components such as a processor, storage memory, and access to GPIO (General Purpose Input Output) pins. Due to its complete features, the ESP32 microcontroller is often used as an alternative to Arduino boards in electronic circuit design [3].

NPK 7-in-1 Sensor

The NPK 7-in-1 sensor is an instrument used to measure and identify nutrient content in the soil [4]. The sensor operates by being inserted into the soil to be analyzed, and the sensor readings are transmitted to the ESP32 microcontroller in the form of analog data signals. The sensor used in this study is a 7-in-1 NPK sensor, which not only measures Nitrogen (N), Phosphorus (P), and Potassium (K) content, but also other parameters such as pH, soil moisture, and temperature.

RS485 to TTL

Communication between the sensor and the microcontroller is carried out using the RS485 protocol, which is then converted into TTL signals using an RS485 to TTL module, allowing the data to be processed optimally by the ESP32 [5]. Most soil monitoring systems that have been developed generally focus only on one or two fertility parameters, such as pH or moisture level. As a result, these systems are not yet capable of providing a comprehensive overview of soil nutrient conditions [6]. Accurately determining NPK levels is very important because the application of fertilizers in the correct and measured dosage greatly affects the growth and development of rice plants. The balance of these nutrients plays a role in increasing plant energy production while optimizing assimilate utilization [7].

It should be noted that NPK nutritional requirements differ from one plant to another. For example, in shallot cultivation, the application of NPK fertilizer at a dosage of approximately 75 g/m² has been proven to provide the best results. Identifying sectors for leadership in agriculture can be viewed as a key step aimed at improving production, competitiveness, and the welfare of citizens [8] This is presumably because the combination of N, P, and K elements at that dosage is able to support vegetative growth while also maximizing the plant's generative phase [9]. On the other hand, for black soybean cultivation, NPK fertilizer at a dosage of 50 kg/ha combined with 10 tons/ha of compost is considered an efficient solution to increase productivity. This study involves the assessment of edaphic factors affecting nutrient availability in soil, as well as an in-depth review of technologies related to NPK sensors and the RS485 to TTL industrial communication protocol, which has become the de facto standard for modern devices. Furthermore, the use of Machine Learning techniques in this research will contribute to transforming raw data into more intelligent information.

METHOD

General Overview of the Research Object

The first stage of this research is called the Preparation phase (Figure 1), which begins with a literature study. The purpose is to gain an understanding of the fundamental concepts of soil fertility, the characteristics of NPK sensors, IoT technology, and machine learning methods that can be applied to predict soil health status. This stage is very important because it serves as the foundation for selecting the appropriate research methodology. After that, a requirements analysis is conducted to determine the necessary hardware, such as the NPK sensor and microcontroller, as well as the software involved in the process. Finally, the results of the requirements analysis serve as guidelines for the two main design phases, namely designing the IoT architecture and designing the machine learning workflow. Regarding the IoT architecture, it involves determining the steps or processes within the system, including data collection, network communication, and data storage on a cloud server. On the other hand, the machine learning workflow includes preprocessing, feature selection, algorithm selection, and model evaluation.

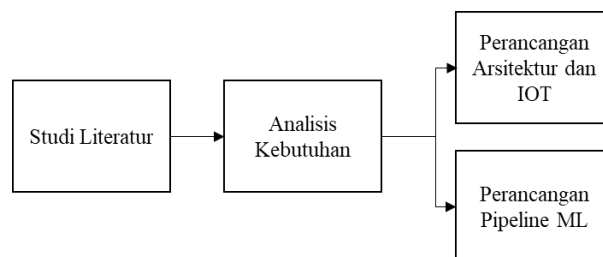


Figure 1. Preparation Phase Flowchart [FF4.1]

The next phase is Development (Figure 2), which focuses on system development. The process begins with the deployment of sensors and IoT devices, where sensors for measuring NPK values and microcontrollers are built and programmed to collect the necessary soil nutrient measurements. Furthermore, the data collection phase involves recording the data collected from the sensors to form a raw data set. Once the data is collected, a preprocessing phase is performed to remove noise, correct reading errors, and normalize the data so that it is ready for analysis. The processed data is then used in the training phase of a machine learning model to recognize patterns and predict soil health conditions based on NPK composition. This phase concludes with the creation of an IoT dashboard as a visual interface that displays real-time monitoring data and prediction results to users.

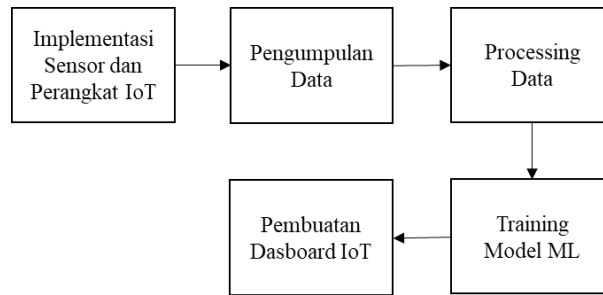


Figure 2. Development Phase Flowchart [FF5.1]

The next stage is Execution (Figure 3), which begins with the integration of the IoT system and the machine learning model. At this stage, the trained model is attached to the IoT device so that information received by the sensors can be transmitted to the trained model for prediction purposes. System testing is conducted through a number of functional tests to ensure the smooth flow of information from the sensors, microcontroller, and model. Testing at this stage also aims to verify sensor functionality and system response. The next and final step is system evaluation, which is the process of evaluating system performance based on specific metrics for effectiveness and accuracy.

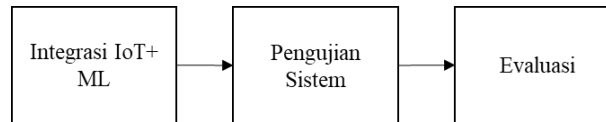


Figure 3. Execution Stage Flowchart [FF6.1]

Research Methodology

This research methodology includes data collection, data processing, data analysis, and system evaluation. Data was obtained from two sources: primary data through direct measurements using an IoT system based on a 7-in-1 NPK sensor, a microcontroller (ESP32), and a WiFi module, and secondary data from scientific literature, government publications, and open datasets. Parameters collected included N, P, K, temperature, humidity, pH, and soil conductivity.

Furthermore, data analysis involved statistical investigation and visualization, after which a machine learning model was developed using several algorithms including Random Forest, XGBoost, SVM, and Neural Networks, using the Grid Search Cross-Validation method for optimization. Model quality was assessed based on accuracy, precision, recall, F1-Score, and confusion matrix. The final stage was the system evaluation stage, where sensor accuracy, model predictive capability, inference time, and IoT system performance were measured.

RESULTS AND DISCUSSION

System Circuit Schematic Design

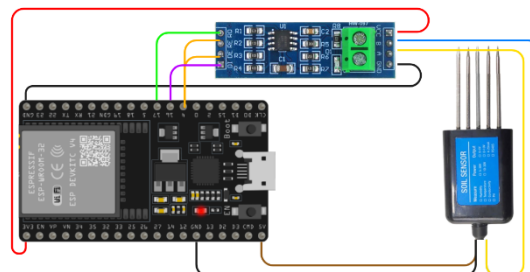


Figure 4. Circuit System Design [FF7.1]

Figure 4 shows the circuit diagram of an IoT system designed using the Fritzing application. This system consists of an ESP32 as the main microcontroller, an NPK sensor as an input device, and an RS485-to-TTL converter module as the data communication medium. The sensor reads soil parameters and sends the data to the ESP32 for processing. The data is then sent in real time to a server via the MQTT protocol for further monitoring and analysis.

Hardware System Implementation

The hardware implementation of this system utilizes an ESP32 microcontroller as the main control center due to its ability to support Wi-Fi connectivity and its sufficient processing capacity to read sensor data and transmit it in real time to an IoT-based server [10].

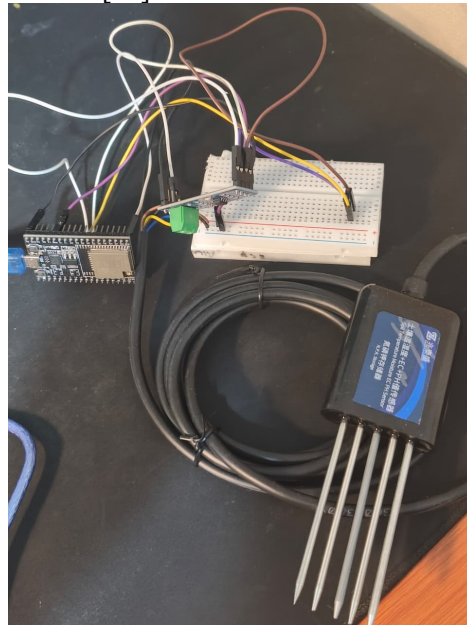


Figure 4. Hardware System [FF8.1]



Image test directly into the ground

This figure illustrates the hardware implementation of an Internet of Things (IoT)-based soil monitoring system utilizing a 7-in-1 soil sensor embedded directly into the soil medium within the testing container. The sensor functions as a data acquisition device to measure several soil fertility parameters in real time, including Nitrogen (N), Phosphorus (P), Potassium (K), pH, Electrical Conductivity (EC), soil temperature, and soil moisture. Data communication is established through an RS485-to-TTL converter module to ensure stable and reliable data transmission from the sensor to the microcontroller. The entire system is operated using an ESP32 microcontroller, which functions to process the sensor data and transmit it via a Wi-Fi network to the server using the MQTT protocol. The sensor measurement data are subsequently visualized on an integrated web-based dashboard, enabling real-time monitoring of soil conditions. In addition, the system is connected to an Artificial Intelligence (AI) model that provides crop recommendations based on the detected soil conditions. The

implementation results demonstrate that the system is capable of performing automated and integrated soil monitoring while supporting crop prediction for smart agriculture applications.

Software System Implementation

a. Data Display in the MQTT-Based Monitoring System

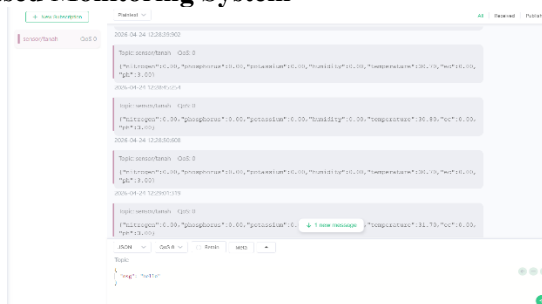


Figure 5. MQTT Monitor Display Results

Figure 5 shows the results of implementing data communication using the MQTT protocol in the designed IoT system. Data obtained from the NPK sensor is sent by the ESP32 to the server via the internet using the MQTT protocol in real time. This data transmission process enables the system to remotely monitor soil conditions with low latency and high bandwidth efficiency. MQTT (Message Queuing Telemetry Transport) is a lightweight, publish-subscription-based protocol that can be used effectively even on IoT devices with limited computing capacity but experiencing unreliable connectivity, making it ideal for use in real-time land development monitoring systems [11]. Based on test results, the system is able to transmit sensor data stably and continuously to the server without significant data loss. This demonstrates that the use of MQTT is highly suitable for IoT system implementation because it supports lightweight, fast, and efficient data communication.

b. Dashboard Page Display

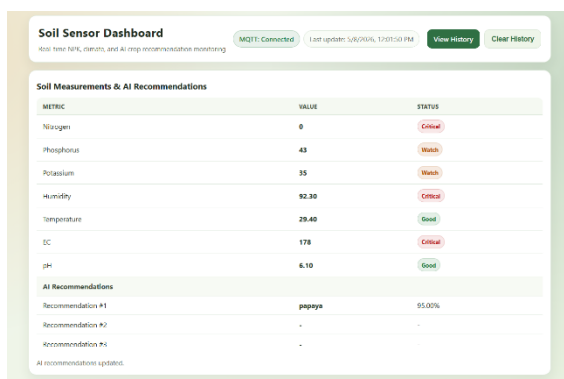


Figure 5. Dashboard page view

This figure presents the interface of a web-based soil monitoring dashboard integrated with an Internet of Things (IoT) system and Artificial Intelligence (AI). The dashboard is designed to display real-time soil sensor readings transmitted by the ESP32 microcontroller through the MQTT protocol. The MQTT connection status displayed on the dashboard indicates “Connected,” signifying that the data communication between the IoT devices and the server is functioning properly. The dashboard displays several key soil condition parameters, including Nitrogen (N), Phosphorus (P), Potassium (K), soil humidity, temperature, Electrical Conductivity (EC), and soil pH. Each parameter is accompanied by the sensor reading value and a condition status classified into three categories: “Good,” “Watch,” and “Critical.” These classifications are intended to facilitate users in quickly monitoring soil fertility and overall soil conditions. Based on the dashboard testing results, the Nitrogen value of 0 and soil humidity value of 92.30 were categorized as “Critical,” while the Phosphorus value of 43 and Potassium value of 35 were classified as “Watch.” Meanwhile, the temperature value of 29.40°C and pH value of 6.10 were categorized as “Good,” indicating that the soil environmental conditions remain suitable for the growth of certain crops.

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In addition to soil parameter monitoring, the dashboard also displays AI-based crop recommendations in the “AI Recommendations” section. Based on the received sensor data, the AI system recommended “papaya” with a confidence level of 95%. This recommendation result was generated using a machine learning model trained on soil condition and crop datasets, enabling the system to automatically provide crop recommendations according to the detected soil conditions.

c. Data History Page View

The screenshot shows a web interface titled "History Data" with a "Back to Dashboard" and "Clear History" button. Below the title is a filter bar for "Filter by Date & Time" set to "dd/mm/yyyy" and "Read Filters" showing 29 records. The main table has columns: TIMESTAMP, NITROGEN, PHOSPHORUS, POTASSIUM, HUMIDITY, TEMPERATURE, EC, PH, and TOP AI CROPS. The data shows periodic updates with values for Nitrogen (0), Phosphorus (43), Potassium (35), Humidity (92.30), Temperature (29.40), EC (178), and PH (6.10). The top AI crop is consistently "papaya" with a 95.00% confidence level.

TIMESTAMP	NITROGEN	PHOSPHORUS	POTASSIUM	HUMIDITY	TEMPERATURE	EC	PH	TOP AI CROPS
5/0/2026, 12:01:56 PM	0	43	35	92.30	29.40	178	6.10	papaya 95.0%
5/0/2026, 11:58:51 PM	0	44	36	91.50	29.40	180	6	papaya 95.0%
5/0/2026, 11:55:58 AM	0	0	0	0	30.10	0	7	orange 95.0%
4/24/2026, 12:41:00 PM	0	0	0	5.42	30.00	0	5	-
4/24/2026, 12:38:57 PM	0	0	0	0	30.00	0	3	-
4/24/2026, 12:36:40 PM	0	0	0	5.42	30.00	0	5	-
4/24/2026, 12:34:59 PM	0	0	0	0	30.00	0	2	-
4/24/2026, 12:32:51 PM	0	0	0	5.70	30.00	0	5	-
4/24/2026, 12:30:56 PM	0	0	0	0	30.00	0	2	-
4/24/2026, 12:28:51 PM	0	0	0	0	30.00	0	5	-
4/24/2026, 12:26:58 PM	0	0	0	0	30.70	0	2	-
4/24/2026, 12:24:59 PM	0	0	0	0	30.00	1	3	-
4/24/2026, 12:22:55 PM	0	0	0	0	30.00	0	5.70	-
4/24/2026, 12:20:54 PM	0	0	0	0	30.00	0	5.00	-
4/24/2026, 12:18:57 PM	0	0	0	0	31.70	0	5.00	-

Figure 6. History Data Page View

This figure shows the History Data page of the web-based soil monitoring system, which functions to store and display the historical records of soil sensor readings periodically. The historical data are obtained from sensor data updates stored in the browser using a local storage mechanism, allowing users to review previous monitoring data without the need to perform direct measurements again. The history page displays several sensor measurement parameters, including Nitrogen (N), Phosphorus (P), Potassium (K), soil humidity, temperature, Electrical Conductivity (EC), soil pH, and AI-based crop recommendation results (Top AI Crops). Each record is accompanied by timestamp information, enabling users to analyze changes in soil conditions over time. In addition, the system provides a “Filter by Date & Time” feature that allows users to search data based on a specific date and time range. This feature assists users in conducting historical monitoring and soil condition analysis in a more structured and efficient manner. Furthermore, a “Clear History” button is available in the upper-right section of the interface to delete all historical data stored in the system.

System Test Results

The data presented in Table 1 represent the results of initial testing of the soil fertility monitoring system. Data regarding sensor metrics (Nitrogen, Phosphorus, Potassium, Moisture, Temperature, EC, and pH) were uploaded to the system every three minutes based on soil environmental readings.

While sufficient for preliminary analysis, the short-term nature of this testing does not capture the variability of soil environmental conditions on a daily or weekly basis. Thus, the results of the status determination (critical, good or watch) should be considered tentative and tested for a longer period of time.

Table 1. Initial Testing

Metric	Value	Status
Nitrogen	0	critical
Phosphorus	43	Watch
Potassium	35	Watch
Humidity	92.30	Critical
Temperature	29.40	Good
EC	178	critical
pH	6.10	Good
AI Recommendation		
n		
Recommendation	papaya	95.00%
n #1		

Machine Learning Modeling Results

Machine learning models such as Random Forest, XGBoost, and Support Vector Machine have been widely used in various studies to make data-driven predictions due to their ability to handle complex patterns [12]. In this study, a comparative analysis of several machine learning algorithms was conducted to select the best one for predicting soil fertility status and crop recommendations. The algorithms used in this experiment were Random Forest, XGBoost, SVM, and Neural Network. The data used to train and test these algorithms consisted of 2,200 datasets, with 80% of the data used for training and 20% for testing.

Model	Accuracy	Precision	Recall	F1 Score
Decision Tree	0.9864	0.9868	0.9864	0.9863
Random Forest	0.9932	0.9937	0.9932	0.9932
KNN	0.9705	0.9740	0.9705	0.9703
SVM	0.9614	0.9673	0.9614	0.9612
XGBoost	0.9854	0.9869	0.9864	0.9863

Figure 7. Model Comparison

Table 2. Model Comparison Results

Model	Accuracy	Precision	Recall	F1 Score
Decision Tree	0.9864	0.9868	0.9864	0.9863
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SVM	0.9614	0.9673	0.9614	0.9612
XGBoost	0.9854	0.9869	0.9864	0.9863

Implementation

Based on the test results in Figure 7 and Table 2, the XGBoost model demonstrated the best performance compared to other models, with the highest accuracy and F1-score. This indicates that XGBoost is better able to capture complex relationships between soil parameters such as nitrogen, phosphorus, potassium, pH, and moisture. XGBoost excels in computational efficiency, with its optimization process running up to 10 times faster than conventional gradient boosting methods [13]. Furthermore, the Random Forest model performed satisfactorily due to its ability to handle non-linear data while minimizing overfitting issues using ensemble methods. Random Forest's primary strength lies in its application of ensemble learning principles by integrating multiple decision trees [14]. The application of Internet of Things (IoT) technology integrated with machine learning, or AIoT, enables agricultural systems to operate automatically and responsively to changing environmental conditions. This system is capable of collecting environmental data in real time through sensors connected to a microcontroller, thus supporting more accurate decision-making [15].

CONCLUSION

This research aims to design and build a soil fertility monitoring system that can not only provide real-time soil conditions but also predict crop viability using the soil conditions provided by the system. From all the processes undertaken in this research, from planning and development to implementation, it can be concluded that the system created in this experiment has achieved this goal. Regarding hardware, a combination of a 7-in-1 NPK sensor, an ESP32 microcontroller, and an RS485-to-TTL converter module successfully combined to capture all seven soil fertility characteristics simultaneously: nitrogen (N), phosphorus (P), potassium (K), moisture, temperature, electrical conductivity (EC), and pH. The obtained data was successfully transmitted to the server using the MQTT protocol every three minutes without data loss. Regarding software, the system is designed with a web dashboard that efficiently displays information about sensor data, data history, and soil condition status. The dashboard is also connected to an AI model capable of providing specific crop recommendations based on sensor readings, enabling users to make informed decisions about agricultural activities.

Regarding machine learning modeling, the evaluation results of five algorithms—Decision Tree, Random Forest, KNN, SVM, and XGBoost—using a dataset containing 2,200 records showed that the Random Forest algorithm produced the highest score with 99.32% accuracy and an F1 score of 0.9932. These findings demonstrate that the ensemble learning approach is capable of capturing the complex relationships between soil parameters and can be considered a key component of a crop suitability prediction system. Overall, the soil fertility monitoring system using Internet of Things and artificial intelligence technology presented in this study is efficient, accurate, and responsive. This soil fertility monitoring system can provide an overview of the soil through multi-parameter sensing and can also assist in precision agriculture practices through predictive analytics. Therefore, there is great potential for practical application of this system for sustainable soil fertility management.

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