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Development of an IoT-based Soil Nutrient Monitoring and GIS Mapping System for Precision Agriculture

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Abstract. Agriculture is a field that contributes to Indonesia's economic development. Unpredictable weather, temperature fluctuations, and the difficulty in assessing soil quality hinder farmers in enhancing crop productivity. The IoT in signifies a beneficial progression that will assist farmers in their endeavors. Precision agriculture is an innovative approach that employs information technology for sustainable agricultural management. This research aims to assess soil nutrients and provide mapping data based on the evaluated agrarian sites. The testing sites are situated in three sub-districts within Kubu Raya Regency: Sungai Kakap, Ambawang, and Rasau Jaya. The soil study indicated a temperature range of 29.40 °C to 36.80 °C. Soil moisture varied from 4 % to 89.10 %. The soil pH varied between 6.90-8.07 PH. The soil salinity was rather modest. Nutrient levels, particularly nitrogen, were slightly lower than those of phosphate and potassium, necessitating fertilizer use to enhance plant vegetative development. Incorporating the Internet of Things onto agricultural land delivers data as real-time monitoring, which will be essential for improving agricultural output. This scalable method mitigates contemporary agricultural difficulties by diminishing environmental impact and enhancing crop resilience. This study facilitates sustainable, intelligent agricultural techniques to address the escalating needs of a swiftly expanding global population.

Keywords: geographic information system, internet of things, precision agriculture, real-time monitoring, soil nutrient

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1. Introduction

Indonesia agricultural sector significantly contributes to economic growth and development. The fulfillment of these requirements is also threatened by converting agricultural land into housing. Climate change greatly affects agriculture, which is important for food security and long term growth. Changes in temperature, rainfall, and severe weather events are some of the ways that climate change affects crops. Agriculture is essential to economic development and nutritional security. Therefore, the negative consequences are more obvious in developing countries[1]. Climate change impacts fertilizer consumption and soil quality, significantly challenging agricultural systems. The changing climatic conditions caused by climate change may harm the sustainability and yield of agriculture[2]. Soil degradation is a primary consequence resulting from extreme weather events, intensified rainfall, and nutrient leaching, leading to compaction and erosion. These processes result in the removal of significant amounts of subsoil, which reduces its fertility and limits the growth of crops.

Variations in temperature and precipitation may exacerbate soil compaction, hindering root growth and nutrient absorption[3]. Overall, studies demonstrate that agricultural output is significantly impacted by climatic factors, with sensitivity varying by crop and season[4]. Precision agriculture signifies a substantial progression in contemporary agriculture, underscoring the growing need to improve food production efficiency while concurrently minimizing environmental effects[5]. This innovative technology provides farmers with an in depth examination of numerous parameters such as climatic conditions, crop development, fertilizer concentrations, and soil moisture levels. The application of IoT in agriculture enhances the collection, transmission, and examination of data in real time, providing farmers with important insights to assist their decision making[6]. Precision Agriculture (PA) has become a revolutionary method that uses cutting edge digital technologies to improve farm management and promote sustainable farming[7]. PA uses GIS, IoT devices, drones, artificial intelligence, and remote sensing technology to get real time, site specific data. Two critical areas in which PA exhibits substantial potential are crop protection and soil health[8]. Healthy soils increase microbial activity, water retention, and nitrogen cycling, which are all beneficial for climate adaptability and long term fertility[9]. Global productivity is at risk due to soil deterioration from erosion, nitrogen depletion, compaction, and an overreliance on synthetic inputs. PA mitigates this problem using conservation tillage, precise nitrogen and water management, and ongoing soil condition monitoring, enhancing soil structure, augmenting organic matter, and fostering biodiversity[10].

Internet of Things in PA makes it easier to gather data from sensors in real time and gives farmers pertinent information, allowing for comprehensive soil health monitoring[11]. Soil sensor devices, which provide farmers with instantaneous data on the pH, mineral composition, and moisture levels of the soil, are among the most important uses of IoT in agriculture[12]. Soil nutrients and pH are chemically, physically, and biologically essential for optimal crop production[13]. Thus, evaluating soil quality has proven difficult due to the significant expenses associated with measurement and the need for specialized expertise, which restricts the timeliness of these assessments.

Chemical analyses are used in laboratories to measure soil quality. As a result, a soil quality measuring tool is required to depict current conditions and serve as the foundation for farmers or stakeholders to take the necessary actions to improve plant performance. Traditional ways of testing soil nutrients and giving agricultural advice have frequently been hard work, took a long time, and relied on subjective judgments. Because of this, farmers often make less effective choices, which leads to wasted resources, lower yields, and more harm to the environment[14]. To address these obstacles, novel methods that provide accurate, real-time data on soil nutrient levels are desperately needed. Soil nutrients are important for growing crops that will last, since they affect how plants grow, stay healthy, and produce[15].

Nitrogen, phosphorus, and potassium are important nutrients that help with metabolism, structure, and resilience to stress. Keeping an eye on and controlling these nutrients well may boost agricultural yields while protecting the environment[16]. Modules like GPS or RTC that support the sensor reading results provide further features. Geographic Information Systems (GIS) are very important because they help organize and show data on maps. This potency aids in identifying and localizing related to a specific parameter and demonstrates its quantities and distribution across different fields. This offers partners a fundamental framework to strategize and execute interventions[17]. Support for GIS will also help stakeholders visualize the soil quality in their area.

The suggested approach can measure soil characteristics, including temperature, moisture levels, pH, soil EC, NPK levels, and soil salinity. It also uses GIS mapping to help stakeholders and farmers get the most up-to-date information about soil quality without waiting for long laboratory test results. Agricultural IoT systems generate substantial data through sensors and devices, easing actual data management, processing, and analysis. The IoT architecture, usually organized in an ordered framework of three to five layers, is traditionally defined with key layers involving perception, connectivity, and application, especially for smart agriculture applications[18][19]. The layers listed are the lower-layer category of the IoT framework[20]. Moreover, the residual layers comprise middleware and processing. Figure 1 illustrates the conventional design diagram for the IoT.

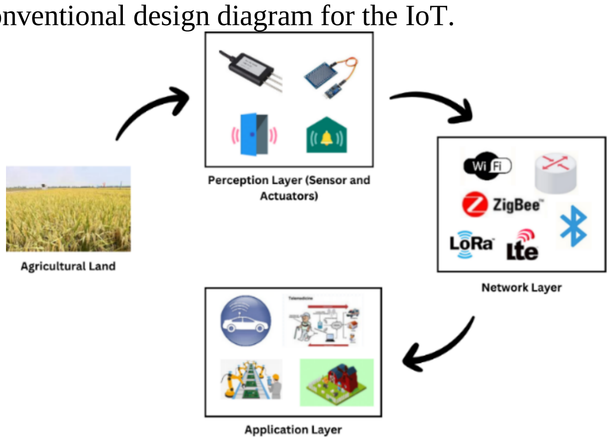

Figure 1. Diagram of the IoT architecture

Several research studies have recently been carried out to develop a measurement design for identifying soil nutrients. They have planned a framework for soil moisture regulation and irrigation management utilizing IoT and ARM. Optimizing water resources is possible and cost effective in all agricultural sectors. The system facilitates agriculture in regions with limited water resources to enhance feasibility. The end user can proficiently control the watering system via the cloud and intuitive mobile devices. Additionally, the end user gets an email soliciting network data. This sophisticated monitoring apparatus also diminishes human presence. The optimal utilization and efficient management of water resources will also conserve time[21]. The research was conducted a research study that helps farmers make educated fertilizer selections by offering a portable IoT solution for continuously monitoring soil nutrients, specifically the NPK level[22].

A successful team created a web-based IoT system for lighting monitoring on Raspberry Pi with data exchange using MQTT brokers and created graphical programming in Node-RED[23]. The authors arranged a study using machine learning in an IoT apparatus to control soil nutrients and deliver precise crop recommendations. Equipment such as the JXBS-3001, DHT11, and FC-28 sensors was used. The systems may converge soil nutrient levels, moisture, temperature, humidity, and composition data in real time. Using MQTT, the aggregated data is sent to a server[14]. The prototype the home gardens to monitor spinach crop growth. Specific factors, including pH and EC, were measured before seeding. Soil temperature and moisture content are measured. The data was transmitted to a cloud MQTT server for future decision making analysis[24]. The implementation of IoT ensures the sustainability of the ecosystem and provides convenience and better control for the users, such as monitoring plant growth[25]. Many studies have demonstrated that IoT might dramatically change the way we manage nutrients. However, a lack of complete data regarding important soil parameters creates a crucial research gap.

2. **Methods**

The method and components for the intended IoT-based system are described in this section, which would measure soil nutrient levels and provide information to farmers and stakeholders. It also offers a GIS, which includes measurement places and times.

2.1 The Suggested Approach and IoT-based System

An IoT-based system is suggested. It has a dirt sensor, a data collection system, a wireless contact network, and a cloud platform. The temperature, wetness, electrical conductivity, pH, salt, and NPK amounts can all be measured by this soil monitor. It is powered by a 5-24 volts source and consists of stainless steel probes sealed in epoxy resin. Because of its high sensitivity and constant performance, the monitor can accurately and consistently display various soils water content and overall health in real time. In farming, a device with data is sent to a cloud-based service through an online connection, where it may be analyzed and displayed. This enables tracking in real time. The sensor uses sophisticated probe technology to measure several soil parameters, including soil moisture, pH, soil EC, salinity, temperature, and NPK levels. The info that is collected is sent wirelessly. The complete system method is shown in Figure 2. Table 1 lists the specific devices and sensors used to create this IoT.

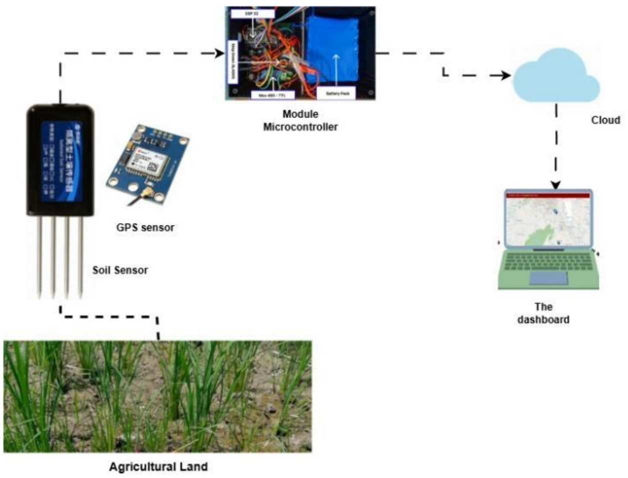

Figure 2. The framework proposed

2.2 Experimental Configuration

Several agricultural fields were researched in the Kubu Raya regency, West Kalimantan, Indonesia, to evaluate soil nutrient value. The suggested system underwent testing via on site assessments.

Figure 3. Field experiment in agricultural land

The places were chosen because the agricultural land in Kubu Raya Regency offers a variety of soil types. Figure 3 depicts agricultural locations from three separate villages: Ambawang (top left), Sungai Rengas (bottom left), and Rasau Jaya (right). In sunny weather, soil nutrient assessments on the three agricultural fields were taken over many hours. Using a mobile hotspot, the measurement prototype was linked to the internet and ran on a 12 volts battery. Ten soil samples were tested in the field at different places in real time. Some samples were also checked for accuracy at a nearby soil testing center. The research tested how effectively and correctly the proposed IoT-based system for data collection and real-time environmental monitoring might be utilized in agriculture. The prototype was built in a portable model to easily obtain as many measurements as possible from various locations on the farm. Figure 4 shows a schematic of the equipment used to make the prototype.

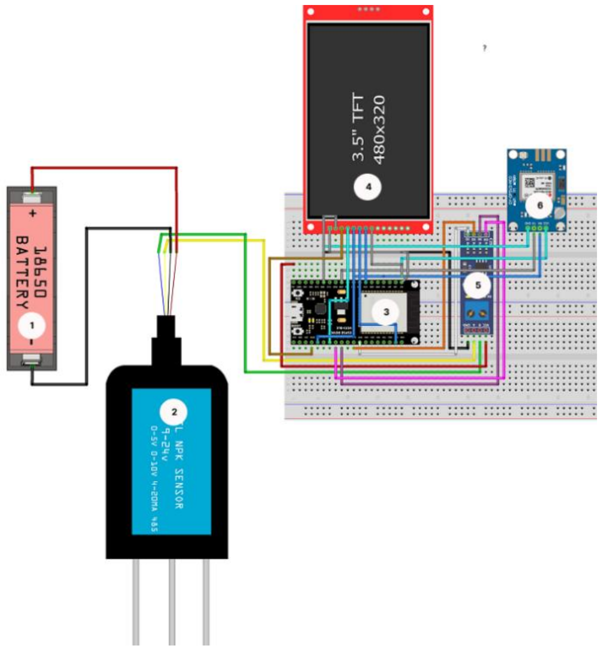

Figure 4. Schematic diagram of the hardware version

Figure 4 involved battery (1), a soil integrated sensor (2), ESP32 (3), LCD 3.5 inch Touch 480x320 TFT SPI Display (4), MAX485 TTL (5), and GPS (6) sensors to measure nine factors, including temperature, moisture, pH, electrical conductivity, NPK, salinity, and wind velocity. The output signal uses RS485 with a reading/measurement stabilization time when the sensor turns on require 5-10 seconds. Data measured using the soil integrated sensor is transmitted using MAX485 TTL, which is connected to the ESP32. In addition to using the soil integrated sensor, this prototype also adds a GPS sensor as a measurement location pin and measurement date so that it can be displayed on the map. Not only that, but the measurement results are also shown on the prototype screen. Because of its portable use, this prototype uses power from 18650 batteries arranged in series and parallel with a total of 8 batteries so that the battery voltage reaches 14.8 volts with a battery capacity of 15000 mAh, which can last 3-4 days with the use of 5-6 measurements per day or 1 day with measurements at 1 location with a stationary position. Because the voltage exceeds the capacity of the ESP32, a step down module is needed with an output voltage that can be adjusted as required, namely 3.3-5 volts.

Table 1. Prototype Soil Measurement Details

Parameter	Range / Description
Sensor type	8 in 1 Soil Sensor
Brand	Hondetec

Applications	Agriculture Soil Tester, Precision Agriculture, Soil Monitoring, Soil Fertilizer
Supply Voltage	5-24 volts DC
Energy Utilization	15 mA @12 volts DC
Communication Protocol	RS485
Transmission Rate	9600 bps
Range of temperatures	-30 °C to 70 °C
Soil Moisture Range	0-100 % (Volume / Volume)
Soil Moisture Accuracy	± 2 % (m^3/m^3)
EC Range of Measurements	0-20000 µs/cm
Accuracy of EC Measurement	± 3 % in the range of 0-10000 µs/cm ± 5 % in the range of 10000-20000 µs/cm
Range of Salinity Measurement	0-10000 ppm
Accuracy of Salinity Measurement	± 3 % in the range of 0-5000 ppm ± 5 % in the range of 5000-10000 ppm
PH Range of Measurement	3-7 PH
Accuracy of pH Measurement	± 0.3 PH
NPK Range of Measurement	0-1999 mg/kg
Accuracy of NPK Measurement	± 2 % FS
Sealing Material	Black Epoxy Resin
GPS Sensor	U-blox Neo 7m
GPS Supply Voltage	Max: 3.6 volts, Min: 1.65 volts
GPS Working Temperature	-40 °C to 85 °C
GPS type	GPS / QZSS, GLONASS
GPS Features	RTC Crystal, Active Antenna
GPS Grade	Professional
Microcontroller	Espressif ESP32 DOIT
Module Converter	RS485-MAX485 TTL
Battery	18650 all brands
LCD	LCD 3.5 inch Touch 480x320 TFT SPI Display

Figure 5 presents the block diagram of the microcontroller and sensors workflow. It outlines the data flow from the sensors to the microcontroller and then to the display and local storage, enabling the display of measurement results on the web.

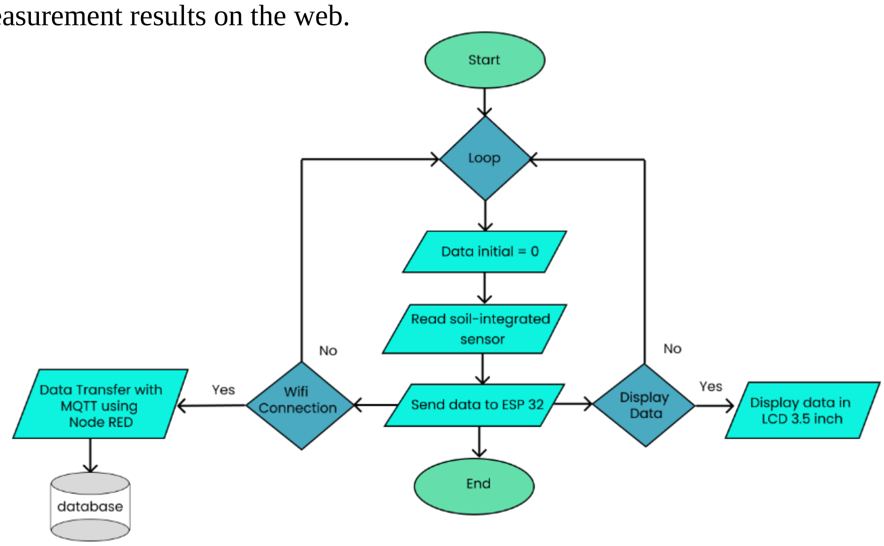

Figure 5. Block diagram of the equipment operating procedure

The overall prototype view is presented in Figure 6. Overall, the prototype display is wrapped in an 18x10 box. Within the enclosure, a 14.8 volts DC battery is configured in series to elevate the voltage, as a single battery possesses a voltage range of 3.7-4.2 volts. Four batteries, each with an average capacity of 3000 mAh, are utilized to augment the capacity, resulting in a total voltage of 14.8 volts and an aggregate capacity of 16000 mAh. That voltage can only be used to turn on the integrated soil sensor, while the ESP32 microcontroller must be lowered to 5 volts. A step down is needed to reduce the voltage. All component requirements are a maximum of 5 volts, except for the sensor, which is 12-24 volts.

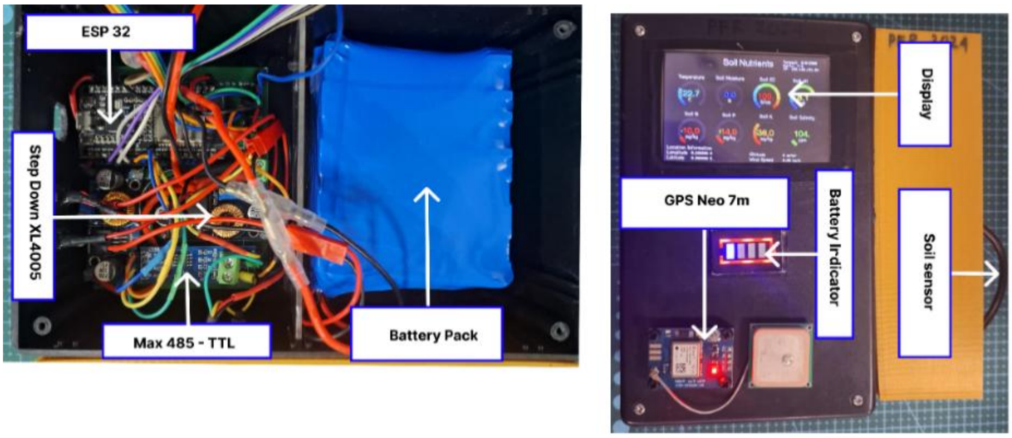

Figure 6. Complete experimental setup of the developed system

2.3 Technical Specification for Data Flow and Processing to Visualize

Soil sensors may be linked to many data collectors. This study included storing measurements obtained from the soil sensor and GPS in a MySQL database. The soil sensor was interfaced with the microcontroller using a supporting device, namely the MAX485 TTL. The connecting mode is indicated in Table 2.

Table 2. The mode of the soil sensor connected with MAX485

Wire Color Soil Sensor	Definition	MAX485 TTL
Red	Positive	Power supply (7-24 volts DC)
Black	Negative	Negative power supply
Yellow	RS485 A	A
Green	RS485 B	B

The data conversion technique uses the common Modbus RTU protocol, which has a default baud rate of 9600 bits/s. The soil sensor is connected to a 5-24 volts DC power source for measurements. The ESP32 microcontroller will inquire about sensor data in the format shown in Table 3.

Table 3. Inquire about the data format and the resulting response

Address	Function code	Start register address high	Start register address low	High register length	Low register length	Low CRC16	CRC16 High
0x01	0x03	0x00	0x00	0x00	0x08	0x44	0x0C
The following data should be returned if the sensor receives it correctly:							
	Address		0x01				

Function code	0x03	
Data length	0x10	
Register 0 data high	0x01	Soil temperature : 34.40 °C
Register 0 data low	0x58	
Register 1 data high	0x02	Soil moisture : 51.90 %
Register 1 data low	0x07	
Register 2 data high	0x05	Soil EC : 500 µS/cm
Register 2 data low	0x12	
Register 3 data high	0x03	Soil pH : 7.70 PH
Register 3 data low	0x02	
Register 4 data high	0x00	Soil Nitrogen : 15 mg/kg
Register 4 data low	0x0F	
Register 5 data high	0x00	Soil Phosphorus : 21 mg/kg
Register 5 data low	0x15	
Register 6 data high	0x00	Soil Potassium : 53 mg/kg
Register 6 data low	0x35	
Register 7 data high	0x00	Soil Salinity : 168 mg/kg
Register 7 data low	0xA8	
Low CRC16	0x50	CRC Code
High CRC16	0x89	

The MAX485 receives the sensor inquiry data and forwards it to the ESP32 microcontroller. The sensor hexadecimal values are transformed into decimal ones. The database is then updated with the decimal value. The ESP32 connects to the mobile hotspot or access point internet network, allowing data to flow. The ESP32 pings the MQTT server when it is connected. The MQTT server used in this investigation was constructed on a local device. Node-RED was used to develop a flow-based programming system that would make it easier to store sensor data in the MySQL database. Figure 7 shows the flow that was used.

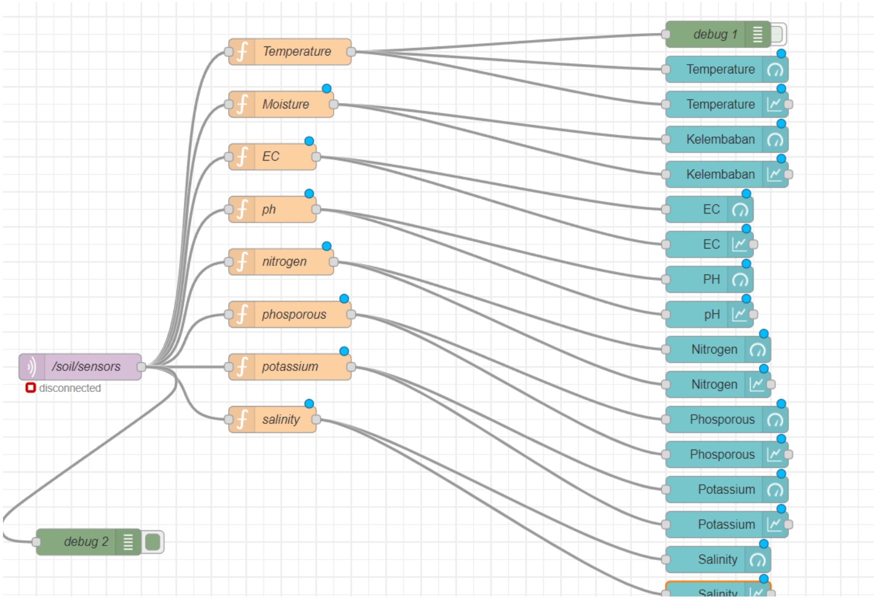

Figure 7. Flow diagram in Node-RED

Sensor data stored in the MySQL database is also displayed on the prototype screen using a LCD 3.5 inch Touch 480x320 TFT SPI Display. The library used is Bodmer/TFT_eSPI with a circuit as shown in Table 4.

Table 4. The communication between LCD 3.5 inch Touch 480x320 TFT SPI Display and ESP32

LCD 3.5 inch Touch 480x320 TFT SPI Display	ESP32
VCC	5v
GND	GND
CS	GPIO15
RST	GPIO4
D/C	GPIO2
SDI	GPIO23
SCK	GPIO32
LCD	3v3

3. Results and Discussion

Table 5 displays each sample temperature, soil moisture, pH, EC, NPK, and salinity levels. The temperature fluctuated between 29.40 °C to 36.80 °C, which is considered optimal for the planting season. Soil moisture varied, indicating that this agricultural land uses a rain fed system. Monitoring soil salinity, generally assessed via electrical conductivity (EC), and managing irrigation water quality through techniques such as leaching and crop rotation are crucial strategies to alleviate the adverse impacts of salinity[26]. The nutritional study revealed an acceptable potassium level, while nitrogen and phosphorus content varied. The pH of the soil was always high in all of the samples, which suggests that the circumstances were alkaline and good for growing and producing crops.

Table 5. Soil properties in the research area

temp	N	P	K	EC	ph	moisture	sal	ws	long	lat
34.40	15	21	53	200	7.70	51.90	168	0.18	109.375	-0.092
32.20	10	14	36	100	8.07	4.00	87	0.62	109.262	-0.004
30.10	20	27	69	295	7.97	48.50	268	0.85	109.390	-0.216
30.20	29	39	99	467	7.93	76.20	423	0.12	109.429	-0.003
29.40	12	17	43	141	7.20	17.00	130	0.91	109.381	-0.098
32.10	13	18	47	161	6.90	15.00	141	0.80	109.428	-0.465
36.80	11	15	38	109	7.88	10.60	88	6.16	109.429	-0.034
33.40	10	14	36	100	7.88	8.90	85	1.05	109.268	-0.005
33.50	15	21	53	200	8.07	89.10	170	1.18	109.268	-0.004
33.90	10	14	36	200	7.97	85.90	169	0.81	109.262	-0.004

One of the indicators used to measure soil quality is soil pH. Soil pH can be a parameter used in the planting process. The recommended pH is in the range of 7-10 PH. It affects the accessibility of plant nutrients, vegetative development, and productivity. Table 5 shows that the pH is in the range of 6.90-8.07 PH, which means that alkaline conditions dominate the agricultural land. EC is a crucial metric for evaluating soil health since it shows how much nutrients are available and how much they are used up, as well as the soil structure and ability to hold water. It affects how productive farms are, how well soil works for certain crops, how easy it is for plants to get water and nutrients, and how active microorganisms are in the soil. The soil in the whole area has an electrical conductivity of less than 2000 μS/cm. The soil beneath is bare of salt[27]. Consequently, this signifies that the soil is devoid of salts. Consequently, the minimal osmotic impact of dissolved salt concentration will prevent plants cultivated in the soil from experiencing water absorption issues.

The fluctuations in EC composition across the soil may result from differences in moisture levels linked to the substantial precipitation in certain regions, particularly in the upper soil zones. The presence of dissolved ions in the water increases soil electrical conductivity when moisture levels are elevated. Water permeates the soil, transporting ions and enhancing its overall conductivity. A comparable outcome was documented by[28] In their study at the Huangshui Watershed. According to[29], the total nitrogen content in the soil varies from 9 mg/kg to 14 mg/kg, while indicate that the optimal total nitrogen level in the soil is between 15 mg/kg to 30 mg/kg, which has been attained in some regions of the landscape. To optimize the soil nitrogen levels, it is necessary to apply both organic and inorganic nitrogen fertilizers. The data in Table 5 indicate that phosphorus concentration varies from 14-39 mg/kg. The phosphorus element recommended for agricultural soils is between 15-50 mg/kg. The potassium (K) element in the soil varies between 36-99 mg/kg, classified as low to high according to the criteria set forth by[30], it puts K levels into five groups: very low (< 50 mg/kg), low (55–210 mg/kg), medium (210-280 mg/kg), high (280-500 mg/kg), and extremely high (> 500 mg/kg). Salinization constitutes a principal challenge in modern agriculture and a significant factor in soil degradation.

The accumulation of water dissolved salts in the soil affects agricultural productivity, environmental integrity, and economic welfare to a degree. Soil salinity is measured by its electrical conductivity. The International System of Units (SI) electrical conductivity (EC) unit is dS/m. Soil that has salinity if it has an EC > 4 dS/m[31]. From Table 5, the units used in EC measurements are µS/cm, which, when converted, is 1000 µS/cm = 1 dS/m. Referring to the EC > 4 dS/m, none of the soil in Table 5 has salinity. The highest value in Table 5 is 467 µS/cm, which means 0.4 dS/m, so it does not have the potential to be saline soil. The data stored in the database will be displayed as a visualization of the measurement location map along with information on the soil nutrient content and the measurement date. More clearly, from the visualization, it can be displayed on a map, as shown in Figure 8.

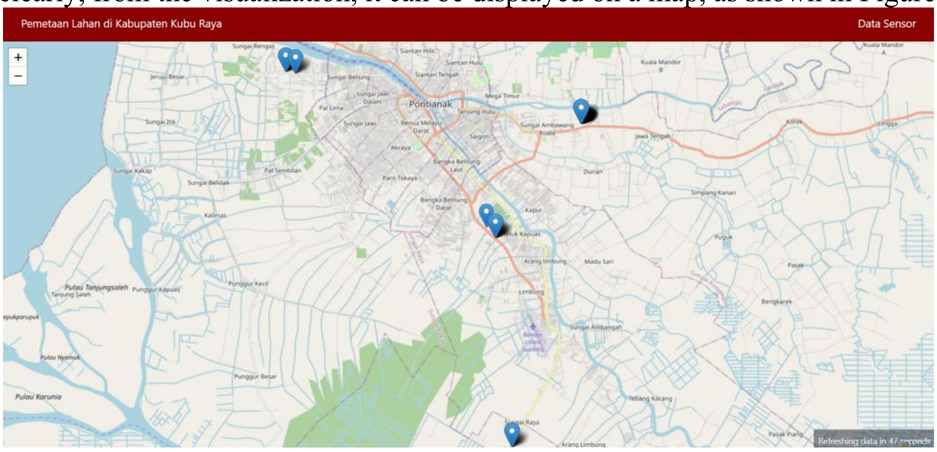

Figure 8. Location pins indicate the measurement area

If measurement data is stored in the database, location pins will be added automatically. To view the information, hover over each location pin. The measurement result information is shown in Figure 9.

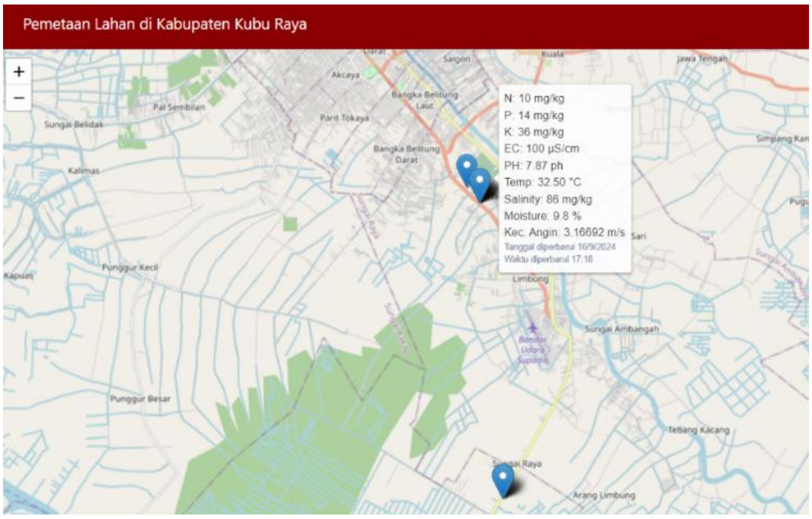

Figure 9. Information contained in the location pins

Figure 9 shows the information stored on the location pin, which is data saved in the database. The research results demonstrate that the developed IoT-based soil nutrient monitoring system successfully met its objective of real time. Numerous aspects influencing development and production include temperature, pH, water content, salinity, electrical conductivity, and nutritional level. The temperature of the soil in the sample ranged from 29.40 °C to 36.80 °C, with an approximate average of 32.6 °C. This range is typical for crops, where higher temperatures can influence microbial activity and nutrient availability. Temperature significantly affects crop development, and the recorded temperatures indicate generally suitable conditions for farming. Soil moisture readings ranged from 4 % to 89.10 %, suggesting significant variability in water retention across samples. Sample 9 had the greatest moisture content at 89.10 %, indicating well hydrated conditions, which may be advantageous for growth. Waterlogging may occur due to excessive moisture, which can impede the assimilation of nutrients and the respiration of roots. In contrast, sample 2 exhibited the lowest moisture content is 4 %, indicating that arid conditions necessitate irrigation management to ensure optimal crop development. The pH of the soil in the samples ranges from 6.90-8.07 PH, suggesting that they are predominantly neutral to mildly alkaline. The pH values recorded are within the permissible range for crop growth, and common plants often flourish in moderately acidic to neutral soil (5.5-7.0 PH). Samples exhibiting pH values beyond eight suggest a possible danger of diminished nutritional absorption, particularly phosphorus, as its availability may be impeded by elevated alkalinity, which can impact the metabolism and maturation of the crop.

A nitrogen concentration of 10-29 mg/kg is typical. An essential part of agricultural output, nitrogen is measured in different amounts to ensure there enough for plant development. It may be necessary to fertilizer. Sample 4 since its maximum nitrogen level of 29 mg/kg is likely insufficient for vegetative growth. Sample 4 had the greatest phosphorus concentration at 39 mg/kg. However, values varied from 14 mg/kg to 39 mg/kg. Soils containing calibrated levels of phosphorus, which are essential for plant root development and blossoming, fall within a typical range for good soil health. Concentrations of potassium range from 36 mg/kg to 99 mg/kg, with sample 4 showing the highest value of 99 mg/kg. The amounts found are sufficient for excellent growth and production, and potassium is essential for sustaining plant water homeostasis and enhancing immunity to diseases.

4. Conclusion

The ultimate objective of this research is to assess soil quality based on eight parameters, namely temperature, moisture, EC, pH, N, P, K, and salinity, owned by the soil integrated sensor implemented on the IoT platform. All types of soil samples are measured using the ESP32 microcontroller, and their values are collected for various indicators. A microcontroller processes measurement data, and the findings are displayed on a map, creating a geographic information system. The agricultural area utilized for testing is spread throughout three sub-districts in Kubu Raya Regency: Sungai Kakap, Ambawang, and Rasau Jaya. Ten soil samples were obtained from the three sub-districts. Water management, such as irrigation, is one way to enhance moisture in agricultural land. Nitrogen is a nutrient that is somewhat deficient and requires fertilizer to compensate. IoT enabled agriculture will provide valuable information to farmers and stakeholders. For future study, combining adaptive artificial intelligence with sensor input data in agriculture may greatly aid farmers.

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