

Development of Internet of Things-Based Soil Sensors for pH and Phosphorus Monitoring in Paddy Fields: Development, Accuracy, and Implementation Challenges

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Abstract: The development of Internet of Things (IoT) technology provides opportunities for faster and continuous soil monitoring to support precision agriculture. Monitoring soil pH and phosphorus is important in rice cultivation because both parameters are associated with soil chemical conditions and nutrient availability. This review aimed to examine the development of IoT-based soil sensors for monitoring soil pH and phosphorus, including sensor performance, factors affecting measurement results, and potential applications. A literature review was conducted on research and review articles published between 2019 and 2026. The literature was descriptively analyzed and synthesized based on technological development, sensor performance, and environmental and soil characteristics. The results indicate that pH and phosphorus sensors have been developed using various sensing approaches and have demonstrated promising performance under certain conditions; however, measurement results vary across parameters and soil conditions. Sensor performance is influenced by the sensing principle, soil characteristics, environmental conditions, calibration, and validation. IoT-based sensors have the potential to support real-time soil monitoring, but their application as quantitative measurement tools still requires validation and calibration under diverse soil conditions.

Keywords: precision agriculture, sensor calibration, sensor validation, soil analysis

1. Introduction

Soil serves as both a growing medium and a source of nutrients for plants, with nutrient availability determined by soil chemical properties and their interactions with soil components, environmental factors, and biological processes[1]. Rice (*Oryza sativa*) is one of the major crops cultivated in paddy fields, where flooded conditions create a soil environment that differs from that of upland systems. Flooded conditions can affect redox dynamics, iron (Fe) transformations, and phosphorus (P) availability in soil[2]. These distinctive characteristics mean that monitoring soil pH and phosphorus in paddy fields cannot entirely rely on the same approach used in upland soils, highlighting the importance of this review. Regular monitoring of these two parameters can support more appropriate nutrient management in rice cultivation.

Phosphorus is an essential nutrient for root development, flowering, seed formation, and overall rice plant growth[3]. The availability of phosphorus in soil is influenced by interactions among various chemical and biological processes involved in phosphorus transformation and mobilization[4]. Soil acidity is one of the key factors affecting phosphorus availability. In acidic soils, phosphorus tends to be bound by Al and Fe, whereas under alkaline conditions, it can react with Ca to form less soluble compounds[5]. This relationship indicates that simultaneous monitoring of soil pH and phosphorus is necessary to obtain a more comprehensive understanding of soil nutrient conditions.

Soil condition monitoring has become increasingly important for improving the efficiency of land and fertilizer management in rice cultivation[6]. Conventional soil analysis through laboratory methods remains an important approach for obtaining information on soil chemical properties; however, it is time-consuming and generally conducted periodically, limiting its ability to provide immediate information on soil conditions[7]. These limitations have increased the need for monitoring technologies capable of providing soil condition information more rapidly, efficiently, and continuously.

One technology that has emerged to address these needs is the Internet of Things (IoT). IoT refers to a concept in which physical devices are connected through networks, allowing them to exchange and continuously provide information[8]. In agriculture, IoT can be used to monitor environmental and crop conditions through sensors and support decision-making based on information collected from the field[9]. The application of IoT technology also enables information on soil, water, fertilizers, and other agricultural inputs to be utilized for more targeted crop management[10].

The development of IoT-based soil sensors has included the monitoring of soil pH and nutrients using various sensing principles. Soil pH sensors are generally developed using electrochemical approaches, whereas

phosphorus monitoring employs more diverse principles, including optical and electrochemical approaches[11], [12]. Differences in sensing principles result in different response characteristics and require sensor performance indicators to be evaluated according to the parameter being measured. In addition to the sensing principle, sensor measurements can also be affected by soil and environmental conditions, such as moisture content, texture, temperature, and pH. Therefore, the ability of sensors to provide real-time data needs to be accompanied by analytical performance evaluation through comparison with reference methods, calibration, and validation.

IoT-based soil sensors can provide information rapidly; however, their application still faces challenges in producing accurate and consistent data. Environmental conditions such as temperature, humidity, light intensity, atmospheric pressure, and pH can affect sensor reading accuracy[13]. These challenges become more complex in phosphorus measurement because phosphorus availability is influenced by soil pH and interactions between phosphorus and soil components. Therefore, sensor measurements need to be evaluated through calibration and validation against the analytical method used as a reference. For example, Dhamu et al. demonstrated that calibrating sensor measurements against laboratory analysis results can be used to evaluate sensor performance[7].

Various studies have explored the application of IoT and soil sensors to support real-time monitoring of soil conditions. Rehman et al. [14] reviewed the application of IoT for monitoring and control in agricultural systems, while Alahmad et al. [15] reviewed the use of IoT sensors and big data in precision agriculture. Rajak et al. [16] examined the development of IoT and smart sensors, as well as the challenges associated with their implementation in agriculture. The development of sensors for monitoring soil pH and nutrients has also been reported in various IoT-based systems[17], [18], [19]. Existing studies have largely focused on technological development, real-time monitoring capabilities, or sensor performance for individual parameters. However, the integration of sensing principles, analytical performance, factors affecting sensor response, and the dynamic characteristics of paddy soils has received limited attention within a single evaluation framework. Consequently, the current development of IoT-based sensors does not yet provide a comprehensive understanding of their technological readiness to move beyond monitoring functions toward the quantitative measurement of soil pH and phosphorus under paddy-field conditions.

The novelty of this article lies in integrating sensor detection principles, analytical performance, soil analytical factors, and paddy soil dynamics to evaluate the readiness of IoT-based sensors for monitoring pH and phosphorus in rice cultivation. This evaluation considers not only the ability of sensors to generate data rapidly and continuously but also the quality of measurement results based on analytical performance and the influence of soil conditions on sensor responses. This approach is used to assess the development of IoT sensor readiness from the monitoring stage toward quantitative measurement of pH and phosphorus that can support soil and fertilizer management in paddy-field cultivation. Accordingly, this article aimed to review the development of IoT-based soil sensors for monitoring soil pH and phosphorus in rice cultivation, including sensor performance, factors affecting measurement accuracy, and potential applications in precision agriculture.

2. Methodology

This article was prepared using a literature review method to examine the development of Internet of Things (IoT)-based soil sensors for monitoring soil pH and phosphorus in paddy-field cultivation. The literature sources were obtained through searches of reputable digital scientific databases, including Google Scholar, ScienceDirect, Scopus, and PubMed. The literature included research articles and review articles published between 2019 and 2026. The literature search was conducted using the keywords “internet of things,” “soil sensors,” “soil phosphorus,” “soil pH,” and “rice paddy.”

The preparation of this review article followed the literature review stages proposed by Snyder [20], beginning with topic selection and formulation of the review focus, followed by the search for and evaluation of relevant literature sources, and synthesis of published research findings. The retrieved literature was then analyzed descriptively and categorized into several topics, including the development of IoT in precision agriculture, sensor performance for soil pH monitoring, sensor performance for soil phosphorus monitoring, factors affecting sensor performance, and the opportunities and challenges of sensor implementation in paddy-field cultivation. The findings were subsequently compared and synthesized to identify technological developments, real-time monitoring capabilities, factors affecting measurement results, and the need for sensor calibration and validation against conventional methods.

3. Results and Discussion

3.1 Development of Internet of Things in Precision Agriculture

The application of Internet of Things (IoT) technology in agriculture has expanded considerably, particularly through the use of connected sensors to monitor crop, soil, and environmental conditions. Dhanaraju et al. [9] explained that IoT can be used to monitor crop and environmental conditions through sensors, while Ali

et al. [10] positioned IoT technology as part of the smart farming approach, which can provide information on soil, water, fertilizers, and other agricultural inputs to support production management. The use of smart sensors further expands these capabilities, as sensors can be used to obtain environmental parameter data directly and connect it to IoT-based communication systems[16].

The use of IoT in agriculture has developed alongside the concept of precision agriculture, which places data-driven information at the core of production management. Alahmad et al. [15] explained that the integration of IoT, big data, and other digital technologies can be used to improve precision crop production, including through the collection of in situ and on-the-go sensor data. Soussi et al.[21] also showed that the development of precision agriculture is increasingly characterized by the convergence of smart sensors, IoT, big data analytics, and artificial intelligence to support crop management optimization, resource-use efficiency, and sustainability. With these developments, the role of IoT is no longer limited to data transmission but has increasingly become part of information processing systems that support agricultural decision-making.

The implementation of IoT in agriculture has also evolved from single-parameter monitoring toward systems that integrate multiple sensors. Pechlivani et al. [13] developed an IoT-based Agro-toolbox that integrates soil and environmental sensors to monitor pH, soil moisture, soil temperature, air humidity, light intensity, and atmospheric pressure. The system was designed to provide continuous monitoring of soil and environmental conditions and was compared with commercial devices used as references. A similar direction was identified by Simamarta et al. [22], whose literature review identified pH, nutrients, temperature, and moisture as parameters that can be integrated into IoT systems for soil health monitoring.

The integration of multiple sensors is becoming increasingly important because soil and environmental conditions can change throughout the cultivation process. IoT systems enable measurements from multiple sensors to be collected and transmitted continuously, allowing changes in soil conditions to be observed without waiting for periodic laboratory measurements. Pechlivani et al. [13] specifically developed a monitoring system that combines several soil and environmental sensors within a single agro-toolbox, while Mansoor et al. [23] identified the integration of smart sensors and IoT as one of the major developments in precision agriculture for providing real-time information on crop and soil conditions.

Although real-time monitoring is one of the main advantages of IoT, the development of this technology still faces challenges in producing reliable data. Rajak et al. [16] identified various challenges associated with the implementation of IoT and smart sensors in agriculture, while Mansoor et al. [23] discussed the need for system reliability, data management, and technological integration under diverse agricultural conditions. Pechlivani et al. [13] also demonstrated that environmental factors such as temperature, humidity, light intensity, atmospheric pressure, and pH need to be considered when using sensor systems for soil analysis and environmental monitoring.

Overall, the development of IoT in agriculture demonstrates a shift from simple monitoring systems toward the integration of sensors, data communication, and information analysis within a precision agriculture framework. The development of smart sensors enables an increasing number of soil parameters to be monitored simultaneously, including pH and nutrients, while IoT technology allows these data to be collected continuously and utilized in crop management. However, the increasing number of monitored parameters and measurement frequency also requires evaluation of the performance of individual sensors because the measurement characteristics of each parameter are not necessarily the same. The following section therefore focuses on the development of IoT sensors for soil pH monitoring, which involves different measurement principles and challenges from those associated with phosphorus.

3.2 IoT Sensor Performance for Soil pH Monitoring

Soil pH is an important parameter for monitoring soil chemical conditions because it is associated with various chemical processes that determine nutrient availability. Because soil pH is related to hydrogen ion (H^+) activity in the soil solution, it can be measured using electrochemical sensors. Several studies have developed and evaluated IoT-based sensors for soil pH monitoring using different sensing principles and system configurations. Sensor performance has been assessed using various indicators, including the coefficient of determination (R^2), measurement error, sensitivity, and coefficient of variation. Table I summarizes selected studies on the use of IoT-based sensors for soil pH monitoring and the reported performance indicators used to evaluate their measurement capabilities.

Table 1: Summary of Studies on the Use of IoT Sensors for Soil pH Monitoring

Reference	Sensor Performance
Eldeeb et al. [12]	The sensor showed a correlation with glass electrodes of $R^2 > 0.97$; error $< 10\%$ across soil textures; coefficient of variation of 1.885%–0.945% during 7 days of monitoring
Arifin et al.[24]	The sensor produced an average error of 0.151%
Rollo et al.[25]	The WSN sensor showed a linear relationship between impedance and pH, with $R^2 = 0.97$
Putri et al. [26]	Sensor errors of 0.96% and 1.6%, with an overall system performance of 93%

Based on the summarized studies, research has shown that soil pH sensors have been developed using various measurement approaches and have demonstrated relatively good performance. Eldeeb et al. [12] developed an electrochemical sensor for in situ and real-time measurement of soil pH across three soil textures. The sensor showed a strong relationship with reference pH values, with $R^2 > 0.97$ and a sensitivity ranging from -50 to -66 mV/pH. Validation results showed an error rate of less than 10%, including for several soil textures that were not used during the calibration process. Seven-day monitoring also demonstrated measurement stability, with coefficients of variation of 1.885% and 0.945% under the two soil conditions tested. These findings indicate that the development of pH sensors is directed not only toward sensitivity but also toward maintaining stable measurement responses under continuous monitoring and different soil conditions.

The integration of sensors with IoT further extends pH measurement beyond simply obtaining numerical values to becoming part of a monitoring and control system. Arifin et al. [24] reported an average pH sensor error of 0.151% compared with a standard measuring instrument. The system integrated the pH sensor with soil moisture and light intensity sensors, enabling real-time monitoring of field conditions. These results indicate that integrating sensors with IoT can maintain a low measurement error while providing direct access to measurement data.

Rollo et al.[25] demonstrated the development of an impedance-based approach using a molybdenum disulfide (MoS_2) pH sensor connected to a wireless sensor network. The relationship between impedance and pH exhibited a linear pattern, with $R^2 = 0.97$ and a sensitivity of 12.9 k Ω /pH at a frequency of 10 Hz. Testing the sensor network against an electrochemical workstation also showed different levels of agreement at different measurement frequencies. At 20 kHz, the accuracy for pH values of 3, 5, and 7 reached 100%, whereas the values varied at higher frequencies. These findings indicate that, in addition to sensor materials, measurement frequency is also a factor affecting the performance of impedance-based sensors.

The development of IoT systems was also demonstrated by Putri et al. [26], who integrated a pH sensor with a NodeMCU ESP8266, Arduino Uno, relay, pump, and Telegram application to control soil pH conditions. The testing results showed sensor errors of 0.96% and 1.6%, while overall system performance reached 93%. The close agreement between sensor measurements and the standard pH meter during the testing period indicates that the sensor can be used as part of an automated soil pH control system.

The studies summarized in Table I demonstrate that soil pH sensors have evolved from portable and electrochemical systems toward systems integrated with IoT and wireless sensor networks. Performance results also vary depending on the indicator used. High R^2 values indicate a strong relationship between sensor responses and pH values, whereas low error values indicate greater agreement between sensor measurements and reference methods. Sensitivity represents the sensor response to changes in pH and is influenced by electrode materials and configuration, while measurement stability can be assessed using the coefficient of variation during repeated monitoring. Because these indicators represent different aspects of sensor performance, comparisons among studies should be made cautiously rather than using a single metric as the sole measure of sensor performance.

3.3 IoT Sensor Performance for Soil Phosphorus Monitoring

Phosphorus (P) sensors have been developed using various sensing principles, including optical, electrochemical, and multi-parameter approaches. Their performance has been evaluated using different indicators, such as accuracy, coefficient of determination (R^2), absolute percentage error (APE), resolution, and sensor drift. Table II summarizes selected studies on the application of IoT-based sensors for soil phosphorus monitoring and presents the reported performance indicators used to assess their measurement capabilities.

Table 2: Summary of Studies on the Use of IoT Sensors for Soil Phosphorus Monitoring

Reference	Sensor Performance
Jain et al. [27]	The optical sensor-based system achieved an average phosphorus (P) accuracy of 96.9%, with a P regression model yielding $R^2 = 0.9517$ and a standard error of 0.5417.
Bouhachlaf et al. [28]	The IoT system for monitoring NPK, pH, and soil moisture was tested at three locations and showed $R^2 > 90\%$ across all sensor measurements; a P-specific R^2 value was not reported separately.
Hartono et al. [29]	The NPK sensor had a resolution of 1 mg/kg and a specified accuracy of $\pm 2\%$ F.S.; however, actual testing showed that P measurements differed significantly from those obtained using the comparison device ($F = 7.42$; $p = 0.0091$).
Fathima et al. [30]	P measurements yielded an absolute percentage error (APE) of 10–19.2%, while the P calibration model had $R^2 = 0.962$ and sensor drift ranged from 2.1–3.5% over 10 minutes.

Research on Internet of Things (IoT)-based sensors for phosphorus (P) monitoring has demonstrated developments in various sensing approaches and data-processing systems. Jain et al. [27] used a TCS3200 optical sensor combined with multilinear regression, ESP8266, and LoRa communication. The system achieved an average accuracy of 96.9% for P, with $R^2 = 0.9517$, indicating a strong relationship between the sensor response and reference measurements. The system was also capable of transmitting data over a distance of up to 1 km and uploading measurement results to the cloud.

Online monitoring capabilities were also demonstrated by Bouhachlaf et al. [28] through an IoT system for NPK, soil pH, and moisture monitoring. Testing showed $R^2 > 90\%$ across the overall sensor measurements, although a P-specific R^2 value was not reported separately. In contrast, Hartono et al. [29] reported different results. Although the NPK sensor had a resolution of 1 mg/kg and a specified accuracy of $\pm 2\%$ F.S., P measurements differed significantly from those obtained using the comparison device ($F = 7.42$; $p = 0.0091$). This finding indicates that sensor specifications do not necessarily reflect actual performance under soil conditions.

Soil conditions are also an important factor affecting P sensor performance. Fathima et al. [30] reported an absolute percentage error of 10–19.2% across five soil types, with a P calibration model yielding $R^2 = 0.962$ and sensor drift of 2.1–3.5% over 10 minutes. Higher errors were observed in peat soils, whereas loamy soils produced more stable results. These differences indicate that soil texture, organic matter, and soil water conditions can affect sensor responses, suggesting that calibration should account for soil characteristics.

The findings indicate that IoT integration primarily provides advantages in terms of the speed of data transmission and access to P measurements. However, these capabilities are not always accompanied by close agreement between sensor measurements and reference methods. Variations in R^2 , error values, and validation results indicate that sensor performance cannot be generalized across all soil conditions. Calibration and validation across different soil characteristics remain necessary to ensure that P measurements can be used reliably to support nutrient management in precision agriculture.

3.4 Factor Affecting Soil Sensor Performances

High sensor performance reported in previous studies needs to be interpreted in relation to the measurement conditions under which the sensors were evaluated. A sensor that provides high accuracy for one parameter does not necessarily demonstrate the same performance for another parameter because each parameter has different physical and chemical characteristics. In soil measurements, sensor responses can be affected by environmental conditions such as temperature, moisture, light intensity, atmospheric pressure, and pH [13]. These factors indicate that sensor accuracy is not solely an inherent characteristic of the device but also results from interactions between the sensor and the environment in which measurements are performed.

Differences in sensor performance are also related to the way each parameter is measured. Soil pH measurement, for example, is based on hydrogen ion activity and can be performed using electrochemical principles. Sensor responses can be affected by soil characteristics such as moisture content and texture, resulting in different responses under in-field conditions compared with more controlled testing conditions [31]. The relationship between electrode potential and pH also follows electrochemical principles described by the Nernst equation; therefore, changes in environmental conditions that affect ion activity may influence measurement results.

Phosphorus measurement presents different challenges because P occurs in various forms and its availability is influenced by interactions with soil components. Sensor approaches for P analysis have been

developed using various principles, including electrochemical sensors, ion-selective sensors, and spectroscopy-based approaches [11], [19]. Available P in the soil solution occurs primarily in the form of phosphate ions, allowing the development of chemical sensing approaches. However, the presence of P in the soil solution is determined not only by total P content but also by the binding and release processes occurring within the soil.

Soil pH is an important factor in interpreting P measurement results. Under acidic conditions, phosphorus tends to be bound by Al and Fe, whereas under alkaline conditions, it can react with Ca, resulting in reduced P availability [32]. This relationship indicates that P measurement cannot be completely separated from the chemical conditions of the soil in which the sensor is used. Monitoring systems that measure pH and P simultaneously may provide more comprehensive information on soil nutrient conditions and help interpret changes in plant-available P in soil.

Calibration is an important approach for improving sensor reliability when sensors are applied under field conditions. Dhamu et al. [7] calibrated IoT sensor data against laboratory reference methods for measuring total carbon, ammonium, nitrate, and soil moisture. The comparison showed no significant differences between the two methods, indicating that the sensors provided adequate accuracy after calibration. This finding demonstrates that calibration against reference methods can be an important step in adjusting sensor responses to actual measurement conditions.

In in-field technologies, improving measurement accuracy depends not only on the sensor itself but also on the overall measurement procedure. Najdenko et al. [33] reviewed developments in rapid analysis of plant-available nutrients and soil pH for precision agriculture, while Najdenko et al. [34] developed a rapid soil extraction procedure for measuring plant-available P and K using an ISFET multisensor. These approaches demonstrate that sample preparation or extraction, sensing principles, and sensor characteristics need to be considered together when developing rapid soil analysis systems.

Based on these studies, the performance of IoT-based soil sensors varies considerably across measurement parameters and conditions. This variation indicates that sensor evaluation cannot rely solely on the ability to generate real-time data but should also consider the measured parameter, soil and environmental conditions, measurement methods, and calibration and validation processes. This approach is important for determining whether a sensor can be used as a general monitoring tool or has progressed sufficiently to provide quantitative measurements that could complement or potentially replace conventional analytical methods.

3.5 Opportunities and Challenges of Implementation in Paddy-Field Cultivation

The application of Internet of Things (IoT)-based soil sensors offers considerable potential to support data-driven management of rice cultivation. Real-time monitoring systems can provide soil condition information more rapidly, allowing changes in field conditions to be identified throughout the cultivation process. In rice cultivation, the application of IoT has been explored as an approach to support crop management and environmental monitoring through technology-based systems [35]. IoT-based environmental monitoring systems can also be used to obtain information on various field condition parameters continuously [36].

The practical value of sensor data increases when measurement results can be directly linked to land management. Real-time monitoring of soil conditions can support more targeted interventions within precision agriculture systems [23]. Information on soil pH and nutrient availability may be used as a basis for adjusting fertilizer management so that inputs can be applied according to field conditions. In paddy-field cultivation, appropriate fertilization is an important component for achieving optimal crop growth and yield [37].

Continuous sensor use has the potential to support more adaptive soil management by providing real-time soil condition data for decision-making within precision agriculture. However, faster measurement does not necessarily guarantee data reliability; therefore, validation against laboratory methods, periodic calibration, and testing across different soil types and environmental conditions are required [38]. These challenges become more complex when monitoring phosphorus because plant-available P is influenced by dynamic soil conditions. The development of laboratory-data-based correction models and integration of sensors with decision support systems are needed to ensure that the information generated is not only rapidly available but also sufficiently accurate to support soil and fertilizer management in paddy-field cultivation.

4. Conclusion

Internet of Things (IoT)-based soil sensors show potential as a faster and more continuous technology for monitoring soil conditions to support precision agriculture in paddy-field cultivation. Technological developments have included soil pH and phosphorus monitoring using various sensing principles, as well as the integration of data communication and remote monitoring systems. Previous studies have shown that sensor performance can vary across measurement parameters and conditions, with low error rates reported for some pH sensor systems and phosphorus measurements showing strong relationships with reference methods, but also differences under certain soil conditions. Sensor performance is influenced by sensing principles, soil

characteristics, environmental conditions, and calibration and validation processes. The wider application of sensors in paddy-field cultivation has the potential to improve monitoring speed and support more efficient nutrient management; however, periodic calibration, validation across diverse soil conditions, and integration with decision support systems are still required to ensure that the resulting data can be used reliably for soil and fertilizer management.

References

- [1] Z. Multazam *et al.*, *Pengelolaan Sumber Daya Lahan*, vol. 2. Padang: Hei Publishing Indonesia, 2024.
- [2] S. Tsumuraya, H. Nasukawa, and R. Tajima, "Estimation of Available Phosphorus Under Phosphorus Fertilization in Paddy Fields of a Cold Region Using Several Extraction Methods: A Case Study from Yamagata, Japan," *Agric.*, vol. 15, no. 13, pp. 1–15, 2025, doi: 10.3390/agriculture15131453.
- [3] K. Maulidan and B. K. Putra, "Pentingnya Unsur Hara Fosfor untuk Pertumbuhan Tanaman Padi," *J. Biopestic. Agric. Technol.*, vol. 1, no. 2, pp. 47–54, Aug. 2024, doi: 10.61511/jbiogritech.v1i2.2024.1163.
- [4] F. Khan, A. B. Siddique, S. Shabala, M. Zhou, and C. Zhao, "Phosphorus Plays Key Roles in Regulating Plants' Physiological Responses to Abiotic Stresses," *Plants*, vol. 12, no. 15, 2023, doi: 10.3390/plants12152861.
- [5] A. Nur Kholifah, N. Pawestri, and M. Utami, "Penetapan Fosfor Tersedia pada Sampel Tanah Menggunakan Metode Olsen & Bray I," *IJCR - Indones. J. Chem.*, vol. 10, no. 2, pp. 23–37, 2025.
- [6] Junaidi and K. Ramadhani, "Efektivitas Internet of Things (IoT) pada Sektor Pertanian," *J. Tek. (Jurnal Teknol. Komput. dan Sist. Informasi)*, vol. 4, no. 1, pp. 12–15, Feb. 2024, [Online]. Available: <http://jurnal.goretanpena.com/index.php/teknisi>
- [7] V. N. Dhamu, M. A. Eldeeb, A. C. Somenahally, S. Muthukumar, and S. Prasad, "SODS: Soil Health On-Demand Sensors—A Multi Parameter Field Study with Temporal Monitoring," *Sensors*, vol. 25, no. 11, Jun. 2025, doi: 10.3390/s25113505.
- [8] W. Andriyani *et al.*, *Teknologi IoT Pada Bidang Pertanian Modern*. TOHAR MEDIA, 2024.
- [9] M. Dhanaraju, P. Chenniappan, K. Ramalingam, S. Pazhanivelan, and R. Kaliaperumal, "Smart Farming: Internet of Things (IoT)-Based Sustainable Agriculture," *Agric.*, vol. 12, no. 10, Oct. 2022, doi: 10.3390/agriculture12101745.
- [10] A. Ali, T. Hussain, N. Tantashutikun, N. Hussain, and G. Cocetta, "Application of Smart Techniques, Internet of Things and Data Mining for Resource Use Efficient and Sustainable Crop Production," *Agric.*, vol. 13, no. 2, Feb. 2023, doi: 10.3390/agriculture13020397.
- [11] M. Nadporozhskaya, N. Kovsh, R. Paolesse, and L. Lvova, "Recent Advances in Chemical Sensors for Soil Analysis: A Review," *Chemosensors*, vol. 10, no. 1, 2022, doi: 10.3390/chemosensors10010035.
- [12] M. A. Eldeeb, V. N. Dhamu, A. Paul, S. Muthukumar, and S. Prasad, "Espial: Electrochemical Soil pH Sensor for In Situ Real-Time Monitoring," *Micromachines*, vol. 14, no. 12, 2023, doi: 10.3390/mi14122188.
- [13] E. M. Pechlivani, A. Papadimitriou, S. Pemas, G. Ntinis, and D. Tzovaras, "IoT-Based Agro-Toolbox for Soil Analysis and Environmental Monitoring," *Micromachines*, vol. 14, no. 9, Sep. 2023, doi: 10.3390/mi14091698.
- [14] A. Rehman, T. Saba, M. Kashif, S. M. Fati, S. A. Bahaj, and H. Chaudhry, "A Revisit of Internet of Things Technologies for Monitoring and Control Strategies in Smart Agriculture," *Agronomy*, vol. 12, no. 1, Jan. 2022, doi: 10.3390/agronomy12010127.
- [15] T. Alahmad, M. Neményi, and A. Nyéki, "Applying IoT Sensors and Big Data to Improve Precision Crop Production: A Review," *Agronomy*, vol. 13, no. 10, Oct. 2023, doi: 10.3390/agronomy13102603.
- [16] P. Rajak, A. Ganguly, S. Adhikary, and S. Bhattacharya, "Internet of Things and Smart Sensors in Agriculture: Scopes and Challenges," *J. Agric. Food Res.*, vol. 14, Dec. 2023, doi: 10.1016/j.jafr.2023.100776.
- [17] G. Santoso, S. Hani, and U. D. Putra, "Monitoring Kualitas Tanah Lahan Pertanian Desa Sidorejo menggunakan Sensor pH Tanah dan Internet of Things," *J. Nusantara. Mengabdikan*, vol. 2, no. 1, pp. 1–10, Oct. 2022, doi: 10.35912/jnm.v2i1.1387.
- [18] D. M. Sari, Jumardi, and N. Rasyid, "Prototype Pengairan Sawah dan Monitoring Kualitas PH Tanah Berbasis IOT," *Infotek J. Inform. dan Teknol.*, vol. 5, no. 2, pp. 240–251, 2022, [Online]. Available: <https://dx.doi.org/10.29408/jit.v5i2.5749> e-ISSN
- [19] S. Postolache, P. Sebastião, V. Viegas, O. Postolache, and F. Cercas, "Sistemas basados en IoT para la evaluación de nutrientes del suelo en horticultura," *Sensores*, vol. 23, no. 1, 2023, [Online]. Available: https://www.researchgate.net/publication/366831394_IoT-Based_Systems_for_Soil_Nutrients_Assessment_in_Horticulture

- [20] H. Snyder, "Literature Review as a Research Methodology: An Overview and Guidelines," *J. Bus. Res.*, vol. 104, no. July, pp. 333–339, 2019, doi: 10.1016/j.jbusres.2019.07.039.
- [21] A. Soussi, E. Zero, R. Sacile, D. Trincherio, and M. Fossa, "Smart Sensors and Smart Data for Precision Agriculture: A Review," *Sensors*, vol. 24, no. 8, 2024, doi: 10.3390/s24082647.
- [22] A. D. Simamarta, V. K. Nisa, R. Maulana, N. Parawansa, I. Khairunnisa, and Y. Budiawati, "Kajian Literatur: Penerapan Internet of Things (IoT) untuk Optimasi Manajemen Kesehatan Tanah," *Hidroponik J. Ilmu Pertan. Dan Teknol. Dalam Ilmu Tanam.*, vol. 2, no. 2, pp. 91–107, Jun. 2025, doi: 10.62951/hidroponik.v2i2.402.
- [23] S. Mansoor, S. Iqbal, S. M. Popescu, S. L. Kim, Y. S. Chung, and J. H. Baek, "Integration of Smart Sensors and IoT in Precision Agriculture: Trends, Challenges and Future perspectives," *Front. Plant Sci.*, vol. 16, 2025, doi: 10.3389/fpls.2025.1587869.
- [24] S. Arifin, N. Kurniawati, R. Agustiani, and G. Elsandika, "Sistem Monitoring Kesuburan Lahan Pertanian menggunakan Sensor pH, Sensor Suhu, Intensitas Cahaya, dan Kelembapan Tanah Berbasis Internet of Things," *J. Ris. Fis. Indones.*, vol. 5, no. 2, 2025.
- [25] A. Rollo *et al.*, "Hybrid Agricultural Monitoring System with Detachable, Biodegradable, and Printed pH Sensors with a Recyclable Wireless Sensor Network for Sustainable Sensor Systems," *ACS Appl. Electron. Mater.*, vol. 7, no. 7, pp. 2731–2740, 2025, doi: 10.1021/acsaelm.4c02141.
- [26] R. E. Putri, W. Darmadi, D. Cherie, and A. T. Puari, "The Design of Automatic Soil pH Control System on Aloe vera Cultivation with an Integration of Internet of Things (IoT)," *J. Tek. Pertan. Lampung (Journal Agric. Eng.)*, vol. 12, no. 3, p. 597, 2023, doi: 10.23960/jtep-l.v12i3.597-609.
- [27] N. Jain, Y. Awasthi, and R. K. Jain, "An IoT-based soil analysis system using optical sensors and multivariate regression," *Int. J. Exp. Res. Rev.*, vol. 31, pp. 23–32, 2023, doi: 10.52756/10.52756/ijerr.2023.v31spl.003.
- [28] L. Bouhachlaf, O. Benslimane, and S. El Hajjaji, "Monitoring Soil Elements for Irrigation Management Using Internet of Things (IoT) Sensors," *World Water Policy*, vol. 9, no. 4, pp. 756–766, 2023.
- [29] R. Hartono, N. M. Yoeseph, F. A. Purnomo, M. A. Safi'ie, and S. A. T. Bawono, "Portable internet of things-based soil nutrients monitoring for precision and efficient smart farming," *Bull. Electr. Eng. Informatics*, vol. 13, no. 5, pp. 3326–3333, 2024, doi: 10.11591/eei.v13i5.7928.
- [30] N. Fathima, S. B. V. Kumar, and M. U. Bagali, "An Embedded IoT-Based System for Real-Time NPK Soil Quality Monitoring in Precision Agriculture," *Eng. Technol. Appl. Sci. Res.*, vol. 16, no. 2, pp. 33211–33217, 2026, doi: 10.48084/etasr.17091.
- [31] S. Vogel *et al.*, "The effect of soil moisture content and soil texture on fast in situ pH measurements with two types of robust ion-selective electrodes," *Soil*, vol. 10, no. 1, pp. 321–333, 2024, doi: 10.5194/soil-10-321-2024.
- [32] C. J. Penn and J. J. Camberato, "A Critical Review on Soil Chemical Processes That Control How Soil pH Affects Phosphorus Availability to Plants," *Agric.*, vol. 9, no. 6, Jun. 2019, doi: 10.3390/agriculture9060120.
- [33] E. Najdenko, F. Lorenz, K. Dittert, and H. W. Olf, "Rapid in-field soil analysis of plant-available nutrients and pH for precision agriculture—a review," *Precis. Agric.*, vol. 25, no. 6, pp. 3189–3218, 2024, doi: 10.1007/s11119-024-10181-6.
- [34] E. Najdenko, V. Riedel, K. Dittert, A. Ruckelshausen, F. Lorenz, and H. W. Olf, "A Rapid In-Field Soil Extraction Procedure to Measure Plant-Available Soil P and K Using an ISFET Multi-Sensor," *J. Plant Nutr. Soil Sci.*, vol. 188, no. 4, pp. 593–603, 2025, doi: 10.1002/jpln.12007.
- [35] Fajar Ramadhan, Febri Pratama, Fauziah Noviani, and I. Albana, "Efektifitas Penerapan Internet of Things Pada Pertanian Padi: Tinjauan Literatur," *J. Teknol. Inf. dan Ilmu Komput.*, vol. 1, no. 2, pp. 40–48, 2025, doi: 10.65258/jutekom.v1.i2.11.
- [36] Y. Natalia and T. Sutabri, "Rancangan Sistem Pemantauan Lingkungan Berbasis IoT untuk Pertanian Padi," *J. Sains dan Teknol. Inf.*, vol. 2, no. 6, pp. 58–67, Nov. 2024, doi: 10.62951/switch.v2i6.282.
- [37] Y. Astuti, I. Lubis, and A. Junaedi, "Penentuan Dosis Pupuk Nitrogen, Fosfor, dan Kalium Optimum untuk Padi Sawah Varietas Bioemas Agritan," *J. AGRO*, vol. 10, no. 1, pp. 16–29, Jul. 2023, doi: 10.15575/23187.
- [38] A. W. Tiyas, D. Erwanto, and I. Yanuartanti, "Peningkatan Akurasi Sensor Suhu dan Kelembaban DHT11 dengan Kalibrasi Suhu Berbasis IoT pada Platform Thingspeak," *J. Pendidik. dan Teknol. Indones.*, vol. 5, no. 3, pp. 625–633, Mar. 2025, doi: 10.52436/1.jpti.709.