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Arduino-Based IoT Soil pH Monitoring System for Automated Horticultural Fertilization

Mukhsin Nuzula[a*], Junaidi Salat[a], Muhammad Ichsan[b], Zetta Fazira[b], Qairul Rahmi[a]

[a]Universitas Jabal Ghafur, Indonesia

[b]Politeknik Negeri Lhokseumawe, Indonesia

E-mail: mukhsinnuzula@unigha.ac.id

*Corresponding author

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Abstract

Precision fertilization is crucial for enhancing nutrient use efficiency and maintaining optimal soil conditions in horticultural crop cultivation. While IoT-based agricultural automation has been extensively researched, most studies focus on soil moisture-based irrigation, whereas the use of soil pH as a real-time control parameter in automated fertilization systems with remote monitoring remains limited. This limitation hinders accurate nutrient management and timely corrective actions in horticultural production. Therefore, this study aims to design and implement an Arduino-based automated fertilization system integrated with soil pH sensors and IoT technology. The proposed system continuously monitors soil acidity levels and automatically regulates liquid fertilizer application based on predefined pH thresholds. Testing results demonstrate that the soil pH sensor effectively measures acidity levels within the 5.32–6.50 pH range. The system successfully activates fertilizer application when pH values fall below the set threshold, delivering a volume of 150–200 mL per 60-second cycle. The findings indicate that integrating pH-based decision-making with IoT-based monitoring has the potential to support precision fertilization in horticultural cultivation.

Keywords*: Automatic Fertilization, Soil pH Sensor, Internet of Things.*

Abstrak

Pemupukan presisi sangat penting untuk meningkatkan efisiensi penggunaan hara dan menjaga kondisi tanah yang optimal pada budidaya tanaman hortikultura. Meskipun IoT untuk otomatisasi pertanian sudah banyak diteliti, sebagian besar masih berfokus pada irigasi berbasis kelembapan tanah, sedangkan penggunaan pH tanah sebagai parameter kendali real-time pada sistem pemupukan otomatis dengan pemantauan jarak jauh masih terbatas. Keterbatasan ini menghambat pengelolaan hara yang akurat dan tindakan korektif yang tepat waktu dalam produksi hortikultura. Oleh karena itu, penelitian ini bertujuan merancang dan mengimplementasikan sistem pemupukan otomatis berbasis Arduino yang terintegrasi dengan sensor pH tanah dan teknologi IoT. Sistem yang diusulkan memantau tingkat keasaman tanah secara kontinu dan mengatur pemberian pupuk cair secara otomatis berdasarkan ambang batas pH yang telah ditentukan. Hasil pengujian menunjukkan bahwa sensor pH tanah mampu mengukur tingkat keasaman pada rentang pH 5,32–6,50 dengan baik. Sistem berhasil mengaktifkan pemberian pupuk saat nilai pH berada di bawah ambang batas yang ditentukan dengan volume pupuk 150–200 mL per siklus 60 detik. Hasil penelitian menunjukkan bahwa integrasi pengambilan keputusan berbasis pH dan pemantauan berbasis IoT berpotensi mendukung pemupukan presisi pada budidaya hortikultura.

Kata kunci: Pemupukan otomatis, Sensor pH tanah, Internet of Things.

Introduction

Horticultural agriculture plays an important role in supporting food security and improving local economic resilience. Horticultural crops, such as vegetables and fruits, require adequate nutrient availability to achieve optimal growth and productivity. One of the most important factors in horticultural cultivation is fertilization management, which directly influences plant development, crop yield, and soil fertility [1]. In practice, fertilization in many small-scale agricultural systems is still applied uniformly without considering variations in soil conditions and crop nutrient requirements [2]. This practice often results in low fertilizer-use efficiency, particularly for nitrogen fertilizers, where crops typically absorb only 30–50% of the applied nitrogen, while the remaining nutrients are lost through leaching, runoff, volatilization, and denitrification [3]. These losses not only increase production costs but also contribute to environmental problems such as groundwater contamination, eutrophication of surface waters, soil degradation, and greenhouse gas emissions [4]. Recent studies reported that the global average nitrogen recovery efficiency in major crops is only about 39%, indicating that more than half of the applied fertilizer may not be utilized effectively by plants [5-6]. Therefore, the development of precision fertilization systems capable of adjusting fertilizer application based on real-time soil conditions is essential to improve nutrient-use efficiency and support sustainable horticultural production [7].

The rapid development of microcontroller and Internet of Things (IoT) technologies has opened new opportunities for implementing automation in agricultural activities [8]. Automation systems allow farmers to monitor environmental conditions and control agricultural processes more precisely and efficiently. Several studies have demonstrated the potential of microcontroller-based systems in improving agricultural management [9]. For example, Akbar and Borman developed an Arduino-based automatic fertilization system equipped with a soil pH sensor and RTC module capable of regulating fertilizer pumps automatically while sending soil condition information through Telegram-based communication [3] [10].

Similarly, research conducted by Furi, Iqbal, and Salahuddin proposed an IoT-based prototype for automated irrigation and fertilization systems for potted plants. Their study showed that the integration of sensors and IoT communication could improve the efficiency of water and nutrient management in plant cultivation [11] [12]. Other studies have also explored automated monitoring systems using various sensors and microcontrollers to support precision agriculture practices [1], [13]. Despite these advancements, the implementation of automated fertilization technology remains limited among smallholder farmers due to issues related to system complexity, cost, and accessibility [14]. Therefore, there is a need to develop a practical and affordable technological solution that can assist farmers in monitoring soil conditions and controlling fertilization processes more efficiently [15].

Based on these considerations, this research aims to design and develop an automated fertilization system for horticultural crops using an Arduino-based microcontroller integrated with a soil pH sensor and IoT communication technology [16]. The proposed system is expected to provide real-time monitoring of soil acidity and automatically regulate fertilizer application according to soil conditions [17]. By

implementing this system, fertilization efficiency can be improved, fertilizer waste can be reduced, and sustainable agricultural practices can be supported through the application of precision farming technologies.

Method

a. System Design

The research employed hardware-software co-design principles with block diagrams (Fig. 1) and flowcharts (Fig. 2) guiding component integration and control logic implementation. The system consists of Arduino Uno microcontroller, soil pH sensor, RTC module for scheduling, relay-driven mini water pump for fertilizer delivery, NodeMCU for IoT communication, and a Telegram bot interface enabling remote monitoring and control. Telegram is a cross-platform messaging application designed with a strong emphasis on user security and privacy [18].

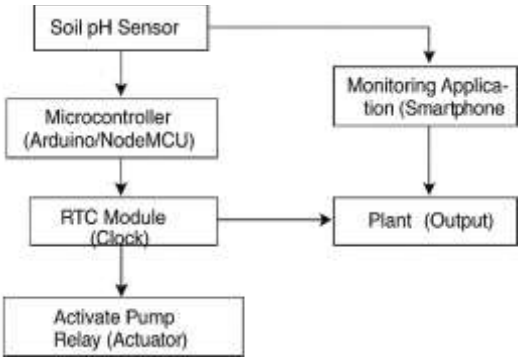


Figure 1. System Block Diagram

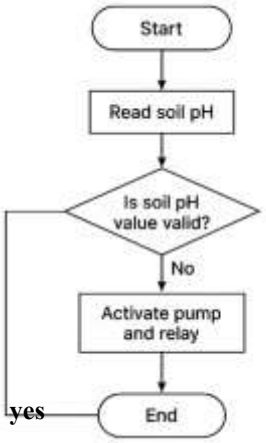


Figure 2. Entity Flowchart of the System

b. Experimental Setup and Testing

Laboratory and field tests evaluated soil pH sensor accuracy, Telegram bot operations, and relay module responsiveness [19]. Soil pH sensor readings (Table 1) were benchmarked against manual pH meters. Relay module functionality was verified across soil pH thresholds (Table 3). The Telegram bot interface commands (Table 2) allowed dynamic system configuration.

Table 1. Soil pH Sensor Experiments

Trial	pH Reading
1	6.5
2	6.1
3	5.46
4	5.32
5	6.0

Table 2. Telegram Bot Interface Testing

Command	Function
/setlimitPH 6.1	Sets the minimum pH threshold
/SystemON	Activates automatic control mode
/status	Checks system status and parameters

Table 3. Relay Module Testing

No.	Soil pH	Relay Status	Description
1	6.54	OFF	Pump inactive
2	4.23	ON	Pump active
3	7.68	OFF	Pump inactive

These experiments assessed the accuracy of soil pH detection, the reliability of relay-based pump control, and the effectiveness of remote communication through the Telegram bot.

Result

The results demonstrate that the proposed system is capable of performing automated monitoring and fertilization processes effectively, while also providing a practical framework for site-specific nutrient management in small-scale horticultural cultivation. The integration of microcontroller technology, soil pH sensing, and IoT communication enable real-time decision-making, allowing fertilizer application to be adjusted according to actual soil conditions rather than fixed schedules. IoT technology facilitates remote access to real-time soil information, enabling farmers and agricultural professionals to monitor field conditions regardless of their location [20]. This capability is particularly important because soil pH directly influences nutrient availability and fertilizer uptake efficiency.

The soil pH sensor produced readings within the range of 5.32–6.50, which were consistent with manual measurements, indicating that the sensor can provide reliable information for automated control. Beyond sensor performance, these results suggest that pH-based monitoring can serve as an effective indicator for adaptive fertilization strategies. Similar studies have highlighted the importance of real-time environmental monitoring in supporting precision agriculture and reducing unnecessary agricultural inputs [5].

Furthermore, the relay-controlled pump successfully delivered fertilizer only when the soil pH fell below the predefined threshold. This condition-based fertilization approach represents an advancement over conventional schedule-based practices, as it enables fertilizer application to be triggered by actual soil requirements. Consequently, the system has the potential to improve nutrient-use efficiency, reduce excessive fertilizer application, and support more sustainable agricultural management [21]. The ability to

integrate automated control with remote monitoring through IoT also enhances operational efficiency by enabling timely intervention without continuous field supervision.

The integration of IoT technology using NodeMCU and Telegram communication significantly enhanced the functionality of the system. Within IoT ecosystems, notification platforms play a significant role in transmitting information and system updates to end users [22]. Through this feature, users were able to monitor system status, adjust pH threshold values, and activate or deactivate the system remotely. This capability is particularly beneficial for farmers because it allows agricultural monitoring without requiring continuous physical presence in the field. Similar implementations of IoT-based agricultural monitoring systems have been shown to improve efficiency and reduce manual labor requirements in farming activities [11].

Additionally, the use of the RTC module allowed the system to perform scheduled fertilization at predetermined times. This feature ensures that fertilization activities are conducted consistently according to crop nutrient requirements. Automation of agricultural operations through microcontroller-based systems has been widely recognized as an effective approach to improving agricultural productivity and resource efficiency [23]. Although the system demonstrated promising performance, several limitations were identified during the testing process. Sensor stability was occasionally affected by soil moisture variations, which could influence measurement accuracy. The substantial variability and complexity of soil moisture present significant challenges in distinguishing the contributions of individual influencing factors [24]. In addition, the communication range of the IoT module depended on network availability and signal strength, which may limit system operation in remote agricultural areas. Cellular networks play a crucial role in enhancing network reliability and operational efficiency [25].

Overall, the developed prototype demonstrates the potential of IoT-based agricultural automation in improving fertilization efficiency and supporting sustainable farming practices. The integration of sensor monitoring, automated control, and remote communication provides a comprehensive technological solution that can assist farmers in implementing precision agriculture techniques. The Arduino circuit (Fig. 3) was realized on a PCB, interconnecting sensor modules (Fig. 4), relay units (Fig. 5), and actuator (aquarium pump, Fig. 6). Jumper cable configuration (Fig. 7) ensured secure signal flow, while NodeMCU (Fig. 8) managed IoT data transmission. Complete hardware integration is depicted in Fig. 9. Soil pH sensor testing setup and results are shown in Fig. 10.

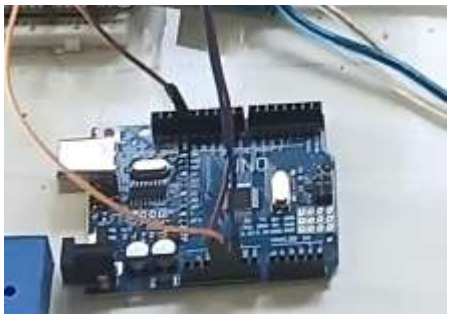


Figure 3. Arduino Circuit Implementation

The soil pH sensor was integrated into the system to detect soil acidity levels in real-time. The assembled sensor unit is shown in Fig. 4.



Figure 4. Soil Ph Sensor Circuit Implementation

The relay module controlled the activation of the fertilizer pump according to soil pH levels and scheduled operation days. The assembled circuit is depicted in Fig. 5.



Figure 5**.** Relay Module Implementation

The aquarium pump circuit was designed to distribute liquid fertilizer or water when the soil was detected to be deficient. The hardware arrangement is presented in Fig.6.



Figure 6. Aquarium Pump Implementation

Jumper cables were used to connect the entire system, enabling data transmission and circuit operation as illustrated at Fig. 7.



Figure 7**.** Jumper Cable Configuration

The NodeMCU served as the IoT module responsible for processing soil pH data and enabling remote monitoring and control. The implementation is shown in Fig. 8.

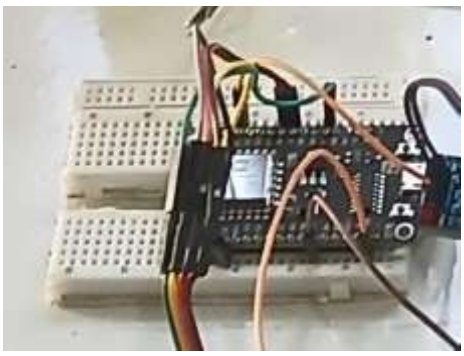


Figure 8. NodeMCU Circuit Implementation

All hardware components, including Arduino Uno, soil pH sensor, LCD, RTC DS3231 module, two-channel relay, aquarium pump, 12 V adapter, switch button, acrylic casing, and jumper cables, were fully integrated into the system. The complete prototype is presented in Fig. 9.



Figure 9. Complete System Integration

The soil pH sensor was tested to ensure proper functionality. The experimental setup is shown in Figure 10, while the results of the trials are summarized in Fig. 10.



Figure 10. Soil pH Sensor Testing

Conclusion

The results demonstrate that the proposed system is capable of performing automated monitoring and fertilization processes effectively, while also providing a practical framework for site-specific nutrient management in small-scale horticultural cultivation. The integration of microcontroller technology, soil pH sensing, and IoT communication enable real-time decision-making, allowing fertilizer application to be adjusted according to actual soil conditions rather than fixed schedules. This capability is particularly important because soil pH directly influences nutrient availability and fertilizer uptake efficiency.

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Overall, the developed system demonstrates significant potential as an appropriate technology solution for improving fertilizer efficiency and promoting sustainable agricultural practices. This prototype can serve as a foundation for the development of more advanced IoT-based smart farming systems. Future research is recommended to enhance sensor stability, expand communication coverage, and develop more user-friendly interfaces to facilitate wider adoption of the technology in agricultural communities.

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