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Real-Time IoT-Based Smart Fertigation System for Sustainable and Precision Agriculture

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Abstract. Inadequate agricultural practices and indiscriminate fertilizer application, especially in parts of Oyo State, Nigeria, have led to reduced crop productivity and worsening environmental conditions, including those related to deforestation-induced climate change. This study presents the design and implementation of an Internet of Things (IoT)-based automated fertigation system aimed at addressing these challenges through data-driven, sustainable soil management. The proposed system integrates real-time soil moisture and nitrogen sensors with a NodeMCU microcontroller, interfaced via the Arduino IDE and controlled through the Blynk IoT platform. The architecture supports remote monitoring, cloud-based data visualization, and precision actuation using solenoid and peristaltic pumps. Experimental validation demonstrated a responsive and efficient feedback mechanism: during a targeted fertigation event at approximately 05:00 a.m., soil nitrogen levels increased from 14.6 mg/kg to 29.4 mg/kg, and moisture content rose from 25.3% to 46.8%, with automated valve deactivation at predefined thresholds. Previous trials similarly recorded a rise in moisture from 29.2% to 40.1% and nitrogen from 18.8 mg/kg to 30.1 mg/kg. Post-fertigation analysis showed a natural decline in both parameters, reinforcing the system's alignment with biological absorption rates and supporting predictive irrigation scheduling. The closed-loop control logic, combined with real-time analytics and an intuitive user interface, enhances operational efficiency and reduces input waste. Furthermore, the system's modularity and ease of use make it adaptable for broader agricultural deployment, especially among farmers with limited technical backgrounds. This work affirms the potential of IoT-based fertigation for improving agricultural output, promoting environmental sustainability, and enabling precision farming in resource-constrained contexts.

Keywords: Smart Agriculture, Fertigation, IoT, Soil Moisture Sensor, Precision Farming, Automation.

1. Introduction

The rapid advancements in technology have led to the emergence of innovative solutions in various sectors, and the field of agriculture is no exception. The integration of the Internet of Things (IoT) in agriculture has opened up new possibilities for enhancing crop yield and optimizes resource utilization. One such application is the IoT Fertilizer System, which aims to revolutionize the way fertilizers are applied to crops. This project focuses on the development of an IoT-based Fertilizer System that monitors soil conditions, analyses data in real-time, and delivers the right quantity of fertilizers to crops thereby ensuring efficient nutrient management environment impingement. Agriculture stands as a cornerstone of global food security and economic stability. Nonetheless, traditional farming methods encounter challenges such as water scarcity, inefficient

resource utilization, and unpredictable weather conditions.

In recent years, the integration of innovative IoT applications has emerged as a promising solution to revolutionize agricultural practices. This review aims to explore the advancements in IoT-based smart irrigation and fertilization systems, focusing on their impact on agricultural sustainability, productivity, and resource efficiency. The rapid advancements in IoT technology have facilitated the development of smart agricultural systems capable of monitoring, analyzing, and optimizing various aspects of crop cultivation. Ragab et al. (2022) emphasize the integration of IoT with center pivot irrigation systems, highlighting the significance of employing specified parameters to determine optimal irrigation timing and quantity. Similarly, Lavanya et al. (2020) introduce an IoT-based Fertilizer Intimation System, which utilizes sensors and fuzzy logic to monitor soil nutrients and optimize fertilizer application.

Numerous studies have demonstrated the effectiveness of IoT-based systems in improving irrigation and fertilization practices. Pezol et al. (2020) present a smart irrigation and fertilization system for chili plants, integrating fuzzy logic to control water flow and pH levels. This system, tested on chili plants, showcases enhanced plant growth compared to traditional methods. Prabha et al. (2018) propose a similar system for chili farming, emphasizing the importance of scheduling irrigation and fertilization based on crop requirements and environmental conditions. IoT-based agricultural systems offer solutions to challenges faced by farmers worldwide. Ahmed et al. (2018) tackled the issues encountered by Sudanese farmers through the design of an automated fertigation system. By utilizing IoT technology to control water usage, adjust pH levels, and monitor soil conditions, this system enhances water and fertilizer use efficiencies, leading to increased production and productivity while conserving resources.

Furthermore, Li et al. (2021) made a contribution to this subject by creating a precision irrigation system for growing vegetables in greenhouses that works with the Internet of Things (IoT). Their technology uses weather data and soil moisture sensors to make the best use of water and increase crop yield. Additionally, Sharma et al. (2019) suggested a new IoT-based soil health monitoring system that uses sensor networks to measure soil factors including moisture content, pH, and nutrient levels. This system gives farmers real-time data to help them make smart choices (Sadiku *et al.,* 2025). The use of IoT in farming has the potential to change traditional farming methods into systems that are more efficient and environmentally friendly. Farmers can use IoT technology to improve their irrigation and fertilization methods, use fewer resources, and adjust to changes in the environment. Continued research and implementation of IoT-based smart agricultural systems are essential for promoting global food security and environmental sustainability.

The rest of this paper was organised as follows: Section 2 is Literature review, while Section 3 details the methodology for this study. In Section 4, the results and discussion presented. Section 5 entails the conclusion and recommendations for future studies.

2. Literature Review

The Technology Acceptance Model (TAM), devised by Davis (1989), aims to elucidate the adoption of technology. The TAM posits that perceived usefulness (PU) and perceived ease of use (PEOU) are pivotal factors in determining technology acceptance behaviour (Adesina *et al.,* 2024). PU stands for how much a potential user thinks that using a certain system will help them do their work better, and PEOU stands for how easy a potential user thinks it would be to utilize that system. TAM does not include social norms (SN) as a factor in determining behavioural intention. This model has found widespread application in forecasting the acceptance of information technology, demonstrating validity across diverse IT systems (Plouffe et al., 2001).

In scholarly discourse, TAM is recognized as "especially well-suited for modeling computer acceptance" (Davis *et al.,* 1989), representing a popular framework for predicting and elucidating future user behavior regarding the acceptance of new technology, even from minimal interaction with a system (Hameed et al., 2012). Empirical evidence has consistently affirmed the high validity of TAM across numerous prior studies. Turner et al. (2010) discovered that the TAM variables of perceived ease of use and perceived usefulness are strongly correlated with the intention to use. Despite its advantages, including those underscored by Chau (1996), Sun and Zhang (2006), and Turner et al. (2010), the standard TAM possesses limitations (Mathieson, 1991; Li et al., 2008), such as oversimplification, a constrained number of constructs characterizing behavior, and the exclusion of various factors influencing users' ultimate behavior, such as personal and organizational attributes, temporal considerations, environmental factors, and subconscious tendencies (Li et al., 2008).

Recent scholarship has delved into technology acceptance variables tailored to specific professional cohorts (Yi et al., 2006). Thie TAM2 includes social influence, which is the tendency to believe information from another source as true, through the subjective norm construct. It also includes self-image and voluntariness to show how important social influence is in technology acceptance. So, social influence shows up in technology acceptance as a subjective norm that indirectly affects behavioural

intention through perceived usefulness, no matter if using the system is optional or required (Mijinet *et. al.,* 2019). Figure 1 illustrates the structure of the TAM model.

IoT-based fertilizer systems represent a significant advancement in precision agriculture, offering sustainable solutions for optimized nutrient management. This literature review highlights the benefits, technologies, case studies, challenges, and future prospects of IoT fertilizer systems. As agriculture faces increasing demands for productivity and sustainability, IoT-based solutions continue to play a crucial role in ad dressing these challenges.

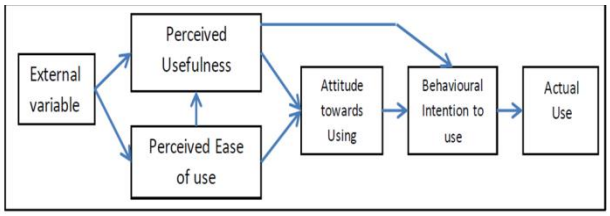


Figure 1: Technology Acceptance Model (Davis, 1989).

2.1 Related Works

In recent years, precision agriculture and the use of IoT technology have gotten a lot of attention as ways to solve problems in the farming industry. Numerous empirical studies have investigated the design, implementation, and impact of IoT-based smart irrigation and fertilization systems. Several researchers have developed and evaluated IoT-based smart irrigation management systems. Al-Rizzo et al. (2019) designed and implemented such a system, incorporating sensors for real-time monitoring of environmental parameters and automating irrigation based on predefined thresholds. Similarly, Ahmed et al. (2018) proposed a design for an automated fertigation system using IoT, aiming to optimize water and nutrient delivery. Bouzid et al. (2017) presented an empirical study of an IoT-based agriculture monitoring and smart irrigation system, highlighting its ability to monitor soil moisture, temperature, and humidity levels remotely.

Braga et al. (2020) conducted a systematic literature review on the application of IoT in agriculture, synthesizing empirical evidence from various studies and identifying potential research gaps. Malhotra and Sharma (2021) reviewed the challenges and opportunities, including issues related to cost, data security, and user adoption. Kaloxylos and Nikolakopoulos (2020) provided a comprehensive review of IoT applications in agricultural operations, discussing empirical findings and future directions. Kuswardhani et al. (2021) developed an IoT-based smart irrigation system with fuzzy logic for precision agriculture, demonstrating improved water management. Pezol et al. (2020) and Prabha et al. (2018) proposed designs for IoT-based smart irrigation and fertilization systems using fuzzy logic, specifically for chili plant cultivation. Chau (1996), Davis (1989), and Mathieson (1991) employed the TAM and related models to predict user intentions and actual use of information technology systems, including IoT-based agriculture solutions.

Mijin et al. (2019) and Yi et al. (2006) explored the moderating effects of self-image and individual characteristics on technology acceptance. Ragab et al. (2022) investigates the integration of Innovative Internet of Things (IoT) applications with centre pivot irrigation systems, aiming to revolutionize agricultural practices. The proposed system streamlines the irrigation process by employing specified parameters to determine the optimal timing and quantity of irrigation, presenting a systematic and effective approach. The study underscores the substantial impact of leveraging IoT advancements to modernize irrigation techniques, ultimately contributing to heightened agricultural productivity. The study by Lavanya et al. (2020) came out with a new IoT-based Fertilizer Intimation System for smart farming. A new Nitrogen-Phosphorus-Potassium (NPK) sensor that uses Light Dependent Resistor (LDR) and Light Emitting Diodes (LED) to check the nutrients in the soil is part of the system.

Fuzzy logic is employed to detect nutrient deficiencies, with a Raspberry Pi 3 and Python used for hardware and software development. The system is tested on various soil types, demonstrating linear variation with soil concentration and aiding farmers in crop yield optimization. Pezol et al. (2020) present an IoT-based smart irrigation and fertilization system for chili plants, integrating fuzzy logic to control water flow and pH levels. The system utilizes WiFi nodes for connectivity and Arduino for fuzzy rule implementation, with Blynk mobile application for data display. Tested on chili plants, the systems control environment enhances plant growth compared to traditional methods. Prabha et al. (2018) suggested an IoT-based smart irrigation and fertilization system for chili farming to help farmers get more food and use less water.

Ahmed et al. (2018) addressed the challenges faced by Sudanese farmers by designing an automated fertigation system using IoT. The system controls water usage efficiency through moisture sensors and adjusts pH levels and soil electrical conductivity. By automating fertilization processes, the system enhances water and fertilizer use efficiencies, leading to increased production and productivity while saving time and resources. The system plans when to water and fertilize crops based on their needs, the weather, and the state of the environment. A mobile app that is easy to use gives farmers information that helps them farm more efficiently and at a lower cost

3. Methodology

Fertigation is a sophisticated fertilizer application technique that uses a drip irrigation system to distribute fertilizers mixed into irrigation water. By ensuring consistent nutrient distribution, this method increases crop availability and absorption. Studies show improvements in nutrient use efficiency of 80% to 90% when water-soluble and liquid fertilizers are used.

3.1 Design Considerations

The design of the fertigation system was influenced by several critical factors:

1. **System Integration** – Ensuring seamless communication among sensors, actuators, and the controller.
2. **Scalability** – The system should be adaptable for future expansion.
3. **Robustness** – Ability to withstand harsh environmental conditions.
4. **Multi-Parameter Sensing** – Capability to monitor parameters such as soil moisture, temperature, and nutrient levels.
5. **Energy Efficiency** – Minimizing power consumption for sustainable operation.
6. **User Interface** – Remote access and monitoring via a user-friendly mobile/web platform.
7. **Affordability** – Maintaining cost-effectiveness for smallholder farmers.
8. **Adaptability** – Usable across diverse soils, climates, and crops.

These considerations guided the structural and functional design of the system, ensuring reliability and relevance in a real-world agricultural context.

3.2 Real-Time Sensor Network for Sensor Monitoring

3.2.1 Temperature and Humidity Sensor (DHT22)

The DHT22 sensor monitors ambient temperature and humidity, combining a thermistor and capacitive humidity sensor to output digital signals. It supports a wide range of temperatures (−40°C to +80°C) with an accuracy of ±0.5°C and ±2% for humidity. The sensor requires a 2-second delay between readings and operates on 3.3V–5V power. It is shown in Figure 2.



Figure 2. Temperature and Humidity Sensor (Velayudham, 2023)

3.2.2 Soil Moisture Sensor

This sensor detects the volumetric water content in soil using open/short circuit principles. An LED indicates the moisture status, and power is supplied only during measurements to prevent corrosion. The sensor is depicted in **Figure 3**.

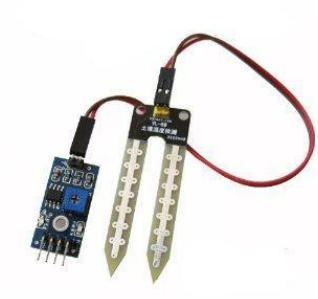


Figure 3. Soil moisture sensor (Sanjay, 2019)

3.3 List of Components

The major components used in building the fertigation system include:

- NodeMCU (ESP8266)
- BC547 and TP122 transistors
- Solenoid valve
- DC voltage booster
- Zero PCB
- Resistors
- Soldering station

3.3.1 Solenoid Valve

In this study, a solenoid was utilized as a key electromechanical actuator to convert electrical signals into mechanical linear motion. The solenoid assembly consists of a tightly wound helical copper coil encasing a movable ferromagnetic plunger. Upon energizing the coil using a DC power source controlled via a microcontroller (such as Arduino), a magnetic field is generated within the coil. This field induces axial motion of the plunger in accordance with Faraday's Law of Electromagnetic Induction and Ampère's Circuital Law. The transient electromagnetic force results in a rapid, repeatable displacement of the core, enabling actuation of connected mechanical components. This characteristic makes the solenoid suitable for applications requiring binary (on/off) movement. Within the context of the system design, the solenoid was programmed to trigger physical mechanisms, such as releasing or engaging a latch, based on digital outputs from the control logic implemented in the microcontroller. The integration of the solenoid allowed for precise and programmable mechanical responses essential for the automation objective of this project.

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3.3.2 NodeMCU (ESP8266)

The NodeMCU board, shown in Figure 4, is based on the ESP8266 chip and integrates Wi-Fi connectivity, serving as the central microcontroller that processes sensor data and controls actuators.

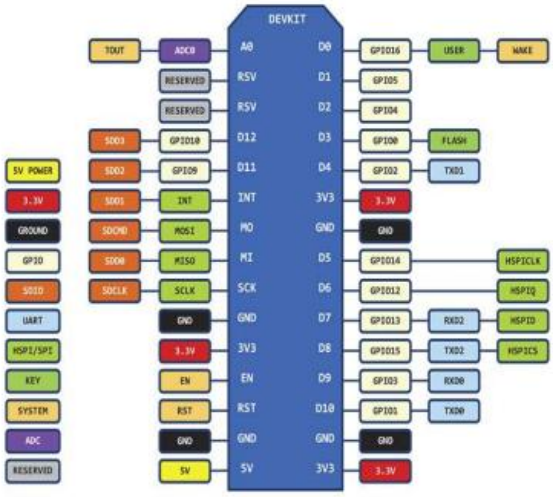


Figure 4. Pin Configuration of NodeMCU (Yashas, 2020)

3.4 Blynk IoT Platform Integration

To facilitate remote control and monitoring of the fertigation system, the Blynk IoT platform was integrated into the project. Blynk offers a user-friendly interface for developing IoT applications, allowing seamless communication between mobile devices and embedded hardware such as the NodeMCU microcontroller. The process began by installing the Blynk mobile application on a compatible Android or iOS device and incorporating the Blynk library into the Arduino Integrated Development Environment (IDE). This integration involved downloading the Blynk ZIP package, which contains essential library files to be manually added to the Arduino libraries directory.

Once the setup was completed and the Arduino IDE restarted, a new Blynk project was created on the mobile application. The hardware model "NodeMCU" was selected, and the application generated an authorization token required for secure communication between the app and the device. This token was emailed to the developer for use in the Arduino source code. Widgets such as buttons, sliders, value displays, and terminal outputs were added to the app interface to allow user interaction and system feedback. These widgets were configured to control and visualize system parameters such as solenoid activation, moisture sensor readings, and pump operation status. The Blynk interface is illustrated in Figure 5.

3.5 Construction of Supporting Frame

To support the mixing and dispensing components of the fertigation system, a wooden frame structure was fabricated using Medium Density Fibreboard (MDF). A 1-foot MDF board was cut to size, and precise holes were drilled to ensure correct spacing between the containers designated for holding the fertilizer solutions. The positioning was carefully calculated to support the flow dynamics and maintain system balance. The layout is illustrated in Figure 6.

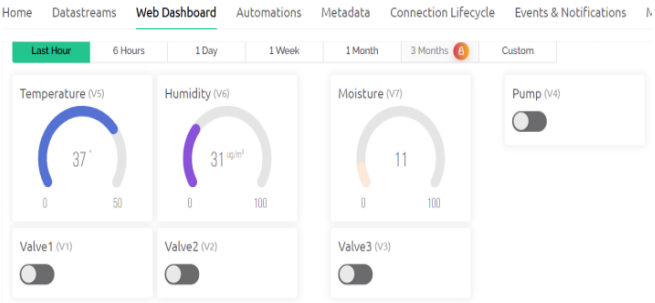


Figure 5. Diagram showing the user interface



Figure 6. The Support Frame Layout Illustration

3.6 Bottle Attachment to Support Rods

Three transparent plastic bottles were utilized as storage tanks for different fertilizer solutions, namely nitrogen, phosphorus, and potassium-based compounds. These bottles were mounted vertically onto the support frame using three evenly spaced vertical rods. The decision to use plastic over metallic containers was driven by the need for visibility, allowing visual inspection of the internal fluid levels and condition. The bottles were securely fastened to prevent dislocation during fluid dispensing operations. The setup is shown in Figure 7



Figure 7. Bottle and Support Rod Assembly

3.7 Operational Principle of the Automated Fertigation System

The automated fertigation system operates on a feedback control mechanism integrating sensors, actuators, and a microcontroller-based control unit. The system's logic is designed to apply fertilizers in response to real-time environmental data, as outlined below:

1. Sensor Input: The system is equipped with various sensors for monitoring soil conditions including moisture content, temperature, and nutrient concentrations. These sensors feed continuous data to the microcontroller.
2. Data Processing: The microcontroller processes incoming sensor data, applying algorithms to determine whether the conditions meet the preset thresholds for fertilizer application.
3. Decision Logic: Based on processed inputs, the control unit determines the appropriate type and volume of fertilizer to be dispensed to meet plant requirements efficiently.
4. Actuation: Solenoid valves and peristaltic pumps are activated accordingly to dispense the precise amount of fertilizer from the reservoirs into the irrigation system.
5. Feedback Loop: The system continuously monitors the post-application environment to evaluate effectiveness. This allows for dynamic adjustment of parameters to maintain optimal soil nutrient levels.

This design enables efficient, resource-conscious fertigation while minimizing manual intervention. The logic flow and signal processing are detailed in Figure 8, while Figure 9 shows the PCB circuit diagram used in the system.

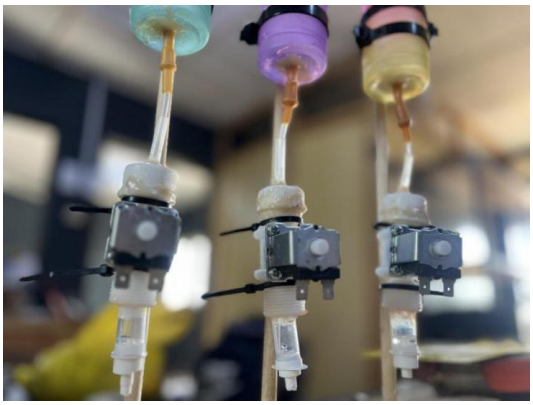


Figure 8. Working Principle of the Developed System

3.8 PCB Design for System Integration

A custom Printed Circuit Board (PCB) as shown in figure 9, was designed to integrate all the electronic components, including the NodeMCU, relay drivers, sensor terminals, and power supply regulators, into a single compact unit. This ensured reliable communication and power distribution across all modules.

3.9 Software Specification

The programming of the system was carried out using the Arduino IDE, which serves as a versatile platform for embedded systems development. It includes essential tools such as:

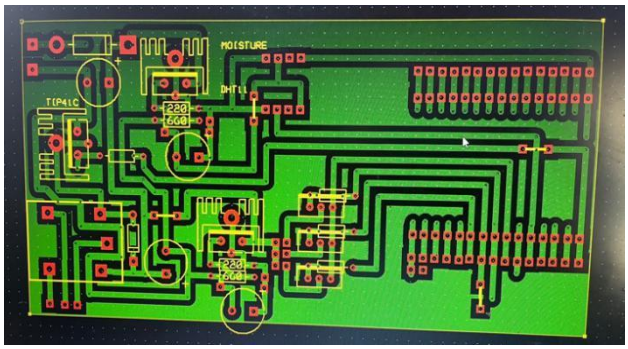


Figure 9. The PCB Diagram of the System

- A script editor for writing control code
- A compiler that converts the code into machine-readable HEX files
- A serial monitor for real-time debugging and data feedback

In addition, Arduino Create, the cloud-based counterpart of the IDE, supports collaborative development, allowing multiple users to contribute and track changes in real time.

The firmware for the NodeMCU microcontroller was written and compiled within this environment. The toolchain processes the source code and uploads the resulting HEX file to the board through a USB interface. Libraries such as Blynk and other sensor-specific packages were integrated to facilitate communication with IoT modules and hardware components. Leveraging Arduino's open-source infrastructure enabled streamlined prototyping, efficient logic testing, and quick iterations throughout the system development cycle.

3.10 Final Assembly of All Components

The final assembly included an aquarium pump for water distribution, with each of the three plastic containers filled with one of the primary macronutrient fertilizers, nitrogen (N), phosphorus (P), and potassium (K). Tubing was used to channel the fluids through solenoid valves controlled by the NodeMCU. The integration of all mechanical and electronic components was finalized on the support frame, ensuring stability and operational coherence.



Figure 10. Diagram of the fully Assembled Fertigation System

3.11 Evaluation Framework Using Technology Acceptance Model (TAM)

The system's usability and adoption potential were evaluated using the TAM as shown in table 1, which assesses users' acceptance of technological innovations based on four constructs: PU, PEOU, SI, and FC. The model, adapted from Gagnon et al. (2014), was employed to interpret feedback across different user groups associated with annual, biennial, and perennial crops.

- **Perceived Usefulness (PU):** Measured how effectively users believed the system enhanced crop yield and resource optimization. Annual crop users emphasized yield improvement, while biennial and perennial users highlighted cost and resource efficiency.
- **Perceived Ease of Use (PEOU):** Evaluated users' comfort with system setup, maintenance, and operation. Installation simplicity and system reliability were significant across all groups.
- **Social Influence (SI):** Assessed the role of peer recommendations and expert advice. Biennial crop users reported moderate influence from community or peer endorsements.
- **Facilitating Conditions (FC):** Examined availability of technical support, training, and infrastructure. Though not explicitly mentioned in responses, these conditions are critical to successful system deployment.

Table 1: Technology Acceptance Model (TAM) for the Fertigation System

Crop Types	Perceived Usefulness (PU)	Perceived Ease of Use (PEOU)	Social influence (SI)	Facilitating Conditions (FC)
Annual Crops	Extremely important - Increased crop yield	Costs, Ease of installation, Reliability	Not mentioned	Not mentioned
Biennial Crops	Very important - Resource savings	Ease of Installation, Reliability	Yes- Some users find it useful	Not mentioned
Perennial Crops	Very important - Resource savings	Ease of installation	Yes- Some users find it useful	Not mentioned

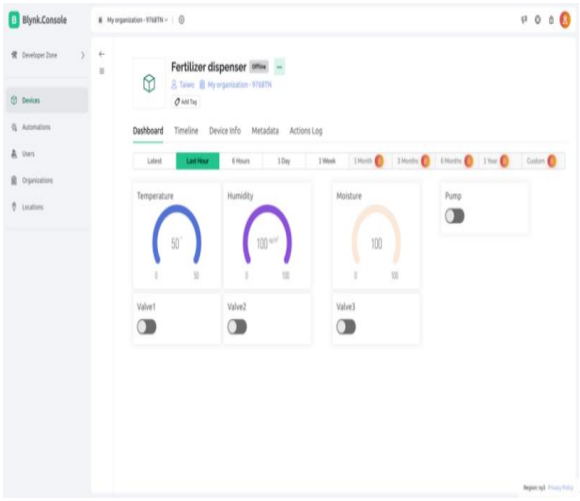
4. RESULTS AND DISCUSSION

4.1 Blynk IoT Dashboard

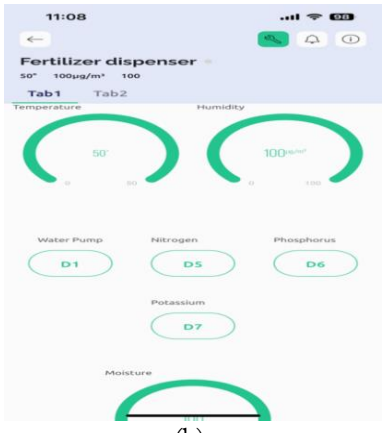
Custom dashboards were developed for both mobile and web platforms using the Blynk IoT environment to support remote monitoring and control functionalities. These dashboards enable users to view and interact with real-time system parameters through internet connectivity. Figures 11a and 11b illustrate the mobile and web interfaces of the dashboard, respectively.

The dashboard includes override switches designed to manually control solenoid valves as a fallback mechanism, providing essential operational flexibility in the event of system malfunction or emergency conditions. This hybrid control strategy ensures resilience in fertigation operations.

Graphical displays were incorporated to show time-series data for key variables such as soil moisture and nitrogen concentration. These trend lines allow users to monitor fluctuations over time, providing actionable insights into soil conditions. Additionally, the dashboard displays numerical sensor data in real-time and supports CSV file export functionality, enabling external data analysis or integration with farm management software.



(a)



(b)

Figure 11. The dashboard of the developed system
(a) Web dashboard; (b) Mobile dashboard

4.2 Fertigation Activation and Real-Time Soil Response

The system's responsiveness to soil nutrient and moisture levels was examined through a controlled fertigation event that occurred in the early morning hours. Figures 12a and 12b illustrate the immediate impact of activating the fertilizer and water valves at approximately 05:00 a.m.

In Figure 12a, soil nitrogen content was initially stable at approximately **14.6 mg/kg**, reflecting baseline nutrient levels before the fertilizer valve was opened. Following the activation, nitrogen levels began a sharp ascent, peaking at **29.4 mg/kg** shortly after 05:20 a.m., when the valve was automatically closed. This rise reflects the system's capability to monitor nitrogen availability and halt nutrient delivery upon reaching a predefined upper threshold, thereby preventing over-fertilization.

Similarly, Figure 12b demonstrates the system's response to irrigation control. The volumetric water content (VWC) of the soil rose dramatically from an initial **25.3%** to approximately **46.8%** within the same timeframe. The rapid moisture increase upon activation of the water valve indicates effective sensor response and irrigation delivery. The water valve was deactivated once the moisture threshold was reached, showcasing precise automated control.

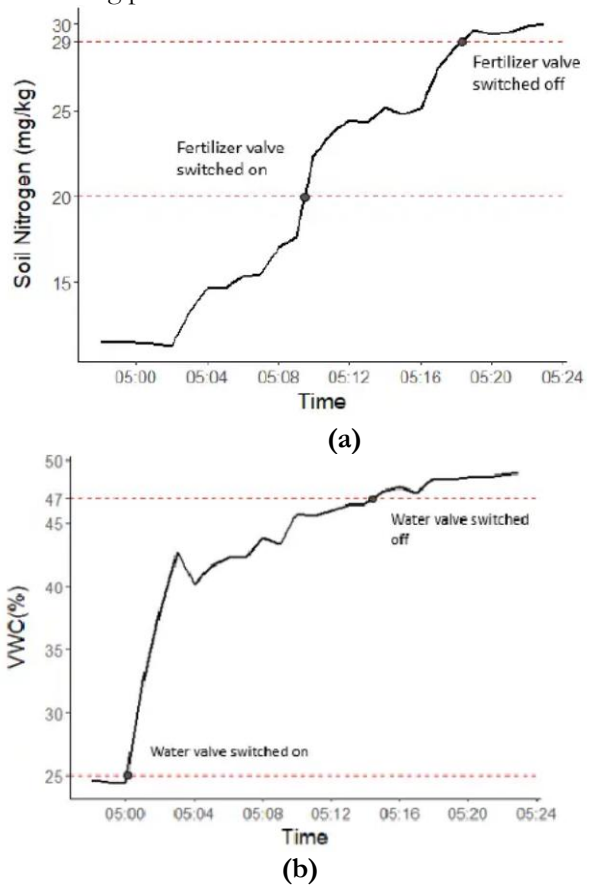


Figure 12. Performance evaluation of sensor-driven fertigation: (a) Nitrogen sensor readings; (b) Soil moisture sensor readings

4.3 Real-Time Feedback and Control Algorithm Efficiency

Figure 13 consolidates the trends of both nitrogen and moisture levels during the fertigation window. The graphical correlation between the sensor data and control actions clearly illustrates that the system executes a feedback loop wherein real-time soil data directly influences actuator behaviour. This closed-loop mechanism minimizes wastage while maintaining optimal nutrient and water levels, confirming the reliability of the control algorithm implemented.

4.4 Post-Fertigation Soil Dynamics

Longitudinal data presented in Figure 13 reflect the gradual depletion of soil resources over an extended time post-fertigation. Between 12:00 p.m. and 18:00 p.m., a steady decline in both soil moisture and nitrogen content was observed. Moisture content dropped from **42% to approximately 37%**, while nitrogen concentration decreased from **24.5 mg/kg to around 18.3 mg/kg**. These observations affirm the expected biological and environmental absorption patterns in real farming conditions.

This long-term monitoring capability not only supports real-time management but also provides historical data essential for refining fertigation schedules, forecasting crop nutrient uptake, and reducing operational guesswork.

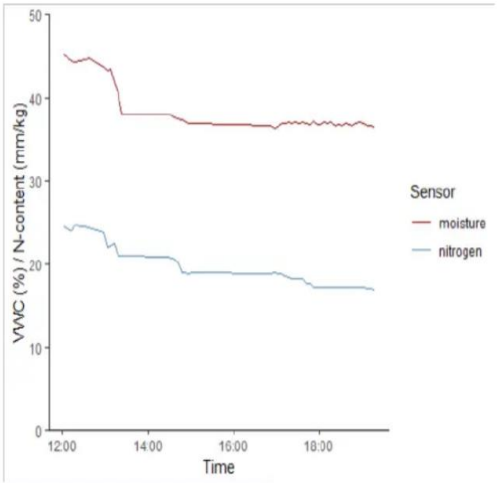


Figure 13: Longitudinal sensor data for soil moisture and nitrogen concentration

4.5 Key Discussion Points:

- Precision: The system reliably maintained soil variables within predefined thresholds, thereby ensuring resource-efficient application.
- Responsiveness: There was minimal lag between sensor detection and actuator response, validating the real-time operational logic.

- Sustainability: Long-term monitoring supports predictive scheduling, reducing over-irrigation and nutrient leaching.
- Scalability: The success of the pilot trial suggests adaptability to larger farm settings, particularly with more diverse nutrient integration in future upgrades.
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5. Conclusions and Recommendations

5.1 Conclusion

This study successfully developed and evaluated an automated fertigation system capable of remote monitoring and control via the Blynk IoT platform. The system integrates soil moisture and nitrogen sensors with an embedded microcontroller that executes an algorithm for optimal fertilizer application. The results demonstrate that sensor-based fertigation offers numerous benefits: precision nutrient delivery, significant reductions in manual labour, lower resource wastage, and enhanced crop management efficiency. When deployed at scale, the system has the potential to transform agricultural operations by improving input utilization and increasing farmers' profit margins. Although this implementation focused primarily on nitrogen as a critical nutrient, future works should consider integrating other essential macronutrients such as phosphorus and potassium to enhance the system's agronomic scope and versatility.

5.2 Recommendations

Investment in Research and Development: Stakeholders, including policymakers, private investors, and research institutions, should prioritize funding for IoT-based agricultural technologies. Areas of focus should include sensor calibration, energy-efficient hardware, and advanced data analytics tailored for soil and crop management.

- Education and Training: Comprehensive training programs should be instituted to equip farmers, extension officers, and agribusiness stakeholders with the knowledge required to operate and maintain IoT-enabled fertigation systems.
- Standardization and Interoperability: The adoption of standardized communication protocols and data formats will improve compatibility across devices and platforms, reducing integration challenges and promoting broader adoption.
- Data Privacy and Cybersecurity: Robust security frameworks—including encryption, authentication, and periodic audits—must be implemented to protect sensitive farm data from unauthorized access or cyber threats.
- Collaboration and Knowledge Sharing: Strategic partnerships between academia, government agencies, and the private sector should be fostered to drive innovation. Knowledge-sharing platforms should be established to disseminate best practices and accelerate adoption.
- Scaling and Demonstration Projects: Large-scale pilot projects should be conducted to demonstrate the practical viability of IoT-based fertigation systems. Such projects, supported by governmental or international agencies, will enhance visibility and build farmer confidence.
- Continuous Monitoring and Impact Assessment: Long-term studies should be conducted to evaluate the economic, environmental, and social outcomes of adopting IoT-enabled fertigation systems. These evaluations will inform policy decisions and guide future system enhancements.

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