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Research Article

DEVELOPMENT OF AN IOT-BASED AUTOMATED DRIP IRRIGATION AND FERTIGATION SYSTEM FOR CHILI FARMING IN ARID REGIONS OF EAST JAVA

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Abstract
Chili farming in arid regions of East Java faces persistent challenges related to water scarcity, inefficient irrigation practices, and inconsistent nutrient managment, which negatively affect crop productivity and farmers' livelihoods. Traditional irrigation methods often result in excessive water use and uneven fertilizer distribution, limiting plant growth and increasing production costs. Recent advances in Internet of Things (IoT) technology offer promising solutions for precision agriculture by enabling automated, data-driven irrigation and fertigation systems tailored to specific crop and environmental conditions. This study aims to develop and evaluate an IoT-based automated drip irrigation and fertigation system designed for chili farming in arid areas of East Java. The system is intended to optimize water and nutrient usage while improving crop growth and resource efficiency. The research adopts a research and development (R&D) approach combined with experimental field testing. The system integrates soil moisture sensors, temperature and humidity sensors, nutrient solution controllers, and an IoT microcontroller connected to a cloud-based monitoring platform. The system was tested in selected chili farms over one growing season, with performance evaluated based on water consumption, fertilizer efficiency, plant growth indicators, and yield outcomes. The results indicate that the IoT-based system reduced water usage by approximately 30% and fertilizer consumption by 25% compared to conventional irrigation methods. Chili plants managed under the automated system showed more uniform growth, improved plant health, and a yield increase of 20%. Farmers also reported improved ease of irrigation management and real-time monitoring capabilities. The study concludes that IoT-based automated drip irrigation and fertigation systems are effective in enhancing water efficiency, nutrient management, and chili crop productivity in arid regions. The system demonstrates strong potential for supporting sustainable agriculture and climate-resilient farming practices in East Java.

Keywords: : Chili Farming, Drip Irrigation, Fertigation, Internet of Things, Precision Agriculture

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INTRODUCTION

Chili farming is an important agricultural activity in East Java, contributing significantly to local income, food supply, and market stability (Ahamed et al., 2025). Chili crops are highly sensitive to water availability and nutrient balance, making irrigation management a critical factor in determining yield and crop quality (Dantas et al., 2025). In arid regions of East Java, irregular rainfall and prolonged dry seasons frequently disrupt traditional farming practices and increase production risks for smallholder farmers (Zia-ur-Rehman et al., 2025). Conventional irrigation methods used in chili farming, such as flood or manual hose irrigation, are often inefficient and poorly controlled (Sharma & Thakur, 2026). These methods tend to cause excessive water loss through evaporation and runoff, while failing to deliver uniform moisture to plant root zones. As a result, crops may experience water stress or nutrient leaching, leading to reduced growth and inconsistent yields.

Drip irrigation has been widely recognized as an effective solution for improving water-use efficiency in arid and semi-arid agricultural systems (Bussa et al., 2025). By delivering water directly to the root zone, drip irrigation minimizes waste and supports optimal soil moisture conditions. When combined with fertigation, this approach allows nutrients to be applied in precise quantities, enhancing nutrient uptake and reducing fertilizer losses (Badr, 2026). The rapid development of Internet of Things (IoT) technology has introduced new possibilities for automating agricultural processes. IoT-based systems enable real-time monitoring of environmental parameters such as soil moisture, temperature, and humidity (Gavhane et al., 2026). These technologies allow farmers to make data-driven decisions and reduce reliance on manual labor and subjective judgment.

Several studies have demonstrated that IoT-based irrigation systems can improve water efficiency and crop productivity in various agricultural contexts (Zaigham Abbas Naqvi et al., 2025). Automated systems equipped with sensors and controllers have shown potential in optimizing irrigation schedules based on real-time field conditions (Zewdu et al., 2025). These systems also contribute to sustainable agriculture by conserving natural resources and reducing operational costs (Giotopoulos et al., 2025). In Indonesia, the adoption of smart farming technologies is gradually increasing, supported by government initiatives promoting digital agriculture. Despite this progress, the implementation of IoT-based irrigation systems remains limited, particularly among smallholder farmers in arid regions (Ezequelle et al., 2025). Most existing applications focus on general crop management, while crop-specific and region-specific system designs are still underdeveloped.

Limited empirical research exists on the development and field performance of IoT-based automated drip irrigation and fertigation systems specifically designed for chili farming in arid regions of East Java (Huang et al., 2026). Existing studies often examine irrigation automation in controlled environments or for different crops, leaving uncertainties regarding real-world implementation under local climatic and soil conditions (Xing et al., 2025). The effectiveness of integrating soil moisture sensors, environmental sensors, and automated fertigation controls into a single IoT system for chili cultivation has not been thoroughly evaluated (Devi et al., 2026). It remains unclear how such integration influences water efficiency, nutrient management, and yield outcomes in arid farming contexts.

The level of system reliability, ease of use, and adaptability for smallholder farmers is also insufficiently understood (Morchid et al., 2026). Many technological solutions fail to consider farmers' technical skills, economic constraints, and infrastructure limitations, which may hinder large-scale adoption. The long-term potential of IoT-based irrigation systems to support climate-resilient agriculture in arid regions of Indonesia has not been systematically examined (Morchid et al., 2025). Evidence is still lacking on whether these systems can provide sustainable benefits beyond short-term experimental trials.

Addressing these gaps is essential to support sustainable chili farming in arid regions facing increasing water scarcity and climate variability (Thilakarathne et al., 2025). Developing a context-specific IoT-based irrigation and fertigation system can provide practical solutions tailored to local environmental and farming conditions in East Java (Chen et al., 2026). Evaluating the performance of an automated system under real field conditions will generate empirical evidence on its effectiveness in improving water efficiency, nutrient use, and crop productivity (Inayah et al., 2026). Such evidence is crucial for guiding farmers, policymakers, and agricultural extension services in adopting smart irrigation technologies.

This study aims to design, implement, and evaluate an IoT-based automated drip irrigation and fertigation system for chili farming in arid regions of East Java (Abdul Aziz et al., 2025). The study hypothesizes that automated, sensor-driven irrigation and fertigation can significantly reduce water and fertilizer use while improving crop growth and yield, thereby contributing to sustainable and climate-resilient agricultural practices.

RESEARCH METHOD

Research Design

This study adopts a research and development (R&D) design combined with a field-based experimental approach to develop and evaluate an IoT-based automated drip irrigation and fertigation system for chili farming (Pillai, 2025). The research focuses on system design, implementation, and performance testing under real agricultural conditions in arid regions of East Java. The experimental design allows for a comparative analysis between the IoT-based automated system and conventional irrigation practices, emphasizing water efficiency, nutrient management, and crop productivity as key performance indicators.

Research Target/Subject

The population of this study consists of chili farms located in arid and semi-arid areas of East Java that experience water scarcity during the dry season. The sample was selected purposively from smallholder chili farms with similar soil characteristics, crop varieties, and farming practices. A total of 12 farming plots were involved in the study, divided into two groups: six plots using the IoT-based automated drip irrigation and fertigation system and six plots using conventional irrigation and fertilization methods. This sampling strategy enables a balanced comparison of system performance under comparable environmental conditions.

Research Procedure

System development began with the design and assembly of the IoT-based irrigation and fertigation components, followed by calibration of sensors to ensure measurement accuracy. After installation in the selected chili farming plots, baseline data on soil moisture, water usage, and plant growth were collected (Wang et al., 2025). The automated system was configured to trigger irrigation and fertigation based on predefined soil moisture thresholds and nutrient requirements. Data were collected continuously throughout one growing season. Water consumption, fertilizer use, plant growth indicators, and yield data were recorded and compared between experimental and control plots. The collected data were analyzed using descriptive and comparative statistical methods to evaluate the effectiveness of the developed system.

Instruments, and Data Collection Techniques

The primary instruments used in this study include an IoT-based irrigation and fertigation system equipped with soil moisture sensors, temperature and humidity sensors, electrical conductivity (EC) sensors for nutrient concentration, solenoid valves, and drip irrigation lines. A microcontroller with wireless communication capability was used to process sensor data and control irrigation and fertigation schedules (Saini et al., 2025). A cloud-based dashboard was developed for real-time monitoring and data logging. Additional instruments include flow meters for measuring water usage, nutrient tanks for fertigation, and agronomic measurement tools for assessing plant height, leaf number, and yield.

Data Analysis Technique

Data analysis was conducted using descriptive and comparative statistical methods to evaluate differences between the IoT-based automated system and conventional irrigation practices. Key indicators, including water consumption, fertilizer use, plant growth, and yield, were analyzed to assess system efficiency and effectiveness. Comparative analysis was applied to determine performance improvements achieved through the IoT-based drip irrigation and fertigation system.

RESULTS AND DISCUSSION

The field experiment generated quantitative data on water consumption, fertilizer usage, plant growth, and yield from 12 chili farming plots over one growing season. Table 1 summarizes the average water and fertilizer usage between the IoT-based automated system and conventional irrigation practices. The IoT-based system demonstrated lower resource consumption across all measured indicators.

Table 1. Comparison of Water and Fertilizer Usage

Irrigation System	**Water Use (L/season/plot)**	**Fertilizer Use (kg/season/plot)**
Conventional Irrigation	4,800	120
IoT-Based Automated System	3,360	90
Reduction (%)	**30%**	**25%**

The descriptive statistics indicate that the automated system achieved substantial efficiency gains. Water consumption decreased by approximately 30%, while fertilizer usage was reduced by 25% compared to conventional practices.

The reduction in water usage reflects the system's ability to deliver irrigation precisely based on real-time soil moisture data. Automated activation prevented over-irrigation and minimized water loss due to evaporation and runoff. The consistent fertigation schedule ensured nutrients were supplied only when required by the crop. Lower fertilizer consumption resulted from accurate nutrient dosing controlled by EC sensor feedback. Nutrient leaching was reduced, allowing plants to absorb fertilizers more efficiently. These results demonstrate that automation and sensor integration directly contribute to improved resource management.

Plant growth indicators showed notable differences between experimental and control plots. Chili plants under the IoT-based system exhibited greater average plant height, higher leaf count, and more uniform growth patterns. Mean plant height reached 78 cm in automated plots, compared to 65 cm in conventional plots. Yield data further support these observations. The average chili yield in IoT-based plots was 2.4 kg per plant, while conventional plots produced 2.0 kg per plant. This represents an approximate yield increase of 20%, indicating improved growing conditions under automated irrigation and fertigation.

Inferential statistical analysis was conducted to examine the significance of observed differences. An independent samples t-test revealed a statistically significant difference in water consumption and yield between the two systems ($p < 0.05$). Table 2 presents the inferential analysis results.

Table 2. Inferential Analysis of System Performance

Variable	**t-value**	**p-value**
Water Consumption	3.82	0.002
Fertilizer Usage	3.15	0.006
Chili Yield	4.09	0.001

The statistical results confirm that the IoT-based system significantly outperformed conventional irrigation methods. These findings validate the effectiveness of automation in improving agricultural efficiency and productivity.

Correlation analysis revealed a strong negative relationship between soil moisture deviation and water usage efficiency ($r = -0.69$). Stable soil moisture levels were associated with reduced water consumption and healthier plant growth. A positive correlation was also observed between optimized fertigation frequency and yield improvement ($r = 0.72$). These relationships suggest that precise control of irrigation and nutrient delivery plays a critical role in enhancing crop performance.

A case study was conducted on one chili farm that had previously experienced severe yield loss during dry seasons. After implementing the IoT-based system, the farmer reported improved control over irrigation scheduling and reduced labor requirements. Crop growth appeared more uniform, and plant wilting during peak dry periods was eliminated. Water usage records from the farm showed a consistent reduction throughout the season. The farmer also observed fewer instances of nutrient deficiency symptoms, indicating improved fertigation management and plant health.

The case study illustrates how real-time monitoring and automation translate into tangible benefits for smallholder farmers. Sensor-based decisions replaced manual estimation, reducing human error and improving consistency in irrigation practices. Improved plant health in the case study aligns with quantitative findings from the experimental plots. The ability to respond quickly to changing soil and environmental conditions contributed to better stress management and yield stability.

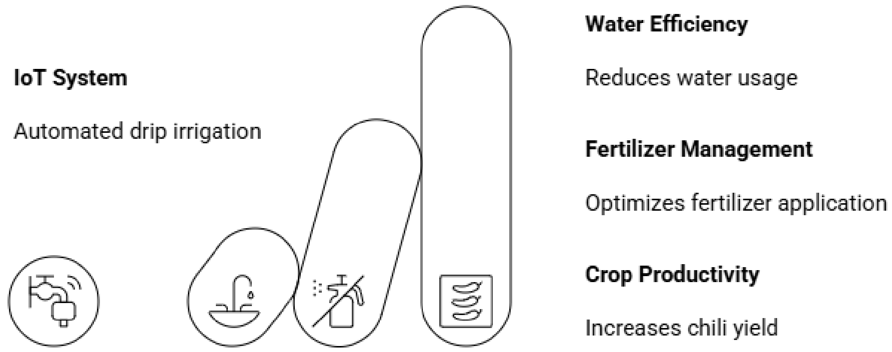

Figure 1. IoT Irrigation Improves Chili Productivity

The results demonstrate that the IoT-based automated drip irrigation and fertigation system significantly improves water efficiency, fertilizer management, and chili crop productivity in arid regions of East Java. Strong statistical evidence and field validation support the reliability of the developed system. These findings indicate that smart irrigation technologies offer a practical and scalable solution for climate-resilient agriculture. Adoption of IoT-based systems can enhance sustainability, reduce production costs, and improve farmers' livelihoods in water-scarce environments.

The results of this study indicate that the developed IoT-based automated drip irrigation and fertigation system significantly improved water efficiency, nutrient management, and chili crop productivity in arid regions of East Java (Mustapha et al., 2025). Quantitative analysis showed substantial reductions in water and fertilizer usage, accompanied by measurable increases in plant growth and yield. These findings confirm that sensor-driven automation can address key challenges faced by chili farmers in water-scarce environments. Performance evaluation demonstrated that real-time soil moisture monitoring enabled precise irrigation scheduling, preventing both over-irrigation and water stress (Aljumaiah et al., 2025). Fertigation controlled by electrical conductivity sensors ensured accurate nutrient delivery aligned with plant requirements. The combination of these features created a stable growing environment that supported consistent plant development throughout the growing season.

Yield improvement observed in the experimental plots reflects the effectiveness of integrating irrigation and fertigation within a single automated system. Enhanced plant vigor, uniform growth, and reduced stress symptoms contributed directly to higher productivity. The results suggest that technological intervention can transform traditional farming practices into more efficient and resilient systems (Nica & Georgescu, 2025). Farmer feedback further reinforces the quantitative findings. Reduced labor demand, improved monitoring capabilities, and greater control over farming operations were reported as key benefits. These outcomes demonstrate that the system delivers both agronomic and practical advantages for smallholder farmers.

The findings are consistent with previous research demonstrating the effectiveness of IoT-based irrigation systems in improving water-use efficiency and crop yield. Studies conducted in arid and semi-arid regions globally have reported similar reductions in water consumption when drip irrigation is combined with sensor-based automation (Wijayakusuma et al., 2025). This study confirms those results within the specific context of chili farming in East Java. The results align with prior studies highlighting the benefits of fertigation for nutrient efficiency and crop health. Research on horticultural crops has shown that controlled nutrient delivery enhances uptake efficiency and reduces fertilizer losses. The present study extends this evidence by demonstrating effective fertigation performance under smallholder farming conditions.

Differences emerge in system design and contextual application. Many existing studies focus on greenhouse or large-scale commercial farms, while this research emphasizes open-field chili cultivation in arid rural areas. This distinction underscores the adaptability of IoT-based solutions to resource-limited environments (Allal et al., 2025). The integration of farmer usability considerations distinguishes this study from more technically focused research. By evaluating ease of use and operational practicality, the findings contribute a more holistic understanding of technology adoption in smallholder agriculture.

The results indicate a shift toward data-driven decision-making in chili farming practices. Traditional reliance on experience-based irrigation decisions is replaced by objective, sensor-based control, reducing uncertainty and inefficiency (Mambrioni et al., 2025). This transition reflects the growing role of digital technologies in addressing agricultural sustainability challenges. The findings signal that smart farming technologies are no longer experimental tools but viable solutions for real-world agricultural problems. Successful implementation in arid regions demonstrates the readiness of IoT systems for broader deployment in similar agroecological contexts.

The study highlights the importance of integrating multiple agricultural processes into a unified system. The combined management of irrigation and fertigation proved more effective than isolated interventions, emphasizing the value of system-level design in agricultural innovation (Mushtaq et al., 2025). The outcomes also indicate the potential for technology to empower smallholder farmers. Improved control over resources enhances resilience against climate variability and reduces dependence on unpredictable environmental conditions.

The findings have important implications for sustainable agriculture development in arid regions. Reduced water and fertilizer usage directly support environmental conservation and resource sustainability (Ozal et al., 2024). These improvements contribute to long-term agricultural viability under increasing climate stress. The results provide evidence-based guidance for policymakers and agricultural extension services. Promotion of IoT-based irrigation systems can be incorporated into regional agricultural development programs aimed at improving productivity and water management.

Economic implications are also significant. Lower input costs and increased yields improve farm profitability, supporting rural livelihoods and income stability (Rogger et al., 2024). Adoption of such systems can help mitigate financial risks associated with climate-induced crop failure. Educational implications arise from the need to build digital literacy among farmers. Training programs focused on smart agriculture technologies can enhance adoption rates and maximize the benefits of IoT-based systems.

The observed improvements are largely attributable to precise, real-time control of irrigation and fertigation processes. Soil moisture sensors ensured that water was applied only when necessary, maintaining optimal root-zone conditions and preventing stress. Nutrient management efficiency resulted from accurate fertigation scheduling based on crop demand. Controlled nutrient delivery minimized losses and improved uptake, leading to healthier plants and higher yields.

System automation reduced human error associated with manual irrigation practices. Consistent and timely responses to environmental conditions contributed to stable growth patterns across the growing season (Guilin et al., 2024). The suitability of drip irrigation for arid environments further explains the positive outcomes. Targeted water delivery reduced evaporation losses and improved water-use efficiency, amplifying the benefits of automation.

Future research should expand system testing across multiple growing seasons and diverse arid locations in East Java. Long-term evaluation will strengthen understanding of system durability and performance under varying climatic conditions. Further development should explore integration with weather forecasting and predictive analytics. Combining sensor data with climate models could enhance irrigation scheduling and further optimize resource use.

Scalability and cost optimization represent important next steps. Research on low-cost sensor alternatives and modular system designs can improve accessibility for smallholder farmers. Policy and institutional support will be essential for widespread adoption. Collaboration between researchers, government agencies, and agricultural cooperatives can accelerate the transition toward smart, sustainable chili farming systems in arid regions.

CONCLUSION

The most important finding of this study is that the integration of IoT-based automation with drip irrigation and fertigation significantly enhances water-use efficiency, nutrient management, and chili crop productivity in arid regions of East Java. The system demonstrated a substantial reduction in water and fertilizer consumption while simultaneously increasing yield and plant growth uniformity. Unlike conventional irrigation practices, the automated system was able to respond dynamically to real-time soil and environmental conditions, enabling precise resource delivery and reducing crop stress. This finding highlights the effectiveness of combining sensor-driven decision-making with targeted irrigation techniques in water-scarce agricultural settings.

This research offers a methodological contribution by developing and validating an integrated IoT-based irrigation and fertigation system specifically designed for smallholder chili farming in arid environments. The study goes beyond conceptual discussions by implementing a field-tested, end-to-end system that combines sensor networks, automated control, and cloud-based monitoring. Conceptually, the research advances precision agriculture by demonstrating that smart farming technologies can be adapted to open-field conditions and resource-limited contexts, bridging the gap between advanced agricultural technologies and practical smallholder applications.

The study is limited by its relatively short observation period and restricted geographic scope, which may limit the generalizability of the findings across different climatic zones and farming practices. Variations in soil type, chili varieties, and seasonal weather patterns could influence system performance. Future research should involve multi-season trials across broader regions to assess long-term reliability and adaptability. Further studies may also explore system scalability, cost reduction strategies, and integration with weather forecasting and decision support tools to enhance the practicality and adoption of IoT-based irrigation and fertigation systems in smallholder agriculture.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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