

IoT-Based Automated Hydroponic System For Precision Lettuce Growth Management

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Abstract

Hydroponic lettuce cultivation requires continuous monitoring and regulation of environmental and nutrient conditions to ensure optimal plant growth and productivity. However, manual monitoring can be labor-intensive, time-consuming, and prone to human error. This study aimed to design, develop, and evaluate an IoT-Based Automated Hydroponic System for Precision Lettuce Growth Management that provides real-time monitoring and automated environmental control. Specifically, the system monitors temperature, humidity, pH level, electrical conductivity (EC), and water level while providing remote access through a web-based dashboard. The study employed a developmental-descriptive research design and followed the Agile Software Development Life Cycle (SDLC) in the design, development, and testing of the system. An ESP32 microcontroller, sensors, and cloud-based technologies were integrated into the prototype. Fuzzy logic control was applied to regulate temperature and humidity through automated misting and exhaust fan operations, while threshold-based control was utilized for pH and EC management. The system was evaluated by 30 purposively selected respondents consisting of IT professionals, agricultural experts, and hydroponic farmers using the ISO/IEC 25010:2011 Software Quality Model. Results revealed an overall mean score of 4.63 (SD=0.56), interpreted as Very Good. Usability and Interaction Capability obtained the highest mean score (4.75), followed by Functional Suitability (4.69), Portability (4.64), Performance Efficiency (4.49), and Reliability (4.46). The findings indicate that the developed system is functional, efficient, reliable, and user-friendly. The study concludes that the IoT-based automated hydroponic system effectively supports precision lettuce growth management, reduces manual intervention, and promotes sustainable agricultural practices.

Keywords: *Fuzzy Logic Control, Hydroponics, Internet of Things (IoT), Precision Agriculture, Smart Farming*

INTRODUCTION

Background and Rationale

Hydroponic farming has emerged as a sustainable agricultural method that enables soil-less crop production with efficient use of water and nutrients. It is particularly suitable for urban agriculture and areas with limited arable land. However, traditional hydroponic systems still rely heavily on manual monitoring of environmental and nutrient parameters such as pH, electrical conductivity (EC), temperature, humidity, and water level. This manual approach is prone to inconsistencies, inefficiencies, and human error, which may affect crop productivity and quality.

Recent advancements in Internet of Things (IoT) technology have enabled the development of automated agricultural systems capable of real-time monitoring and control. These systems improve efficiency, reduce labor requirements, and enhance precision in farming operations. Despite these advancements, there remains a need for affordable, scalable, and locally adaptable hydroponic automation systems, particularly for small-scale farmers in developing regions such as the Philippines.

Review of Related Literature

Existing studies emphasize that IoT-based smart farming systems significantly enhance agricultural productivity through continuous monitoring and automation of environmental conditions. Chandra and Dubey (2020) highlighted that IoT integration in hydroponics reduces human error and improves decision-making through real-time data acquisition. Similarly, Tatas et al. (2022) and Jain and Kaur (2024) emphasized improved resource efficiency and crop management through sensor-based systems.

Fuzzy logic control is widely used in agricultural automation to manage uncertain environmental conditions, particularly in temperature and humidity regulation. Meanwhile, threshold-based control systems are effective in maintaining nutrient stability by regulating pH and EC levels. However, literature also identifies limitations such as high implementation costs, system complexity, and limited adoption in local farming contexts, highlighting the need for simplified IoT-based hydroponic solutions.

Statement of the Problem

This study aimed to design and develop an IoT-based automated hydroponic system for precision lettuce growth management. Specifically, it sought to answer:

1. What system design and components are required for the development of the automated hydroponic system?
2. How can the system effectively monitor and control temperature, humidity, pH, EC, and water level?
3. How can fuzzy logic and threshold-based control be implemented in the system?
4. What is the level of acceptability of the system in terms of ISO/IEC 25010:2011 software quality characteristics?

Objectives of the Study

The study aimed to design, develop, and evaluate an IoT-based automated hydroponic system. Specifically:

1. Gather data needed for the design and development of the automated hydroponics system for lettuce growth.
2. Design a prototype of the lettuce hydroponics system integrating IoT-based monitoring of water acidity (pH), nutrient levels, temperature, humidity and water level.
3. Develop a web-based dashboard system that provides real-time monitoring and remote control of water acidity (pH), nutrient levels, temperature, humidity, and water level, allowing users to manage and monitor the hydroponics system without physically visiting the farm location.
4. Evaluate the developed automated hydroponic system in accordance with the ISO 25010:2011 software quality model.

MATERIALS AND METHODS

Research Design

The study employed a developmental and descriptive research design. The developmental aspect focused on system design and development, while the descriptive aspect focused on evaluating the system based on software quality characteristics. The Agile Software Development Life Cycle (SDLC) guided the development process.

Participants

The study involved 30 ($n = 30$) purposively selected respondents composed of IT professionals, agricultural experts, and hydroponic farmers. These respondents were chosen based on their expertise in information technology, agriculture, and hydroponic farming, ensuring that the evaluation reflected informed and relevant perspectives on the developed system.

Instruments

The system utilized: ESP32 Microcontroller, Arduino Uno, DHT11 Sensor, pH Sensor, EC Sensor, Water Level Sensor, Relay Module, Exhaust Fan, Misting System, Web-Based Dashboard. The evaluation instrument was adapted from the ISO/IEC 25010:2011 Software Quality Model.

Procedure

The study followed Agile SDLC phases including Project Initiation, Requirements Gathering, System Design and Prototype Development, Development, Testing, and Maintenance. The developed system continuously monitored environmental parameters and automatically regulated greenhouse conditions through fuzzy logic and threshold-based control.

Data Analysis

Weighted mean and standard deviation were used to analyze respondent evaluations. Software quality characteristics evaluated included Functional Suitability, Interaction Capability, Performance Efficiency, Usability, Reliability, and Portability.

RESULTS

Data Gathering Results

Data gathered from the review of related literature and interviews with a hydroponic farm owner identified the key requirements for the development of the IoT-Based Automated Hydroponic System for Precision Lettuce Growth Management. Both sources emphasized the importance of continuously monitoring temperature, humidity, pH, electrical conductivity (EC), and water level to maintain optimal lettuce growth. The interview findings confirmed the practical use of these parameters in hydroponic farming, particularly within a Nutrient Film Technique (NFT) system.

Both literature and interview results highlighted the need for proper pH and EC management, environmental regulation, and real-time monitoring to address challenges such as nutrient imbalance and environmental fluctuations. The findings also supported the use of IoT technologies, automated control mechanisms, and cloud-based monitoring to improve efficiency and reduce manual intervention.

Based on these findings, the developed system integrated sensors for monitoring key environmental parameters, ESP32-based communication for real-time data transmission, fuzzy logic control for temperature and humidity regulation, threshold-based control for pH and EC management, and a web-based dashboard for remote monitoring and data visualization. These requirements served as the foundation for the design and development of the proposed system.

Designed IoT-Based Automated Hydroponic System Prototype Result

Figure 1

Developed IoT-Based Automated Hydroponic System Prototype

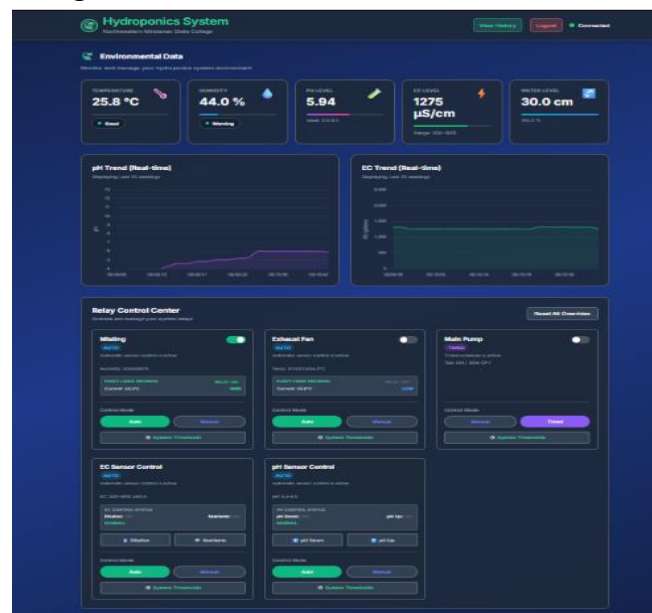


Figure 1 shows the developed hydroponic system prototype consisting of sensors, an ESP32 microcontroller, Arduino Uno, relay modules, nutrient reservoir, exhaust fan, misting system, and hydroponic growing channels. The prototype was designed to automate environmental monitoring and nutrient management for lettuce cultivation.

Developed Web-Based Dashboard for Real-Time Monitoring and Remote-Control Result

Figure 2

Web-based Monitoring Dashboard



The developed system includes a web-based monitoring dashboard that enables users to remotely monitor and manage hydroponic operations in real time. It successfully displayed real-time sensor data including temperature, humidity, pH, EC, and water level. It also provided graphical trends, historical records, and control functions for connected devices, allowing efficient remote monitoring and management.

Evaluation of the IoT-Based Automated Hydroponic System Result

Table 1 presented the evaluation results of the developed IoT-Based Automated Hydroponic System for Precision Lettuce Growth Management based on the ISO/IEC 25010 software quality characteristics.

Table 1

Descriptive Statistics of Participant Responses on System Quality Attributes

Software Quality Characteristic	Mean	SD	Interpretation
Functional Suitability	4.69	0.55	Very Good
Reliability	4.46	0.14	Good
Usability	4.75	0.50	Very Good
Performance Efficiency	4.49	0.60	Good
Interactive Capability	4.75	0.46	Very Good
Portability	4.64	0.62	Very Good
Overall	4.63	0.56	Very Good

The developed IoT-Based Automated Hydroponic System obtained an overall mean score of 4.63 (SD = 0.56), interpreted as Very Good, indicating high user acceptance and software quality. Usability and Interactive Capability received the highest ratings (M = 4.75), followed by Functional Suitability (M = 4.69) and Portability (M = 4.64), all interpreted as Very Good. Meanwhile, Reliability (M = 4.46) and Performance Efficiency (M = 4.49) were rated Good. These results suggest that the system effectively performs its intended functions, provides a user-friendly experience, and supports reliable hydroponic monitoring and control for precision lettuce growth management.

DISCUSSION

The findings of the study indicate that the developed IoT-based automated hydroponic system is highly acceptable, with an overall mean of 4.63 interpreted as “Very Good.” This result suggests that the system effectively satisfies user requirements in terms of monitoring, automation, and usability. The high ratings obtained in usability and interaction capability imply that the system is easy to use, intuitive, and supports effective real-time monitoring of

hydroponic parameters. Meanwhile, the good ratings in reliability and performance efficiency indicate that the system performs its intended functions consistently, although further improvements are still needed to enhance stability and operational efficiency under continuous use.

These results are consistent with previous studies that emphasize the effectiveness of IoT-based smart farming systems in improving agricultural productivity and resource management. Prior research such as Chandra and Dubey (2020) and Tatas et al. (2022) similarly found that IoT integration enhances real-time monitoring and reduces human error in hydroponic and agricultural systems. The use of fuzzy logic control in this study aligns with existing literature that highlights its effectiveness in handling uncertain environmental conditions such as temperature and humidity variations. Likewise, the implementation of threshold-based control for pH and EC regulation supports findings from earlier studies that emphasize its reliability in maintaining stable nutrient conditions. However, similar to related works, challenges in system reliability and performance optimization remain evident, indicating the need for further refinement in future implementations.

In terms of practical implications, the results suggest that IoT-based hydroponic systems can serve as an effective solution for precision agriculture, particularly for small-scale farmers. The system can reduce manual labor, improve monitoring accuracy, and enhance overall crop productivity. From a policy perspective, agricultural institutions and government agencies may consider supporting the adoption of low-cost IoT-based farming technologies as part of sustainable agriculture and food security initiatives. This can help promote digital transformation in agriculture and encourage the adoption of smart farming practices in both urban and rural settings.

Despite these positive outcomes, the study has several limitations. The evaluation was conducted using a relatively small sample size of 30 respondents, which may limit the generalizability of the findings. In addition, the system was tested in a controlled environment rather than in large-scale commercial hydroponic operations. The focus was also limited to lettuce cultivation, which may restrict applicability to other crops. Furthermore, long-term performance and durability testing were not conducted, limiting insights into the system's reliability over extended periods.

CONCLUSION

The study successfully designed, developed, and evaluated an IoT-based automated hydroponic system for precision lettuce growth management. The system integrated real-time monitoring of key environmental and nutrient parameters, including temperature, humidity, pH, electrical conductivity (EC), and water level, using sensor-based technology connected to an ESP32 microcontroller. The incorporation of fuzzy logic control for temperature and humidity regulation, along with threshold-based control for pH and EC management, enabled effective automation of the hydroponic environment. Evaluation results based on the ISO/IEC 25010:2011 software quality model yielded an overall mean of 4.63, interpreted as "Very Good," indicating

high acceptability in terms of functionality, usability, reliability, performance efficiency, interaction capability, and portability. These findings confirm that the developed system is effective in reducing manual intervention while supporting efficient and sustainable hydroponic lettuce cultivation.

To further enhance the system, future implementations should consider improving the physical infrastructure of the hydroponic setup. Respondents suggested the use of durable roofing materials such as plastic film or similar protective coverings to improve environmental protection. In addition, electrical components should be enclosed in waterproof and heat-resistant boxes or power stations to prevent electrical faults caused by heavy rainfall, excessive heat, or other environmental factors. These improvements can enhance the safety, reliability, and longevity of the system during actual field deployment.

Future researchers are encouraged to conduct additional testing involving a larger number of users and diverse agricultural settings to further validate the system's performance and identify areas for improvement. Long-term testing under different environmental conditions and cultivation cycles is also recommended to assess the system's stability, effectiveness, and adaptability. Furthermore, the system may be implemented and evaluated in larger-scale agricultural environments to determine its suitability for commercial hydroponic production and broader agricultural applications.

Additional enhancements may include the integration of more advanced sensors, mobile application support, automated notification systems, and data analytics features to further improve monitoring capabilities and user convenience. The incorporation of artificial intelligence, machine learning, and predictive analytics may also be explored to provide smarter decision-making and more efficient resource management. Lastly, future studies may investigate the adaptability of the system for other crops and farming environments, enabling wider adoption of automated hydroponic technologies and supporting the modernization of agricultural practices.

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