Applied Computer Science 2025, vol. 21, no. 4, pp. 47–58
https://doi.org/10.35784/acs_7793

Submitted: 2025-05-21 | Revised: 2025-06-24 | Accepted: 2025-06-30

Keywords: smart indoor farming, hydroponics, internet of things, data-driven control, environmental monitoring

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IoT-driven environmental optimization for hydroponic lettuce: A data-centric approach to smart agriculture

Abstract

An IoT sensor network enables real-time monitoring of key environmental parameters, including temperature, humidity, nutrient solution pH, and concentration. This system employs a rule-based expert system with dynamic threshold adjustments for automated control. Over a 35-day growth cycle (Days After Transplanting - DAT), the experiment revealed statistically significant improvement in lettuce growth within the smart indoor farming system compared to outdoor farming. Average increases were observed: 17.1% in plant weight, 16.9% in plant height, and 20.0% in the number of leaves. The IoT-based control system robustly maintained environmental parameters within optimal ranges, creating a stable and conducive growth environment. This approach highlights the transformative potential of integrating IoT and intelligent control logic for optimizing indoor hydroponic crop production, paving the way for more efficient and sustainable agriculture. The findings offer insights for future smart farming developments by demonstrating how IoT and intelligent control improve hydroponic lettuce yield.

1. INTRODUCTION

1.1. Background and motivation

Meeting the growing global demand for food requires innovative approaches to increasing agricultural production (Nikolov et al., 2023). However, Indonesia's food security situation faces challenges and is below average according to international assessments (Deswina & Priadi, 2020). Limiting factors such as land availability, infrastructure development, and the adverse effects of climate change, such as extreme weather events, contribute significantly to this decline (Widiastuti et al., 2024). Weakening food security has detrimental effects on community well-being and nutritional health. To address these challenges, utilizing limited space for independent food production through hydroponic cultivation is a viable solution (Qomariyah et al., 2022; Gaikwad et al., 2024). Hydroponics, a soilless cultivation method, relies on the precise management of water and nutrient solutions to support plant growth. Lettuce (Lactuca sativa), a leafy green vegetable, was selected for this study due to its rapid growth cycle, sensitivity to environmental conditions, and high economic relevance as a widely consumed crop.

While hydroponic systems can be implemented both indoors and outdoors, traditional environmental control in these systems often relies on manual adjustments or simple automated timers that may not dynamically respond to fluctuating environmental conditions or the specific needs of plants at different growth stages (Fidelis & Idim, 2020). This often results in static thresholds and a lack of real-time optimization. With the advent of Smart Farming 4.0, there is significant potential to increase agricultural sustainability and improve farmer decision making through data-driven insights from sensors and software (Prakash et al., 2023). Building on this, smart indoor farming is emerging as an advanced approach to overcome the limitations of conventional agriculture by providing a more controlled and intelligent growing environment (Martini et al., 2021). These systems often include artificial lighting, automated pest control, precise temperature control, and nutrient delivery.

Previous research has explored the application of automation in hydroponics to increase efficiency and yield (Oudah et al., 2024). In addition, the integration of Internet of Things (IoT) technologies has shown promise in enabling remote monitoring and control of agricultural environments, providing valuable data for optimizing resource use and improving crop health. However, the full potential of data-driven environmental control, where real-time data from IoT sensors is actively used to adjust and optimize environmental parameters, remains an area of active research. This gap in the effective use of real-time data for dynamic environmental adjustments, and the deeper integration of IoT sensing and expert control logic in innovative hydroponic systems, is the core motivation for this research. Our system uniquely combines real-time sensing, expert control logic, and dynamic thresholds to address these limitations.

1.2. Objective

The primary objective of this research is to investigate the impact of a data-driven environmental control system, enabled by the integration of Internet of Things (IoT) devices, on enhancing the growth and productivity of hydroponic lettuce within an innovative indoor farming system. Specifically, this study aims to: (1) Design and implement an IoT-based system for real-time acquisition of key environmental parameters relevant to lettuce growth, (2) Develop and apply data-driven strategies for automated adjustment of environmental control mechanisms based on the acquired sensor data, (3) Evaluate the effectiveness of the implemented data-driven control system in improving lettuce growth metrics and overall yield compared to a control group with potentially less dynamic environmental management, (4) Analyse the performance and reliability of the integrated IoT-based data acquisition and control system.

1.3. Significance

The findings of this research are expected to significantly contribute to the advancement of innovative indoor farming practices, particularly in hydroponic cultivation. This study provides a pathway towards more efficient, resource-optimized, and ultimately more productive indoor agriculture by demonstrating the effectiveness of a data-driven environmental control system powered by Internet of Things (IoT) technology. The insights gained can guide researchers, agricultural practitioners, and technology developers in designing and implementing intelligent ecological management systems for hydroponic farms. Furthermore, the successful application of such systems can enhance food security, especially in regions facing land limitations and climate variability, by enabling consistent and high-yield crop production in controlled environments. The emphasis on utilizing real-time data for informed decision-making in environmental control can also serve as a model for other applications within the broader scope of smart agriculture and data-driven resource management optimization.

2. RELATED WORKS

2.1. Smart hydroponic system and the imperative for advanced environmental control

Smart indoor farming, particularly hydroponics, has emerged as a promising alternative to traditional agriculture, offering controlled environments that mitigate the challenges of land scarcity and climate variability (Siregar et al., 2016). The success of these systems hinges on the precise management of environmental parameters critical for plant growth. While early innovative hydroponic implementations relied on basic automation and preset schedules (Suresh et al., 2024), the increasing availability of sophisticated sensors and control technologies necessitates a shift toward more dynamic and responsive environmental management strategies (Oudah et al., 2024). Studies have extensively documented the impact of individual environmental factors, such as temperature, humidity, and nutrient concentration, on the growth and yield of various crops in hydroponic settings (Chowdhury & Asiabanpour, 2024). However, optimizing these interconnected parameters in real-time based on actual plant needs and environmental fluctuations remains a significant challenge that motivates the current research.

2.2. The role of internet of things (IoT) in enabling real-time data acquisition for smart agriculture

The Internet of Things (IoT) has fundamentally transformed agricultural practices by enabling the collection and analysis of real-time data across various operational aspects (Bilal et al., 2023). In smart hydroponics, IoT devices provide continuous information about the growing environment, including sensors that measure the temperature, humidity, light intensity, pH, and electrical conductivity (EC) of the nutrient solution (Nikose & Mehare, 2023; Tatas et al., 2022). Research has focused on deploying diverse sensor technologies and wireless communication protocols for efficient data acquisition in agricultural settings(Oudah et al., 2024). Furthermore, developing robust and scalable IoT infrastructures for managing the large volumes of data generated in smart farms has been a subject of considerable attention (Tzounis et al., 2017). The ability of IoT to provide granular, real-time environmental data forms the crucial foundation upon which advanced, data-driven control strategies can be built, addressing the limitations of static or rule-based control systems. Many IoT-based agricultural platforms have emerged, though our system aims to improve upon them by offering a wider range of integrated parameters and a more dynamic closed-loop feedback mechanism.

2.3. Data-driven approaches to environmental optimization in hydroponic systems

Researchers have increasingly explored data-driven approaches to optimize environmental control in hydroponic systems by leveraging data from IoT sensors (Huang et al., 2024). In this context, "data-driven" refers to the system's ability to make automated control decisions and adjustments based on real-time sensor readings (Oudah et al., 2024) and predefined logical rules, rather than solely relying on static schedules or complex predictive models. Machine learning algorithms have been investigated for their potential to predict optimal ecological conditions based on historical data and real-time sensor readings. For instance, other studies utilized a recurrent neural network (RNN) to predict future temperature and humidity levels within a greenhouse environment, enabling proactive adjustments to maintain optimal conditions for tomato growth. While their study demonstrated the potential of RNNs for environmental forecasting, it focused on a greenhouse setting rather than a fully enclosed, innovative indoor hydroponic system, and the control actions were based on predictions rather than direct feedback from plant responses (Dhal et al., 2022; Soussi et al., 2024).

Furthermore, studies have explored the development of intelligent control systems that can automatically adjust parameters such as lighting duration and intensity, temperature, and nutrient delivery based on plant responses and environmental feedback (Lakhiar et al., 2018; Oudah et al., 2024). For example, Fu proposed a PID (Proportional-Integral-Derivative) controller integrated with sensor feedback to regulate the pH of a nutrient solution in a hydroponic system. Their work demonstrated improved stability in pH levels compared to manual control (Fu et al., 2021). However, their system focused on a single parameter and did not leverage the interdependencies between multiple environmental factors for holistic optimization. Other control paradigms like fuzzy logic systems and reinforcement learning have also been explored in smart agriculture for specific applications, often requiring complex model training or extensive data sets.

Recent work by Nikose and Mehare (2023) and Tatas et al. (2022) explored IoT-based hydroponic monitoring and control systems focusing on parameters like temperature, humidity, light intensity, pH, and EC, similar to our study. Similarly, a system by also presented an IoT-based automated indoor hydroponic farming system. Another relevant study by Oudah et al. (2024) discusses an IoT-based data-driven real-time monitoring system for controlling heavy metal concentrations in aquaponic solutions using a Linear Support Vector Machine (Linear-SVM). While innovative in addressing specific heavy metal issues through ML, their primary focus differs from our broader environmental parameter optimization (Dhal et al., 2023). Furthermore, the IoT-Based Hydroponic Monitoring and Control System for Sustainable Food Production also outlines a system that monitors temperature, humidity, pH, water, and light levels, employing AWS and Raspberry Pi for remote control (Ogbolumani & Mabaso, 2023). Our research distinguishes itself from these by specifically focusing on a rule-based expert system enhanced with dynamic threshold adjustments based on real-time data analysis, allowing for more nuanced and responsive control actions that consider the interplay of multiple environmental factors explicitly tailored for optimizing hydroponic lettuce growth.

Building upon these advancements, this research contributes by implementing and evaluating a specific IoT architecture for real-time environmental optimization in an innovative indoor hydroponic system for lettuce growth. Our approach differs from previous work by integrating data from a comprehensive suite of environmental sensors (temperature, humidity, light intensity, nutrient solution pH, and EC) into a rule-based expert system enhanced with dynamic threshold adjustments based on real-time data analysis. This enables more nuanced and responsive control actions that consider the interplay of multiple environmental factors, explicitly tailored for optimizing hydroponic lettuce growth. Moreover, we provide a detailed evaluation of the system's performance in a real-world experimental setup, assessing its impact on lettuce growth metrics and system reliability within the unique context of a fully controlled indoor environment.

3. RESEARCH METHODOLOGY

This research employs a quantitative experimental methodology focused on the design and implementation of an intelligent environmental control system for intelligent indoor hydroponic lettuce cultivation. At the core of this system is an integrated Internet of Things (IoT) architecture carefully designed for real-time data collection and automated adjustment of critical environmental parameters. This data-driven approach aims to optimize growing conditions and increase lettuce productivity.

3.1. System design and data acquisition

The IoT system consists of a tiered network of interconnected components, as shown conceptually in Figure 1 and detailed in Table 1. At the sensing layer, environmental sensors continuously monitor key parameters within the growth chamber. These include the PH Module 4520, which provides accurate measurements of the acidity of the nutrient solution (±0.1 pH based on typical sensor specifications for hydroponic applications); the TDS Analog V1.0 sensor, which quantifies nutrient concentration in parts per million (PPM); accuracy of ±10 PPM within its operating range); and the DHT11 sensor, which measures ambient temperature and humidity (accuracy of±2∘C for temperature and ±5% for humidity). The strategic placement of these sensors ensures comprehensive data collection throughout the hydroponic system. The tools and materials used in this smart indoor farming setup are listed in Table 1.

Tab. 1. Tools and materials used in smart indoor farming

No	Tools and Materials
1	5-Tier Storage Rack 120 cm x 40 cm x 180 cm
2	Insar Pipe 1.5 Inch & 2.5 Inch
3	8 Channel 5 Volt Relay
4	ESP 32 Shield BreadBoard & ESP 32 Development Board Wifi
5	Sensors: PH Module 4520, TDS Analog V1.0 & DHT11 Temperature Sensor
6	LED Strip Grow Light 5050 12v (5 Red & 1 Blue)
7	Aluminum Foil 1.2m x 25m
8	12V DC Pump & AQ 105 35W Water Pump
9	8cm Hydroponic Netpot
10	"Lettuce FORMOSA Rapids" Lettuce Seeds
11	Hydroponic Rockwool

The processing layer is anchored by an ESP32 microcontroller (specifically the ESP 32 Development Board Wifi), which serves as the central hub for data aggregation and execution of control logic. The ESP32 was chosen for its integrated Wi-Fi capabilities, sufficient processing power for real-time data processing, and its suitability for IoT applications due to its low power consumption and robust development community. Upon receiving raw data from the sensors via established communication protocols, the ESP32 processes these inputs in real time. The microcontroller generates actuation commands based on a predefined rule-based expert system augmented with the capability for dynamic threshold adjustments, as elaborated in Section 3.3.

The actuation layer translates these commands into physical actions via an 8-channel 5V relay. This relay controls various actuators, including the LED strip grow lights (which manage photoperiod and intensity), the 12V DC water pump (regulating nutrient solution circulation to the plant roots), and auxiliary components such as fans (used for temperature and humidity regulation within the enclosed environment).

Crucially, the system incorporates a closed-loop data logging mechanism, forming a continuous feedback loop. All sensor readings, corresponding control actions, and timestamps are recorded and stored. The system is designed to sample and respond to environmental changes approximately every 15 minutes, aligning with the data logging interval. This comprehensive dataset forms the foundation for subsequent analysis, enabling a thorough evaluation of the effectiveness of data-driven control strategies in maintaining optimal environmental conditions and their direct impact on the growth metrics of hydroponic lettuce plants. Furthermore, the Future Farmers mobile application, connected to a centralized server and database for hosting (as depicted in Figure 1), provides a user interface for real-time monitoring of sensor data and system status, offering the potential for manual intervention and system oversight. This centralized network architecture allows for efficient data integrity and minimizes latency for real-time monitoring. While energy consumption efficiency was beyond the primary scope of this study, the system was designed with sustainability in mind, incorporating a solar panel and charge controller for power management, and the overall electricity usage was quantified (as detailed in Table 3).

3.2. Experimental setup and data collection

The effectiveness of the developed data-driven environmental control system was evaluated through a controlled experiment conducted within a dedicated smart indoor farming chamber. The growth chamber dimensions were implicitly defined by the 5-Tier Storage Rack measuring 120 cm×40 cm×180 cm. For lighting, LED Strip Grow Light 5050 12V (5 Red & 1 Blue) were used, operating on a 12-hour light cycle. Airflow within the enclosed environment was managed by auxiliary fans, controlled by the system for temperature and humidity regulation.

Thirty-three (33) 'Lettuce FORMOSA Rapids' plants served as the experimental units, cultivated using a Nutrient Film Technique (NFT) system. The NFT setup, facilitated by Insar pipes and a recirculating 12V DC pump (as detailed in Table 1 and Figures 1 and 2), ensured consistent nutrient solution delivery to the plant roots. Before the experiment, all sensors (PH Module 4520, TDS Analog V1.0, and DHT11) were calibrated according to manufacturer specifications to ensure accurate and reliable readings. The initial environmental baseline conditions in the smart indoor farming chamber were established according to the setpoints outlined in Table 2

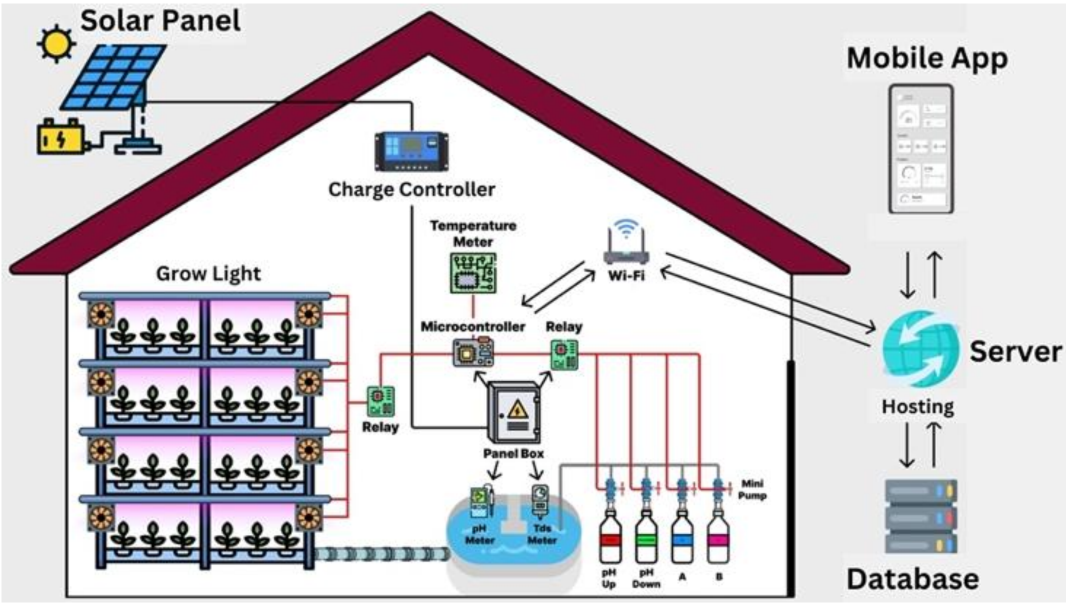

Fig. 1. Smart indoor farming design

Fig. 2. 3D Smart indoor farming rack

The experiment spanned 35 days after transplantation (DAT), during which the data-driven control system autonomously managed the environmental conditions within the growth chamber. The target setpoints for these conditions are outlined in Table 2, and the IoT-based control system actively worked to maintain these parameters, dynamically adjusting them based on the real-time data and control logic described in Section 3.3. Environmental data, including temperature(°C), relative humidity (%), light intensity (lux), nutrient solution pH, and nutrient concentration (PPM), were automatically collected by the integrated IoT sensor network. Data was collected and actions were taken approximately every 15 minutes, which served as the sampling frequency for the closed-loop control system.

Tab. 2. Smart indoor farming conditions for lettuce growth

Environmental Parameter	Setpoint
Room Temperature	24°C-32°C
LED Light Intensity	5,000 Lux
LED Light Color	Blue and Red
LED Light Duration	12 hours
pH	6.0-7.0 pH
Nutrient Concentration	560-840 PPM
Solution Temperature	22°C-29°C

In parallel, key plant growth metrics were meticulously measured by direct observation at regular intervals (e.g., every 3 days) to assess the impact of the data-driven environmental control. Specific growth parameters quantified included (1) plant height (cm): Measured from the base of the stem to the tip of the largest leaf, (2) Number of leaves: Counted all fully developed leaves on each plant, (3) Plant fresh weight (grams): Measured using a calibrated digital scale immediately after harvesting a subset of plants at the end of the experimental period. In addition to quantitative metrics, qualitative observations of plant health, such as leaf color and visible signs of stress or nutrient deficiencies, were tracked periodically to provide a holistic view of plant well-being.

To provide a robust baseline for comparison and to further isolate the impact of the data-driven control, a control group of ten (10) Lettuce FORMOSA Rapids plants (n=10) was grown in a separate, identically sized Smart Indoor Farming setup. This control group used a less dynamic approach to environmental management, relying on fixed lighting and nutrient delivery schedules with manual adjustments for other parameters. This design ensured that both experimental and control groups were of the same variety and grown under controlled conditions, with the key differentiating factor being the level of environmental management dynamism. Environmental data were also recorded in the control group setup to quantify the differences in environmental stability achieved by the data-driven system. Growth metrics for the control group were measured using the same methods and intervals as the experimental group, allowing for a direct quantitative comparison of the two cultivation strategies.

Statistical analysis was performed on the collected growth metrics. Differences between the experimental group (intelligent indoor farming with data-driven control) and the control group (outdoor farming, based on section 4.1 for comparison) were assessed using a t-test, with statistical significance set at $p<0.05$. The nutrient concentration was dynamically adjusted based on the control logic of the system, which monitored pH trends as an indicator of nutrient uptake and triggered periodic replenishment of the nutrient solution as described in Section 3.3. For transparency and reproducibility, the authors are considering making the raw sensor data and plant growth metrics publicly available through a data repository or on request.

3.3. Data processing and environmental control logic

The core of this study's intelligent environmental control lies in the real-time processing of data acquired from the IoT sensor network by the ESP32 microcontroller. This microcontroller executes a rule-based expert system, where predefined optimal ranges and tolerance thresholds for each critical environmental parameter (as specified in Table 2) trigger specific actuation commands to maintain the desired growing conditions for the hydroponic lettuce.

The control logic follows: Raw data packets from the pH, TDS, and DHT11 sensors are continuously received and processed by the ESP32. These readings are then compared against the predefined setpoints and their allowable deviations. For instance, if the room temperature, as measured by the DHT11 sensor, falls below 24°C or exceeds 32°C for a continuous period of 10 minutes, a signal is sent to the relay to activate or deactivate the ventilation fans, respectively, until the temperature returns to the optimal range. Similarly, suppose the pH of the nutrient solution deviates from the 6.0-7.0 range. In that case, the microcontroller will activate a small peristaltic pump to introduce pH-up or pH-down solutions in a controlled manner until the desired pH level is achieved. The duration and frequency of these adjustments are governed by predefined rules based on the magnitude and persistence of the deviation. The rule-based expert system consists of approximately 15-20 distinct rules, covering various environmental parameters and their corresponding actuation logic, along with rules for dynamic threshold adjustments.

To enhance the system's adaptability and responsiveness to the dynamic needs of the lettuce plants throughout their growth cycle, the control logic incorporates dynamic threshold adjustments for specific parameters. For example, the optimal light intensity of LED grow lights can be adjusted based on the Days After Transplanting (DAT). During the initial vegetative growth phase (e.g., 1-10 days after transplanting), the target light intensity may be set at 4,500 Lux. As the plants mature and enter a more rapid growth phase (e.g., 11-25 days after transplanting), the target intensity can be increased to 5,500 Lux. This adjustment is implemented through a lookup table stored in the microcontroller's memory, which is updated based on the elapsed data time (DAT). The microcontroller references this table in real-time to determine the appropriate light intensity setpoint.

Furthermore, the nutrient concentration (in parts per million, PPM) is managed based on a combination of predefined ranges and feedback from the pH sensor. A consistently declining pH trend over 12 hours, even within the acceptable range, may indicate increased uptake of plant nutrients. In such cases, the microcontroller can briefly activate the main solution pump to replenish the reservoir with a slightly more concentrated solution, proactively addressing potential nutrient deficiencies.

The microcontroller logs all sensor readings and corresponding actuation commands, along with precise timestamps, and transmits them wirelessly to the Future Farmers mobile application for real-time monitoring and data visualization. This comprehensive logging enables post-experiment analysis of the control system's performance in maintaining stable environmental conditions and its correlation with observed plant growth metrics. The user also retains the ability to manually override automated controls via the mobile application if necessary, providing an additional layer of intervention.

4. RESULTS AND DISCUSSION

4.1. Impact of data-driven environmental control on lettuce growth

This research investigated the impact of a data-driven environmental control system, enabled by integrated Internet of Things (IoT) technology, on the growth and yield of hydroponic lettuce cultivated in a controlled indoor environment. The experiment, conducted over a 35-day growth cycle (Days After Transplanting - DAT), involved the continuous monitoring and automated adjustment of key environmental parameters (temperature, humidity, light intensity, nutrient solution pH, and nutrient concentration) based on real-time sensor data and a predefined rule-based expert system with dynamic threshold adjustments (as detailed in Section 3.3).

To evaluate the effectiveness of this system, the final average growth metrics of lettuce plants grown within the smart indoor farming setup utilizing data-driven environmental control were compared to those cultivated in a traditional outdoor farming environment over the same 35-day period. The comparative results are summarized in Table 3.

Tab. 3. Comparison of final average plant growth metrics (35 DAT)

Metric	Outdoor Farming (n=10)	Smart Indoor Farming (Data-Driven Control) (n=33)	Percentage Change (%)
Average Weight (g)	76 ± 5.2	89 ± 6.8	+17.1%*
Average Height (cm)	20.1 ± 1.8	23.5 ± 2.1	+16.9%*
Average Leaves	10 ± 1.1	12 ± 1.3	+20.0%*

Note: Asterisk indicates statistically significant difference ($p < 0.05$) based on t-test

The data presented in Table 4 shows a statistically significant improvement in key lettuce growth metrics in the intelligent indoor farming system using data-driven environmental control compared to the outdoor farming method. The average fresh weight of lettuce grown indoors was 89 grams, a 17.1% increase over the 76 grams observed in the outdoor group. Similarly, the average plant height reached 23.5 cm in the controlled environment, a 16.9% improvement over the 20.1 cm in outdoor conditions. The number of leaves per plant also showed a significant increase of 20.0%, with an average of 12 leaves in the innovative indoor system versus 10 leaves in the outdoor environment. All of these improvements were statistically significant ($p<0.05$), confirming the robustness of the results.

These results strongly suggest that the controlled and optimized environmental conditions of the smart indoor farming system, facilitated by data-driven control, are significantly more conducive to robust lettuce growth than the fluctuating and less predictable conditions of outdoor farming. This is consistent with existing literature highlighting the benefits of controlled environment farming in maximizing crop yield and quality (Miller et al., 2020; Zhao et al., 2024). The consistent maintenance of optimal environmental parameters achieved by the IoT-based system is expected to contribute to these improved growth results.

4.2. Performance of the IoT-based environmental control system

In addition to evaluating the impact on plant growth, a critical objective of this research was to assess the performance and stability of the implemented IoT-based environmental control system in maintaining the predefined optimal ranges for key ecological parameters within the smart indoor farming chamber (as shown in Table 2). Continuous data logging from the integrated sensor network provided a detailed temporal record of temperature, relative humidity, nutrient solution pH, and nutrient concentration (ppm) throughout the 35-day experimental period.

The average room temperature was maintained at 27.8 ± 1.2 °C, demonstrating high stability around the desired set point of24∘C-32∘C. Fluctuations were minimal and typically occurred within a narrow range in response to internal heat generation from the LED lights and variations in ambient temperature. The system responded effectively to detected environmental variations, demonstrating its ability to maintain parameters within optimal ranges. Relative humidity was maintained at an average of 65±4%, within the optimal range for lettuce growth. The automated fan system, controlled by a microcontroller based on temperature and humidity readings, effectively mitigated significant deviations from these set points. The system was designed to minimize adverse trade-offs by ensuring that maintaining a stable temperature did not unduly affect other parameters, such as humidity, or result in excessive energy consumption beyond the operational design of the system.

The pH of the nutrient solution was tightly controlled within the target range of 6.0-7.0 pH, with an average of 6.5±0.2 pH. The automated pH adjustment mechanism, triggered by pH sensor readings and the controlled release of pH up or down solutions, proved effective in counteracting natural drifts in solution acidity due to nutrient uptake by the plants. The frequency and duration of these adjustments were dynamically managed by the control logic (as described in Section 3.3) to ensure a stable and optimal pH environment for nutrient uptake. The nutrient concentration, measured in parts per million (PPM), was maintained within the desired range of 560-840 PPM, with an average of 710±35 PPM. The control system's strategy of monitoring pH trends as an indicator of nutrient uptake and triggering periodic replenishment of the nutrient solution demonstrated a proactive approach to nutrient management. The relatively small standard deviation indicates stable nutrient availability throughout the experiment.

The consistent maintenance of environmental parameters within target ranges, facilitated by real-time data collection and automated adjustments in our IoT-based system, is in stark contrast to the challenges often encountered in traditional hydroponic systems. As discussed in Section 2.1, these conventional setups rely on periodic manual checks and adjustments, resulting in greater fluctuations in temperature, pH, and nutrient levels. Our data-driven approach minimizes this variability, providing a more stable and consistently optimal environment for improved lettuce growth.

During the 35-day trial period, the system operated reliably. There were no significant system failures or prolonged sensor failures that would compromise data integrity. The integrated control logic handled minor environmental variations and maintained system stability, demonstrating the robustness of the design.

5. DISCUSSION

The results of this study provide compelling evidence for the effectiveness of a data-driven environmental control system, enabled by an integrated Internet of Things (IoT) architecture, in enhancing the growth and yield of hydroponic lettuce within a controlled indoor environment. The significant improvements observed in plant weight (17.1%), height (16.9%), and number of leaves (20.0%) compared to outdoor farming, as detailed in Table 4, underscore the substantial benefits of precisely managed environmental conditions. This finding is consistent with the broader literature on controlled environment agriculture (Dutta et al., 2023; Zhao et al., 2024).

The successful implementation of a rule-based expert system with dynamic threshold adjustments enabled nuanced and responsive control of the growing environment. For instance, adjusting light intensity based on the plant's developmental stage (as outlined in Section 3.3) likely contributed to the enhanced biomass accumulation and leaf production. Similarly, the proactive management of nutrient solution pH, informed by real-time sensor data, ensured optimal nutrient availability for plant uptake—a critical factor in maximizing yield (Chowdhury & Asiabanpour, 2024; Islam et al., 2014). The system's ability to maintain stable temperature and humidity levels also minimizes potential stress factors hindering plant growth, particularly when compared to the conditions often experienced outdoors.

While previous studies may have focused on specific environmental parameters or employed different control algorithms, this research demonstrates the effectiveness of an integrated IoT system in managing multiple critical factors in a cohesive and data-driven manner for lettuce cultivation (Liu & Xu, 2018). A rule-based expert system with dynamic adjustments offers a practical and potentially scalable approach for optimizing indoor hydroponic environments. The achieved growth metrics for lettuce in this study are competitive with optimal yields reported in existing literature for indoor hydroponic cultivation, indicating the system's effectiveness in creating highly conducive growth conditions.

Regarding scalability, the modular design of the IoT architecture, particularly the use of standard sensors and microcontrollers, suggests a strong potential for scaling to larger indoor farming operations or even commercial greenhouse settings by adding more sensing and actuation nodes within a centralized control framework. However, such large-scale deployments would necessitate more robust network infrastructure and potentially distributed processing capabilities to handle increased data volumes.

For cost analysis, while beyond the scope of this experimental study, the initial hardware costs are relatively low for a small-scale setup, as indicated by the components listed in Table 1. A detailed economic analysis, including hardware, installation, maintenance, and operational costs (like electricity usage, which was quantified in Table 3), along with a potential Return on Investment (ROI) estimation, would be crucial for commercial viability assessments and is suggested as a vital area for future research.

Although direct energy consumption efficiency was not the primary focus of this study , the system's design considered sustainable power integration through a solar panel and the overall electricity usage was quantified. Future work should indeed focus on optimizing energy use while maintaining optimal growing conditions, integrating more advanced renewable energy sources, or utilizing more energy-efficient control algorithms.

Limitations of the current system include: Its rule-based nature, while effective, might exhibit rigidity compared to more adaptive AI-driven approaches, especially in unforeseen environmental scenarios or for different plant varieties. The system also currently lacks advanced predictive capabilities, such as real-time weather prediction or sophisticated plant growth modeling, relying instead on immediate sensor feedback and dynamic thresholds. While demonstrating controlled indoor environment benefits, scalability limits in extreme commercial settings without architectural re-evaluation also remain a consideration.

The successful implementation of this data-driven environmental control system in a smart indoor farming setup has significant implications for enhancing food security, particularly in urban environments and regions facing land and water scarcity (Hebert et al., 2022). Such systems can contribute to more resilient and sustainable food systems by enabling consistent and high-yield crop production in controlled environments. The principles demonstrated in this research can also be applied to other areas of smart agriculture, underscoring the potential of IoT and data analytics to enhance resource management and improve agricultural productivity.

6. CONCLUSION

This research has successfully demonstrated the significant potential of a data-driven environmental control system, enabled by integrated Internet of Things (IoT) technology, to enhance the growth and yield of hydroponic lettuce within a controlled indoor farming environment. The real-time monitoring and automated adjustment of critical environmental parameters, including temperature, humidity, pH, and nutrient concentration, driven by an implemented rule-based expert system with dynamic threshold adjustments, resulted in substantial improvements compared to traditional outdoor farming methods. Specifically, the innovative indoor farming system yielded a 17.1% increase in average plant weight, a 16.9% increase in average plant height, and a 20.0% increase in the number of leaves (as detailed in Section 4.1).

The stability and precision of the environmental conditions maintained by the IoT-based control system (as evidenced in Section 4.2) played a crucial role in achieving these enhanced growth metrics. By proactively responding to sensor data and dynamically adjusting actuators such as LED grow lights and nutrient delivery systems, the system created a consistently optimal environment for lettuce development, mitigating the challenges associated with fluctuating external conditions and less automated hydroponic setups (as discussed in Section 2.1). Furthermore, the enclosed nature of the smart indoor farm contributed to effective pest control, reducing the risks associated with infestations often encountered in open agricultural systems.

The successful implementation of this data-driven approach highlights the transformative potential of integrating IoT and intelligent control logic in smart agriculture. The ability to monitor and manage environmental variables in real time optimizes plant growth and facilitates more efficient resource utilization, including water and nutrients. This smart agricultural method directly contributes to achieving Sustainable Development Goal (SDG) 9 by fostering resilient infrastructure and promoting inclusive and sustainable industrialization. Although the system's energy consumption was quantified (as shown in Table 3), future research could investigate strategies for further enhancing energy efficiency.

Despite the promising results, this study also identifies avenues for future development. Integrating more sophisticated sensors for detailed plant phenotyping, early stress detection, and advanced machine learning algorithms for predictive environmental control and resource optimization could enhance the system's intelligence and efficiency. Specific areas for AI integration include fuzzy logic for more nuanced decision-making, reinforcement learning for optimal policy discovery, or LSTM (Long Short-Term Memory) networks for predictive modeling of parameters like pH trends or nutrient uptake. Exploring such systems' scalability and economic viability for broader adoption in commercial agriculture remains another critical direction for future research.

Founding

This research was supported by The LPPM Universitas Pelita Harapan Grants No. 154/LPPM-UPH/VII/2024 and The Kemdiktisaintek Grants No. 070/C3/DT.05.00/PL/2025.

Conflicts of Interest

The authors declare no conflict of interest.

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