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Development of an Artificial Intelligence-Based Smart Greenhouse System to Optimize Vegetable Production

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ABSTRACT

Purpose: *This study aims to assess the effesctiveness of an Artificial Intelligence (AI)-based smart greenhouse system in improving vegetable growth and yield, particularly lettuce, compared to conventional greenhouse methods. The primary focus of the study is to evaluate the system's effect on microenvironmental stability, vegetative growth, and crop yield.*

Subjects and Methods: *The research subjects were lettuce plants cultivated for eight weeks in two treatments: an AI-based smart greenhouse and a conventional greenhouse. The smart greenhouse system uses temperature, humidity, and light sensors, as well as AI algorithms to automatically regulate environmental and nutritional conditions. Observed parameters included average temperature and humidity, plant height, leaf number, and wet and dry harvest weights. Data were analyzed descriptively and comparatively by calculating the average, standard deviation, and percentage increase between treatments.*

Results: *The results showed that the smart greenhouse was able to maintain a more stable temperature (25.8–26.2 °C) compared to the conventional greenhouse (28.3–29.4 °C) and higher humidity (68–69% vs. 58–60%). Lettuce growth was also more optimal, indicated by an average height of 36.2 cm and a leaf count of 29.2 in the smart greenhouse, higher than the conventional greenhouse (28.7 cm and 23.8 leaves). Harvest weight in the smart greenhouse reached 325.7 g (wet) and 47.8 g (dry), higher than the conventional greenhouse (245.3 g and 36.4 g).*

Conclusions: *AI-based smart greenhouse systems have proven more effective in optimizing vegetable growth and yields. This technology can be a strategic solution for increasing agricultural productivity in a sustainable, efficient, and environmentally friendly manner.*

INTRODUCTION

Modern agriculture currently faces significant challenges in the form of increasing global food demand, climate change, and limited natural resources (Devlet, 2021; Khatri et al., 2024; Calicioglu et al., 2019). One sector severely impacted is vegetable production, which requires specific environmental conditions for optimal growth. Climate instability, erratic rainfall, and extreme temperatures often lead to decreased productivity and crop quality (Janmohammadi & Sabaghnia, 2023; Raza et al., 2024). Therefore, technological innovation in agricultural cultivation systems is needed to create a more controlled and sustainable environment.

Greenhouses are a technology widely used in vegetable cultivation to protect plants from external environmental disturbances (Ahmed et al., 2024). However, manual greenhouse management is often inefficient, labor-intensive, and difficult to ensure optimal conditions for plant growth. In this context, the need for digital technology integration in greenhouse management is increasingly pressing to increase productivity and resource efficiency.

According to Soheli et al. (2022), the development of Internet of Things (IoT) technology, sensors, and automated control systems has brought significant changes to the implementation of the smart greenhouse concept. Smart greenhouses enable real-time monitoring of environmental conditions such as temperature, humidity, light intensity, and nutrient levels (Bersani et al., 2022). The collected data can then be used to automatically regulate watering, lighting, ventilation, and nutrient application (Ali et al., 2023). Duan et al. (2019) said that, however, for this system to be truly effective, algorithms capable of analyzing data and making intelligent decisions are needed.

Artificial Intelligence (AI) presents a potential solution for optimizing smart greenhouse performance. With its capabilities in machine learning and deep learning, AI can predict crop needs, detect potential disturbances, and provide more precise management recommendations. For example, AI can analyze plant growth patterns and identify the relationship between environmental factors and crop yields (Malashin et al., 2024). Thus, this technology not only automates the system but also improves the quality of data-driven decision-making.

The application of AI in smart greenhouses also supports the concept of precision agriculture, which emphasizes input efficiency and increased crop yields (Hoseinzadeh & Garcia, 2024). Through AI integration, greenhouse systems can adjust environmental conditions to suit the specific needs of crops, thereby reducing water, fertilizer, and energy waste. This is highly relevant to efforts to achieve sustainable agriculture amidst global resource constraints.

Furthermore, AI-based smart greenhouses can help small and medium-sized farmers increase productivity by leveraging data-driven technology. With easier access to automated monitoring and control systems, farmers can reduce the risk of crop failure due to unforeseen environmental factors (Gupta et al., 2024). Another advantage of this system is its ability to provide historical data that can be used for evaluation and long-term cultivation planning.

Several previous studies have demonstrated the effectiveness of smart greenhouse applications, but most are limited to simple automation without the full utilization of artificial intelligence (Maraveas, 2022; Escamilla-García et al., 2020). Therefore, there is still significant opportunity to develop more adaptive and responsive smart greenhouse systems by integrating advanced AI algorithms. This will result in a system that is not only reactive to environmental conditions but also proactive in predicting future crop needs (Sivakumar, 2006).

Therefore, research into the development of AI-based smart greenhouse systems is crucial to support food security and agricultural sustainability. Through the integration of this technology, it is hoped that more efficient, productive, and environmentally friendly vegetable cultivation models will be developed. This research is also expected to contribute to improving farmer welfare and serve as a strategic step in addressing global challenges related to food security and climate change.

METHODOLOGY

Research Design

This study employed an experimental approach with a comparative design to evaluate the performance of lettuce (Lactuca sativa) grown in an AI-based smart greenhouse versus a conventional greenhouse. The experimental design involved two treatments: the first treatment consisted of lettuce cultivation in a smart greenhouse equipped with automated control systems, while the second treatment involved lettuce grown in a conventional greenhouse managed manually. The comparison aimed to investigate the impact of AI-based environmental and nutrient regulation on plant growth, productivity, and resource efficiency. The experimental period lasted eight weeks, covering the complete growth cycle of lettuce from transplanting to harvest, which allowed the collection of sufficient data to assess short-term production and physiological responses.

Study Site and Greenhouse Setup

The experiment was conducted in a controlled greenhouse facility with two separate cultivation areas of comparable size and structure to minimize environmental bias. Both greenhouses were designed to support hydroponic cultivation using the Nutrient Film Technique (NFT), which allows nutrient solution to continuously flow along channels to the plant roots. The smart greenhouse was equipped with IoT-enabled sensors, including temperature, relative humidity, light intensity, and water quality sensors such as pH and Total Dissolved Solids (TDS). These sensors were integrated into an AI system capable of monitoring real-time environmental conditions and adjusting ventilation, irrigation, and nutrient supply automatically based on plant growth requirements. The conventional greenhouse, in contrast, was managed manually by experienced operators who monitored and adjusted conditions based on visual inspection and standard horticultural practices. Both greenhouses were located in the same area to ensure comparable exposure to ambient weather conditions such as light, temperature, and humidity.

Crop and Cultivation Practices

Lettuce (Lactuca sativa) was chosen due to its short cultivation cycle, high economic value, and sensitivity to environmental conditions, making it an ideal model crop to evaluate the effectiveness of AI-controlled systems. Seedlings were germinated under standard nursery conditions and transplanted into NFT channels at uniform spacing to ensure consistency in plant density. Both treatments used the same nutrient solution formulation and channel dimensions, ensuring that differences in growth and yield were primarily due to the greenhouse management method rather than cultivation practices. Routine maintenance, such as pest monitoring and cleaning of NFT channels, was conducted in both greenhouses to maintain plant health and minimize confounding factors.

AI System Configuration

The AI-based smart greenhouse utilized a combination of sensor data and predictive algorithms to optimize plant growth. Environmental sensors measured air temperature, relative humidity, and light intensity, while pH and TDS sensors monitored nutrient solution quality. The AI system processed this data in real time, generating control signals for actuators that regulated ventilation fans, LED lighting, and nutrient and irrigation pumps. The AI algorithm applied rules derived from historical crop performance and plant physiological models to maintain conditions within optimal ranges for lettuce growth. The system was capable of predictive adjustments, such as preemptively increasing irrigation based on projected evapotranspiration or adjusting lighting to compensate for changes in natural sunlight. Data from all sensors were continuously recorded and stored in a cloud-based database for later analysis.

Data Collection

Data were collected weekly over the eight-week experimental period. Environmental parameters recorded included air temperature and relative humidity in both greenhouses. Plant growth metrics included average height, number of leaves, and biomass accumulation. Yield was measured as wet weight and dry weight at harvest, with samples taken from representative plants across the cultivation channels. In the smart greenhouse, data were obtained directly from sensors and verified through manual observation, whereas in the conventional greenhouse, measurements were obtained entirely through manual observation and recording. All collected data were standardized to ensure consistency across treatments and minimize measurement bias.

Data Analysis

The collected data were analyzed using a descriptive-comparative approach. For each parameter, the mean, standard deviation, and percentage change between the AI-based and conventional treatments were calculated to evaluate the impact of the smart greenhouse system on environmental regulation, plant growth, and productivity. Comparative analysis focused on identifying improvements in plant height, leaf number, biomass accumulation, and overall yield attributable to AI-based environmental control. Trends over the eight-week period were also examined to assess the consistency of the system’s performance. This analysis provided quantitative evidence of the potential advantages of AI-driven greenhouse management in terms of growth optimization, resource efficiency, and crop yield.

RESULTS AND DISCUSSION

To determine the effectiveness of the AI-based smart greenhouse system in creating optimal environmental conditions, temperature and humidity measurements were conducted over four weeks in both conventional and smart greenhouses. The observation data are shown in Table 1.

Table 1. Temperature and Humidity Data in Smart Greenhouse and Conventional Greenhouse

Week	Avg. Temperature (°C) Smart	Avg. Temperature (°C) Conventional	Humidity Smart (%)	Humidity Conventional (%)
1	26.1	28.3	68.5	60.2
2	25.9	28.7	69.0	59.8
3	26.2	29.1	68.7	58.5
4	25.8	29.4	69.2	58.1

The data in the table shows that the smart greenhouse system is able to maintain stable temperature and humidity compared to conventional greenhouses. The temperature in the smart greenhouse ranges between 25.8–26.2 °C, lower and more stable than the conventional system, which tends to fluctuate up to 29.4 °C. This indicates that AI-based controls are effective in controlling temperature. Air humidity in the smart greenhouse is also consistently higher (68–69%) than in the conventional system (58–60%). Stable humidity conditions support plant physiological processes, such as photosynthesis and transpiration. The significant difference between the two systems indicates that AI-based automated controls are able to create a more optimal microenvironment for vegetable growth.

Table 2. Average Height of Lettuce Plants (cm)

Week	Smart Greenhouse (cm)	Conventional (cm)
2	9.3	7.8
4	18.7	14.9
6	27.4	21.8
8	36.2	28.7

Lettuce plant height growth in the smart greenhouse showed a significant increase compared to conventional systems. By week 8, the plants in the smart greenhouse reached 36.2 cm in height, 7.5 cm higher than the conventional system. The faster growth in the smart greenhouse system is due to the stable environmental management and AI-based nutrient delivery tailored to the plant's needs. This reduces physiological stress on plants caused by changes in the external environment. These data demonstrate that the AI-based system can increase productivity by accelerating the vegetative growth phase of horticultural crops.

Table 3. Average Number of Lettuce Plant Leaves

Week	Smart Greenhouse (cm)	Conventional (cm)
2	6.4	5.1
4	13.7	11.0
6	21.5	17.6
8	29.2	23.8

The number of lettuce leaves also showed a significant difference between the smart greenhouse and conventional plants. At the end of the study, plants in the smart greenhouse produced an average of 29.2 leaves, compared to the conventional greenhouse's 23.8. This difference indicates that the AI-based system is able to optimize factors supporting photosynthesis, particularly light intensity and nutrients. More leaves indicate a larger photosynthetic surface area, enabling plants to produce higher biomass. These results confirm that the smart greenhouse system not only influences plant height but also the development of other vegetative organs essential for vegetable production.

Table 4. Lettuce Harvest Weight (g/plant)

Treatment	Fresh Weight (g)	Dry Weight (g)
Smart Greenhouse	325.7	47.8
Conventional	245.3	36.4

Lettuce harvest weight in the smart greenhouse was significantly higher than in the conventional greenhouse. Plants in the smart greenhouse had an average wet weight of 325.7 g and a dry weight of 47.8 g, compared to only 245.3 g (wet) and 36.4 g (dry) in the conventional greenhouse. This difference indicates that AI-based nutrient, temperature, and humidity management can increase plant metabolic efficiency, resulting in greater biomass production. This data demonstrates that the AI-based smart greenhouse system not only improves growth parameters but also significantly impacts the final harvest yield, a key indicator of successful cultivation.

Discussion

Microclimate Stability and Plant Physiology

The findings of this study indicate that the AI-based smart greenhouse effectively stabilizes temperature and humidity within the optimal ranges required for lettuce growth (Lee et al., 2024; Bicamumakuba et al., 2025). Maintaining such a controlled microenvironment ensures that key physiological processes, including photosynthesis, transpiration, and respiration, proceed efficiently. Unlike conventional greenhouses, where environmental fluctuations can expose plants to heat or humidity stress, the AI system adjusts conditions in real-time to prevent these stresses. This stability reduces the risk of growth inhibition caused by abiotic factors and allows lettuce plants to maintain consistent metabolic activity, ultimately supporting overall health and productivity.

Vegetative Growth Enhancement

The study also demonstrates that lettuce plants in the smart greenhouse exhibited faster and more uniform vegetative growth compared to the conventional greenhouse. Increased plant height and accelerated leaf development are likely the result of the AI system's ability to dynamically regulate nutrient delivery, light exposure, and humidity throughout the growth cycle. By providing resources precisely when needed, the system enables plants to enter critical growth phases more efficiently, shortening the time required for vegetative development. This observation suggests that AI-assisted cultivation not only supports plant health but also has the potential to reduce cultivation cycles, increasing the number of harvests achievable within a given period (Sujatha et al., 2025; Ugwu et al., 2025).

Leaf Production and Photosynthetic Efficiency

In addition to height, the AI-managed environment contributed to an increase in the number of leaves per plant. A larger leaf area enhances photosynthetic capacity, allowing plants to convert more light energy into chemical energy and produce additional biomass. This result indicates that the smart greenhouse improves physiological efficiency beyond merely supporting survival; it actively promotes optimal growth conditions. The increase in leaf number is therefore a clear indicator that AI-driven environmental control can enhance the photosynthetic potential of crops, which translates directly into greater biomass accumulation and overall productivity (Kaya, 2025; Kumari et al., 2025).

Productivity and Resource Use Optimization

The improvements in vegetative growth and leaf production were reflected in higher harvest weights, both wet and dry, in the smart greenhouse. These outcomes suggest that the AI system not only maintains favorable growing conditions but also optimizes the efficiency of water and nutrient utilization. By continuously adjusting environmental parameters in response to real-time sensor data, the system minimizes waste and ensures that resources are allocated according to plant demand. The higher yield achieved under AI management underscores the potential of smart greenhouse technology as a strategy for sustainable intensification of vegetable production, particularly in environments where conventional management may struggle to maintain optimal conditions.

Implications for Sustainable Horticulture

Overall, the results highlight the strategic advantages of integrating AI in greenhouse management. Beyond increasing productivity, the system supports precise and adaptive resource management, which can contribute to more sustainable horticultural practices. By reducing environmental stress and maximizing physiological efficiency, AI-based smart greenhouses can help meet the growing demand for high-quality vegetables while minimizing inputs such as water and nutrients. These findings provide strong evidence that technological adoption in controlled-environment agriculture can be a viable approach to enhancing both yield and resource-use efficiency, with potential applications in tropical regions where climatic variability poses a challenge to conventional methods.

CONCLUSION

This study proves that the implementation of an Artificial Intelligence-based smart greenhouse system can provide a more stable and optimal growing environment compared to conventional greenhouses, demonstrated by more consistent temperature and humidity control. These controlled environmental conditions have a positive impact on increasing lettuce growth, including plant height, leaf number, and both wet and dry weight. The application of AI in greenhouse management allows for precise nutrient delivery, light regulation, and humidity adjustments according to plant needs at each growth phase, thereby increasing physiological efficiency and productivity. Thus, the development of an AI-based smart greenhouse has the potential to be a strategic solution in increasing vegetable production in a sustainable, efficient, and environmentally friendly manner.

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