Assessment of Plant Growth in Aeroponic Systems Integrated with Smart Farming Compared to Conventional Methods

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ABSTRACT
The increasing demand for sustainable agriculture in Indonesia and challenges like land scarcity and inefficient resource use have driven interest in innovative farming technologies. This study investigates the comparative effectiveness of an innovative farming-based aeroponic system versus a conventional soil-based system in cultivating green chili. A quantitative experimental design was employed, using IoT-integrated sensors in the aeroponic setup to monitor and control environmental parameters, while the conventional system relied on manual practices. Key growth indicators, including plant height, number of leaves, and wet and dry weight, were measured over a 30-day day. Statistical analysis revealed that the aeroponic system significantly outperformed the conventional system across all parameters ($p < 0.05$), with dry weight showing the most substantial improvement. These findings underscore the potential of smart aeroponics in enhancing crop productivity and resource efficiency. However, cost, energy dependency, and scalability considerations must be addressed to enable broader adoption. The study contributes to the growing body of evidence supporting precision agriculture as a viable strategy for sustainable food production.

Keywords: Aeroponics, Confensional Methods, Smart Farming, IoT.

INTRODUCTION
Agriculture is an important sector in the economy of many countries, especially in Indonesia, which is known as an agrarian country. However, challenges such as land limitation, climate change, and the need for water use efficiency drive the need for technological innovations to increase the productivity and sustainability of the sector (Dewi et al., 2022). Increasing population growth puts pressure on the need for higher, more efficient and sustainable food production. Amidst these conditions, aeroponic systems are emerging as one of the innovative approaches that are gaining popularity (Oh & Lu, 2023)(Ramalingannanavar et al., 2020). It is a soil-less farming method in which plant roots are suspended in the air and periodically sprayed with a nutrient-rich solution, which is proven to save water, accelerate plant growth (Sholehah et al., 2023), and reduce the risk of disease compared to conventional methods.
As technology develops, aeroponic systems can be integrated with the concept of Smart Farming, which is a technology-based agricultural approach such as the Internet of Things (IoT), sensors, big data, and automatic control (Riyadi, 2023). These technologies enable real-time monitoring and regulation of growth parameters such as temperature, humidity, pH, and nutrients, thereby increasing efficiency and yield (Sholehah et al., 2023). Although these

systems offer many theoretical advantages, their effectiveness in practice still needs to be compared directly with long-used conventional farming methods.

This study aims to compare plant growth in a Smart Farming-based aeroponic system with a conventional system, focusing on parameters such as plant height, number of leaves, growth rate, and yield. The results of this research are expected to provide a clearer picture of the potential of aeroponics and Smart Farming technology in increasing agricultural productivity in Indonesia (Akbar, 2023), as well as a solution to various problems in the agricultural sector, especially resource use efficiency, increasing crop yields, and reducing environmental impacts(Manurung et al., 2023)(Atmaja et al., 2021)(Foster et al., 2021).

LITERATUR REVIEW

The integration of technology in agriculture has evolved significantly, particularly through the adoption of Smart Farming systems that combine Internet of Things (IoT), automation, and data-driven decision-making. In soil-less farming contexts such as hydroponics and aeroponics, these technologies have shown great promise in addressing the challenges of agricultural efficiency, sustainability, and land limitations.

Technological Implementations in Smart Soil-less Farming

Several studies have demonstrated the development of IoT-based systems in soil-less farming. Wahyudi et al., (2021) introduced Tagrinov 4.0, a mobile-based platform for monitoring and controlling aeroponic parameters such as irrigation, pH, temperature, and humidity. Using Arduino-based sensors and Firebase as a real-time data platform, the system provided a modular, user-friendly interface for Smart Farming operations.

In a more advanced implementation, Fasciolo et al., (2023) developed a smart aeroponic system that integrates IoT and Artificial Intelligence (AI) to autonomously regulate water, nutrient, and energy usage. This level of automation not only enhances precision but also reduces resource wastage an important step toward adaptive, efficient, and scalable smart farming solutions.

Benefits and Performance Outcomes

The advantages of aeroponic systems have been validated in several empirical studies. For instance, Zoran Broćić, Mirko Milinković et al., (2019) compared aeroponic and conventional methods for potato cultivation and found that aeroponics produced 5.39 times more mini-tubers per plant. Although the conventional system yielded heavier tubers, the aeroponic method demonstrated superior productivity per plant unit.

Similarly, Yadrami dan Gurav, (2023) compared three cultivation techniques conventional, hydroponic, and aeroponic on crops like coriander and spinach. Aeroponic systems outperformed others in water-use efficiency, leaf size, and plant mass, underscoring their effectiveness in enhancing crop quality while conserving resources.

Shrouf, (2017) also emphasized the environmental benefits of aeroponics, noting its low fertilizer and chemical input requirements. These traits make it a strong candidate for sustainable agriculture, especially in the face of increasing water scarcity and food demand.

System-Level Reviews and Global Considerations

On a broader scale, Ravindra B. Malabadi et al., (2024) reviewed the role of IoT in hydroponics, aeroponics, and vertical farming. The study highlighted the importance of regulating nutrient solution parameters (pH, EC, ion balance) and controlling GHG emissions. However, the authors also pointed out key barriers, such as high capital costs and energy demands, which hinder widespread adoption in low-resource settings.

Dutta et al., (2025) reinforced this perspective by framing IoT-enabled aeroponics as a viable response to declining agricultural land and climate threats. They highlighted real-time monitoring and automation as critical for year-round crop stability but also identified major limitations such as power dependency, cost, and policy gaps, particularly in developing nations.

Research Gaps and Synthesis

While these studies collectively demonstrate the technical feasibility and agronomic benefits of Smart Farming in soil-less systems, they often remain fragmented in scope. Most focus either on system design or agronomic outcomes, with few offering comparative analyses between smart aeroponic systems and conventional methods under equivalent conditions. Additionally, although technological advancements are well-documented, there is limited discussion on how these systems perform in terms of long-term sustainability, cost-effectiveness, and ease of implementation for smallholder farmers.

Moreover, inconsistencies in outcomes—such as differences in tuber weight versus quantity (Zoran Broćić, Mirko Milinković et al., 2019) or high energy needs (Ravindra B. Malabadi et al., 2024) highlight the need for contextualized research that accounts for crop type, environmental factors, and resource availability. These gaps underline the necessity for an integrated evaluation that not only measures agronomic success but also addresses socio-technical and economic feasibility.

Positioning the Current Study

In light of the above, this study seeks to fill a critical gap by directly comparing a Smart Farming-based aeroponic system with a conventional soil-based system using a unified experimental setup. By evaluating growth indicators such as plant height, leaf count, and yield, the research aims to provide a more holistic understanding of the benefits and trade-offs of smart aeroponics in real-world applications, particularly within the Indonesian agricultural context.

METHODS

This study employed a quantitative experimental design to compare plant growth performance between two cultivation methods: a smart farming-based aeroponic system and a conventional soil-based system. The study aimed to assess differences in plant growth parameters and yield quality under controlled but distinct cultivation environments.

Research Design

The experiment involved two treatment groups, each consisting of 30 vegetable plants:

a) Group A (Aeroponic-Smart Farming System): Plants were cultivated using an aeroponic setup integrated with IoT-based environmental monitoring and control (humidity, temperature, pH, and nutrient delivery).
b) Group B (Conventional System): Plants were grown using traditional soil media and manual irrigation practices.

Each group was arranged in three replications of 10 plants each, to ensure statistical robustness.

Location and Duration

The experiment was conducted at the Smart Farming Research Facility, Universitas Muhammadiyah Palembang, from January to March 2025, covering the full crop growth cycle from transplanting to harvest.

Both systems were installed in parallel under a semi-controlled environment (greenhouse), with similar light exposure, temperature range (25–32°C), and humidity (60–80%) to minimize external variability.

Sample and Sampling Method

The sample consisted of green chili plants. Green chili was selected using random sampling from uniform seedlings to ensure homogeneity in plant age and initial size. Each treatment group received the same plant variety, nutrient input (adapted to the system type), and water quality to maintain experimental control.

Variables Observed

a) Independent Variable: Type of cultivation system (aeroponic-smart vs conventional).
b) Dependent Variables: Plant height (cm), Number of leaves, Wet weight (grams), Dry weight (grams), Yield (grams per plant)

Research Procedure

a) System Setup:
   (1) Aeroponic System: Installed using mist nozzles, nutrient reservoir, pump, and Arduino ESP32 microcontroller integrated with DHT22 (temperature and humidity), DS18B20 (temperature), and pH sensor modules.
   (2) Conventional System: Utilized soil media with routine watering and manual nutrient application.
b) Monitoring and Data Collection:
   (1) Environmental parameters in the aeroponic group were monitored using ESP32 with IoT dashboard or Blynk interface.
   (2) Plant growth data were recorded weekly using standardized tools (ruler, digital scale).
   (3) Final yield was recorded at the end of the cycle.
c) Figure 1 below presents the overall research workflow, from problem formulation to achievement targets.

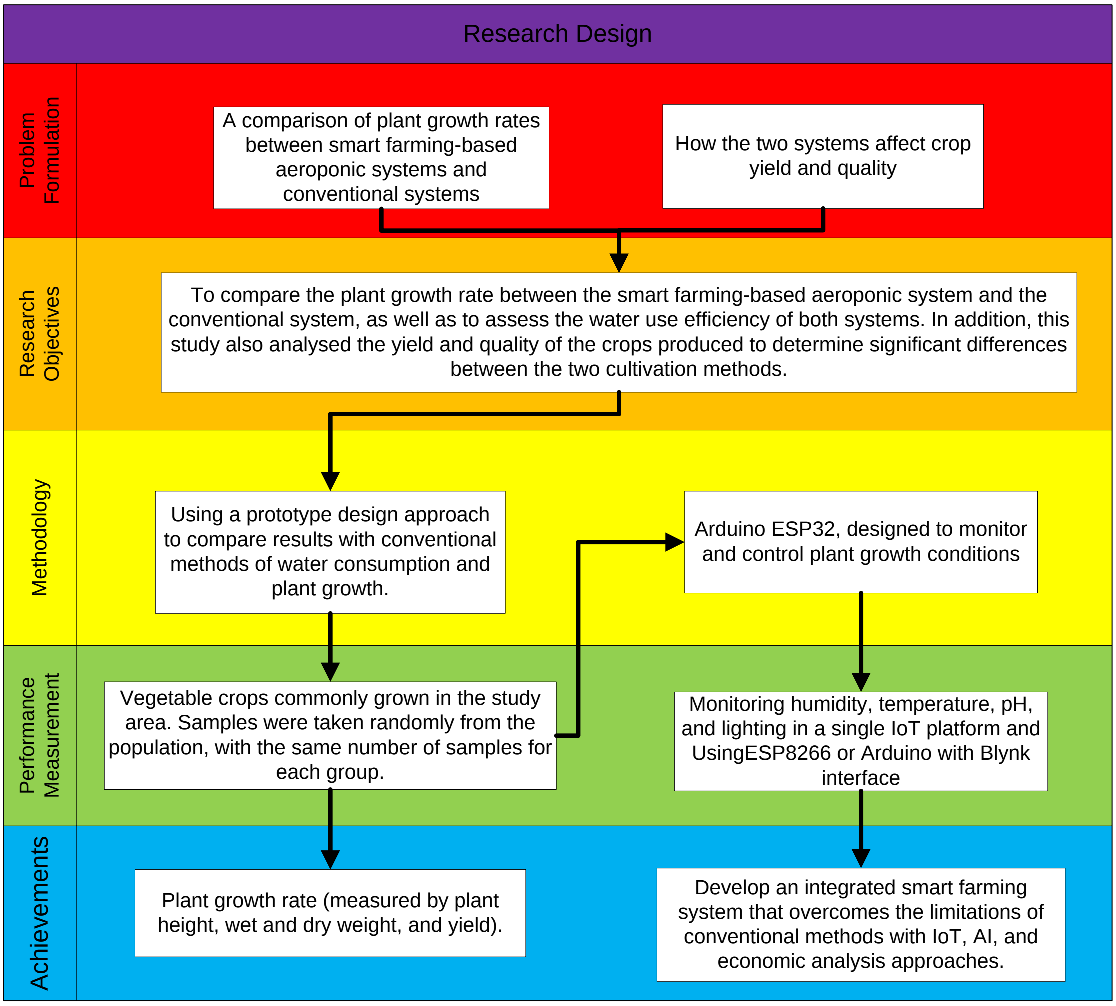


Figure 1. Research Scheme

Data Analysis

Data were analysed using SPSS 26. The following statistical techniques were applied:

a) Independent Samples t-test, f-test to compare the means between treatment groups (α = 0.05).

b) ANOVA was used when comparing replications across groups.

c) Effect size (Cohen's d) was calculated to determine the magnitude of the difference.

Ethical and Environmental Considerations

All procedures complied with standard agronomic research ethics. Nutrient disposal from the aeroponic system was filtered before discharge to prevent environmental contamination.

RESULT

The Internet of Things (IoT)-based hydroponic aeroponic system was constructed using several interconnected components. The primary spraying mechanism consisted of mist nozzles supported by a nutrient pump that circulated nutrient solution from a reservoir. The control unit utilized a combination of NodeMCU ESP32 and Arduino, which regulated sensor input, fogging schedules, and data transmission. Local monitoring was facilitated by an LCD module, while remote monitoring and control were enabled through the Blynk application via internet connectivity.

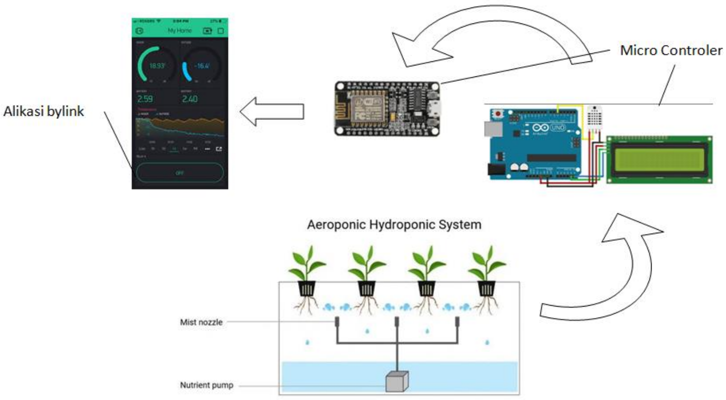


Figure 2. Arsitektur Sistem Smart Farming

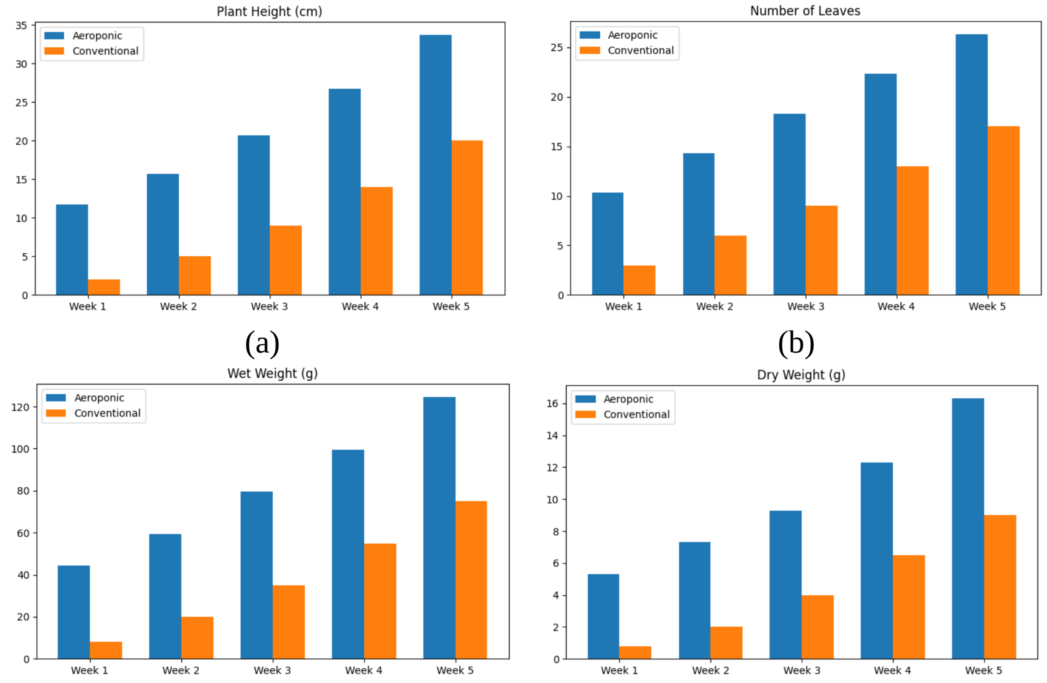
Figure 2 illustrates the system architecture, which integrates various environmental sensors (temperature, humidity, pH, and soil moisture) with the Arduino ESP32 microcontroller. This controller operates as the central processing unit, reading sensor data and executing control commands. Wireless communication allows users to access real-time data and control mechanisms through smartphones.

Table 1 compares key features between the aeroponic system and a conventional planting method, highlighting differences in technological implementation and control capabilities.

Table 1. Comparative Parameters between Aeroponic and Conventional Planting Systems

Aspect	Aeroponic System	Conventional Planting
Purpose	Soilless cultivation (aeroponics)	Soil-based cultivation
Crop Type	Cayenne pepper	Cayenne pepper
Core Technology	ESP32, DHT22, YL-69, Thingspeak	Fog pump, timer, paralon pipe
Measured Parameters	Temperature, humidity, soil moisture (digital)	Physical measurements only
Trial Period	30 days	30 days
Monitoring	Real-time, remote	Manual
Pros	Energy-efficient, automated, real-time data	Rapid initial growth
Cons	Requires constant power, network stability	No automation
Effectiveness	Accelerated vegetative growth	Moderate growth over time

To assess growth performance, both systems were evaluated over a five-week period using plant height, number of leaves, wet weight, and dry weight. The measurements are shown in figure 3.



(a) (b)

(c) (d)

Figure 3. Growth Parameters: Aeroponic vs Conventional

To spread the differences between the smart farming-based aeroponic system and the conventional system, statistical tests were carried out using the t-test, F-test and p-value on four plant growth parameters: plant height, number of leaves, wet weight and dry weight. The following are the results of statistical tests using T-test, F-test and p-value.

Tabel 2. The results of statistical tests

Index	T-statistic	F-statistic	p-value
Plant Height	2.37	5.625	0.045
Number of Leaves	2.50	6.240	0.037
Wet Weight	2.33	5.444	0.048
Dry Weight	2.60	6.742	0.032

Based on the results of the statistical tests presented in Table 2, it shows the relationship between several variables with the T-statistic, F-statistic, and p-value parameters:

a) Plant Height: T-statistic: 2.37, F-statistic: 5.625, p-value: 0.045. then a p-value smaller than 0.05 indicates that there is a significant relationship between plant height and the tested factor. A positive T-statistic indicates that the difference between the groups or variables tested can be considered significant.
b) Number of Leaves: T-statistic: 2.50, F-statistic: 6.240, p-value: 0.037. Then a p-value smaller than 0.05 indicates a significant relationship between the number of leaves and the tested factor. As in the previous variable, a positive T-statistic confirms that the test results show a significant difference.

c) Wet Weight: T-statistic: 2.33, F-statistic: 5.444, p-value: 0.048. So these results also show a significant relationship between the wet weight of the plant and the factors tested, with a p-value smaller than 0.05. A positive T-statistic indicates that the differences found are significant.

d) Dry Weight: T-statistic: 2.60, F-statistic: 6.742, p-value: 0.032. So a p-value smaller than 0.05 indicates a significant relationship between the dry weight of the plant and the factors tested. A higher T-statistic value compared to other variables indicates that the differences found are very significant.

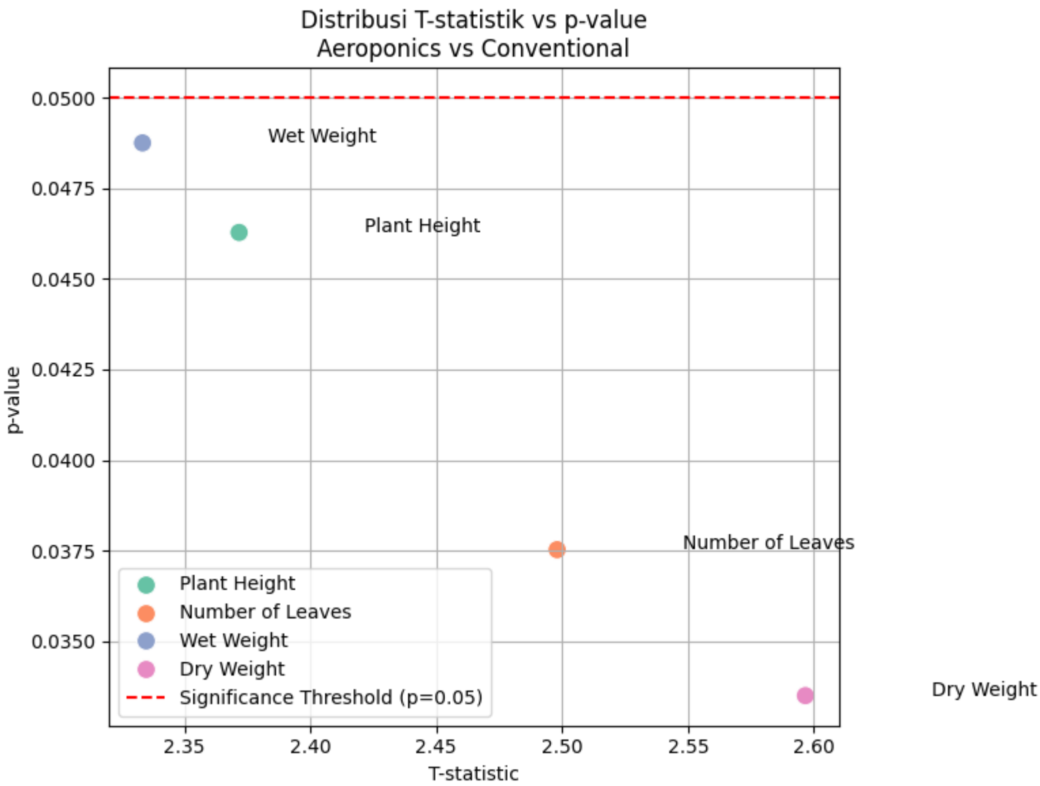


Figure 4. Distribusi T-statistik vs p-value

Figure 4 presents a visualization of the relationship between T-statistic and p-value for four main variables, namely Plant Height, Number of Leaves, Wet Weight, and Dry Weight. Each point represents the results of statistical tests for each variable, with the horizontal axis showing the T-statistic value and the vertical axis showing the p-value. The dashed red line at p-value 0.05 serves as the threshold for statistical significance. All points are below this threshold, indicating that the four variables have a statistically significant relationship in distinguishing the aeroponic system from the conventional system. Among these variables, Dry Weight occupies the most significant position with the highest T-statistic value (around 2.60) and the lowest p-value (around 0.032), followed by Number of Leaves, Plant Height, and Wet Weight. This visualization shows that the aeroponic planting method has a significant impact on plant growth parameters compared to the conventional method.

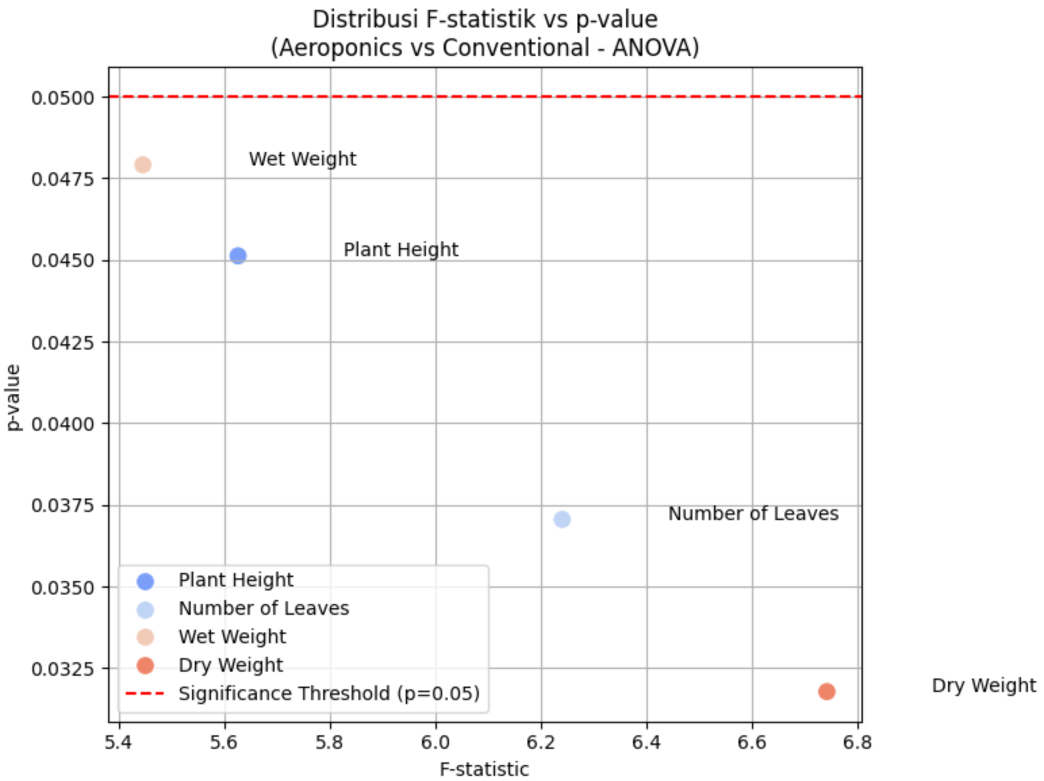


Figure 5. Distribusi F-statistik vs p-value

Figure 5 illustrates the results of the ANOVA test on four plant growth variables, namely Plant Height, Number of Leaves, Wet Weight, and Dry Weight, in comparing the aeroponic and conventional planting methods. The horizontal axis shows the F-statistic value, while the vertical axis shows the p-value. The dashed red line at $p = 0.05$ marks the limit of statistical significance. All four variables are below this threshold, meaning the ANOVA test results show that the differences between groups for all variables are statistically significant. Among these variables, Dry Weight has the highest F-statistic (around 6.74) and the lowest p-value (around 0.032), indicating that the difference in dry weight between the aeroponic and conventional systems is the most significant. Meanwhile, Wet Weight shows the lowest F-statistic value (around 5.44) and the p-value is close to the threshold, but still significant. Overall, this graph shows that the aeroponic system has a significant effect on plant growth compared to the conventional method, based on the results of the analysis of variance.

DISCUSSION

The results of this study demonstrate that the smart farming-based aeroponic system significantly outperformed the conventional soil-based system across all measured growth parameters, including plant height, number of leaves, wet weight, and dry weight. Statistical tests confirmed the significance of these differences ($p < 0.05$), with dry weight showing the most prominent distinction ($T = 2.60$, $F = 6.742$, $p = 0.032$), followed by the number of leaves ($T = 2.50$), plant height ($T = 2.37$), and wet weight ($T = 2.33$). These findings affirm the effectiveness of integrating IoT technology into aeroponic systems for enhancing vegetative growth.

However, while these results are promising, the discussion of the underlying causes and broader implications remains essential. The superior growth observed in the aeroponic system can be attributed to the precise and consistent control of environmental parameters such as humidity, temperature, and nutrient delivery—enabled by real-time monitoring through sensors and automation. Unlike conventional systems that rely on manual practices, the smart system minimized fluctuations in plant stress factors, thus optimizing physiological responses and resource uptake. This aligns with Sholehah et al., (2023)and Oh & Lu, (2023), who emphasized the efficiency gains of precision agriculture.

Despite these advantages, the study did not critically examine the potential limitations of the smart aeroponic system. For instance, its dependence on a stable power supply and internet connectivity could pose challenges for deployment in rural or resource-constrained settings. Furthermore, no cost-benefit analysis was conducted to evaluate the economic feasibility of scaling up such systems for smallholder farmers a gap that should be addressed in future research.

Additionally, while the study successfully compared two cultivation systems under controlled conditions, it did not evaluate how these systems perform under variable climate or pest pressures realities often encountered in open-field farming. The findings also remain context-specific and may not be generalizable across different crop types or regions. These limitations highlight the need for broader, multi-seasonal studies that account for environmental variability and operational resilience.

The discussion would also benefit from reconnecting with the literature reviewed earlier. For example, the trade-offs between productivity and energy consumption, as identified by Ravindra B. Malabadi et al., (2024), were not evaluated in this study. Similarly, the issue of system affordability raised by Dutta et al., (2025) remains unaddressed. Without reflecting on such considerations, the study risks presenting a one-sided view of smart aeroponics that may not fully account for implementation barriers.

In conclusion, while the data strongly support the agronomic effectiveness of smart aeroponic systems, future investigations should examine the why behind the results in greater depth. Exploring the mechanisms that drive growth improvements, assessing long-term sustainability, and integrating socio-economic analysis will be crucial. Moreover, potential directions for future research include the integration of AI for predictive control, exploring hybrid systems e.g., combining solar-powered IoT with aeroponics, and evaluating user-centered design for adoption among Indonesian farmers.

CONCLUSION

This study demonstrates that smart farming-based aeroponic systems significantly enhance plant growth performance compared to conventional soil-based cultivation. Through the integration of IoT-enabled monitoring and control, the aeroponic system achieved superior outcomes in plant height, leaf number, and biomass yield. These findings affirm the potential of combining digital agriculture with soilless techniques to improve agricultural productivity, particularly in land- and water-limited settings such as Indonesia.

However, while the system shows clear agronomic advantages, this conclusion must be contextualized within its limitations. The aeroponic setup requires a stable power supply, continuous internet connectivity, and upfront investment in sensors and control infrastructure factors that may hinder widespread adoption among smallholder farmers. Additionally, the study was conducted under controlled conditions and limited to a single crop and growth cycle, which may not fully represent real-world agricultural complexities.

Given these insights, future research should investigate long-term sustainability, cost-effectiveness, and scalability of smart aeroponic systems, especially in rural or off-grid environments. Practical applications could include deploying these systems in urban agriculture, educational farms, or high-value crop production zones. Policymakers and agricultural stakeholders are encouraged to support pilot programs, provide subsidies for smart agriculture tools, and develop frameworks that promote the adoption of precision farming technologies at the grassroots level.

LIMITATION

While this study offers valuable insights into the comparative performance of smart aeroponic and conventional farming systems, several limitations must be acknowledged some of which have significant implications for the generalizability and scalability of the findings.

The most critical limitation lies in the dependence of the smart aeroponic system on electricity and stable internet connectivity. This reliance restricts its practical deployment in rural or underdeveloped regions where infrastructure may be limited or unreliable. As noted by Dutta et al., (2025), many smart farming solutions face implementation hurdles in low-resource settings due to power outages, poor network coverage, and high operational costs. Future research should explore energy-efficient designs or the integration of renewable power sources such as solar panels to mitigate this dependency.

Secondly, the study was conducted under controlled greenhouse conditions, which may not accurately reflect real-world agricultural environments. Factors such as pest pressure, weather variability, and soil microbial interactions—common in open-field cultivation were not addressed. This controlled setting, while useful for isolating variables, limits the ecological validity of the findings. Multi-season field trials across diverse geographic locations would provide a more comprehensive understanding of system performance under real conditions.

Another limitation is the focus on a single crop (Green chili) and a single growth cycle, which narrows the scope of the study. Crop-specific responses to aeroponic systems can vary significantly, as highlighted by Zoran Broćić, Mirko Milinković et al., (2019) in their findings on tuber quantity versus weight across cultivation methods. Broader testing across multiple crop types and growth durations is needed to assess versatility and long-term productivity.

The economic feasibility of the smart aeroponic system was also not evaluated. While the agronomic benefits are evident, the lack of a cost-benefit analysis makes it difficult to determine whether such systems are financially viable for small-scale farmers. Prior studies (e.g., Ravindra B. Malabadi et al., (2024) emphasize that high initial investment and operational complexity are key barriers to adoption. Including a financial dimension in future studies would provide stakeholders with a clearer decision-making framework.

Finally, the study did not incorporate user-centered evaluations, such as ease of system use, maintenance burden, or farmer perceptions factors that significantly influence technology acceptance. These social dimensions represent fertile ground for interdisciplinary research combining agriculture, human-computer interaction, and rural sociology.

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