Asian Journal of Agriculture and Rural Development
Volume 16, Issue 1 (2026): 76-88

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Optimizing rainwater utilization for lettuce cultivation in smart greenhouses for sustainable agriculture in tropical Indonesia

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Article History

Received: 21 July 2025
Revised: 24 December 2025
Accepted: 13 January 2026
Published: 30 January 2026

Keywords

Automated irrigation system
Climate-resilient farming
Hydroponic lettuce
IoT-based irrigation
Precision agriculture
Rainwater harvesting
Smart greenhouse
Sustainable agriculture
Vegetative growth performance
Water quality analysis.

ABSTRACT

This study examines the integration of a rainwater harvesting system with a smart greenhouse for hydroponic lettuce (Lactuca sativa L.) cultivation to improve water-use efficiency and support sustainable precision agriculture. The system incorporates IoT-based environmental monitoring and automated irrigation using real-time data on temperature, humidity, light intensity, water quality, and nutrient conditions. A 30-day comparative experiment was conducted using two irrigation sources: filtered harvested rainwater and groundwater. Measurements included environmental parameters, water use, and plant traits such as leaf number, leaf size, biomass, root length, and chlorophyll content (SPAD). Independent Sample T-Test results showed that groundwater significantly enhanced vegetative growth, increasing fresh weight by up to 62.5% and root length by 44.45% compared to rainwater treatment. In contrast, rainwater-grown plants exhibited 16.67% higher SPAD values, suggesting greater chlorophyll concentration and physiological quality. Laboratory analysis indicated that filtration improved rainwater pH and TDS but increased turbidity and total hardness, while groundwater demonstrated more stable quality across all parameters. These findings highlight the potential of integrating smart irrigation and alternative water sources to support climate-resilient agriculture. Future work should optimize filtration processes and investigate nutrient uptake and physiological responses under varying water qualities in hydroponic systems.

Contribution/Originality: This study contributes to the existing literature by integrating rainwater harvesting with smart greenhouse systems for sustainable hydroponic lettuce cultivation. It provides new empirical evidence on water quality impacts and crop performance, offering a replicable model for precision agriculture in tropical regions.

DOI: 10.55493/5005.v16i1.5857
ISSN(P): 2304-1455/ ISSN(E): 2224-4433

How to cite: Asnaning, A. R., Putra, S. D., Jaya, M. H. I. S., Putrantri, D. A., & Zulkarnain, I. (2026). Optimizing rainwater utilization for lettuce cultivation in smart greenhouses for sustainable agriculture in tropical Indonesia. *Asian Journal of Agriculture and Rural Development*, *16*(1), 76–88. 10.55493/5005.v16i1.5857

1. INTRODUCTION

Agriculture remains a cornerstone of national development, underpinning economic growth, food security, employment generation, and rural livelihoods (Benzaouia, Hajji, Mellit, & Rabhi, 2023). However, the sector is increasingly challenged by rapid population expansion and the accelerating impacts of climate change, both of which undermine the sustainability of conventional agricultural systems (Hoque, Islam, & Khaliluzzaman, 2023). To address these pressures, the transformation toward innovative, resource-efficient technologies has become imperative. Among such advancements, the smart greenhouse stands out as a key enabler of precision agriculture, creating controlled microenvironments that optimize plant growth and resource utilization. All these systems leverage real-time data on climatic variables, plant physiology, and substrate conditions to regulate irrigation, nutrient delivery, and pest management (Benyezza, Bouhedda, & Rebouh, 2021). With facilitating data-driven, site-specific management, smart greenhouses enhance water-use efficiency, improve yield consistency, and reduce environmental footprints relative to traditional open-field cultivation (Mathur, Kathyal, Gunwal, & Chandra, 2023).

Despite all, water resource management remains a critical bottleneck for sustainable agriculture, particularly in drought-prone regions or areas with limited freshwater availability (Ali, Hussain, & Zahid, 2025; Amare, 2020). Over-reliance on surface and groundwater accelerates environmental deterioration and jeopardizes agriculture's long-term sustainability (Bedaso & Wu, 2021; Dalin, Taniguchi, & Green, 2019). In this context, rainwater harvesting proves to be a practical and climate-resilient approach that reduces dependency on declining freshwater supplies while allowing rainfall to be collected and reused for irrigation (Krishnan et al., 2020). Rainwater harvesting offers a closed-loop approach that improves water-use efficiency, facilitates precision irrigation scheduling, and strengthens system resilience under fluctuating climatic circumstances when integrated into smart greenhouse infrastructure (Amos et al., 2020). By reducing runoff, preserving natural resources, and encouraging environmental stewardship, this integrative strategy aligns with the principles of the circular economy and global sustainability goals (Cumo, Piras, Pennacchia, & Cinquepalmi, 2020).

These global demands highlight the urgent need to adopt sustainable agricultural practices, particularly in tropical regions such as Indonesia, where climate vulnerabilities and food security challenges are most severe. To address these issues, it requires not only innovation in resource management but also the redesign of cultivation systems to enhance resilience and productivity in the face of environmental instability. For high-value crops such as lettuce (*Lactuca sativa L.*), one promising avenue is integrating smart greenhouse technologies with efficient rainwater utilization strategies, which can significantly enhance water-use efficiency and agricultural productivity in such demanding environments (Benzaouia et al., 2023).

An increasingly appealing alternative to soilless cultivation techniques, notably hydroponics, within smart greenhouse settings, provides a sustainable solution to conserve water and space while shortening growing periods. These factors offer an attractive option for farmers in Indonesia (Putra, Ambarwari, Asrowardi, & Jaya, 2024). With maintaining tightly controlled microclimates, these systems could minimize the effects of external weather fluctuations and support consistent, high-quality crop production (Bua, Adami, & Giordano, 2024).

Within the global context, agriculture accounts for around 70% of freshwater use, underscoring the need for innovative water management technologies (Hoque et al., 2023). Smart greenhouses that are enhanced by advanced sensors and artificial intelligence offer a sophisticated means of regulating key environmental parameters, such as temperature, humidity, light, and nutrient flow, to optimize plant growth and resource efficiency (Daniels, Fink, & Wollherr, 2024). These systems integrate Internet of Things (IoT) devices, sensor networks, and data analytics to ensure sustainable resource management and high productivity, aligning with the global transition toward smart farming ecosystems that promote both competitiveness and sustainability (Agussabti et al., 2022). By providing real-time insights into soil moisture, nutrient concentration, and ambient environmental conditions, these technologies enable proactive decision-making that minimizes waste while maximizing plant growth potential (Krishnan et al., 2020).

Empirical evidence demonstrates that precision agriculture systems can reduce water consumption by 50–90% compared to conventional open-field farming, while enabling year-round production independent of external climatic conditions (Abou-Mehdi-Hassani et al., 2023). Building upon this foundation, the integration of rainwater harvesting within smart greenhouse frameworks has emerged as a practical innovation to further enhance sustainability. This combination delivers tangible agronomic benefits, particularly for fast-growing and water-sensitive crops, such as lettuce.

Due to its short development cycle, high nutritional content, and steady market demand, lettuce is a popular crop and a perfect example of smart farming (Touliatos, Dodd, & McAinsh, 2016; Zhang, Shen, Takagaki, Kozai, & Yamori, 2015). In addition to ensuring access to clean water, using collected rainwater as an irrigation source improves microclimatic stability in the regulated environment of a smart greenhouse. Prior studies indicate improvements in water-use efficiency, leaf biomass, and crop quality when rainwater harvesting systems are effectively integrated (Asnaning & Putra, 2018; Viani, Bertolli, Salucci, & Polo, 2017). These outcomes suggest that such systems can sustain productivity while reducing environmental impact, providing a viable model for strengthening the resilience of small- and medium-scale horticultural enterprises under increasingly variable climatic conditions. Therefore, this study investigates the design and application of rainwater harvesting technology within smart greenhouse systems, with a focus on its impact on water efficiency and the performance of lettuce crops.

This research paper is structured into six sections. Section I presents the introduction, outlining the background, significance, and objectives of the study. Section II describes the research methodology, including the design of the smart greenhouse system, integration of rainwater harvesting technology, data collection methods, and parameters for evaluating water efficiency and lettuce growth performance. Section III discusses the results of system implementation and performance evaluation.

Section IV presents an in-depth discussion of the findings, including an analysis of water use efficiency, environmental control, and the impact on lettuce crop yield. Section V outlines the study's implications for sustainable agricultural practices and potential applications in other crop systems. Finally, Section VI presents the conclusions and recommendations for future research.

2. RESEARCH METHODOLOGY

This study employed an applied experimental approach to evaluate the implementation of a rainwater harvesting system integrated with a smart greenhouse for enhancing water-use efficiency and improving the growth response of lettuce (*Lactuca sativa L.*). This study did not involve human or animal subjects; therefore, ethics approval was not applicable. The research methodology consisted of four key components: system design, technology integration, data collection, and evaluation based on morphological plant responses.

The smart greenhouse was designed to maintain optimal environmental conditions through automated control of temperature, humidity, soil moisture, and light intensity. An ESP32 microcontroller was linked to a network of sensors to provide real-time monitoring of these metrics. By using these data points, the system was able to precisely regulate the environment by automating ventilation and irrigation procedures. Two experimental zones were created in the greenhouse: one a control group irrigated with conventional water sources and the other a treatment group irrigated with harvested rainwater.

The rainwater harvesting system was installed on the greenhouse roof and included a gutter collection system, a first-flush diverter, a filtration unit, and a storage tank. The collected rainwater was filtered and stored in a closed tank before being distributed to the irrigation lines. The rainwater-treated zone's lettuce crops were irrigated at certain times and volumes by the smart irrigation system using capacitive soil moisture sensors.

Data collection was conducted throughout the entire lettuce growth cycle, for approximately 30 days. Parameters observed included environmental conditions (temperature, humidity, light intensity, and soil moisture), total water usage, and detailed plant growth characteristics. The primary evaluation indicators were based on the morphological responses of lettuce, including plant height, leaf number, leaf width, and biomass accumulation (both fresh and dry weight). Additionally, qualitative observations were made to assess leaf color uniformity and visible signs of water stress or nutrient deficiency.

The effectiveness of rainwater harvesting integration was assessed by comparing the morphological development of lettuce plants between the two groups. This approach allowed for the identification of trends and differences in plant performance that are directly attributable to the use of harvested rainwater under smart greenhouse conditions. The findings aim to demonstrate the practical benefits of sustainable water management practices in enhancing crop productivity within a precision agriculture framework.

2.1. Experimental Design

The smart greenhouse was designed to create a controlled microenvironment suitable for growing lettuce *(Lactuca sativa L.)*. The structure was equipped with sensors and actuators to monitor and regulate key environmental variables, including temperature, humidity, soil moisture, and light intensity. The system employed an automated control mechanism based on real-time sensor data to optimize irrigation and ventilation.

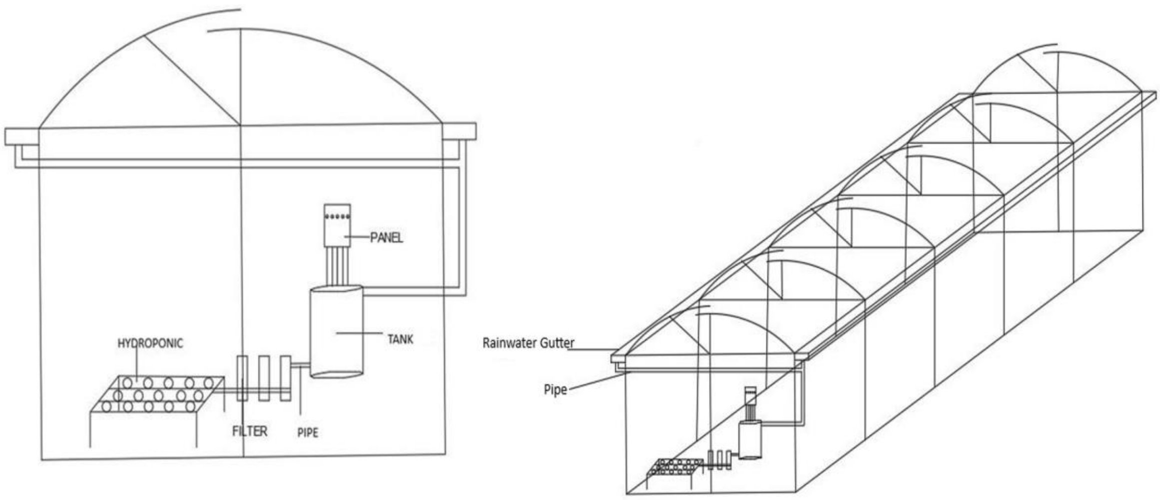

Figure 1. The smart greenhouse architecture.

The smart greenhouse used in this study was designed to integrate a rainwater harvesting system with an automated hydroponic cultivation setup, as shown in Figure 1. The structure features a transparent greenhouse roof (1) that serves as the primary surface for collecting rainwater. Rainwater flows into a rain gutter (3) installed along the edge of the roof and is channeled through a water filter unit (4) to remove debris and contaminants. Filtered water is then stored in a water tank (2) made of high-density polyethylene, ensuring it remains clean and ready for use in irrigation. A network of water pipes (5) connects the tank to the hydroponic growing bed (6), where lettuce plants are cultivated in a nutrient-rich solution. The system is automated with the use of sensors to track environmental conditions and initiate irrigation in response to soil or media moisture levels. This arrangement maintains ideal circumstances for controlled plant growth while enabling the effective utilization of collected rainfall.

2.2. Sensor Calibration and IoT Architecture

The rainwater harvesting system consisted of a rooftop collection unit, a filtration system, and a storage tank. Rainwater was directed from the greenhouse roof through gutters to a first-flush diverter and then filtered before being stored in a high-density polyethylene tank. The stored water was connected to the smart irrigation system in the experimental zone. The irrigation schedule and volume were automated and controlled via an IoT device based on soil moisture data. The system ensured that water was delivered only when needed, maximizing water-use efficiency.

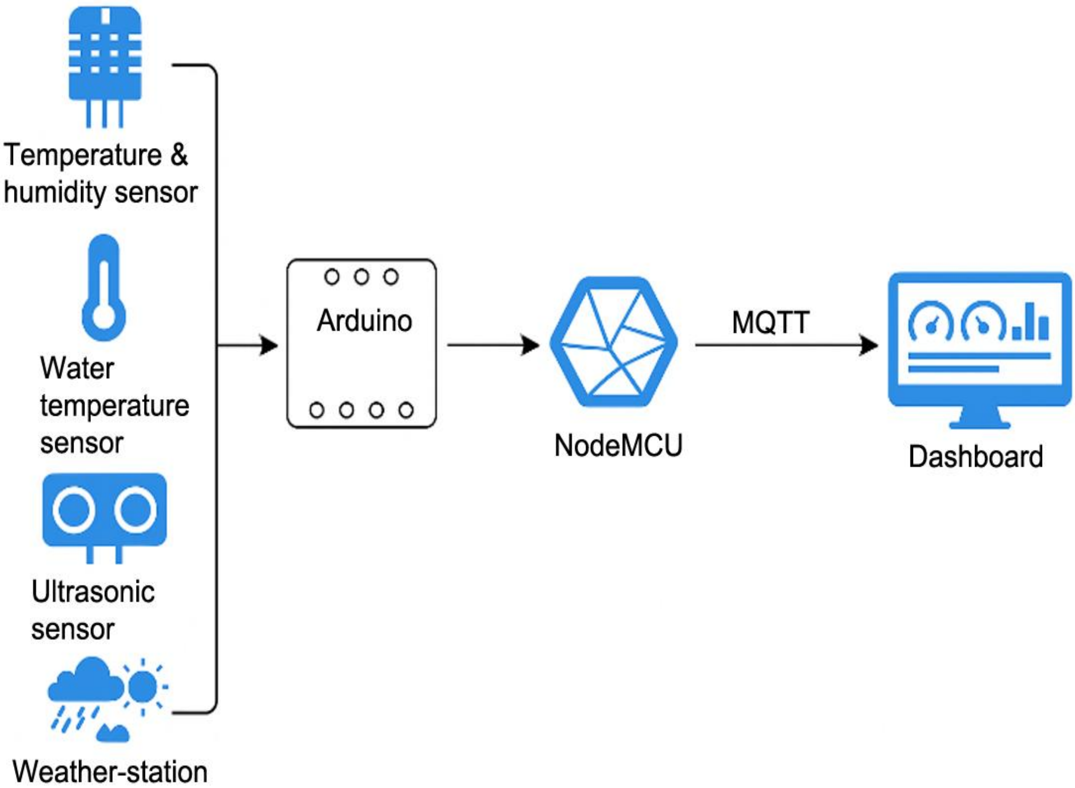

Figure 2. IoT architecture for rainwater-optimized lettuce farming.

Following the installation of sensors, the next stage involved integrating the DHT22 sensor to monitor ambient temperature and humidity, which are critical environmental parameters influencing hydroponic crop growth. The DHT22 sensor was connected to an IoT device, enabling real-time data transmission via the MQTT protocol to a centralized monitoring dashboard. In addition to environmental monitoring, a DS18B20 sensor was employed to measure water temperature within the storage tank, ensuring it remains within optimal thresholds for plant development.

To prevent water shortages that could interfere with irrigation, a complementary ultrasonic sensor was placed to measure the water level in the rainwater storage tank and provide real-time volume data. This sensor also transmitted data continuously via MQTT, allowing remote, uninterrupted monitoring as shown in Figure 2. To capture external weather conditions, a Weather Station Kit comprising rainfall, wind speed, and atmospheric pressure sensors was deployed around the greenhouse to anticipate climatic shifts that might affect rainwater availability and plant water needs.

All sensor data was managed through a robust IoT architecture, where the IoT device acted as the primary controller and data gateway. This device transmitted sensor readings wirelessly to a cloud server using MQTT, a lightweight and efficient protocol ideal for continuous IoT communication. Collected data including TDS levels, temperature, humidity, and water height were stored in InfluxDB, a time-series database optimized for handling high-frequency sensor data.

Each sensor was configured to publish its readings to specific MQTT topics, such as "rainwater/tds1" or "hydroponic/tds2," allowing for an organized data flow to the database and visualization system. To ensure the optimal functioning of the smart hydroponic and rainwater harvesting systems, trends in sensor data were displayed on a Grafana-powered dashboard. This enabled users to monitor system status in real-time and receive automated alerts when parameters exceeded pre-defined criteria.

2.3. Statistical Analysis Tools

This study utilized lettuce (*Lactuca sativa L.*) as the test crop, with seedlings transplanted at 15 days after sowing (DAS). The selected seedlings exhibited uniform characteristics, including an average height of approximately 4 cm, two true leaves, normal growth morphology, straight leaf orientation, and no visible signs of pest or disease infestation. The seedling phase was conducted using parallel polyvinyl chloride (PVC) pipes as planting channels. Rockwool was used as the growing medium, and the plants were supplied with a hydroponic AB Mix nutrient solution formulated for leafy vegetables. Lettuce was harvested at 50 days after sowing, representing a complete vegetative cycle.

The lettuce plants were set up on a hydroponic Nutrient Film Technique (NFT) system inside a smart greenhouse during the cultivation phase. The NFT racks were separated based on water treatment types, with one system using filtered groundwater and the other utilizing filtered harvested rainwater. The entire experiment was conducted in the greenhouse facility at Politeknik Negeri Lampung, located at coordinates 5°21'30"S, 105°14'04"E, at an elevation of approximately 110 meters above sea level. The study was conducted during the dry season, from June to August 2024, to ensure consistent environmental conditions throughout the lettuce growth cycle.

The performance of the integrated rainwater harvesting and smart greenhouse system was evaluated using a multi-dimensional assessment framework. To assess the morphological effects of using different water sources groundwater and harvested rainwater all morphological observations and measurements were conducted four weeks after treatment (WAT). Morphological characteristics of lettuce plants were visually assessed and documented through photographic evidence to support the observed differences. Quantitative measurements included the number of leaves, leaf length (in cm), leaf width (in cm), leaf weight (in g), total fresh biomass (in g), greenness index (SPAD), and root length (in cm). Leaf and root dimensions were measured manually using a ruler, while leaf weight and plant fresh weight were determined using a precision digital scale. The greenness index, indicative of chlorophyll content and photosynthetic potential, was measured using a chlorophyll meter (SPAD-502, Konica Minolta).

These indicators provided insight into the overall vegetative development and health of the crops under both treatment and control conditions. Yield comparison was also conducted by measuring the total harvest output from the experimental group (utilizing harvested rainwater) and the control group (using conventional water sources), allowing for a direct evaluation of the system's effectiveness in supporting productive growth. In addition to agronomic parameters, system sustainability was assessed through laboratory testing conducted by the Industrial Standardization and Services Center of Indonesia. The tests analyzed water quality indicators, including Total Dissolved Solids (TDS in mg/L), turbidity (NTU), dissolved iron (Fe in mg/L), pH, total hardness (as $CaCO_3$ in mg/L), and dissolved lead (Pb in mg/L). These chemical and physical parameters were used to evaluate the safety, suitability, and potential environmental impact of using rainwater as an irrigation source in hydroponic cultivation systems.

In order to reduce external disruptions such as pest infestations and uncontrolled exposure to rainwater, a greenhouse was constructed. Groundwater and collected rainfall were the two water resources used in this experiment, and each treatment group included 15 replications. Five lettuce plants were used in each replication, and their placement was entirely randomized. Throughout the experimental period, regular monitoring was conducted, including weekly checks on nutrient solution concentration and plant health, as well as inspections for pests and diseases to ensure optimal growing conditions. All data collected during the study were subjected to statistical analysis using the Independent Samples T-Test to determine the significance of differences between treatment groups. Statistical processing and visualization were performed using R Studio version 2023.06.2 + 561.

3. RESULT AND DISCUSSION

3.1. Smart Greenhouse System Implementation Results

Through the successfully developing a regulated environment for the hydroponic production of lettuce *(Lactuca sativa L.)*, the smart greenhouse system demonstrated the effectiveness of sensor-based automation and the incorporation of rainwater harvesting. The system maintained stable environmental parameters throughout the 30-day growth cycle, with average temperature and humidity levels kept within optimal ranges for lettuce development. Real-time monitoring using DHT22, soil moisture, and light sensors allowed for automated irrigation and ventilation control, minimizing manual intervention and reducing resource consumption. The rainwater harvesting unit operated effectively, capturing and filtering precipitation through the gutter and filtration system, with water quality remaining consistent and free of debris, as verified by both visual inspection and laboratory results.

The filtered water, stored in the high-density polyethylene tank, was delivered efficiently to the hydroponic beds via a pressure-controlled piping system. No significant clogging or contamination was observed during the trial period, indicating that the system's filtration and distribution mechanisms functioned as intended. Furthermore, the automated irrigation system, triggered by soil moisture thresholds, demonstrated precise water delivery using harvested rainwater without causing nutrient dilution or oversaturation. This integration of water source and automation proved to be efficient and sustainable, supporting healthy lettuce growth under consistent and optimized microclimatic conditions within the greenhouse structure.

Figure 3. Lettuce cultivation using an NFT hydroponic system inside a controlled-environment smart greenhouse.

Figure 3 illustrates the implementation and outcomes of the smart greenhouse system used in this study. The image on the left shows the interior of the smart greenhouse equipped with a hydroponic system arranged in parallel lines under a controlled microclimate environment. Lettuce plants are cultivated in nutrient-rich water using a recirculating system connected to rainwater harvesting storage. This setup demonstrates the integration of environmental sensors, shading, and automated irrigation, which together maintain stable conditions conducive to lettuce growth.

3.2. Results of Rainwater Harvesting System Integration

The integration of the rainwater harvesting system into the smart greenhouse functioned effectively throughout the lettuce cultivation cycle, demonstrating its capability to support automated irrigation in a resource-efficient manner. Rainwater collected from the greenhouse rooftop was successfully channeled through the gutter and first-flush diverter, with minimal debris observed post-filtration, confirming the efficiency of the filtration system. The filtered water, stored in a high-density polyethylene tank, maintained a stable volume throughout the test period, supported by the automated refill and monitoring process. The IoT-based smart irrigation system responded accurately to soil moisture readings, ensuring that water was delivered only when required. This precision not only minimized water wastage but also maintained optimal moisture levels in the root zone for lettuce growth.

Figure 4. Dashboard monitoring of the rainwater harvesting system.

Real-time environmental monitoring using the DHT22 sensor revealed that the temperature and humidity within the greenhouse remained within the optimal range for lettuce cultivation, contributing to consistent plant health, as shown in Figure 4.

The DS18B20 sensor installed in the storage tank recorded water temperature fluctuations that stayed within acceptable thresholds, preventing thermal stress in the hydroponic system. The ultrasonic sensor proved effective in monitoring water level dynamics in the rainwater tank, transmitting continuous readings to the IoT device and subsequently to the cloud-based dashboard via MQTT. The weather station installed outside the greenhouse provided valuable supplementary data on rainfall intensity, wind speed, and atmospheric pressure, which were integrated into the system's monitoring dashboard.

3.3. Results of After Treatment

3.3.1. Results of Water Quality After Treatment

The data collection process, conducted over a 30-day lettuce (Lactuca sativa L.) growth cycle, successfully captured a comprehensive dataset that combined sensor-based monitoring with manual field observations. Environmental parameters recorded by the DHT22, BH1750, and capacitive soil moisture sensors consistently demonstrated stable and controlled conditions within the smart greenhouse. Average daily air temperatures remained within the optimal range of 23–27°C, while relative humidity fluctuated between 65% and 80%, supporting healthy vegetative growth. Light intensity levels, measured using the BH1750 sensor, followed natural diurnal patterns and were effectively moderated by the greenhouse's shading structure, thereby avoiding excessive light stress.

Table 1. The characteristics of the water.

Parameter testing	Groundwater	Rainwater
pH	7.6	6.8
TDS (mg/L)	141	57
EC (μmhos/cm)	220	89.06
Nutrition AB Mix (ppm)	850	850

Water quality plays a crucial role in hydroponic cultivation, particularly concerning nutrient absorption and overall plant health. Ideally, soft water with minimal concentrations of dissolved minerals should be used for hydroponic nutrient solutions. Both water types used in this study were filtered prior to use to minimize the presence of undesirable elements such as salts, lime, and iron. The characteristics of the water used for cultivation are summarized in Table 1. Groundwater exhibited a higher pH (7.6), total dissolved solids (TDS) of 141 mg/L, and electrical conductivity (EC) of 220 μmhos/cm. In contrast, harvested rainwater showed a slightly more acidic pH of 6.8, with lower TDS (57 mg/L) and EC (89.06 μmhos/cm). Despite these differences, both water sources were supplemented with an identical AB Mix nutrient solution at a concentration of 850 ppm, ensuring uniformity in nutrient supply.

A laboratory analysis was conducted by the Standardization and Industrial Services Center of the Agency for the Assessment of Industrial Technology of Indonesia to evaluate the quality of rainwater used in the IoT-based rainwater harvesting system. The objective was to assess the quality of rainwater before and after filtration, to support its application in precision irrigation systems within smart greenhouses. The laboratory tests included assessments of physical, chemical, and biological parameters, in compliance with national standards for water quality indicators such as Total Dissolved Solids (TDS), turbidity, pH, total hardness, dissolved iron, and lead. The analysis was conducted between September 13 and October 8, 2024, using valid sample conditions provided by the industrial partner involved in this research.

Table 2. Comparison of water quality parameters between rainwater, filtered rainwater, and groundwater sources for hydroponic lettuce cultivation.

Parameter	Rainwater	Rainwater with filtration	Groundwater
Total dissolved solids (TDS) (mg/L)	65	56.33	54
Turbidity (NTU)	1.53	2.11	0.67
Dissolved iron(Fe) (mg/L)	<0.06	<0.06	<0.06
pH	6.61	7.99	8.18
Total hardness (CaCO3) (mg/L)	60	101.2	75.2
Dissolved lead (Pb) (mg/L)	<0.002	<0.002	<0.002

Table 2 presents the laboratory test results comparing three water sources: raw rainwater, filtered rainwater, and groundwater. The TDS level in raw rainwater was 65 mg/L, which decreased to 56.33 mg/L after filtration. Groundwater exhibited the lowest TDS level at 54 mg/L, indicating that it had undergone natural filtration through the soil layers. These results confirm that the filtration process effectively reduced dissolved solids, improving water quality for hydroponic use.

However, a notable increase in turbidity was observed after filtration, from 1.53 NTU to 2.11 NTU, possibly due to the release of fine particles from the filtration media. In contrast, groundwater exhibited the lowest turbidity level at 0.67 NTU, indicating its superior clarity and suitability for agricultural applications without the need for further treatment.

Dissolved iron (Fe) was found to be below the detectable limit (<0.06 mg/L) in all samples, suggesting that none of the water sources pose a risk of iron contamination. Regarding pH levels, raw rainwater was slightly acidic (pH 6.61), while filtration raised the pH to a neutral value (pH 7.99). Groundwater exhibited a slightly alkaline pH of 8.18, likely due to the presence of natural minerals such as calcium and magnesium.

Total hardness, expressed as $CaCO_3$, increased significantly in filtered rainwater (from 60 mg/L to 101.2 mg/L), compared to 75.2 mg/L in groundwater. The increase in hardness in filtered rainwater may be attributed to the leaching of minerals, such as calcium or magnesium, from the filtration media. Lastly, dissolved lead (Pb) was undetectable (<0.002 mg/L) in all samples, confirming their safety for irrigation and potential consumption.

3.3.2. Morphological Differences Due to Water Source Quality

Distinct morphological differences were observed between lettuce plants irrigated with harvested rainwater and those irrigated with groundwater. These variations are attributed to differences in water quality, particularly in terms of dissolved solids, pH, and mineral content. Lettuce plants grown with rainwater exhibited smaller overall size and less intense leaf coloration compared to those grown with groundwater. In contrast, the plants irrigated with groundwater demonstrated more vigorous vegetative growth, characterized by larger leaf size and a deeper green pigmentation, indicating higher chlorophyll concentration and possibly better nutrient uptake (Figure 5). These visual differences suggest that water quality, especially the mineral and nutrient content inherent to each water source, plays a crucial role in determining plant morphology and growth performance under hydroponic conditions.

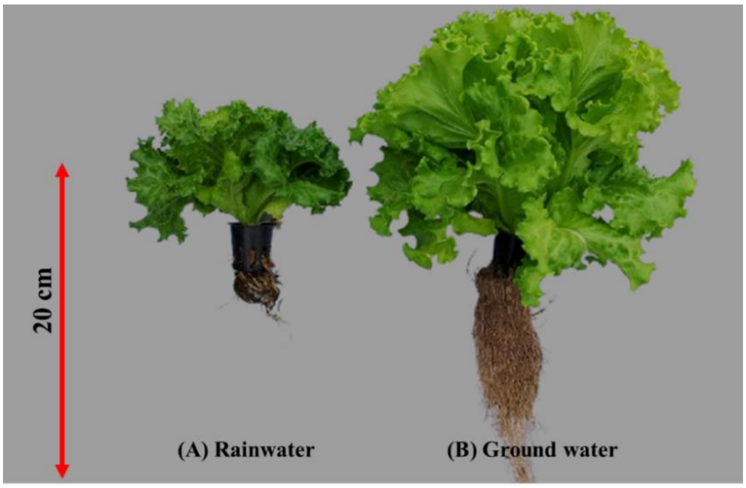

Figure 5. Morphological appearance.

Figure 5 displays the morphological appearance of lettuce plants at harvest time, grown under two different water source treatments: harvested rainwater (A) and groundwater (B). Visual assessment revealed apparent differences in plant size and leaf color. Lettuce grown with rainwater appeared smaller in stature, with lighter green leaves, whereas those irrigated with groundwater showed more robust growth and darker green foliage. These differences suggest a correlation between water quality and vegetative growth characteristics. The red reference line in the image represents a scale of 20 cm, highlighting the relative size differences between treatments.

3.3.3. Number of Leaves

Statistical analysis showed that water quality had a significant effect on the number of leaves produced per plant. As shown in Figure 6, lettuce irrigated with groundwater had approximately 40% more leaves compared to those grown with rainwater, and this difference was statistically significant ($p < 0.001$) based on the Independent Sample T-Test. The higher mineral content in groundwater likely contributed to improved nutrient absorption and vegetative development.

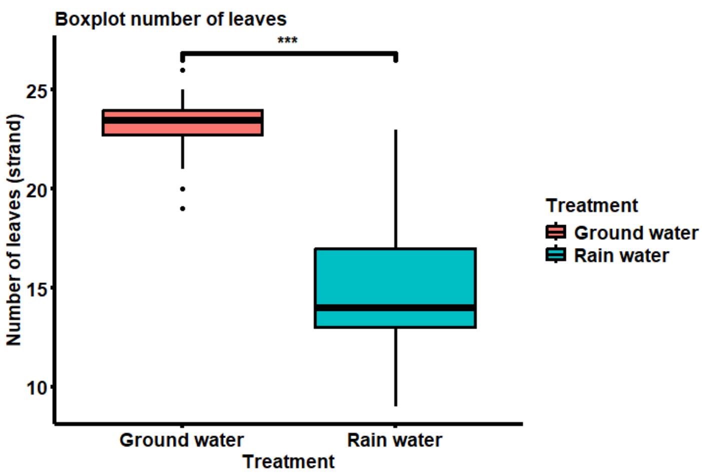

Figure 6. Boxplot comparison showing a significantly higher number of lettuce leaves under groundwater treatment compared to rainwater irrigation (***p < 0.001).

Mineral-rich water improves nutrient availability, supporting vigorous leaf development by maintaining nutrient stability, enhancing uptake efficiency, preventing contamination, and regulating pH and electrical conductivity in hydroponic systems.

3.3.4. Leaf Length

Further statistical analysis revealed that the quality of irrigation water had a significant impact on the leaf length of lettuce plants. As illustrated in Figure 7, lettuce treated with groundwater showed an average leaf length increase of 25% compared to those irrigated with harvested rainwater. These findings reinforce the notion that water quality has a measurable impact on the morphological expression of hydroponically grown crops, particularly in parameters closely tied to vegetative vigor and nutrient availability.

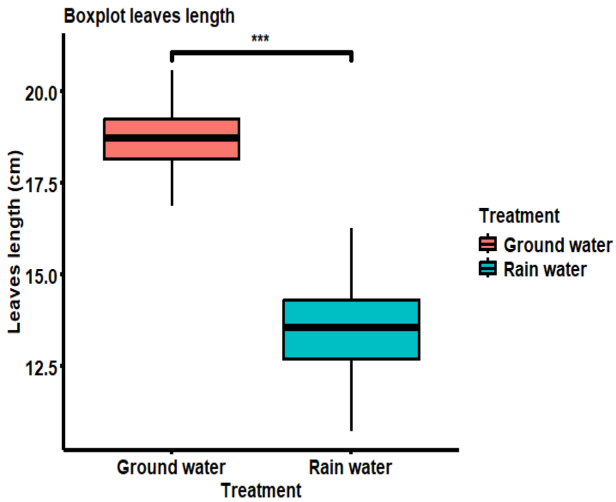

Figure 7. Boxplot showing significantly longer lettuce leaves under groundwater treatment compared to rainwater irrigation (***p < 0.001).

3.3.5. Leaf Width Response

The statistical analysis confirmed that the quality of irrigation water had a significant influence on the leaf width of lettuce plants. As illustrated in Figure 8, lettuce irrigated with groundwater exhibited a noticeably broader leaf structure compared to those grown with harvested rainwater. On average, the leaf width in the groundwater treatment was approximately 20% greater, and the difference was statistically significant at the $\alpha = 0.001$ level, as determined by the Independent Sample T-Test. Since groundwater typically has a higher mineral content, plants treated with it are likely to have wider leaf development, which is connected to improved cellular expansion and nutrient absorption. Leaf width is a vital morphological characteristic often linked to increased photosynthetic area and overall plant vigor. It plays a crucial role in biomass accumulation and productivity, especially under hydroponic conditions.

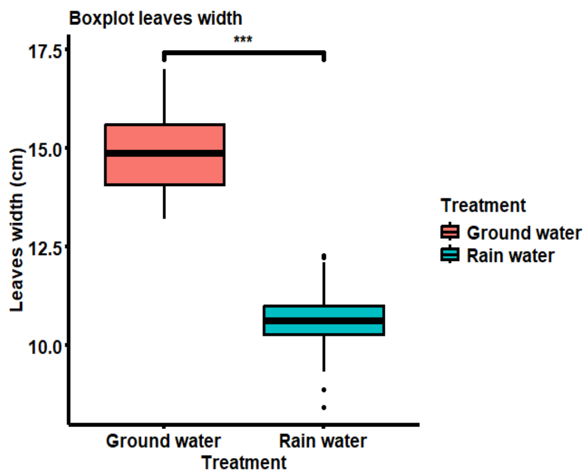

Figure 8. The boxplot shows significantly narrower leaves width under groundwater treatment compared to rainwater irrigation (***p < 0.001).

3.3.6. Leaf Weight Analysis

Statistical analysis revealed a significant effect of irrigation water quality on the leaf weight of lettuce plants. As shown in Figure 9, lettuce grown with groundwater demonstrated a substantially higher average leaf weight compared to plants irrigated with harvested rainwater. Quantitatively, groundwater irrigation resulted in a 55.56% increase in leaf weight, a difference that was statistically significant at the α=0.001 level, as determined by the Independent Sample T-Test. This increase in leaf biomass may be attributed to the higher concentration of dissolved minerals present in groundwater, which can enhance nutrient uptake and photosynthetic capacity, thereby promoting vegetative growth. Leaf weight is a crucial indicator of plant productivity in hydroponic systems, directly correlating with yield potential and marketable quality.

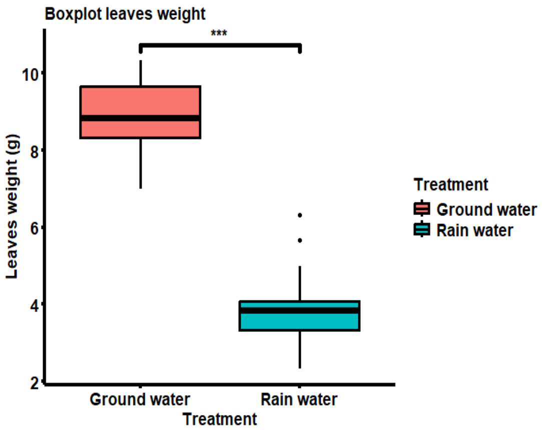

Figure 9. Boxplot showing significantly lower leaves weight under groundwater treatment compared to rainwater irrigation (***p < 0.001).

3.3.7. Greenness Index (SPAD Value)

The analysis of chlorophyll content, measured using the SPAD value, revealed a significant difference between treatments with different water sources. As illustrated in Figure 10, lettuce plants irrigated with harvested rainwater exhibited a 16.67% higher greenness index compared to those irrigated with groundwater. This difference was statistically significant at the α = 0.001 level, as determined by the Independent Sample T-Test. The higher SPAD values in rainwater-treated plants may indicate more favorable conditions for chlorophyll synthesis, possibly due to the lower salinity and softer composition of rainwater. Elevated SPAD readings reflect improved photosynthetic efficiency, which can contribute to plant resilience and quality even when overall biomass is comparatively lower. These results highlight that while groundwater may enhance structural growth parameters such as leaf weight and width, rainwater can promote physiological quality as measured by chlorophyll concentration.

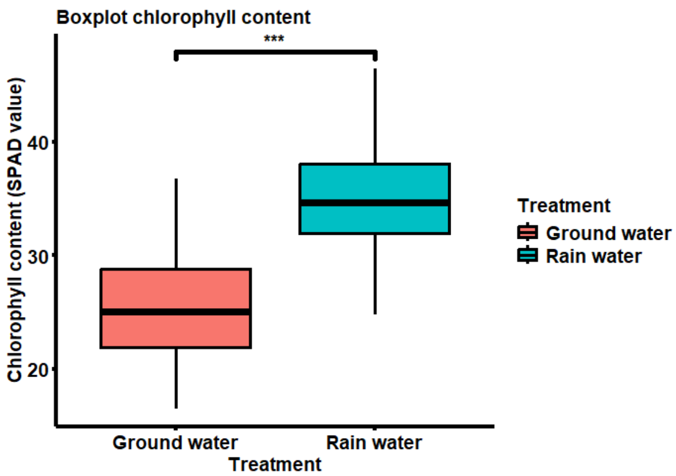

Figure 10. A boxplot illustrating significantly higher chlorophyll content under groundwater treatment compared to rainwater irrigation (***p < 0.001).

3.3.8. Fresh Weight of Lettuce Plants

Statistical analysis indicated that irrigation water quality had a highly significant effect on the fresh weight of lettuce plants. As shown in Figure 11, plants irrigated with groundwater exhibited a 62.5% higher fresh weight compared to those treated with harvested rainwater, with the difference being statistically significant at the **α** level of 0.001 based on the Independent Sample T-Test. The increased fresh biomass in the groundwater treatment may be attributed to the higher levels of minerals and dissolved nutrients naturally present in groundwater, which can enhance vegetative growth and water uptake. Fresh weight is one of the most critical parameters for evaluating the commercial yield of leafy vegetables in hydroponic systems, and the observed improvement suggests that groundwater may offer more favorable conditions for biomass accumulation under the tested conditions.

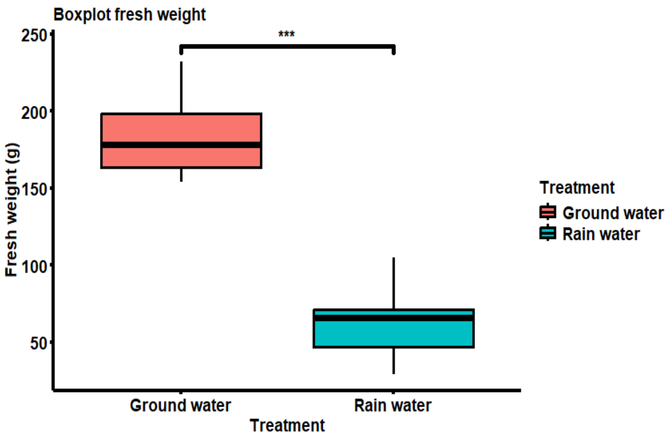

Figure 11. Boxplot showing significantly fresh weight under groundwater treatment compared to rainwater irrigation (***$p < 0.001$).

3.3.9. Root Length

The statistical analysis revealed that the quality of irrigation water had a significant impact on the root length of lettuce plants. As depicted in Figure 12, plants irrigated with groundwater developed root systems that were on average 44.45% longer than those irrigated with harvested rainwater. This difference was statistically significant at the $\alpha=0.001$ level, as determined by the Independent Sample T-Test. Longer root development is often associated with improved water and nutrient acquisition, as well as enhanced anchorage and stress resilience. The extended root length observed in the groundwater treatment suggests that the mineral composition of groundwater may have stimulated root elongation more effectively than the relatively softer rainwater. In hydroponic systems, root morphology plays a crucial role in determining plant performance and nutrient uptake efficiency, making root length an essential parameter for evaluating treatment effectiveness.

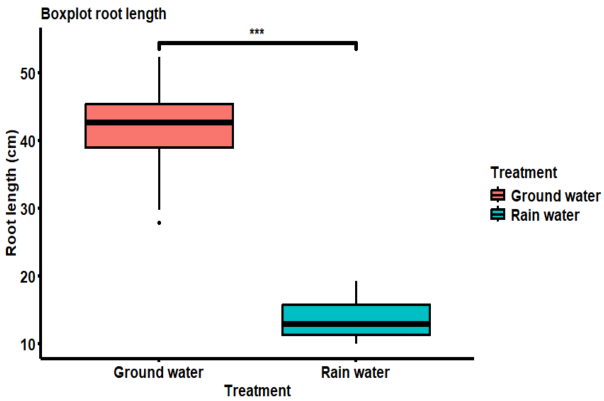

Figure 12. Boxplot showing significantly shorter root length under groundwater treatment compared to rainwater irrigation (***$p < 0.001$).

4. CONCLUSION

This study demonstrated the feasibility and effectiveness of integrating a rainwater harvesting system with a smart greenhouse to promote sustainable hydroponic lettuce cultivation in tropical environments. The application of IoT-based environmental monitoring and automated irrigation successfully maintained optimal growth conditions, improved water-use efficiency, and ensured precise environmental control throughout the cultivation cycle. Comparative analysis between groundwater and harvested rainwater revealed significant differences in lettuce morphological characteristics, including leaf number, leaf size, fresh biomass, root length, and SPAD value. Groundwater consistently enhanced vegetative growth and biomass accumulation, achieving up to 62.5% higher fresh weight and 44.45% longer root length, while rainwater-irrigated plants exhibited higher SPAD readings, indicating improved chlorophyll concentration and reduced salinity stress factors associated with superior physiological leaf quality.

The analysis of water quality parameters further substantiated these findings. Filtration improved several aspects of harvested rainwater, particularly pH and total dissolved solids (TDS), though it also increased turbidity and hardness. On the contrary, without further treatment, groundwater maintained more stable physicochemical properties, indicating that it is more suitable for hydroponic systems. As a whole, these findings demonstrate how using diverse sources of water in precision agricultural systems involves trade-offs between quantitative yield performance and qualitative physiological response.

To advance understanding of plant physiological responses under varying irrigation sources, future research should include comprehensive chlorophyll and pigment profiling quantifying chlorophyll a, chlorophyll b, and carotenoid concentrations through HPLC or spectrophotometric analysis. Additionally, leaf nutrient profiling (e.g., nitrogen, magnesium, and iron content) and temporal SPAD measurements across growth stages could reveal dynamic trends in chlorophyll synthesis, providing early diagnostic tools for nutrient imbalance and stress detection.

Beyond the experimental outcomes, this research contributes to the broader agenda of sustainable agriculture and rural development by demonstrating how smart farming technologies can optimize resource use and support climate-resilient food production in tropical regions such as Indonesia. Integrating renewable water sources, such as harvested rainwater, with IoT-enabled precision management offers a scalable pathway to reduce water dependency, minimize environmental impact, and strengthen the resilience of small- and medium-scale horticultural enterprises.

In conclusion, the findings affirm that the combination of smart monitoring systems and alternative water resources represents a viable and scalable innovation for achieving sustainable, resource-efficient, and climate-adaptive agriculture. Continued optimization of filtration design, sensor integration, and data-driven irrigation algorithms will be crucial for ensuring consistent water quality, improving system reliability, and maximizing both yield and environmental sustainability in future agricultural applications.

Funding: This research was funded by the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia, under the Applied Research Program – Vocational Product Scheme (2024), in accordance with Main Contract No. 126/SPK/D.D4/PPK.01.APTV/IV/S2024 and Official Letter No. 175/PL15.8/PP/2024, dated May 7, 2024. The funding agency had no role in the study design, data collection, analysis, or interpretation of results.
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Disclosure of AI Use: The authors used OpenAI's ChatGPT (GPT-5, 2025 version) and Grammarly (2025 edition) to enhance the clarity, coherence, grammar, and academic tone of the Introduction and Conclusion sections. Both tools were used exclusively for language refinement and did not generate or alter the scientific content, data interpretation, or analytical results. All outputs from these tools were critically reviewed, verified, and edited by the authors to ensure factual accuracy, contextual integrity, and consistency with the study's original research findings.

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