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Aeroponic System Engineering to Optimize Horticultural Plant Growth

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ABSTRACT

Purpose: *This study aims to evaluate the effectiveness of aeroponic systems in optimizing horticultural plant growth compared to conventional soil-based cultivation methods, with a focus on vegetative growth, biomass accumulation, and water use efficiency.*

Subjects and Methods: *The research subjects were lettuce horticultural plants cultivated for eight weeks in two different systems, aeroponic and conventional. In the aeroponic system, plants were grown with roots suspended in the air and sprayed with nutrient solution in the form of mist at certain intervals, while in the conventional system, plants were grown in soil media with standard fertilization. Parameters observed included plant height, number of leaves, wet and dry weight, and water use efficiency. Data were analyzed descriptively and comparatively by calculating the average, standard deviation, and percentage increase for each treatment.*

Results: *The results showed that the aeroponic system provided significant improvements in all growth parameters compared to the conventional method. Aeroponic plants reached an average height of 35.4 cm in the 8th week, higher than 27.8 cm in the conventional system. The number of leaves in the aeroponic system reached 30, while the conventional system had 23. The wet and dry weights of aeroponic were 245.3 g and 45.6 g, respectively, greater than 178.4 g and 32.7 g in the conventional system. The water use efficiency of aeroponics was also much higher, namely 19.6 g/L compared to 5.6 g/L in the conventional system.*

Conclusions: *Aeroponic systems have proven superior in enhancing horticultural plant growth while simultaneously conserving water. These findings support aeroponics as a sustainable, efficient, and relevant alternative modern agricultural technology for application in areas with limited land and water resources.*

INTRODUCTION

The rapid growth of the world's population has led to an increasing demand for food, including horticultural products such as vegetables, fruits, and medicinal plants (Zhilyakov et al., 2020; Silva, 2010). Indonesia, as an agricultural country, has significant potential for developing horticultural commodities (Pitaloka, 2017; Sahri et al., 2022; Fetra et al., 2021). However, challenges include limited productive land and soil degradation due to long-term intensive use. This situation demands innovative cultivation technologies that can produce high-quality, resource-efficient, and environmentally friendly products.

Hussain et al. (2014) and Gruda (2019) said that, conventional horticultural cultivation still relies heavily on soil conditions as a growing medium. This dependence creates various problems, such as decreased soil fertility, pest and disease attacks, high fertilizer requirements, and wasteful water consumption. Furthermore, global climate change is causing uncertainty in planting seasons, making horticultural crop productivity increasingly difficult to predict (Malhotra, 2017; Glenn et al.,2013; Dixon et al., 2014). Therefore, soilless cultivation technologies are beginning to be considered as an alternative to overcome the limitations of conventional agricultural systems.

One emerging technology is hydroponics, a soil-free plant cultivation system using nutrient solutions (Rajendran et al., 2024; Rajaseger et al., 2023). Hydroponics has been proven to increase land use efficiency and produce higher-quality products (Treftz & Omaye, 2016; Verdoliva et al., 2021). However, this method still requires a relatively large volume of water and an intensive nutrient solution management system. To increase efficiency, aeroponics emerged, a plant cultivation technique that sprays nutrient solutions in the form of mist directly onto roots suspended in the air.

Regmi et al. (2024) said that, aeroponic systems have several advantages over both hydroponics and conventional systems. Plants grown aeroponics tend to have healthier root growth, optimal nutrient absorption, and require less water. Lakhiar et al. (2018) and Tunio et al. (2020) said that, Furthermore, aeroponics allows for better environmental control, resulting in the production of high-quality horticultural products in a relatively short time. This efficiency makes aeroponics a potential solution to limited land and water resources.

However, implementing aeroponic systems is not without technical challenges that must be overcome (Garzón et al., 2023; Lakhiar et al., 2020). The design of the misting system, the size of the mist particles, the pump pressure, the spraying frequency, and the composition of the nutrient solution are all critical factors influencing the success of this system (Wang et al., 2022). If the system design is not appropriate, nutrient distribution to the plant roots will be disrupted and plant growth will be suboptimal. Therefore, a proper engineering approach is required to ensure that aeroponic systems function efficiently.

In the context of horticultural crops, aeroponic system engineering is crucial because these crops generally have high economic value and a relatively short harvest cycle (Lakhiar et al., 2025; Khan et al., 2020). Leafy vegetables such as lettuce, kale, and spinach, for example, are highly responsive to nutrient availability and the growing environment. With proper aeroponic system engineering, it is hoped that productivity and crop quality can be increased, while simultaneously providing economic benefits for farmers and agribusinesses (Lakhiar et al., 2018).

Furthermore, aeroponic systems have the potential to support sustainable agricultural development. This technology can reduce pesticide use due to a more controlled growing environment, save up to 90% of water compared to conventional systems, and produce more hygienic horticultural products. Aeroponics can also be implemented in urban areas through the concept of urban farming, thus meeting the growing food needs of urban populations (Tunio et al., 2020).

Based on this description, research on aeroponic system engineering to optimize horticultural crop growth is crucial. This research is expected to contribute to the development of modern cultivation technologies that are more efficient, productive, and environmentally friendly. In addition, the research results can serve as a reference for the development of sustainable agriculture in Indonesia, while also supporting the achievement of national food security.

METHODOLOGY

Research Design

This study employed a comparative experimental design aimed at evaluating the differences in growth performance between horticultural plants cultivated using an aeroponic system and those grown in a conventional soil-based system. The comparative approach was selected to clearly identify variations in plant responses under distinct cultivation methods, particularly in relation to nutrient delivery efficiency, biomass accumulation, and water use. Both systems were observed under identical environmental conditions to ensure that any differences in outcomes could be attributed specifically to the cultivation method rather than external factors. The experimental design also allowed for systematic measurement of growth indicators at predetermined intervals to ensure consistency and reliability in data collection.

Study Site and Environmental Conditions

The experiment was conducted inside a controlled greenhouse environment to minimize external disturbances and maintain consistent growing conditions. The greenhouse was maintained at a temperature range of 25–30°C and relative humidity levels between 60–70%, as these conditions are optimal for vegetative growth of leafy horticultural crops. Light exposure was standardized using a combination of natural sunlight and supplemental lighting when necessary to achieve uniform photoperiod and light intensity across treatments. The use of a greenhouse ensured that all plants, regardless of treatment group, were exposed to the same climate conditions, thereby enhancing internal validity of the study.

Plant Materials

The plant material used in this study consisted of 10-day-old seedlings of horticultural leafy vegetables, such as lettuce, chosen due to their short life cycle and sensitivity to nutrient availability, making them ideal for experiments evaluating cultivation systems. All seedlings were sourced from the same batch to ensure genetic uniformity and reduce variability in early growth stages. Prior to treatment allocation, seedlings were acclimatized for 24 hours to minimize transplant shock and ensure uniform initial growth conditions for both experimental groups.

Aeroponic System Treatment

In the aeroponic treatment, seedlings were positioned on custom-designed aeroponic racks where their roots were suspended freely in the air. This design allowed direct exposure of roots to oxygen, which is known to enhance root metabolism and nutrient absorption. Nutrient delivery was conducted using an ultrasonic nozzle capable of generating fine mist droplets to ensure even distribution and rapid nutrient uptake. The nutrient solution was formulated using standard AB Mix hydroponic nutrients at a concentration of 1,200 ppm with an adjusted pH of 5.8–6.0 and electrical conductivity (EC) of 1.6–2.0 mS/cm. Two spray interval regimes 5-minute and 15-minute intervals were applied to assess differences in nutrient supply frequency. All nutrient reservoirs were monitored and replenished regularly to maintain consistent concentration and prevent nutrient depletion throughout the experimental period.

Conventional Soil System Treatment

For the conventional cultivation method, seedlings were planted in pots filled with sandy loam soil, a commonly used medium known for good drainage and moderate nutrient retention. Prior to planting, the soil was homogenized to ensure uniform texture and composition across all samples. Standard fertilization practices were followed using NPK fertilizer applied according to recommended dosages for leafy vegetable cultivation. Watering was conducted manually to maintain adequate soil moisture, ensuring that plants did not experience water stress but also avoiding excessive irrigation. This treatment provided a baseline comparison reflective of typical soil-based horticulture practices.

Observed Parameters

Four primary parameters were measured throughout the study to evaluate plant performance under each cultivation system. First, plant height was measured every two weeks using a standardized ruler to track vertical growth trends. Second, the number of leaves was counted manually to assess vegetative development and canopy expansion. Third, at the end of the experiment, wet and dry biomass were recorded using an analytical balance after appropriate drying procedures to determine overall biomass accumulation. Finally, water use efficiency was calculated by comparing total water consumption with the final biomass produced, providing insight into the sustainability and resource efficiency of each system.

Sampling and Data Collection Procedures

A total of 20 plant samples were assigned to each treatment group to ensure sufficient statistical representation and minimize the impact of individual plant variability. Data collection was performed uniformly across treatment groups following a predefined schedule. All measurements were conducted manually by trained personnel to maintain consistency. For biomass assessment, plants were harvested at the same growth stage to ensure valid comparison. Water usage in the aeroponic system was tracked through reservoir monitoring, while in the soil system it was measured through controlled manual irrigation records.

Data Analysis Techniques

Data obtained from all observed parameters were processed using descriptive-comparative analysis. The mean, standard deviation, and percentage increase were calculated for each growth parameter to identify trends and quantify improvements in plants grown under the aeroponic system relative to the soil-based system. Comparative analysis focused on determining the degree of difference between treatments rather than establishing causal inference, consistent with the study's design. The results were presented in the form of tables, graphs, and narrative explanations to provide a comprehensive interpretation of how each cultivation method affected plant growth.

RESULTS AND DISCUSSION

Before discussing the research results presented in Table 1, it is important to clarify that plant growth observations were conducted periodically to monitor plant height development in both aeroponic and conventional cultivation systems. Monitoring was conducted every two weeks for eight weeks to ensure that growth changes were clearly visible at each developmental stage. This data served as the basis for comparing the effectiveness of the two methods in supporting horticultural plant growth, particularly in terms of vertical growth rate. By presenting data in stages at each observation period, a more comprehensive evaluation of performance differences between the two systems was possible.

Table 1. Height Growth of Horticultural Plants in Aeroponic and Conventional Systems

Treatment	Week 2 (cm)	Week 4 (cm)	Week 6 (cm)	Week 8 (cm)
Aeroponic	7.5	15.2	26.8	35.4
Conventional	5.1	11.4	19.7	27.8

Based on observations of plant growth, the aeroponic system demonstrated significantly better results than conventional methods. By week 8, plants in the aeroponic system reached an average height of 35.4 cm, while plants in the conventional system only reached 27.8 cm. This demonstrates that the improved availability of oxygen and nutrients to the roots in the aeroponic system has a positive effect on growth rate. The difference in growth began to become apparent in week 4, when the aeroponic plants grew 15.2 cm, while the conventional plants only grew 11.4 cm. This advantage is due to the more efficient distribution of nutrients in the form of mist, allowing roots to absorb nutrients more easily than roots growing in soil.

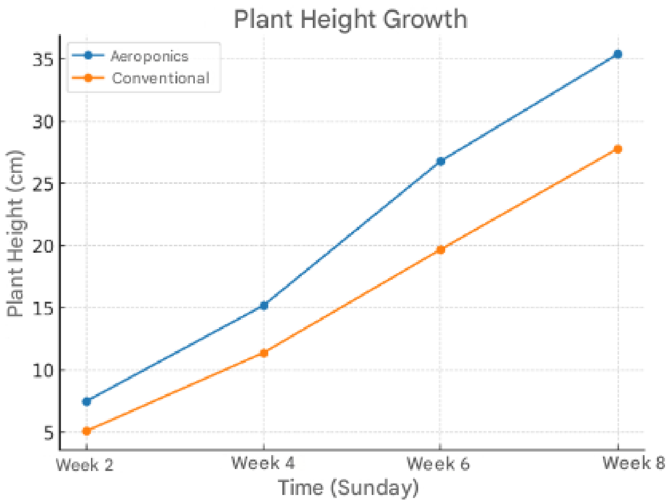

Figure 1. Plant Height Growth Chart (Weeks 2–8)

Thus, the aeroponic system has proven superior in supporting the vegetative growth of horticultural plants. These results indicate that aeroponic technology can accelerate the growing cycle, potentially increasing horticultural productivity in the long term.

Table 2. Number of Plant Leaves in Aeroponic and Conventional Systems

Treatment	Week 2	Week 4	Week 6	Week 8
Aeroponic	5	12	21	30
Conventional	3	9	16	23

Leaf number is an indicator of plant vegetative growth, directly related to the process of photosynthesis. The data in Table 2 shows that plants in the aeroponic system produced more leaves than those in the conventional system. By week 8, the average number of leaves in aeroponic plants reached 30, compared to only 23 in conventional plants.

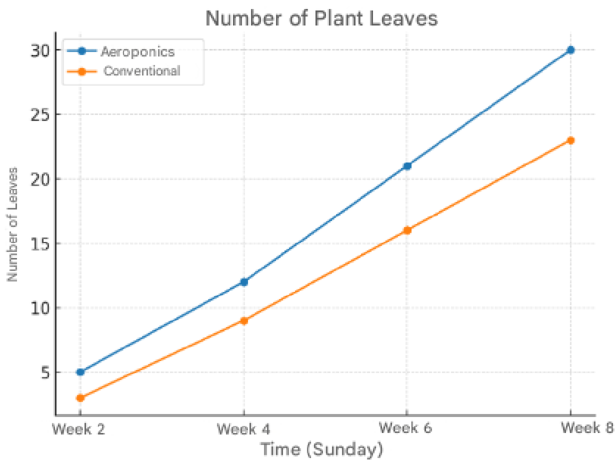

Figure 2. Plant Leaf Count Graph (Weeks 2–8)

This increase in leaf number correlates with the availability of nutrients, which are more readily absorbed in the aeroponic system. With roots suspended and directly exposed to the nutrient mist, nutrient uptake becomes more efficient. This allows plants to develop more leaf tissue in response to optimal environmental conditions. These results indicate that aeroponic system engineering can increase the photosynthetic capacity of horticultural plants. A greater number of leaves will impact biomass production and crop quality.

Table 3. Wet and Dry Weight of Plants in Aeroponic and Conventional Systems

Treatment	Fresh Weight (g)	Dry Weight (g)

Aeroponic	245.3	45.6
Conventional	178.4	32.7

Wet and dry weight measurements showed that plants grown using the aeroponic system had higher weights than plants grown using conventional methods. The average wet weight of aeroponic plants was 245.3 g, compared to only 178.4 g for conventional methods. Similarly, aeroponic plants produced 45.6 g of dry weight, higher than the 32.7 g for conventional methods. High wet weight reflects better water availability in aeroponic systems. Despite the lack of soil, plant roots still receive an optimal water supply through nutrient mist. Meanwhile, higher dry weight indicates greater plant biomass accumulation, which translates to optimal plant tissue growth.

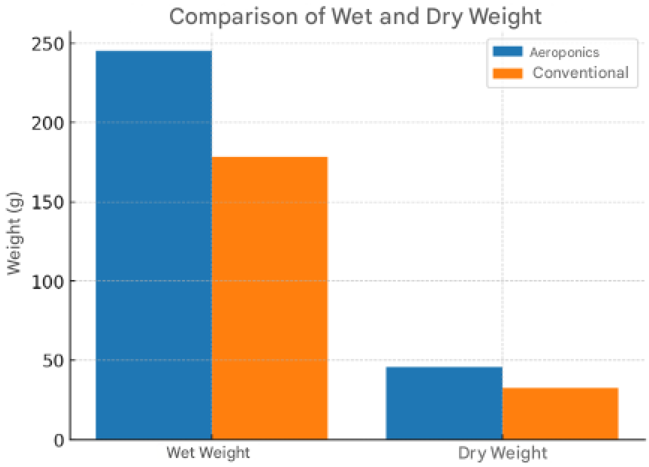

Figure 3. Plant Wet and Dry Weight Graph

This data demonstrates that aeroponics not only accelerates plant height growth but also increases biomass production. This is crucial in horticulture, as plant dry weight is directly related to crop quality and yield.

Table 4. Water Use Efficiency in Aeroponic and Conventional Systems

Treatment	**Water Volume Used (L)**	**Biomass Production (g)**	**Water Use Efficiency (g/L)**
Aeroponic	12.5	245.3	19.6
Conventional	32.0	178.4	5.6

Water efficiency is one of the main indicators of the success of an aeroponic system. Research shows that aeroponics requires only 12.5 liters of water to produce 245.3 g of biomass, with a water efficiency of 19.6 g/L. In contrast, a conventional system requires 32 liters of water to produce 178.4 g of biomass, with an efficiency of only 5.6 g/L.

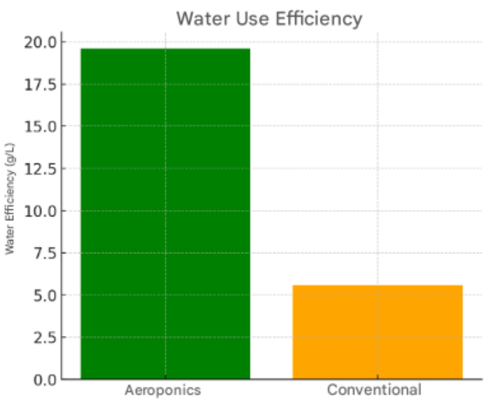

Figure 4. Water Usage Efficiency Graph

These results indicate that aeroponics can save more than 60% on water compared to conventional systems. This is due to the nutrient mist spraying mechanism, which minimizes water loss due to percolation or excessive evaporation. High water efficiency makes the aeroponic system highly relevant for applications in areas with limited water resources. In addition to being environmentally friendly, this system also supports the concept of sustainable agriculture with high productivity and low resource consumption.

Discussion

The results of the study showed that the aeroponic system significantly increased plant height compared to conventional methods. By week 8, the aeroponic plants had reached 35.4 cm in height, compared to only 27.8 cm for conventional methods. This demonstrates that the aeroponic system is able to provide nutrients and oxygen more efficiently through nutrient mist that directly reaches the roots. This absorption efficiency accelerates the plant's vegetative growth rate, which is crucial in the early stages for determining final productivity. Furthermore, the increase in leaf number in the aeroponic system was also higher than in conventional methods. Leaves function as the primary organs of photosynthesis, so a greater number of leaves allows for increased photosynthetic capacity. By week 8, the aeroponic plants produced an average of 30 leaves, compared to only 23 for conventional methods. This indicates that the rooting environment in the aeroponic system supports optimal vegetative biomass formation, thus strengthening the positive relationship between nutrient availability, leaf growth, and photosynthetic rate.

Regarding wet and dry weight parameters, the results also confirmed the superiority of the aeroponic system. The wet weight of aeroponic plants reached 245.3 g, higher than the 178.4 g achieved with conventional methods. Meanwhile, the dry weight of aeroponic systems reached 45.6 g, compared to 32.7 g with conventional methods. Higher dry weight indicates higher biomass accumulation, reflecting the efficiency of nutrient and photosynthetic energy use. This confirms that aeroponics not only accelerates growth but also improves the quality of horticultural crops. Water use efficiency was a key finding of this study. The aeroponic system required only 12.5 liters of water to produce 245.3 g of biomass, with an efficiency of 19.6 g/L, significantly higher than the conventional method, which requires 32 liters of water to produce 178.4 g of biomass with an efficiency of 5.6 g/L.

These results indicate that aeroponics is highly relevant for application in areas with limited water, while also supporting the principles of sustainable agriculture that is resource-efficient and environmentally friendly. Overall, the results of this study demonstrate that aeroponic system engineering has the potential to be an innovative solution for developing modern horticultural agriculture. Increased plant height, leaf number, wet and dry weight, and water use efficiency are clear evidence that this system is superior to conventional methods. With higher productivity and more efficient resource use, aeroponics can be a superior strategy for meeting food needs while reducing negative impacts on the environment.

CONCLUSION

This research shows that aeroponic system engineering can optimize the growth of horticultural crops compared to conventional methods. Plants cultivated with aeroponics exhibited significantly higher growth, leaf number, fresh weight, and dry weight. Furthermore, the aeroponic system proved to be significantly more efficient in water use, with an efficiency nearly four times greater than conventional cultivation. These results confirm that aeroponics not only increases crop productivity but also supports sustainable agricultural practices by saving resources and reducing environmental impacts. Therefore, aeroponic technology has great potential to be developed as an alternative for modern horticultural cultivation, especially in areas with limited land and water.

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