Hydroponic Farming of Leafy Vegetables: A Soil-less Approach to Sustainable Cultivation

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Abstract

Background: Hydroponics, a soilless cultivation technique, has emerged as a sustainable alternative to traditional agriculture. With increasing urbanization, limited arable land, and climate variability, hydroponics offers efficient resource use and consistent crop production. Leafy vegetables are particularly responsive to hydroponic systems, making them ideal for evaluating productivity and nutritional outcomes.

Purpose: The purpose of the present research was to assess the growth performance, yield, and adaptability of selected crops, mustard greens, radish greens, Swiss chard, strawberries, and long beans, cultivated in a hydroponic vertical pipe system. The study aimed to determine crop suitability, nutrient uptake patterns, and overall system productivity.

Research Methodology: Four Horizontal pipes were established, each containing a different crop group. Pipe 1 contained mustard greens, Pipe 2 radish greens, Pipe 3 Swiss chard, and Pipe 4 a mixed system of strawberries and long beans. Growth parameters, including leaf expansion, stem strength, chlorophyll intensity, biomass accumulation, and flowering, were monitored. Observations were recorded systematically to evaluate crop performance under uniform nutrient solution and controlled environmental conditions.

Results Mustard greens showed rapid vegetative growth and produced the highest biomass among leafy crops. Radish greens demonstrated moderate growth, with high chlorophyll intensity and adaptability. Swiss chard produced the largest leaf area and highest leaf quality, making it visually and nutritionally optimal. Strawberries established strong root systems and flowered early, while long beans displayed vigorous vine elongation and required support structures. Overall, the horizontal hydroponic system supported robust development across all crop groups.

Conclusions: The study confirms that leafy vegetables such as mustard greens and Swiss chard are highly suitable for hydroponic vertical systems, while radish greens provide resilience under varying conditions. The successful establishment of strawberries and long beans highlights the versatility of hydroponics for mixed cropping strategies.

Implication: These findings underscore hydroponics as a sustainable, resource-efficient farming method capable of addressing food security challenges. Future applications include scaling vertical systems for urban agriculture, integrating automation and Internet of Things technologies, and expanding crop diversity to enhance productivity and resilience in both urban and rural contexts.

Keywords: Hydroponics, Soil-less cultivation, Leafy vegetables, Vertical farming, Nutrient uptake, and Sustainable agriculture

1. Introduction

The use of nutrient-enriched water solutions to cultivate plants without soil is known as hydroponics, and it has emerged as a key component of contemporary agricultural innovation (Thapa et al., 2024). The promise of this soilless method to address urgent issues, including dwindling arable land, water shortages, and the need for sustainable food production in both urban and rural environments, is increasingly recognized (Velazquez-Gonzalez et al., 2022a). Compared to conventional agricultural methods, hydroponics improves crop yields and quality by precisely controlling nutrients, pH, and environmental variables, thereby eliminating soil as the primary growth medium (Shareef et al., 2024; Velazquez-Gonzalez et al., 2022a). The effective delivery of vital nutrients directly to plant roots, often via methods such as nutrient film technique (NFT), deep water culture (DWC), and aeroponics, is the foundation of hydroponics. Hydroponics is a highly regulated and durable production method, as these systems not only maximize plant growth but also reduce the prevalence of soil-borne diseases and pests (Korsa et al., 2025). Because of their short growth cycles and high demand in international markets, leafy plants like lettuce, spinach, and kale are especially well-suited to hydroponic systems. Research has shown that, compared with soil-based farming, hydroponically grown leafy greens frequently produce higher yields and better nutritional quality (Chhetri et al., 2022). Additionally, hydroponics is essential to achieving sustainability objectives. Hydroponic systems are extremely resource-efficient, as they can use up to 90% less water and 60% less fertilizer than conventional agriculture (Regmi et al., 2024). In areas where water is scarce and the climate is unpredictable, this efficiency is especially important. Additionally, by enabling year-round production under controlled conditions, hydroponics reduces reliance on natural cycles. It lowers the risk of crop failure from extreme weather events, aligning with global food security objectives (Zee, 2024).

Perhaps the most prospective application of hydroponics is agriculture in urban areas. With rooftop gardens, vertical farms, and containerized systems, hydroponic farming offers a modular alternative for growing fresh vegetables in cities amid rapid urbanization and land scarcity. These developments improve local food security and resilience while also shortening the distance that food must travel (Ghimire et al., 2023a). Technological breakthroughs have further boosted the global popularity of hydroponics. Growing crops in hydroponics is now more effective and flexible, thanks to the combination of automation, robots, and IoT-enabled monitoring systems that have enhanced ventilation, nutrient delivery, and climate control. Advances in artificial intelligence (AI) now enable early disease diagnosis, optimal resource utilization, and predictive modeling of plant growth, all of which increase production and profitability (Dennison et al., 2025).

Emerging food systems, especially alien agriculture, are expected to rely heavily on hydroponics. The viability of hydroponic systems on space missions, where soil is unavailable, and resource efficiency is crucial, has been shown by research conducted by the National Aeronautics and Space Administration and other organizations. Hydroponics demonstrates its adaptability to support sustained food production for astronauts and prospective settlements on Mars (Srivastava et al., 2024).

The application of hydroponics as a soil-less cultivation technique, particularly for green crops, is the main emphasis of this study. The main focus is on understanding the fundamentals of hydroponic cultivation, including system designs such as the nutrient film technique (NFT). The study identifies crops that respond well to hydroponic systems because of their short growth cycles and high market demand, focusing on green vegetables such as lettuce, spinach, mustard, and strawberries.

2. Review of Literature

a. Principles of Hydroponics Farming

The foundation of hydroponics is soil-less cultivation, in which water solutions directly supply vital nutrients to plants. Unlike traditional farming, hydroponics provides precise control over nutrient concentrations, pH levels, and oxygen delivery, maximizing plant growth and reducing unpredictability from soil conditions. Research highlights that hydroponics is a reliable method for consistent crop production, as it improves nutrient uptake efficiency and reduces the risk of soil-borne diseases (Choi et al., 2025; Nikolov et al., 2023).

b. System Designs in Hydroponics

Through many successful system designs that apply soilless farming principles, hydroponic farming has evolved. Aeroponics, Ebb and Flow systems, Deep Water Culture (DWC), and Nutrient Film Technique (NFT) are some of the most popular.

i. Wick system

One of the most basic types of hydroponic farming, the wick system is popular for indoor and small-scale farming. Because it requires no electricity or pumps, this passive hydroponic method is affordable and accessible to novices. This device uses capillary action to move the nutrient solution from a reservoir to the plant root zone via a wick made of absorbent material like cotton or nylon. The fertilizer solution's constant flow ensures the growing medium stays moist and plants receive a consistent supply of water and vital nutrients. The efficiency of wick hydroponic systems for crop production has been assessed in several studies.

(Rajendran et al., 2024) examined how wick quantity and orientation affected seed potato growth in a hydroponic system. According to their research, vertical wick layouts were more effective in transporting water and nutrients than horizontal ones. Higher tuber yield, greater plant vigor, and improved root development were all demonstrated by plants cultivated with optimal wick designs. The study also showed that wick hydroponic systems, which require less electricity and upkeep, can support sustainable crop production. These results demonstrate the promise of wick-based hydroponic systems as a workable alternative for controlled-environment production, urban agriculture, and small-scale farming, especially in areas with limited access to sophisticated hydroponic infrastructure.

ii. Drip system

The drip hydroponic method works especially well for growing crops such as tomatoes and peppers. In these systems, a nutrient solution is delivered directly to the plant roots through pipes and hoses. The flow of the solution is carefully controlled to ensure the right amount reaches the plants at the right time. The solution is delivered at set intervals, allowing precise control over how many nutrients the plants receive. In closed-loop systems, any excess solution not used by the plants is collected and returned to the storage tank for reuse. This makes the system very efficient and helps save water. Overall, this method creates a controlled environment that supports healthy plant growth while using resources wisely (Rajendran et al., 2024; Sambo et al., 2019).

iii. Nutrient Film Theory System

The Nutrient Film Technique (NFT) involves keeping a thin layer of nutrient solution, usually just a few millimeters thick, at the bottom of a deep tank. This method allows the lower part of the plant roots to be in contact with the nutrient film, ensuring they receive sufficient water and nutrients. In contrast, the upper part of the roots remains exposed to air, which helps oxygenate and supports healthy root growth. First, the plants grow roots that reach the nutrient film and then spread out horizontally, helping them absorb more nutrients. The roots are not completely covered in water but are constantly or periodically washed by a flowing nutrient solution that moves through a series of pipes. This flow exposes the root surfaces to air, which improves aeration. A pump continuously checks and circulates the nutrient solution, which is then returned to a storage tank by gravity for reuse, making the system efficient. While NFT uses less nutrient solution than floating root systems, it requires additional energy and equipment to function properly. This system is especially well-suited for plants that require well-oxygenated roots, such as tomatoes and peppers, and provides a controlled environment that supports healthy growth (Korsa et al., 2025; Velazquez-Gonzalez et al., 2022).

iv. Aeroponics

Tubers and root vegetables are well-suited to aeroponic cultivation. In this method, the plant's roots hang in the air and receive nutrients through regular misting by a sprinkler system. The main benefit of this approach is that it does not require a separate aeration system, as oxygen is included in the nutrient spray. By allowing roots to remain in the air while receiving nutrients via gentle misting, aeroponics supports strong root growth and improved nutrient uptake, making it a suitable method for growing tubers and root crops (Velazquez-Gonzalez et al., 2022b).

c. Leafy Vegetable in a Hydroponic System

Because of their short growth cycles and strong market demand, green crops are especially well-suited to hydroponic production. Compared with soil-based agriculture, crops such as lettuce, spinach, kale, and basil flourish in NFT and DWC systems, yielding higher yields and better nutritional quality. According to research, hydroponically cultivated leafy greens often exhibit higher survival rates and faster growth in controlled environments (Ekka, 2024). Additionally, hydroponics enables the year-round production of leafy vegetables, ensuring a consistent supply of fresh produce in both urban and rural areas (Shareef et al., 2024).

i. Advantages and Challenges of the Hydroponics System

Water savings of up to 90%, reduced pesticide use, and space efficiency in urban settings are just a few of the benefits of hydroponics. Additionally, by reducing fertilizer consumption and facilitating output in non-arable areas, it promotes sustainable agriculture (Regmi et al., 2024). There are still issues, though, such as high setup costs, the need for technological expertise, and reliance on power for lighting and pumps, which might restrict accessibility. Crop health can be rapidly jeopardized by system malfunctions such as pump malfunctions or nutrient imbalances, highlighting the necessity of effective management techniques (Gurung et al., 2024).

d. Global Application and the prospect

Hydroponics has been used worldwide in a variety of settings, from urban rooftop gardens in North America to commercial vertical farms in Asia and Europe. By facilitating domestic production and lowering dependency on imports, it promotes food security (Ghimire et al., 2023). The scalability and effectiveness of hydroponics are increasing thanks to technological advancements like IoT sensors, AI monitoring, and robotics (Dennison et al., 2025). With NASA and other organizations investigating its potential for space missions, hydroponics is expected to play a role in future extraterrestrial agriculture (Srivastava et al., 2024).

3. Methodology

a. System Design and Construction

Four 100-mm-diameter PVC pipes were arranged in a multi-tier horizontal configuration, supported by a metal frame, to create a Nutrient Film Technique (NFT) hydroponic system. There were uniformly spaced holes in each PVC channel for positioning net pots. PVC elbows were used to connect the channels sequentially, allowing the nutrient solution to flow by gravity from the highest to the lowest.

The main source of nutrients was an elevated nutrient reservoir tank. At the system's base was a nutrient-collection tank labeled. A continuous recirculating loop was created by a submersible pump placed inside the collection tank, which pumped the nutrient solution back to the raised reservoir via flexible tubing (Fig 1).

Figure 1 : *Hydroponics System Design*

b. Nutrient Solution Preparation

In accordance with recommended concentrations for leafy crops, a standard hydroponic fertilizer solution containing essential macronutrients and micronutrients was prepared. The pH of the solution was maintained between 5.5 and 6.5, while the electrical conductivity (EC) was maintained between 1.2 and 1.8 mS/cm. Every day, portable meters were used to measure pH and EC. Every 10 to 15 days, the entire reservoir was replenished with a fresh fertilizer solution to account for evaporation and plant uptake.

c. Seedling Preparation and Transplanting

To guarantee consistent germination and root development, seedlings were first grown in cocopeat. Seedlings were moved into net pots with cocopeat once they had two or three real leaves. The lower part of the roots was then kept in contact with the flowing nutrient film by inserting the net pots into the openings in the PVC tubes.

d. Operation of the Hydroponics System

The system operated on a continuous flow principle. The submersible pump fed the nutritional solution from the collection tank to the top PVC channel, from which it flowed downward through each channel by gravity. To ensure that the root zone always had access to nutrients and oxygen, a thin layer of nutrient solution (about 2–3 mm thick) was applied along the base of each channel. The recirculation cycle was completed when the solution reached the collection tank.

To ensure proper flow, identify leaks, and prevent blockages in the channels and tubes, daily checks were conducted.

e. Environmental condition

The hydroponic system was set up inside a greenhouse that had a green shade net covering it. This semi-controlled setting helped regulate ventilation, temperature, and light intensity. In addition to shielding the system from rain, dust, and external pollutants, the shade net reduced exposure to direct sunlight and minimized heat buildup. Throughout the cultivation phase, temperature and overall plant health were tracked.

f. Maintenance and Data observation

Checking water levels, cleaning algae-prone areas, and ensuring the pump and connections were operating properly were all part of routine maintenance. Before adding a new solution, the collection tank and nutrient reservoir were cleaned. Visual observations of leaf growth, color, and vigor were used to track plant development. Throughout the culture phase, observations were made about root development, nutrient deficits, and system performance.

4. Results

All four crop groups were grown using the hydroponic horizontal pipe system: mustard greens (Raya) in Pipe 1, radish greens in Pipe 2, Swiss chard in Pipe 3, and a mixed cultivation of long beans and strawberries in Pipe 4. The variable growth performance of the crops suggests that they differ in their adaptation to the hydroponic environment. The system supported physiological activities, including photosynthesis and nutrient uptake, by continuously circulating nutrients.

a. Growth performance Across the pipe

Over the course of the trial, mustard greens grown in Pipe 1 showed rapid vegetative growth. Plants reached an average height of about 19-20 cm and produced 9-12 leaves per plant at 25 days after transplanting (day after transplanting). The favorable growing conditions and effective nutrient assimilation in the hydroponic system are demonstrated by the average fresh biomass of 43.5 g per plant.

Additionally, the radish greens cultivated in Pipe 2 showed steady vegetative growth. Plants reached an average height of 17-18 cm and produced roughly 10-11 leaves per plant at harvest (25 days after transplanting). The average fresh biomass per plant was found to be between 45 g, indicating adequate nutrient consumption and plant growth.

Among the leafy vegetables assessed in this study, Swiss chard grown in Pipe 3 showed the greatest vegetative development. At 25 days after transplanting, the average plant height was 24-25 cm, and each plant produced 13-14 leaves. The average fresh biomass per plant was approximately 58 g, indicating improved vegetative performance, likely due to the plant's greater leaf surface area and more effective utilization of available nutrients.

The fruiting crops grown in Pipe 4 showed relatively restricted growth under the experimental conditions, in contrast to the green vegetables. Early in their lives, long bean plants showed little vegetative development. Within 25 days after transplanting, each plant barely produced two to four leaves, and there was very little vine elongation. Additionally, no pod formation was observed during the trial period, indicating that the hydroponic conditions used in this investigation were not ideal for long-term bean growth.

Table 1: Growth performance of crops cultivated in the hydroponic horizontal pipe system

Crop	Pipe No.	Observation Period (Days)	Average Height / Vine Length	Leaves per Plant
Mustard greens (Raya)	Pipe 1	25	19-20 cm	12
Radish greens	Pipe 2	25	17-18 cm	11
Swiss chard	Pipe 3	25	24-25 cm	14
Long bean	Pipe 4	20-25	4-5 cm	2-4
Strawberry	Pipe 4	30-40	-	-

The comparative growth performance of five crops grown in a hydroponic horizontal pipe system is shown in Figure 2. After 25 days of culture, Swiss chard reached an average height of 24.5 cm, the highest vegetative growth among the assessed species. With mean heights of 19.5 cm and 17.5 cm, respectively, mustard and radish greens both showed significant growth. Long bean plants, on the other hand, showed little early-stage development; over the 25-day observation period, their average vine length was only 4.5 cm. During the 30-40-day cultivation period, strawberry plants showed no discernible growth, indicating a lack of adaptation to the hydroponic conditions used in this system. The hydroponic horizontal pipe layout is particularly conducive to leafy vegetable growth, as evidenced by significant differences in plant height among the investigated crops. This is probably because leafy vegetables have shorter growth cycles and require less structural support than fruiting crops.

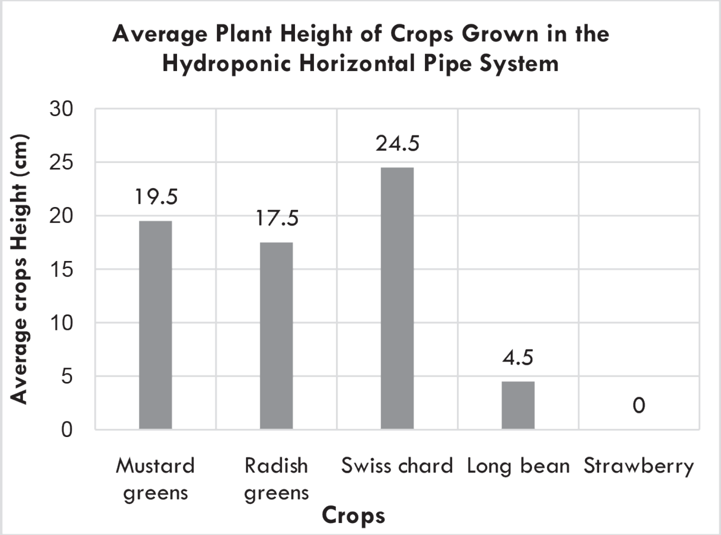

Figure 2 : *Growth performance of crops cultivated in a hydroponic horizontal pipe system*

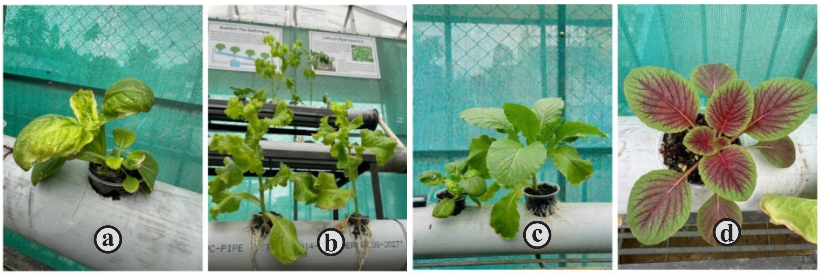

Figure 3 *: Representative growth stages of crops cultivated in the hydroponic horizontal pipe system*

(a) Young mustard plant showing early vegetative development;
(b) Swiss chard exhibiting vigorous leaf growth and characteristic pigmentation;
(c) Mature mustard greens demonstrating expanded leaf development;
(d) Radish greens grown under hydroponic conditions with moderate vegetative growth

5. Discussion

The hydroponic vertical pipe system demonstrated strong adaptability across diverse crop groups, with growth performance varying according to species and nutrient uptake patterns.

Mustard greens (Pipe 1) showed rapid vegetative growth and produced the highest biomass among leafy crops. This result is consistent with findings that hydroponic mustard greens can yield up to 10 times more per square foot than traditional soil farming, due to precise nutrient delivery and controlled environments (Rochester Hydroponics, 2024; Agri Farming, 2024). Their uniform height and broad leaf expansion highlight their suitability for vertical hydroponic systems.

Radish greens (Pipe 2) exhibited moderate growth, with thicker leaves and stronger stems, and showed high chlorophyll intensity. Hydroponic radishes are known for rapid germination and adaptability, with success rates of up to 80% under controlled nutrient conditions (Hydrobuilder Learning Center, 2024; Henry's Hydroponics, 2024). The adaptability observed here reinforces radish greens' potential in vertical hydroponic farming.

Swiss chard (Pipe 3) produced the largest leaf area and highest leaf quality, with glossy leaves and minimal nutrient stress. Hydroponic Swiss chard has been reported to achieve superior nutrient absorption, higher yields, and reduced water usage compared to soil cultivation (Gardening Tips, 2024; Rochester Hydroponics, 2024). These findings confirm Swiss chard's reliability as a visually and nutritionally optimal crop in vertical systems.

The **mixed-crop system (Pipe 4) highlighted the versatility of hydroponics**. Strawberries established strong root systems and flowered early, consistent with studies showing that hydroponic strawberries thrive in nutrient-rich water solutions and enable year-round production (Hydroponic Systems EU, 2023). Long beans demonstrated vigorous vine elongation and responded well to nutrient cycling, aligning with reports that hydroponic beans achieve high yields and require structural support for optimal growth (Agri Farming, 2024).

Overall, the results confirm that leafy vegetables such as mustard greens and Swiss chard are highly suited to hydroponic vertical systems, while radish greens demonstrate resilience and adaptability. The successful establishment of strawberries and long beans underscores the potential of hydroponics for mixed cropping strategies, expanding beyond leafy vegetables to include fruiting and vining crops.

6. Conclusion

The study emphasizes the effectiveness of hydroponic horizontal pipe systems for a variety of crop types. Mustard greens produced the most biomass and showed quick vegetative growth, demonstrating their feasibility for cultivation without soil. Despite growing more slowly, radish greens demonstrated adaptation and resilience with robust stems and high chlorophyll intensity. Swiss chard produces huge, glossy leaves with no nutrient stress, making it the most aesthetically pleasing leafy crop. Long beans showed significant vine elongation and responsiveness to nitrogen cycling, while strawberries established robust root systems and flowered early, further demonstrating the adaptability of hydroponics. The majority of the findings indicate that while radish greens offer flexibility across a variety of settings, leafy plants such as Swiss chard and mustard greens are especially well-suited to hydroponic systems. The ability of hydroponics to diversify production beyond leafy vegetables is demonstrated by the effective integration of fruiting and vining crops. This study supports hydroponics as a flexible, resource-efficient, and sustainable farming technique that can encourage creative agricultural practices in both urban and rural settings and address issues related to food security.

7. Limitation and Direction of Study

This study has several shortcomings despite the encouraging outcomes. First, the horizontal pipe system was tested on a small scale, which may not accurately reflect the challenges encountered in commercial hydroponics at larger scales.

Second, insights into crop performance across varying conditions were limited because environmental factors, including temperature, humidity, and light intensity, were controlled rather than varied.

Third, all crop groups used the same nutrient solution, which might not have maximized development for species with different nutrient needs. Furthermore, Pipe4's mixed-cropping method created resource competition, making it challenging to separate the performance of long beans and strawberries.

Lastly, long-term productivity and sustainability were not investigated because the study period was restricted to early growth and initial yield data.

To assess the commercial viability and economic sustainability of hydroponic vertical systems, further study should focus on scaling them up. A deeper understanding of crop resilience and adaptability would be possible through comparative trials conducted under various environmental conditions. To optimize production and quality, customized fertilizer formulas for individual crops, especially in mixed systems, should be investigated. Long-term research is required to evaluate system longevity, nutrient cycling efficiency, and continuing productivity. Incorporating cutting-edge technologies such as automated nutrient delivery, AI-driven monitoring, and Internet of Things sensors could improve accuracy and reduce labor costs. Lastly, investigating hydroponics for a variety of crop types, such as fruit plants, legumes, and medicinal herbs, would expand its use and improve food security worldwide.

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8. Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this research article.

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