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Nutrient film technique hydroponic system for lettuce production

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ABSTRACT

Background: This study's primary goal is to evaluate the growth characteristics and marketable yield of lettuce (Lactuca sativa L.) cultivated by using the Nutrient Film Technique (NFT) hydroponic system. This study demonstrated the effectiveness of the Nutrient Film Technique (NFT) hydroponic system in producing high quality lettuce (Lactuca sativa L.) with optimized water and nutrient use. Across two consecutive winter seasons, the NFT system consistently supported robust vegetative growth, as reflected in the increases in shoot fresh weight (up to 400 g plant^{-1}), root mass (up to 61 g plant^{-1}), root length (34 cm), plant height (48 cm), and leaf area (144 cm²). The number of leaves also followed a progressive trend, reaching 26 leaves per plant under optimal conditions. Moreover, the system exhibited substantial efficiency in resource use, with total water consumption averaging only 1.93 liters per plant, and water use efficiency values reaching 238.86 kg·m^{-3}. These findings highlight the NFT system's potential as a sustainable alternative for leafy vegetable production, particularly in resource-limited or urban environments. The results reinforce the suitability of NFT hydroponics for integration into controlled environment agriculture and modern hydroponics systems. In the end, the hydroponic method yielded the fastest growth rates.

Keywords*:* Hydroponic, Lettuce, Nutrient Film Technique, Production

1. INTRODUCTION

Hydroponic systems have become increasingly important in modern agriculture due to their efficient use of water and space, and their ability to produce high-quality crops in controlled environments. Although the concept has existed for decades, the commercial acceptance of hydroponic production began approximately 70 years ago (Resh, 2013; Abd-Elmoniem et al., 2006). Hydroponics is technically defined as the cultivation of plants in nutrient-enriched water without soil (Raviv and Lieth, 2008). In practice, however, various inert substrates such as coconut fiber, gravel, sand, and Rockwool are often used to support root systems and stabilize plant growth (Sikawa and Yakupitiyage, 2010).

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Most hydroponic systems function within closed-loop environments, where the nutrient solution is recirculated to minimize water waste. While this approach conserves resources, it also increases the risk of microbial contamination, making it essential to regularly treat and monitor the nutrient solution (Avila-Vega et al., 2014; Christie, 2014; Lopez-Galvez et al., 2014). Nutrient management is a central component of hydroponics. Concentrated fertilizers are diluted in water and delivered to plants through injectors or blending systems.

Parameters such as pH and electrical conductivity (EC) are constantly monitored and adjusted to maintain optimal growing conditions (Jordan et al., 2018; Walters, 2015).

Hydroponics (HP) has proven effective in producing a wide range of vegetables and high-value crops such as lettuce (Makhadmeh et al., 2017), tomatoes, and peppers (Al-Ajmi et al., 2008; Othman et al., 2008). Among the most efficient hydroponic techniques for leafy greens is the Nutrient Film Technique (NFT), which circulates a thin film of nutrient solution over plant roots. NFT has shown particular promise in the cultivation of lettuce (Ako and Baker, 2009), a crop known for its rapid growth and high market demand.

Lettuce (Lactuca sativa L.) is a widely consumed leafy vegetable with significant nutritional and economic importance. Common types include butterhead, romaine, crisphead, and loose-leaf varieties (Kaiser and Ernst, 2012). Though low in calories, lettuce provides important vitamins, minerals, and omega-3 fatty acids that contribute to human health (Oh et al., 2009). The global production of lettuce reached nearly 25 million metric tons in 2014, with strong demand across Asia, North America, and Europe (Mitova et al., 2017).

The hydroponic system offers several advantages over soil-based agriculture, including higher yields, reduced labor, lower water consumption, and year-round production. However, these benefits require advanced technical knowledge, careful environmental control, and significant financial investment (Kaiser and Ernst, 2012). Key environmental variables, including nutrient solution temperature and oxygen availability, can directly influence root activity, nutrient uptake, and plant health (Sachit and Veenstra, 2013; Santos et al., 2010).

In semi-arid regions with limited freshwater resources, hydroponics offers an opportunity to utilize brackish underground water more efficiently (Soares et al., 2007). Furthermore, hydroponic systems are increasingly recognized for their potential in sustainable and organic agriculture. Soilless organic systems utilize biological pest control and organic nutrient sources, aligning with global trends in health-conscious and environmentally friendly food production (Schmutz et al., 2014; Moncada et al., 2021).

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As land degradation, soil salinization, and population pressures escalate, hydroponics provides a sustainable alternative that reduces environmental impact and optimizes resource use (Gomiero, 2016; Lal, 2015). According to the Nutrition Business Journal (2022), consumer demand for organically grown produce, including lettuce, has significantly increased, with U.S. sales of organic lettuce reaching $276 million in 2021 (NASS, 2021).

Therefore, the objective of this study was to evaluate the growth characteristics and marketable yield of lettuce (Lactuca sativa L.) cultivated by using the Nutrient Film Technique (NFT) hydroponic system.

2. Materials and methods

The experiment was conducted using a vertical recirculating Nutrient Film Technique (NFT) hydroponic system. The study was carried out over two consecutive winter seasons (2022 and 2023) at the greenhouse facility located on the rooftop of the Agricultural Engineering Department, Faculty of Agriculture, Zagazig University, Zagazig, Egypt. A separate experimental setup was designed specifically for the NFT hydroponic system, which involved continuous circulation of the nutrient solution through inclined channels to provide a thin film of nutrients around the plant roots. This design ensured adequate oxygenation and nutrient availability throughout the plant growth cycle.

2.1 Lettuce Plants

Seedlings of lettuce (*Lactuca sativa* L.) were grown in plastic cups with dimensions of 7 cm in diameter and 7 cm in height. The cups were filled with inert rock material to provide mechanical support and facilitate root aeration. Seedlings were irrigated daily using Hoagland and Arnon's (1950) nutrient solution to ensure adequate supply of macro- and micronutrients. Sowing was carried out on November 1st in both growing seasons 2022 and 2023. After six weeks of nursery growth, healthy and uniform seedlings were transplanted into the NFT hydroponic channels using net cups. Each net cup was inserted into the pre-designed openings of the NFT system, allowing root contact with the flowing nutrient film.

2.2 NFT System Design and Operation

The hydroponic setup was based on a vertical Nutrient Film Technique (NFT) system constructed using plastic PVC tubes measuring 3 meters in length and 4 inches in diameter. The structure was designed in a pyramid configuration with three tiers, having overall dimensions of 300 cm (length) × 90 cm (width) × 280 cm (height) with a 500-liter capacity reservoir. Each system contained a total of 72 planting sites, with one seedling transplanted into each net cup as shown in Figure 1.

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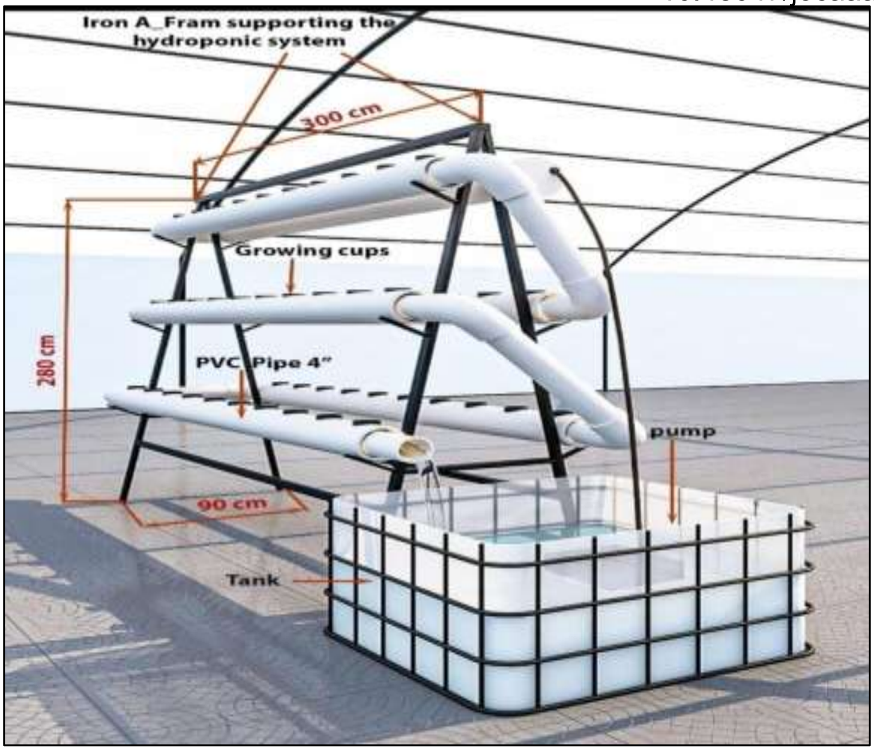

Fig .1. The NFT hydroponic system

The nutrient solution used in the system was based on Hoagland's formula, prepared according to the method described by Cooper (1979). The solution was housed in a 500-liter capacity reservoir and continuously circulated through the system using a submersible pump. The flow of nutrient solution started from the top tier, passing downward through each layer by gravity. Excess solution was collected at the base, replenished when needed, and reused ensuring efficient water and nutrient utilization.

In this closed-loop design, the nutrient solution was not replaced regularly but was continuously monitored and adjusted based on pH and electrical conductivity (EC) measurements. These parameters were measured daily using calibrated meters to maintain optimal nutrient availability and root-zone stability throughout the growing cycle.

3. Measurements

3.1 Growth Parameters and Water Use Efficiency

Throughout the experimental period, key growth parameters were recorded at weekly intervals. These included: (The fresh weight of lettuce plants, Plant height (cm), Root length (cm), Number of leaves and Leaf area). Both parameters were measured using a standard ruler from the base of the plant to the highest point or deepest root, respectively. At the end of the cultivation cycle, the following final measurements were taken: (Fresh shoot mass, (g), Fresh root mass (g), Total water consumption (L) and Water use efficiency (WUE).

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Water Use Efficiency (WUE) was calculated based on the formula described by Djidonou et al. (2013):

$$WUE = \frac{CY}{CWU}$$

Where:

- CY = Crop yield (kg plant^{-1})
- CWU = Crop water uptake (m³ plant^{-1})

These measurements were used to assess the physiological response of lettuce plants to the hydroponic NFT system and to evaluate resource utilization.

4.1. Results

Lettuce plants were harvested 45 days after transplanting. Data were collected to evaluate plant responses under the vertical NFT hydroponic system. The variables measured included (The fresh weight of lettuce plants, Plant height (cm), Root length (cm), Number of leaves, Total Leaf area, Fresh shoot mass, (g), Fresh root mass (g), Total water consumption (L) and Water use efficiency (WUE) The following subsections present detailed results for each growth parameter, supported by figures where applicable. Each result is discussed in the context of physiological significance and compared with findings from previous studies.

4.2. Effect of NFT hydroponic system on lettuce total fresh weight

The results illustrated in Figure 2. showed that the fresh weight of lettuce plants (shoot and root combined) in the NFT hydroponic system ranged from 371 to 461 grams per plant. In the first season, the highest fresh weight was recorded at 461 grams per plant, while in the second season, it was 371 grams per plant. The mean total fresh weight across both seasons was 416 grams per plant.

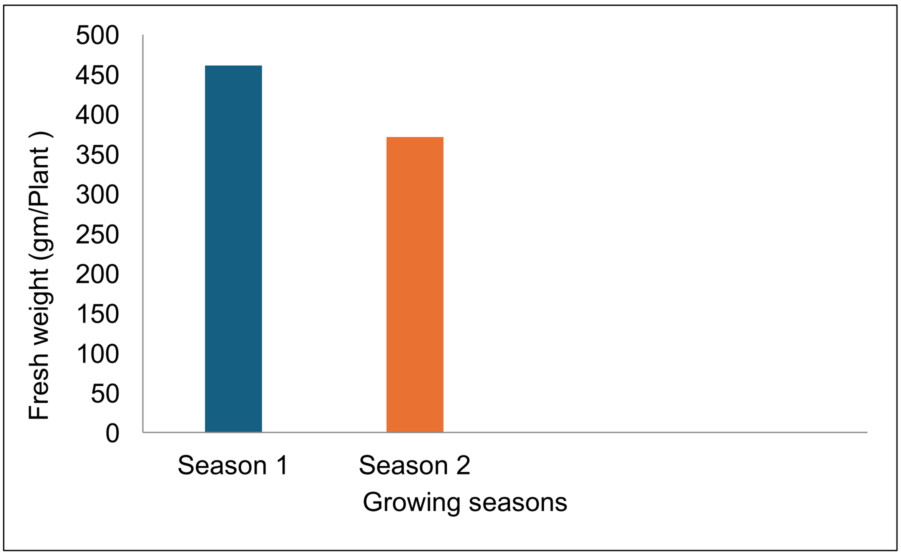

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Fig. 2. Effect of NFT hydroponic system on lettuce total fresh weight

4.3. Effect of NFT hydroponic system on root length

Root length of lettuce plants increased progressively with plant age under the NFT hydroponic system during both growing seasons. The root length increased from 10.0 cm to 34.0 cm in the first season and from 6.5 cm to 20.0 cm in the second season over the six-week growth period. These values reflect an increase of 70.59% and 67.5%, respectively, compared to the first week after transplanting. The highest recorded root length was 34.0 cm at week six during the first season, while the minimum was 6.5 cm during the first week of the second season. The average maximum and minimum root lengths across the two seasons were approximately 27.0 cm and 8.25 cm, respectively as shown in Figure 3.

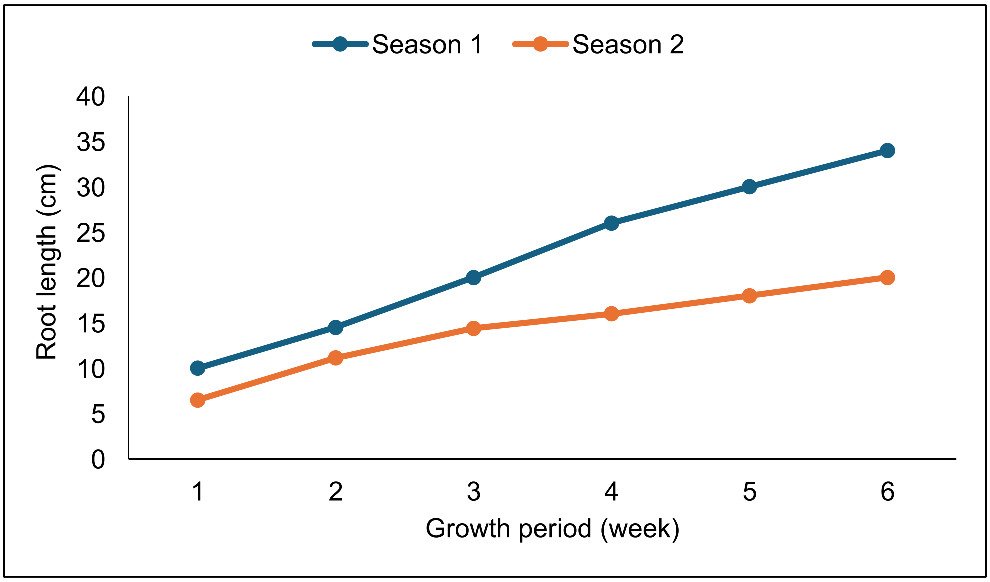

Fig. 3. Effect of NFT hydroponic system on root length

4.4. Effect of NFT hydroponic system on plant height

Plant height of lettuce increased progressively with plant age across both growing seasons under the NFT hydroponic system. Plant height ranged from 17.5 cm to 50.0 cm in the first season and from 16.5 cm to 40.0 cm in the second season over a 6-week period presented in Figure 4. This represents an increase of 65% and 58.75%, respectively, from week 1 to week 6 after transplanting. The average plant height across the two seasons was 45.0 cm, with the maximum observed value 50.0 cm recorded during week six of the first season. The minimum plant height was 16.5 cm, observed during the first week of the second season.

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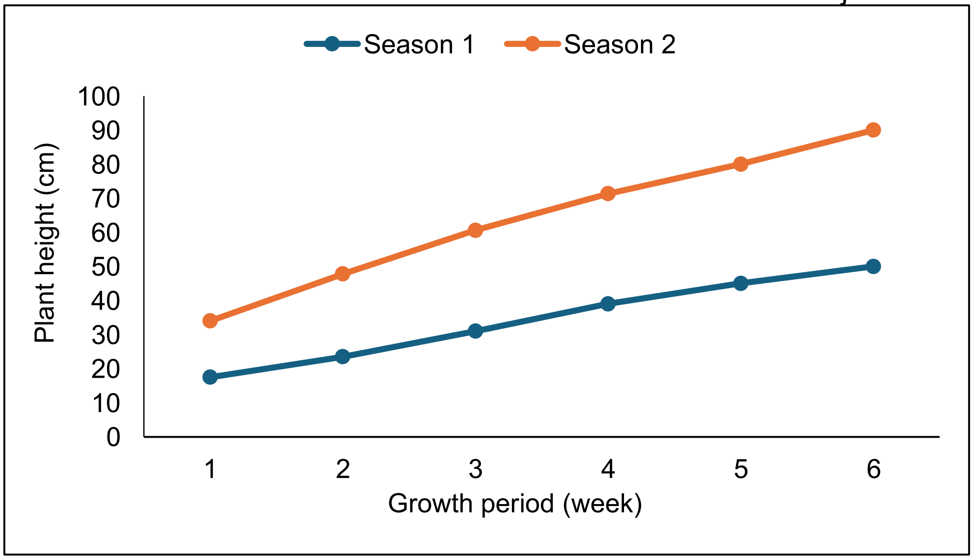

Fig. 4. Effect of NFT hydroponic system on plant height

4.5. Effect of NFT hydroponic system on number of leaves

The number of leaves per lettuce plant increased steadily with plant age across both growing seasons as shown in Figure 5. Leaf number increased from 6 to 26 leaves in the first season, and from 6 to 14 leaves in the second season, over the six-week growing period. This represents an increase of 76.92% and 57.14%, respectively, compared to the first week after transplanting. The maximum recorded number of leaves was 26 in the first season, while the lowest was 14 in the second season, both observed at week six. The average number of leaves across both seasons was 20 leaves per plant, with superior leaf production recorded in the first season.

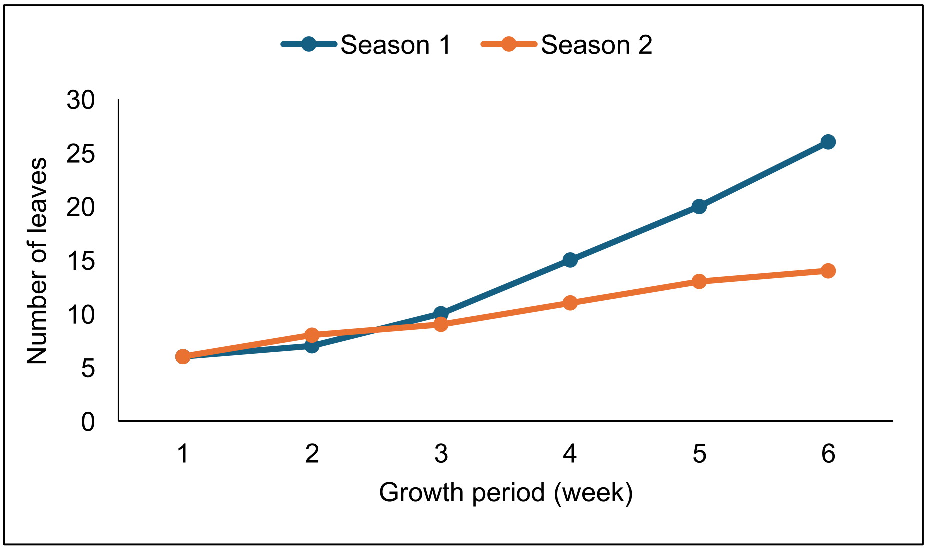

Fig. 5. Effect of NFT hydroponic system on number of leaves

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4.6. Effect of NFT hydroponic system on leaf area

Leaf area expanded steadily with plant age in both growing seasons under the NFT system as presented in Figure 6. Leaf area increased from 29 cm² to 144 cm² in the first season and from 16 cm² to 100 cm² in the second season over the six-week cultivation period, corresponding to gains of 79.86% and 84.0%, respectively. The greatest leaf area (144 cm²) occurred at week 6 in season 1, whereas the minimum (16 cm²) was observed at week 1 in season 2. Averaged across both seasons, the maximum leaf area reached 122 cm².

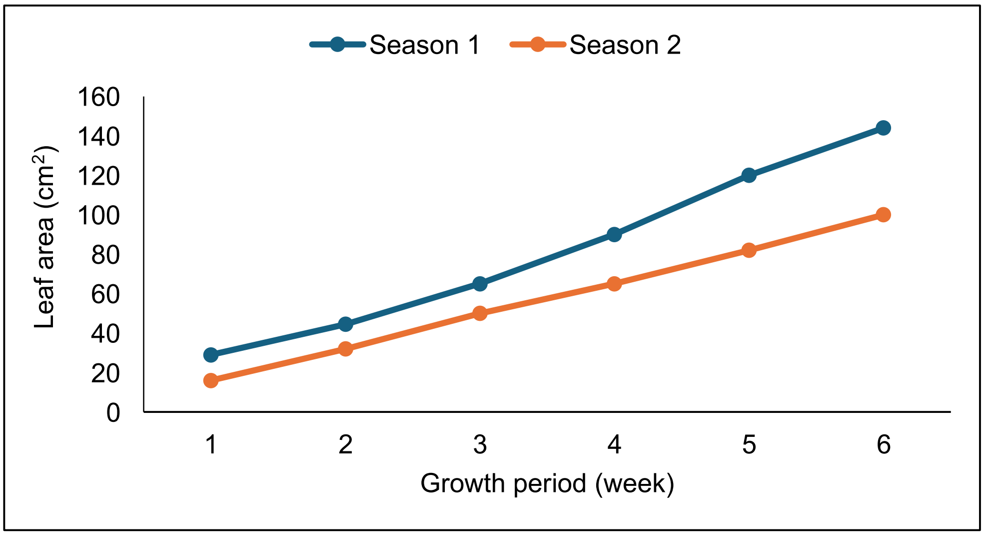

Fig. 6. Effect of NFT hydroponic system on leaf area

4.7. Effect of NFT hydroponic system on fresh mass of shoot

At the end of the 6-week cultivation period, the fresh shoot mass of lettuce plants grown under the NFT hydroponic system showed substantial differences between the two growing seasons as shown in Figure 7. The shoot fresh weight ranged from 316 g plant^{-1} in the second season to 400 g plant^{-1} in the first season. The mean fresh shoot mass across both seasons was 358 g plant^{-1}.

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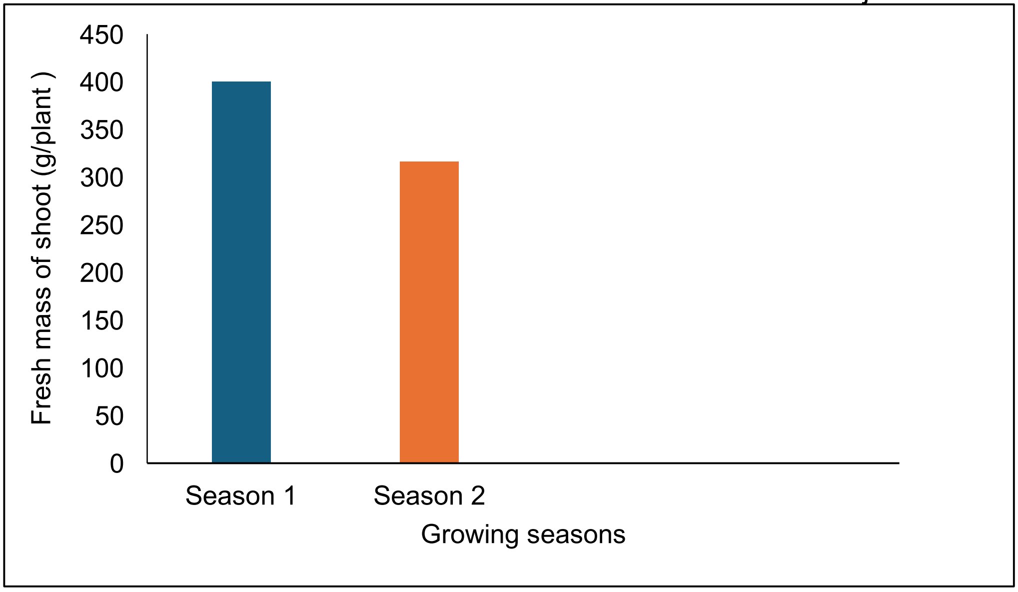

Fig. 7. Effect of NFT hydroponic system on fresh mass of shoot

4.8. Effect of NFT hydroponic system on fresh mass of root

At the end of the 6-week growing period, root fresh mass exhibited moderate variation across seasons as shown in Figure 8. The fresh mass of roots reached 61 g plant^{-1} in the first season and 55 g plant^{-1} in the second season under the NFT hydroponic system.

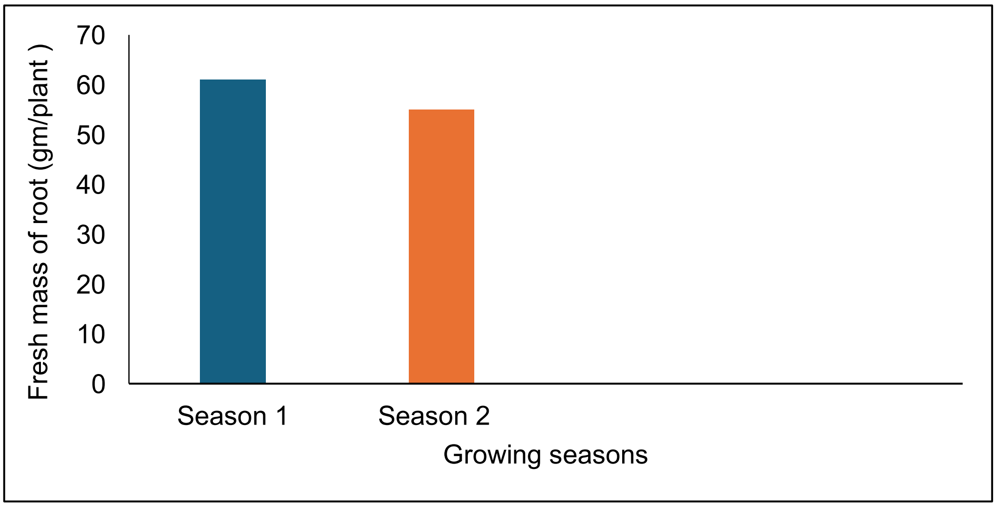

Fig. 8. Effect of NFT hydroponic system on fresh mass of root

4.9. Effect of NFT hydroponic system on lettuce water consumption

The average water consumption pattern of lettuce plants under the NFT hydroponic system varied significantly across the weeks, reflecting the nutrient uptake dynamics of the plants as presented in Figure 9. The volume of water used ranged from 40 liters in the first week to 10 liters in the sixth week. The cumulative water consumption over the entire 6-week period was 139 liters for an 8 m^2 growing area, which accommodated 72 lettuce plants. This translates to an average water use of 1.93 liters per plant throughout the cycle.

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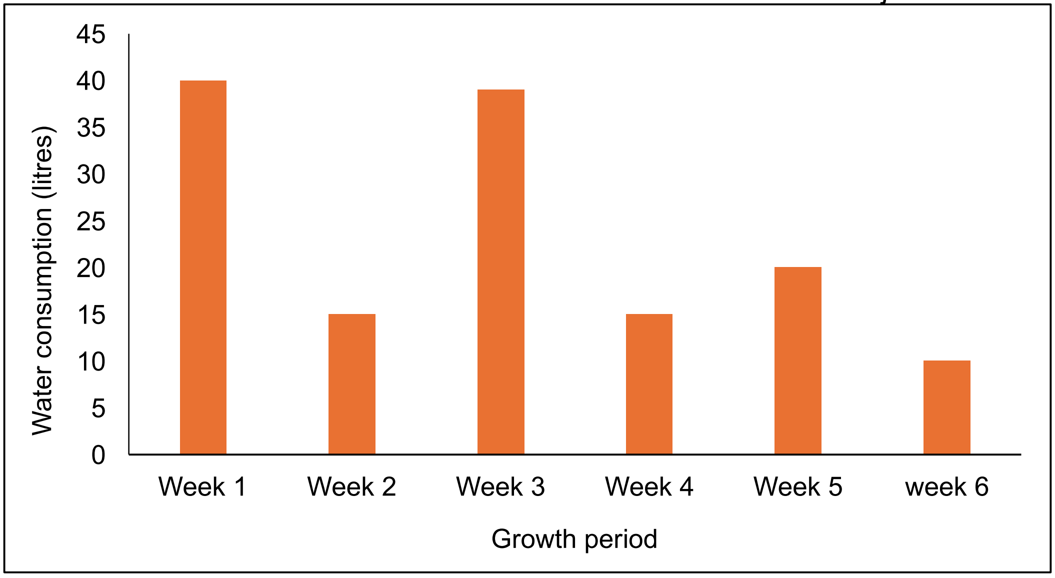

Fig. 9. Effect of NFT hydroponic system on the average lettuce water consumption

4.10. Effect of NFT hydroponic system on water use efficiency

The WUE values for lettuce plants under the NFT system were 238.86 kg·m^{-3} in the first season and 192.23 kg·m^{-3} in the second season as shown in Figure 10. The higher WUE in the first season suggests superior growing conditions and more effective nutrient and water uptake efficiency.

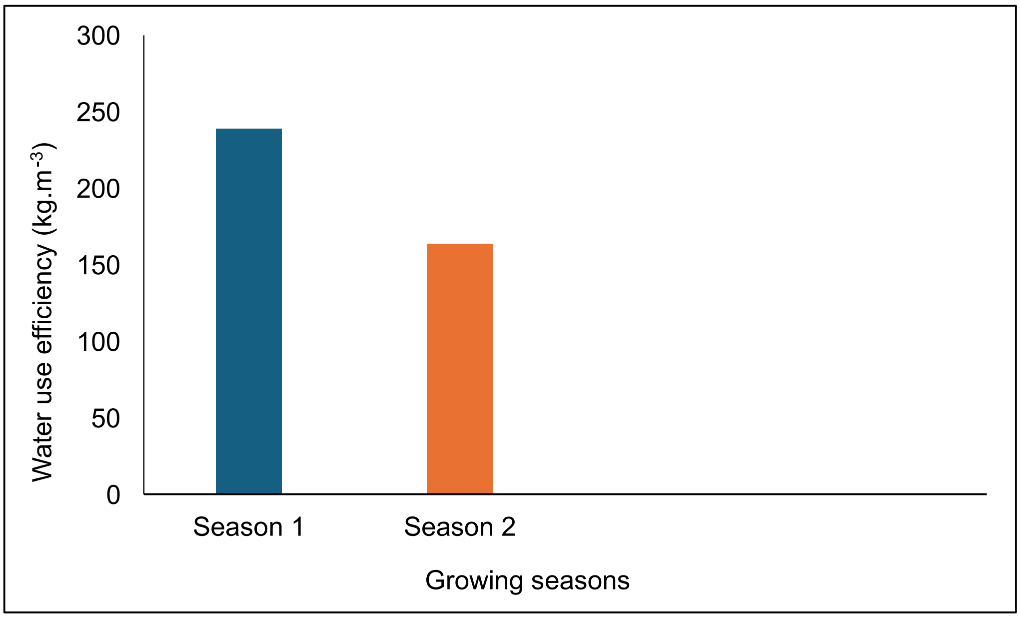

Fig. 10. Effect of NFT hydroponic system on water use efficiency

4.11. Statistical evaluation of growth parameters

Data were analyzed using the F-test (ANOVA) at $P < 0.05$ are shown in Tables (1 and 2). The following statistical evaluation highlights the performance and growth dynamics of lettuce (*Lactuca sativa L.*) cultivated using the vertical Nutrient Film Technique (NFT) system over two consecutive winter

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seasons (2022 and 2023). This table evaluates the growth parameters (e.g., Shoot Fresh Weight) across the two successive seasons to determine if the environmental variations led to significant differences in yield.

Table 1: Statistical analysis of the study data

Source of Variation	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	Fvalue	Significance (P-value)
Between Seasons	1	2916.0	2916.0	12.45*	P < 0.05
Within Groups (Error)	142	33228.0	234.0	--	--
Total	143	36144.0	--	--	--

The asterisk (*) indicates that the effect of the season is statistically significant at the 5% level.

The growth and yield data were subjected to a statistical analysis to evaluate the performance of the NFT system. The results are expressed as Mean ± Standard Deviation (SD) where applicable, and the significance of the differences between the two seasons was determined using the F-test (ANOVA).

Table 2: Statistical evaluation of growth parameters

Parameter	Season 1 (S1)	Season 2 (S2)	Significance (P-value)
Total Fresh Weight (g)	461.0±12.5	371.0±10.2	* (P<0.05)
Shoot Fresh Mass (g)	400.0	316.0	** (P<0.01)
Root Fresh Mass (g)	61.0	55.0	ns (P>0.05)
Plant Height (cm)	50.0	40.0	* (P<0.05)
Root Length (cm)	34.0	20.0	** (P<0.01)
WUE ($kg \cdot m^{-3}$)	238.86	192.23	* (P<0.05)

*****: Statistically Significant (P<0.05). ******: Highly Significant (P<0.01). **ns**: Non-Significant.

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5. Discussion

From the experimental results, the results indicate that the NFT hydroponic system can be effective in enhancing the growth of lettuce plants. This is consistent with previous studies that have shown that NFT systems can promote plant growth by improving nutrient availability and root oxygenation. The increased fresh weight in the first season may be attributed to more favorable environmental conditions and improved nutrient delivery. The consistent performance of the NFT system across two growing seasons confirms its potential as a reliable method for lettuce cultivation in controlled environments. The improved water and nutrient flow dynamics inherent in NFT systems, along with their low energy requirement and reduced substrate dependency, contribute to their effectiveness, particularly in urban agriculture and indoor farming.

The findings of this study are consistent with the results reported by (Khater, 2006) and (Khater *et al*., 2015), who noted that root elongation in hydroponic systems is directly influenced by nutrient accessibility and oxygen availability in the root zone. The elongated root system in the first season may reflect more favorable temperature and nutrient dynamics that supported deeper root penetration. The NFT system's continuous nutrient flow and aeration likely contributed to enhanced root development, which plays a crucial role in nutrient uptake efficiency and overall plant vigor. The consistent performance of the NFT system in promoting root elongation highlights its potential as a sustainable method for leafy vegetable production.

The improved performance in the first season may be attributed to more favorable climatic conditions and potentially more stable nutrient uptake. These findings align with the work of (Khater, 2006 and Khater *et al*., 2015), who observed similar patterns of vegetative growth under nutrient-rich hydroponic conditions. The NFT system's continuous nutrient delivery likely contributed to the steady elongation of lettuce plants over time. The consistent growth pattern observed in this study highlights the potential of NFT hydroponics for producing lettuce with desirable morphological characteristics.

The findings highlight the efficiency of the NFT hydroponic system in promoting vegetative growth, particularly under favorable environmental conditions. Results are consistent with previous studies that reported accelerated leaf formation in hydroponic systems due to improved nutrient availability and water use efficiency. The steady increase in leaf number over the growing period suggests that the NFT system provides a conducive environment for lettuce growth, supporting the development of a robust leafy canopy. The difference in leaf production between the two seasons may be attributed to variations in environmental conditions, emphasizing the importance of optimizing growing conditions in hydroponic systems.

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The higher leaf-area expansion in the first season may reflect more favorable light and temperature conditions enhancing photosynthetic capacity and assimilate allocation to leaf tissue. These findings corroborate earlier reports that NFT systems support rapid canopy development through continuous nutrient and water delivery. The steady increase in leaf area over the growing period suggests that the NFT system provides a conducive environment for lettuce growth, supporting the development of a robust leafy canopy. The continuous nutrient and water delivery in NFT systems likely contributed to the observed leaf area expansion, highlighting the potential of this system for producing high-quality lettuce.

The superior shoot biomass in the first season may be attributed to improved nutrient flow, optimal plant spacing, and more favorable environmental conditions. According to (C. Maucieri *et al.,* 2018), enhanced fresh mass in NFT systems may also result from lower energy consumption and more efficient nutrient uptake dynamics, which improve both vegetative growth and biomass partitioning. These results suggest that the NFT hydroponic system is a suitable method for producing high-quality lettuce in controlled environments such as indoor vertical farms and aquaponic units. The findings support previous research that highlights the potential of NFT systems for efficient and sustainable crop production.

The increase in root biomass was generally correlated with shoot growth, suggesting a parallel rise in nutrient uptake and translocation efficiency. This observation supports the findings of (Lichun Wang *et al.,* 2023), who reported that greater shoot development in hydroponic systems is often accompanied by enhanced root mass due to improved nutrient availability and environmental control. The results affirm that the NFT system provides adequate conditions for root development, contributing positively to the overall productivity of lettuce plants. The NFT system's ability to support healthy root growth is crucial for optimal plant performance and crop yield.

The findings emphasize the water-saving nature of the NFT system, where recirculation of nutrient solution in a closed loop minimizes wastage. This observation is consistent with (Albright and Langhans 2014), who noted that NFT hydroponics rely on shallow, circulating streams of solution in enclosed channels, making them inherently more water-efficient compared to conventional irrigation methods. The NFT system's water efficiency is crucial for sustainable agriculture, particularly in waterscarce regions or applications where water conservation is a priority.

The range of WUE values (192.23 - 238.86 $kg \cdot m^{-3}$) falls within the expected range for high-efficiency closed-loop systems and highlights the role of hydroponics in conserving water while maintaining high productivity. These results confirm the environmental and economic sustainability of NFT systems for

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leafy vegetable production. The NFT system's ability to optimize water use while promoting healthy plant growth makes it an attractive option for sustainable agriculture practices.

The statistical evaluation demonstrates that while the NFT system is highly productive, the marketable yield is sensitive to the cultivation season. The high F-value for vegetative parameters indicates that the first season (2022) significantly outperformed the second (2023), likely due to improved nutrient uptake dynamics and environmental stability. The data suggests a strong positive correlation between root health and marketable yield. The increased root mass (up to 61 g) in the first season supported a higher shoot weight (400 g), confirming that the NFT system's ability to maintain high oxygen levels in the root zone is a primary driver for lettuce productivity. While both seasons were successful, the statistical variance suggests that optimizing light and temperature (as seen in Season 1) is key to maximizing the potential of NFT technology.

Variance in Biomass: The significant difference ($P<0.01$) in Root Length (34.0 vs 20.0 cm) suggests that environmental factors in S1 significantly enhanced the physiological development of the root zone. Growth Trends: The Mean (μ) total fresh weight across both seasons was 416 g. The progressive increase in leaf area from 29 to 144 cm^2 in S1 represented a growth rate (ΔG) of 79.86%. Efficiency Metrics: The Water Use Efficiency (WUE) reached its maximum value (max) of 238.86 $kg \cdot m^{-3}$ in S1, indicating that for every cubic meter of water (m3), the system produced significantly more biomass compared to S2.

6. Conclusion

The results show that the NFT hydroponic system can be effective in enhancing the growth of lettuce plants and increasing water use efficiency. The findings suggest that the system can provide a suitable environment for plant growth, with improvements in fresh weight, root length, and leaf area. Additionally, the system demonstrated high water use efficiency, making it a sustainable option for lettuce production in controlled environments.

The results of this study demonstrate that the Nutrient Film Technique (NFT) is a highly effective and sustainable method for the production of high-quality lettuce (*Lactuca sativa L.).* Across two consecutive winter seasons, the NFT system consistently supported robust vegetative growth, achieving a mean total fresh weight of 416 g per plant and a maximum leaf area of 144 cm^2.

Statistically, the system proved its efficiency through: Growth Performance, Resource Sustainability and Operational Reliability.

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In conclusion, the NFT hydroponic system offers a viable alternative to traditional soil-based agriculture, providing a pathway for intensive, high-yield vegetable production in controlled environments and urban landscapes.

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