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Comparative Response of Lettuce (Lactuca sativa L.) Varieties to Nutrient Film Technique (NFT) Hydroponics in an Advanced Greenhouse Setup: Impacts on Yield and Quality

[1] Emanuela Cojocaru, [2] Denisa Dumitrașcu, [3] Ionut Ovidiu Jerca, [4] Elena Dobrin, [5] Adnan Arshad, [6] Elena Maria Drăghici

[1, 2, 3, 4, 5, 6] University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Marasti Blvd, District 1, Bucharest, Romania

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Corresponding Author: **Elena Maria Drăghici**

Abstract

In the face of rapidly changing climatic conditions that are increasingly threatening the stability of the present agricultural economy, it has now become mandatory to evaluate the response of different plants varieties to conventional greenhouse conditions versus artificially controlled environments, particularly under LED lighting. Present study was carried out to evaluate the comparative response of four lettuce (Lactuca sativa L.) varieties to Nutrient Film Technique (NFT) hydroponics under precisely controlled LED lighting versus conventional greenhouse conditions, with the aim of optimizing yield and quality. A randomized complete block design with four varieties (V1-Lugano, V2-Aleppo, V3-Carmesi, V4-Kineta), five repetitions, and two blocks was implemented over two years (2023–2024) in the Plant Factory research greenhouse of USAMV Bucharest. Plants were grown in an NFT system at EC 1.2–2.2 mS cm^{-1} and pH 6.0, comparing natural sunlight (average 274.3 µmol m^{-2} s^{-1}) with LED lighting (181.7 µmol m^{-2} s^{-1}, 18 h photoperiod, red + blue spectrum). Morphometric parameters (fresh mass, rosette diameter, leaf number), sugar content, and nitrate levels were measured and analyzed by two-way ANOVA and Tukey's HSD test. The LED Plant Factory system (LED) significantly outperformed the conventional greenhouse across all varieties ($p < 0.0001$), increasing fresh biomass by 16.9–68.4 % (highest in Kineta: 238.41 g $plant^{-1}$ vs. 141.56 g $plant^{-1}$), enlarging rosette diameter, and elevating soluble sugar content (4.23 vs. 3.71 °Brix). A highly significant variety × growing-system interaction ($p < 0.0001$) revealed genotype-specific responses, with Kineta showing the strongest positive reaction. Nitrate accumulation was higher under LED (1243.3 vs. 811.4 mg kg^{-1}), remaining below critical thresholds. These results demonstrate that LED-supplemented NFT hydroponics, when matched to cultivar-specific responses, substantially improves lettuce productivity and nutritional quality while highlighting the need for integrated spectral and varietal optimization in controlled-environment agriculture.

Keywords: Lettuce, LED Lighting, Sun Light, Greenhouse, NFT, Biochemical Content

1. Introduction

In the context of intensifying agricultural practices and the need to produce high-quality food on limited land areas, hydroponic systems have gained significant importance, particularly for leafy green crops such as lettuce (Lactuca sativa L.). Among these, the Nutrient Film Technique (NFT) represents one of the most efficient soilless cultivation methods. It was initially described by Cooper (1965) as a system capable of optimizing the use of water and nutrients. Subsequent foundational works, such as those by Resh (2004), have further consolidated the importance of hydroponics in modern horticultural production. Early and review studies have highlighted the major advantages of soilless cultivation, including precise control of nutrition and the reduction of edaphic factor impacts (Sardare & Admane, 2013) [11]. In this context, NFT systems have proven particularly effective for lettuce cultivation, enabling rapid and uniform growth while remaining sensitive to variations in the composition of the nutrient solution.

In recent decades, scientific interest has focused on optimizing growing conditions in controlled environments, especially in greenhouses. Studies have demonstrated that environmental parameters such as temperature, humidity, and nutrient solution composition significantly influence the yield and quality of hydroponically grown lettuce (Miller *et al*., 2020) [4]. Wang *et al*. (2023) [14] showed that hydroponic production systems exhibit greater sensitivity to ambient temperature but deliver superior performance compared to soil or solid-substrate cultivation, recording substantial increases in production (+134%) and water-use efficiency (+50%), along with improvements in quality (ascorbic acid and soluble sugars). Despite higher initial and operational costs, integrated agronomic, qualitative, and economic analyses indicate that HPS (particularly treatment H2) is more profitable for commercial lettuce production. The dynamics of macro- and micronutrients in NFT systems also play an essential role in determining final yield (Vought *et al*., 2024) [13].

A major technological advancement is the use of artificial LED lighting, which enables precise control of light spectrum and radiation intensity. Recent research has shown that different combinations of red and blue light influence photosynthesis, morphogenesis, and the accumulation of bioactive compounds in plants (Nițu *et al*., 2024; Nițu *et al*., 2025a) [5, 6]. Thus, LED lighting has become a key factor in optimizing production in closed or semi-closed systems. In addition to environmental factors, the genetic variability of lettuce varieties significantly influences their response to growing conditions. Differences among cultivars have been observed in growth parameters, yield, and product quality in NFT hydroponic systems (Pastor *et al*., 2025; Nitu *et al*., 2025b) [9, 7]. Furthermore, the concentration of the nutrient solution and the type of hydroponic system can directly affect plant development (Soares *et al*., 2020; Febriani *et al*., 2025) [12, 1].

Recent studies also emphasize the importance of integrating smart technologies and automated systems in optimizing hydroponic crops, thereby enhancing production efficiency and sustainability (Rajaseger *et al*., 2023; Herrera-Arroyo *et al*., 2025) [10, 3]. These modern approaches enable real-time monitoring of environmental parameters and adjustment of growing conditions to maximize yield. Excessive fertilization in soil-based crops can lead to nitrate pollution of the soil (Marinov și col, 2010; Qin și col., 2019) [23, 22]. The NFT cultivation system allows the growing of other species with small root systems (Drăghici și col 2016; Chan și col., 2023; Funk, 2025) [18, 27, 17]. Certain environmental factors can affect the root growth of lettuce plants, such as temperature, water quality, and oxygenation of the nutrient solution (Adams P. 1991; Stoica și col., 2022) [21, 20], the type of water used for plant growth (Enache și col., 2019) [19], or the type of substrate (Schie, 1999; Urechescu și col., 2022; Micu și col., 2022; Micu și col. 2023) [16, 28, 25, 24].

The hydroponic Nutrient Film Technique (NFT) system has been widely used for the cultivation of short-cycle vegetables due to the continuous circulation of the nutrient solution, which facilitates efficient absorption of nutrients and oxygen. This has enabled high and uniform yields, superior to those obtained in traditional soil-based cultivation systems (Carrasco *et al*., 2024) [2]. Analyzing the impact of growing conditions on the yield and quality of various lettuce varieties cultivated in the NFT system in greenhouses and under LED lighting has represented a relevant research direction in modern agriculture. The results obtained have contributed to the development of efficient and sustainable technologies capable of ensuring high, consistent, and superior-quality production. In hydroponic crops grown under controlled environments, lighting represents one of the environmental factors with a major impact on plant growth and development. Light influences essential physiological processes, such as photosynthesis, biomass accumulation, leaf development, and the synthesis of bioactive compounds. In recent years, concerns regarding light-emitting diode (LED) technology have led to its increasing adoption in modern horticulture, owing to its high energy efficiency, long operational lifespan, and the ability to adjust the light spectrum according to plant requirements. Panter *et al*. (2014) [26] state that the use of LED lighting allows the delivery of specific wavelengths that can stimulate photosynthesis and improve the yield and quality of horticultural crops.

Numerous studies have demonstrated that light intensity, photoperiod, and spectral composition significantly influence the growth and quality of hydroponically grown lettuce. For example, the level of illumination and the duration of light exposure can affect biomass accumulation as well as the content of sugars, proteins, and carotenoids in the leaves. Moreover, certain combinations of red and blue light provided by LEDs can optimize seedling development and contribute to higher yields and improved nutritional quality. The interaction among environmental factors has driven complex physiological processes that influence plant growth, nutrient uptake, and the accumulation of biochemical compounds in plant tissues. Optimizing these conditions has proven essential for achieving high yields and enhancing the quality of the final product. Considering the importance of hydroponic crops and the role of environmental factors in plant development, the present study aimed to analyze the impact of growing conditions on the yield and quality of various lettuce varieties cultivated in the NFT system in greenhouses under LED lighting. The research sought to evaluate the performance of lettuce varieties under controlled conditions and to identify the optimal cultivation parameters that could contribute to increased yield and improved product quality. The results obtained have contributed to the optimization of hydroponic cultivation technologies and to the development of modern, efficient, and sustainable agricultural systems

2. Materials and Methods

2.1 Experimental Location and Study Design

The study was conducted over two years (2023–2024) inside the greenhouse at University of Agronomic Sciences and Veterinary Medicine of Bucharest (USAMV Bucharest), and in the Plant Factory (LED) research greenhouse (Fig 1). This facility was established within the framework of the China–Romania Demonstration Park for Science and Technology in Agriculture, a joint project partially funded by the Chinese Academy of Agricultural Sciences and USAMV Bucharest. The study was conducted using a robust randomized complete block design with repetition, designated as Varianta Repetitia, to comprehensively evaluate four variants: V1 (Lugano), V2 (Aleppo), V3 (Carmesi), and V4 (Kineta). The experimental layout consisted of two identical blocks, with each block containing all four variants tested across five independent repetitions (R1 to R5). This structure resulted in a total of 40 experimental units, calculated as 4 variants × 5 repetitions × 2 blocks. Within each block, the variants were arranged randomly to minimize systematic bias, while the five repetitions per variant served as technical or spatial replicates.

Fig 1: Comparative View of Lettuce Cultivation: LED Plant Factory (Left) vs. Conventional Greenhouse NFT System (Right)

2.2 Growth Conditions

All experiments were carried out in an NFT hydroponic system. In the Plant Factory section, environmental parameters were strictly controlled as follows: air temperature of 20 °C, nutrient solution temperature of 19–20 °C, photoperiod of 18 h light/6 h dark, and a constant light intensity of 181.7 µmol m^{-2} s^{-1} provided by LED lamps. plants were also cultivated under naturally fluctuating light conditions, with the light intensity varying around an average of 274.3 µmol·m^{-2}·s^{-1}. The nutrient solution had an electrical conductivity (EC) of 1.2 mS cm^{-1} during the initial growth stage, which was increased to 2.2 mS cm^{-1} two weeks after planting. The pH was maintained at 6.0 throughout the experiment in both cultivation environments.

2.3 Data Collection and Statistical Analysis

The following morphometric parameters were measured: plant height, plant diameter, total plant fresh mass, root length, and root volume. Quality parameters were also assessed. Dry matter content was determined by drying 1 g samples of fresh leaves at 105 °C for 24 hours. Soluble solids content (°Brix) was measured using a reflectometer. Nitrate concentration was quantified separately in the basal, middle, and upper leaves of each plant using a portable Greentest ECO nitrate meter. Statistical analysis was performed using STATISTICA software (StatSoft Inc., version 10). Two-way ANOVA and independent t-tests was applied to determine significant differences among treatments at $p \leq 0.05$, 0.01, and 0.001. When significant effects were detected, means were compared using Tukey's Honestly Significant Difference (HSD) test at $p \leq 0.05$.

3. Results

Environmental conditions in the greenhouse were continuously monitored throughout the experiment (Fig 2). Photoperiod of 18 h light/6 h dark, and a constant light intensity of 181.7 µmol m^{-2} s^{-1} provided by LED lamps. plants were also cultivated under naturally fluctuating light conditions, with the light intensity varying around an average of 274.3 µmol·m^{-2}·s^{-1}. Nighttime minimum air temperatures remained stable between 17°C and 18°C, avoiding cold stress, while daytime maxima ranged from 22°C to 26°C, peaking at 26°C on day 20 after transplanting. Although these peaks slightly exceeded the optimal daytime range for lettuce (18–24°C), the overall thermal regime was generally suitable; however, occasional elevations may have induced mild heat stress, potentially increasing bolting and reducing leaf quality (Fig 1). Relative humidity showed an increasing trend, with minimum values rising from ~30% to 37% (mean minimum 33%), maximum values from 46% to 58% (mean maximum 52%), and average humidity from 38% to 48% (overall mean 43%). These levels remained below the recommended optimum for lettuce (50–70%), suggesting a relatively dry atmosphere that could limit transpiration and nutrient uptake (Fig 2). Carbon dioxide (CO_2) concentrations were enriched compared to ambient levels (~400 ppm), with minimum values of 601–690 ppm (mean ≈651 ppm), maximum values of 660–787 ppm (mean ≈738 ppm), and an overall mean of 694 ppm.

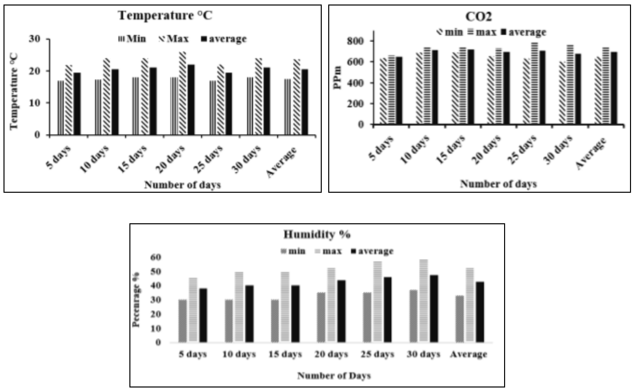

Fig 2: Temporal Variation of Temperature, CO_2 Concentration, and Humidity Over Different Time Intervals in growing compartments

Significant differences in plant performance were observed between the two growing systems (Table 1). The advanced Plant Factory setup demonstrated consistent superiority over the conventional greenhouse environment across all four lettuce varieties tested. This enhanced performance is attributed primarily to the precise control of light spectrum and photoperiod provided by LED technology, which promoted more efficient biomass accumulation compared to the variable natural solar radiation in the greenhouse. Fresh biomass production, averaged per plant across three replications, revealed the following results: V1 (Lugano) reached 141.11 g in the greenhouse and increased to 189.40 g under Plant Factory conditions, corresponding to a 34.2% yield improvement. V2 (Aleppo) achieved 145.28 g in the greenhouse and 210.81 g in the Plant Factory, representing a 45.1% increase. V3 (Carmesi) recorded the highest greenhouse biomass at 164.14 g, which rose to 191.83 g under LED lighting, indicating a moderate relative improvement of 16.9%. V4 (Kineta) exhibited the strongest response to artificial lighting, with fresh weight increasing from 141.56 g in the greenhouse to 238.41 g in the Plant Factory. This represents the highest individual plant productivity in the experiment, with a yield gain of 68.4%. These findings highlight substantial genotype × environment interactions, with certain varieties, particularly Kineta, exhibiting markedly higher responsiveness to the optimized lighting and controlled conditions of the Plant Factory system.

Table 1: Effect of Growing System (Natural Sun Light vs. LED) on Plant Mass, Rosette Diameter, and Number of Leaves in Different Lettuce Varieties

Variety	*Growing System*	*Plant Mass (g/plant)*	*Rosette Diameter (cm)*	*Number of leaves*
V1 -Lugano	Natural Sun Light	141.11 ± 14.99	21.3 ± 2.08	26.2 ± 2.7
V1 -Lugano	LED	189.40 ± 23.09	28.2 ± 1.63	26.2 ± 1.8
V2 - Aleppo	Natural Sun Light	145.28 ± 12.21	29.26 ± 2.73	30.4 ± 2.9
V2 - Aleppo	LED	210.81 ± 27.31	32.6 ± 1.66	29.2 ± 3.5
V3 -Carmesi	Natural Sun Light	164.14 ± 22.70	28.2 ± 1.71	25.0 ± 1.8
V3 Carmesi	LED	191.83 ± 17.81	28.8 ± 1.88	19.8 ± 1.8
V4 - Kineta	Natural Sun Light	141.56 ± 15.61	27.4 ± 1.77	32.0 ± 3.1
V4 – Kineta	LED	238.41 ± 21.40	32.66 ± 2.11	39.8 ± 3.3

The analysis revealed a highly significant main effect of the growing system ($p < 0.0001$), indicating that plants grown under LED lighting produced substantially greater biomass overall compared to those under natural sunlight. There was also a significant effect of variety ($p < 0.01$), showing inherent differences in growth potential among the varieties. Most importantly, a highly significant interaction between variety and growing system was detected ($p < 0.0001$). This means the benefit of LED lighting on plant mass was not uniform; some varieties responded much more strongly than others. In particular, V4 - Kineta exhibited the largest increase in mass under LED, while V3 - Carmesi showed a relatively smaller improvement.

Regarding rosette diameter, both growing system and variety had highly significant main effects ($p < 0.0001$ for both). Plants grown under LED developed significantly larger rosettes on average (Fig 3). A significant interaction effect was also present ($p < 0.01$), suggesting that the positive impact of LED on rosette size varied depending on the variety. Varieties such as V1 - Lugano and V4 - Kineta generally showed clearer gains in diameter under LED, whereas the response was more modest in others.

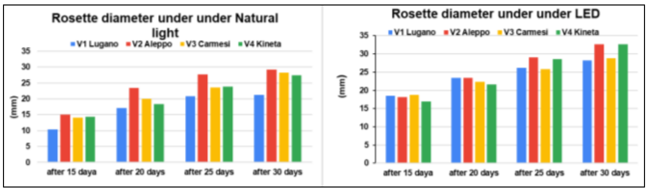

Fig 3: Comparative Rosette Diameter Development of Lettuce Varieties under Natural Light and LED Conditions over Time

For the number of leaves, variety exerted a very strong main effect ($p < 0.0001$), highlighting that this trait is largely determined by genetic differences among the varieties, with V4 - Kineta naturally producing more leaves. The growing system had a moderate significant effect ($p < 0.05$), with LED showing an overall influence on leaf number. However, the interaction between variety and growing system was highly significant ($p < 0.0001$). This interaction indicates that LED lighting affected leaf production differently across varieties — for example, V4 - Kineta produced considerably more leaves under LED (39.8 versus 32.0), while V3 - Carmesi tended to have fewer leaves under LED (19.8) compared to natural sunlight (25.0).

The sugar content and nitrate content of the four lettuce varieties (V1-Lugano, V2-Aleppo, V3-Carmesi, and V4-Kineta) were evaluated under two growing systems: conventional greenhouse and LED plant factory. Overall, the LED plant factory system resulted in significantly higher sugar content (4.23 ± 0.21) compared to the greenhouse system (3.71 ± 0.31). Similarly, nitrate content was markedly higher under LED conditions (1243.3 ± 163.5 mg/kg) than in the greenhouse (811.4 ± 260.9 mg/kg) (Fig 4).

Table 2: Sugar and Nitrate Content in Lettuce Varieties under Different Growing System

Variety	*Growing System*	*Sugar contents*	*Nitrate Contents (mg/kg)*
V1 - Lugano	Greenhouse (Sera)	3.86	992.667
V1 - Lugano	LED Plant Factory	4.25	1336.67
V2 - Aleppo	Greenhouse (Sera)	3.47	810
V2 - Aleppo	LED Plant Factory	4.42	1220
V3 - Carmesi	Greenhouse (Sera)	4.07	443
V3 - Carmesi	LED Plant Factory	4.31	1023.33
V4 - Kineta	Greenhouse (Sera)	3.44	1000
V4 - Kineta	LED Plant Factory	3.94	1393.33

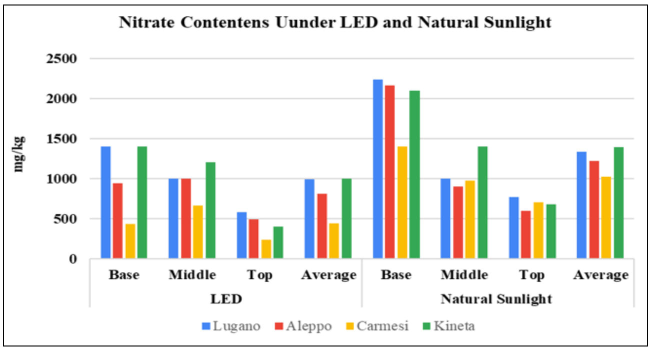

Fig 4: Comparitive Nitrate Contents in Lettuce Varieties under Natural Light and LED Conditions over Time

4. Discussion

The present study demonstrates that LED-based Plant Factory systems significantly enhance lettuce growth and quality compared to conventional greenhouse production, with cultivar-dependent responses. Under LED lighting, fresh biomass increased by 30-56% across varieties, with V4-Kineta showing the strongest response (56% increase, reaching 238.41 g/plant). This superior performance is attributed to several biological mechanisms. First, the precise spectral composition of LEDs—combining red (623-673 nm) and blue (427-478 nm) wavelengths—optimizes photosynthetic efficiency by matching chlorophyll absorption peaks, driving electron transport and ATP synthesis. A comprehensive review by Olle and Viršilė (2013) [33] confirmed that light intensity between 200-250 μmol m^{-2} s^{-1} with 16-18 h photoperiods using red and blue LEDs (5-20% blue) optimizes lettuce growth and light use efficiency. The extended 18-hour photoperiod increases daily light integral, providing more total photosynthetic energy for carbon fixation. Importantly, Liu *et al.* (2017) [32] demonstrated that adding green light (480-560 nm) to growth spectra enhances biomass accumulation, photosynthetic pigments, and CO_2 assimilation efficiency, as lettuce grown under full-spectrum LED showed significantly higher shoot dry mass, stomatal conductance, and maximum Rubisco carboxylation rates compared to plants grown without green wavelengths. The highly significant variety × growing system interaction ($p < 0.0001$) reflects genetic variation in photosynthetic capacity and photoreceptor signaling efficiency, consistent with Soufi *et al*. (2023) [36] who reported cultivar-dependent responses to LED spectra in Lollo Rossa and Lollo Bionda varieties.

Morphological development was substantially enhanced under LED conditions, with plants developing significantly larger rosette diameters ($p < 0.0001$), particularly for V1-Lugano (from 21.3 to 28.2 cm) and V4-Kineta (from 27.4 to 32.66 cm). This expansion is mediated by blue light activation of cryptochromes and phototropins, triggering downstream signaling involving HY5 transcription factor, which regulates cell expansion genes. Izzo *et al*. (2018) [31] found that increasing percentages of blue light (up to 66%) increased photosynthetic rate, stomatal conductance, and SPAD index in lettuce, though very high blue percentages (100%) decreased edible biomass. However, leaf number responses were divergent—V4-Kineta produced more leaves under LED (39.8 vs. 32.0), while V3-Carmesi showed reduced leaf number (19.8 vs. 25.0)—suggesting genetic variation in shoot apical meristem regulation. Chen *et al*. (2018) reported that intermittent red-blue LED exposure with specific light/dark cycles (8h/4h) increased shoot biomass and soluble sugar content, particularly fructose, while improving lettuce taste via enhanced sweetness and crispness. Regarding quality parameters, sugar content was significantly higher under LED (4.23 vs. 3.71), representing a 14% average increase. This elevation results from enhanced photosynthetic carbon fixation, reduced photorespiration due to stable 20°C temperatures, and red-light upregulation of sucrose phosphate synthase genes, consistent with Viršilė *et al*. (2020) [37] who found that multi-color LED lighting affects soluble sugar accumulation cultivar-specifically.

The most concerning finding was markedly higher nitrate accumulation under LED conditions (1243.3 vs. 811.4 mg/kg), with V4-Kineta showing the highest levels (1393.33 mg/kg). This elevation can be explained by enhanced transpiration-driven nitrate uptake under lower humidity (mean 43% vs. recommended 70-80%), combined with assimilation limitations where nitrate reduction by nitrate reductase may be rate-limited. However, recent research by Seyrek *et al*. (2025) [35] found that specific LED spectra can actually reduce nitrate accumulation—white LED (1039 mg/kg), red+blue+far-red (1118 mg/kg), and red+blue (1167 mg/kg) treatments produced significantly lower nitrate levels compared to other spectra, while blue lighting produced the highest marketable yield. Similarly, Choi *et al*. (2016) [30] demonstrated that under LED lighting (red:blue 2:1 mixture), nitrate levels were lowest compared to LEP or HPS lamps, though sugar content was also lower under LED in that study. Importantly, Philips Lighting research (2020) confirmed that combining light recipes with dynamic irrigation strategies can achieve nitrate levels below 1500 mg/kg without affecting yield or quality. The significant cultivar differences reflect genetic variation in nitrate reductase activity, as V3-Carmesi showed the lowest nitrate accumulation (443 mg/kg greenhouse, 1023 mg/kg LED). The greenhouse environment experienced mild heat stress (26°C peaks exceeding the 22-25°C optimum identified by (Olle & Viršilė) and low humidity (43% RH versus optimal 70-80%), which reduces stomatal conductance and increases photorespiration, while CO_2 enrichment (694 ppm) partially compensated. Overall, these findings demonstrate substantial genotype × environment interactions, emphasizing that variety selection and spectral optimization must be integrated for controlled environment agriculture.

5. Conclusion

The LED-based Plant Factory NFT system proved markedly superior to conventional greenhouse cultivation for all four lettuce varieties, delivering 17–68 % higher fresh biomass, larger rosettes, and elevated sugar content while maintaining commercially acceptable nitrate levels. The strong genotype × environment interaction underscores that variety selection is as critical as technological optimization; Kineta exhibited the greatest yield gain and leaf production, whereas Carmesi showed more modest morphological benefits. Although the lower relative humidity (mean 43 %) in the controlled environment contributed to elevated nitrate uptake, levels remained well below regulatory limits and did not compromise overall quality. These findings confirm that precise LED lighting (red + blue spectrum, 18 h photoperiod, ~182 $\mu mol\ m^{-2}\ s^{-1}$) combined with stable temperature (20 °C air / 19–20 °C nutrient solution) and CO_2 enrichment significantly enhances photosynthetic efficiency, biomass accumulation, and soluble solids in hydroponically grown lettuce. Future research should focus on fine-tuning light recipes (including green and far-red wavelengths), dynamic humidity management, and real-time nutrient monitoring to further reduce nitrate accumulation and maximize both yield and sensory quality. The study provides clear evidence that advanced NFT hydroponics under LED illumination represents a sustainable, high-efficiency pathway for year-round production of premium leafy greens, offering substantial agronomic and economic advantages over traditional greenhouse systems.

6. References

1. Annisa Gita Febriani, Aisyah Aisyah, Edi Minadji Pribadi, Bagas Elang Samudra. Effect of Different Nutrient Concentrations on the Growth and Yield of Curly Lettuce (Lactuca sativa L.) in Two Hydroponic System. Journal of Smart Agriculture and Environmental Technology. 2025; 3(1):37-43. Doi: https://doi.org/10.60105/josaet.2025.3.1.37-43
2. Carrasco G, Fuentes-Penailillo F, Manríquez P, Rebolledo P, Vega R, Gutter K, *et al*. Enhancing Leafy Greens' Production: Nutrient Film Technique Systems and Automation in Container-Based Vertical Farming. Agronomy. 2024; 14:1932. Doi: https://doi.org/10.3390/agronomy14091932
3. Herrera-Arroyo R, Martínez-Nolasco J, Botello-Álvarez E, Sámano-Ortega V, Martínez-Nolasco C, Moreno-Aguilera C. Smart Hydroponic Cultivation System for Lettuce (Lactuca sativa L.) Growth Under Different Nutrient Solution Concentrations in a Controlled Environment. Appl. Syst. Innov. 2025; 8:110. Doi: https://doi.org/10.3390/asi8040110
4. Miller Alexander, Langenhoven Petrus, Nemali Krishna. Maximizing Productivity of Greenhouse-grown Hydroponic Lettuce during Winter, Hortscience.

2020; 55(12):1963-1969. Doi: https://doi.org/10.21273/HORTSCI15351-20

5. Nitu OA, Ivan ES, Tronac AS, Arshad A. Optimizing Lettuce Growth in Nutrient Film Technique Hydroponics: Evaluating the Impact of Elevated Oxygen Concentrations in the Root Zone under LED Illumination. Agronomy. 2024; 14:1896. Doi: https://doi.org/10.3390/agronomy14091896
6. Nitu OA, Ivan ES, Arshad A. Optimizing Microclimatic Conditions for Lettuce, Tomatoes, Carrots, and Beets: Impacts on Growth, Physiology, and Biochemistry Across Greenhouse Types and Climatic Zones. International Journal of Plant Biology. 2025a; 16(3):100.
7. Nitu OA, Ivan EŞ, Tronac AS, Arshad A. Variety-specific lettuce responses to oxygen-enriched water and led light in a controlled greenhouse: A multivariate analysis across two cycles. International Journal of Plant Biology. 2025b; 16(1):29.
8. Nolasco C, Moreno-Aguilera C. Smart Hydroponic Cultivation System for Lettuce (Lactuca sativa L.) Growth Under Different Nutrient Solution Concentrations in a Controlled, 2025.
9. Pastor-Arbulú P, Rodríguez-Delfín A. Enhancing the growth, yield and physiological response of two lettuce (*Lactuca sativa* L.) cultivars through NFT system optimization. Front. Plant Sci. 2025; 16:1639002. Doi: https://doi.org/10.3389/fpls.2025.1639002
10. Rajaseger G, Chan KL, Yee Tan K, Ramasamy S, Khin MC, Amaladoss A, *et al*. Hydroponics: Current trends in sustainable crop production. Bioinformation. 2023; 30(19) (9):925-938. Doi: 10.6026/97320630019925. PMID: 37928497; PMCID: PMC10625363
11. Sardare Mamta D, Admane Shraddha V. A Review on Plant Without Soil - Hydroponicsijret: International Journal of Research in Engineering and Technology. 2013; 2(3). ISSN: 2319-1163
12. Soares Cláudio Silva, Alde Cleber Silva de Lima, Jeneilson Alves da Silva, Marina Suenia de Araújo Vilar, André Luiz Pereira da Silva, Joaquim Alves de Lima Junior, *et al*. Production of lettuce in NFT hydroponic system at different planting seasons and irrigation regimes. Australian Journal of Crop Sciences. 2020; 14(7):1042-1047. ISSN: 1835-2707, Doi: 10.21475/ajcs.20.14.07.p1828
13. Vought Kelsey, Bayabil Haimanote K, Pompeo Jean, Crawford Daniel, Zhang Ying, Correll Melanie, *et al*. Dynamics of micro and macronutrients in a hydroponic nutrient film technique system under lettuce cultivation, liyon. 2024; 10(11):e32316. ISSN: 2405-8440, Doi: https://doi.org/10.1016/j.heliyon.2024.e32316
14. Wang L, Ning S, Zheng W, Guo J, Li Y, Li Y, *et al*. Performance analysis of two typical greenhouse lettuce production systems: Commercial hydroponic production and traditional soil cultivation. Front Plant Sci. 2023; 4(14):1165856. Doi: 10.3389/fpls.2023.1165856. PMID: 37469780; PMCID: PMC10353484.
15. Yan Zhengnan, He Dongxian, Niu Genhua, Zhai Hao. Evaluation of growth and quality of hydroponic lettuce at harvest as affected by the light intensity, photoperiod and light quality at seedling stage, Scientia Horticulturae. 2019; 248:138-144. Doi: 10.1016/j.scienta.2019.01.002
16. Schie W. Standardization of Substrates. Acta Hortic. 1999; 481:71-78. Doi: 10.17660/ActaHortic.1999.481.4, https://doi.org/10.17660/ActaHortic.1999.481.4
17. Funk B. Vertical Farming Hydroponics Business of Vertical Farming, Egen Green technology, 2025. https://www.edengreen.com/blog-collection
18. Drăghici EM, Dobrin E, Jerca IO, Lagunovschi Luchian V, Bărbulescu IM, Jurcoane S. Organic fertilizer effect on Lettuce (Lactuca sativa L.) cultivated in Nutrient Film Technology, 2016, Romanian Biotechnological Letters. 2016; 21(5):11905-11913.
19. Enache F, Matei S, Matei GM, Jerca IO, Drăghici EM. Stimulation of plant growth and rhizosphere microbial communities by treatments with structured water, Scientific Papers. Series B, Horticulture. 2019; 63(1):365-370. Print ISSN: 2285-5653, CD-ROM ISSN: 2285-5661, Online ISSN: 2286-1580, ISSN-L 2285-5653
20. Stoica Claudia Maria, Velcea Marian, Chira Lenuța, Jerca Ovidiu Ionuț, Velea Marius Alexandru, Drăghici Elena Maria. The nutrient solution oxygenation influence on the growth of the species lactuca sativa l. Root system cultivated in the nutrient film technique (NFT) system, Scientific Papers. Series B, Horticulture. 2022; 66(1):533-540.
21. Adams P. Hydroponic Systems for Winter Vegetables. Acta Hortic. 1991; 287:181-190. Doi: 10.17660/ActaHortic.1991.287.18, https://doi.org/10.17660/ActaHortic.1991.287.18
22. Qin S, Quan Z, Ma J, Chen Xin, Shi Yi, Huang Bin. Regulating nitrate excess in lettuce-planted greenhouse soil with available carbon addition through irrigation. Environ Sci Pollut Res. 2019; 26:19241-19249. Doi: https://doi.org/10.1007/s11356-019-05125-x
23. Marinov A, Pele M, Draghici EM, Vasile G, Artimon M. Experimental field research on nitrate balance in agricultural soil, Water Pollution X, Tenth International Conference on Water Pollution: Modelling, Monitoring, and Management, Section 5 Agricultural contamination, WIT PRESS, Southampton, Boston, 2010, 181-193. ISBN:978-1-84564-448-2, ISSN: 1746-448X, British Library Cataloguing-in-Publication Data. http://www.witpress.com/images/stories/content_images/contents/c44482.pdf
24. Micu (Balint) D, Chan S, Drăghici EM. Study on the influence of nutrient conditions on the production and quality of lettuce grown on perlit substrate, Scientific Papers. Series B, Horticulture. 2023; 67(2):355-361. IF 0,404, Print ISSN 2285-5653
25. Micu (Balint) D, Dobrin E, Jerca OI, Drăghici EM. Preliminary study regarding the influence of nutrient concentration on production and quality parameters for lettuce grown on perlite substrate, Scientific Papers. Series B, Horticulture. 2022; 66(2):285-294. Print ISSN: 2285-5653, CD-ROM ISSN 2285-5661.
26. Panter E, Pele M, Draghici EM. The influence LED illumination on the development and quality of lettuce seedlings. Journal of Biotechnology, September 2014; 185. Supplement, ISSN: 0168-1656, Doi: http://dx.doi.org/10.1016/j.jbiotec.2014.07.277
27. Chan S, Jerca OI, Arshad A, Drăghici EM. Study regarding the influence of different sowing dates on the production of some brassica species cultivated in

nutrient film technique (NFT), Scientific Papers. Series B, Horticulture. 2023; 67(1):550-557. Online ISSN: 2286-1580, ISSN-L 2285-5653.
28. Urechescu LL, Peticilă A, Drăghici EM. Preliminary study on the influence of the use of vermicompost as a culture substrate on the quality of lettuce seedlings (Lactuca sativa L.), Scientific Papers. Series B, Horticulture. 2022; 66(2):418-423. Print ISSN: 2285-5653, CD-ROM ISSN 2285-5661.
29. Hen XL, Yang QC. Effects of intermittent light exposure with red and blue light emitting diodes on growth and carbohydrate accumulation of lettuce. Scientia Horticulturae. 2018; 234:220-226.
30. Choi S, Kim C, Wu Z, Lee CW. Influence of artificial lights on nitrate and sugar contents of leaf lettuce. ASHS Annual Conference, 2016.
31. Izzo LG, Mickens M, Aronne G, Gomez C. Gas exchange and leaf anatomy of lettuce in response to red and blue sole-source lighting from LEDs. ASHS Annual Conference, 2018.
32. Liu H, Fu Y, Wang M, Liu H. Green light enhances growth, photosynthetic pigments and CO_2 assimilation efficiency of lettuce as revealed by 'knock out' of the 480-560 nm spectral waveband. Photosynthetica. 2017; 55(1):144-152.
33. Olle M, Viršilė A. The effects of light-emitting diode lighting on greenhouse plant growth and quality. Agricultural and Food Science. 2013; 22(2):223-234.
34. Philips Lighting. How different growing environments can influence nitrate levels in leafy greens. Philips Horticulture Blog, 2020.
35. Seyrek GC, Sahin O, Demir K, Gunes A. Nitrate accumulation and mineral nutrition of lettuce under varied light emitting diode lighting. Journal of Plant Nutrition. 2025; 48(9):1425-1438.
36. Soufi HR, Roosta HR, Fatehi F, Ghorbanpour M. Spectral composition of LED light differentially affects biomass, photosynthesis, nutrient profile, and foliar nitrate accumulation of lettuce. Food Science & Nutrition. 2023; 11(12):8143-8162.
37. Viršilė A, *et al*. The distinct impact of multi-color LED light on nitrate, amino acid, soluble sugar and organic acid contents in lettuce. Food Chemistry. 2020; 310:125799.