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Study on the Influence of the Growing Season on the Production of Leaf Parsley (*Petroselinum Crispum*) in the NFT Hydroponic System

[1] Emanuela Cojocaru (Jerca), [2] Ionut Ovidiu Jerca, [3] Elena Dobrin, [4] Adnan Archad, [5] Elena Maria Drăghici
[1, 2, 3, 4, 5] Bioengineering of Horticultural and Viticultural Systems Department, Faculty of Horticulture, University of Agronomic Sciences and Veterinary Medicine of Bucharest 011464, City Bucharest, Romania

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Corresponding Author: **Elena Maria Drăghici**

Abstract

Hydroponic cultivation using the Nutrient Film Technique (NFT) offers a sustainable approach for year-round production of leafy greens like parsley (Petroselinum crispum), but seasonal variations in environmental factors can influence growth, biomass accumulation, and nitrate levels, impacting nitrogen use efficiency (NUE) and product quality. This study evaluated the effects of spring and autumn-winter growing seasons on the vegetative growth, leaf production, fresh biomass, and nitrate accumulation in two parsley varieties (Ory and Grüne Perle) cultivated in an NFT system, aiming to optimize NUE and minimize nitrate buildup for enhanced sustainability. Methods: Parsley seedlings were grown in an NFT hydroponic setup with a nutrient solution (pH 6.0, EC initially 1.2 mS/cm increasing to 2.2 mS/cm) at a flow rate of 1.5 L/min. Growth parameters (plant height, leaf number, fresh weight) and nitrate content were monitored over 30 days in greenhouse conditions during 2023–2024. Data were analyzed for seasonal and varietal differences. Spring conditions promoted superior growth, with Grüne Perle achieving higher heights (28.33 cm), leaf counts (27.00), and fresh weights (118.00 g/plant) compared to Ory (25.67 cm, 12.67 leaves, 98.70 g/plant). Autumn-winter reduced these metrics by 4–20%, but Grüne Perle maintained better performance. Nitrate levels were lower in spring (47–53 mg/kg) than autumnwinter (71–76 mg/kg), indicating improved NUE under favorable light and temperature. Seasonal modulation favors spring cultivation for optimal NUE and reduced nitrate accumulation, with Grüne Perle exhibiting greater adaptability. These findings support sustainable NFT-based parsley production by aligning cultivation with environmental optima, potentially reducing fertilizer inputs and enhancing year-round viability.

Keywords: Nutrient Film Technique (NFT), Leaf parsley (*Petroselinum Crispum*), Growing Season, Growth Parameters, Nitrate Accumulation, Nitrogen Use Efficiency (NUE).

1. Introduction

The growing season exerts a profound influence on plants physiology through fluctuations in temperature, light intensity (daily light integral, DLI), photoperiod, and humidity, which directly affect photosynthesis, nutrient uptake, and metabolite accumulation in hydroponically grown plants (Shibaeva *et al*., 2022) [1]. In the Nutrient Film Technique (NFT) hydroponic system—where a thin, recirculating film of nutrient solution continuously bathes the roots—this interdependence is particularly critical: external seasonal conditions in greenhouse or controlled-environment setups modulate internal parameters such as solution temperature and dissolved oxygen, thereby altering growth rates, yield stability, and quality traits like nitrate levels (Arshad *et al*., 2024; Nitu *et al*., 2024) [2, 3]. The strategic combination of seasonal awareness with NFT optimization enables year-round, resource-efficient production by mitigating environmental variability, enhancing nutrient-use efficiency, and supporting sustainable intensification—advantages that have been quantified in multi-season trials showing up to 20–65% variation in herb biomass and nitrate content between summer and autumn (Jerca *et al*., 2024; Arshad *et al*., 2023) [4, 5].

Leafy vegetables, prized for rapid growth cycles and high nutritional density, are ideally suited to hydroponic systems (Fathidarehnijeh, E. 2024) [6]. Species such as lettuce, spinach, basil, arugula, and especially leaf parsley (*Petroselinum crispum*) benefit from precise environmental control, yielding consistent, pesticide-free biomass rich in vitamins (notably vitamin C), minerals, and antioxidants. Hydroponic systems, particularly the Nutrient Film Technique (NFT), have emerged as efficient alternatives to traditional soil-based agriculture for producing high-quality leafy vegetables. These systems enable precise control over nutrient delivery and environmental factors, supporting year-round sustainability with minimal water and nutrient waste (Palmitessa, *et al*., 2024) [8]. The NFT method involves recirculating a thin film of nutrient solution over plant roots, which is especially advantageous for short-cycle crops such as parsley (*Petroselinum crispum*). While successfully applied to greens like lettuce and basil, research on aromatic herbs like parsley in NFT remains limited, particularly concerning seasonal influences on growth dynamics and nitrate accumulation; recent studies have begun addressing this gap through comparisons of NFT versus aquaponic systems and modeling of temperature–DLI responses (Misal *et al*. 2023) [9].

Leaf parsley is highly valued for its rich nutritional profile, including high levels of vitamins (Especially vitamin C), minerals, and antioxidant compounds, making it a staple in global cuisine (Chauhan, 2026) [10]. Conventional field or soil-based cultivation frequently encounters challenges such as soil-borne pathogens, water inefficiency, compaction, and high production variability, driving increased interest in hydroponics for consistent, clean, and contaminant-free output (Khatri *et al*., 2024) [11]. By systematically examining seasonal effects within NFT, the present study aims to refine production protocols for this high-value herb, contributing to broader advancements in controlled-environment agriculture. Evaluating the impact of growing season on parsley is critically important for several reasons. First, it enables optimization of NUE, reducing fertilizer inputs and environmental nutrient runoff in hydroponic systems (Thomas & Bhat, 2026) [12]. Second, it minimizes nitrate accumulation — a health concern linked to methemoglobinemia and potential carcinogenic effects when levels exceed regulatory limits in leafy greens. Third, it supports sustainable year-round production by identifying varietal adaptations and environmental adjustments (e.g., supplemental lighting), ensuring consistent yield and quality regardless of external climate variability (Bian *et al*., 2020; Oliveira *et al*., 2024) [24, 13].

Recent studies confirm that NFT systems generally enhance plant height, biomass, and yield in parsley relative to other hydroponic configurations, yet seasonal environmental modulation remains a key unoptimized factor influencing nitrogen dynamics (Chan *et al*., 2023) [14]. Nitrate buildup in leafy vegetables is modulated by electrical conductivity, nutrient composition, and light conditions; high salinity exacerbates accumulation and reduces biomass, while precise management mitigates stress (Gruda *et al*., 2024) [15]. Varietal differences in root morphology and regeneration capacity further affect NFT adaptation, where low solution volumes and partial root exposure require careful operational control. This study investigates the influence of growing seasons on parsley production in NFT systems, with a focus on how seasonal environmental modulation optimizes NUE and minimizes nitrate accumulation for sustainable year-round output. By comparing two varieties (Ory and Grüne Perle) under controlled greenhouse conditions, it addresses critical gaps in the literature regarding aromatic crops.

2. Materials and Methods

2.1 Plant Material and Varieties

The experiment utilized two varieties of leaf parsley (Petroselinum crispum): 'Ory', a biennial Romanian cultivar with smooth, intensely green leaves, yielding up to 15 t/ha; and 'Grüne Perle', a semi-early variety with curly leaves and rich foliage. These cultivars typically reach harvest maturity in approximately 70–90 days after sowing, while 'Grüne Perle' can generally be harvested after about 70–80 days, depending on growing conditions (AgribioShop, n.d.; Cultivated Earth, n.d.; Forestry.com) [16, 17, 18]. Sowing for seedling production was conducted in two seasonal cycles: spring (March–April) and autumn (October–November) during 2023 and 2024. Seeds were sown densely and then transplanted into Jiffy-type cubes for initial growth. Seedlings were subsequently planted in the NFT hydroponic system within a greenhouse, aligned with the respective seasonal timelines.

2.2 Hydroponic System Setup

The NFT system was configured with a continuous nutrient solution flow rate of 1.5 L/min across both seasons (Fig 1). The nutrient solution comprised macro- and microelements, maintained at an initial pH of 6.0 and electrical conductivity (EC) of 1.2 mS/cm for the first 14 days post planting, after which the EC was increased to 2.2 mS/cm and held constant until harvest. Greenhouse conditions were monitored throughout the cultivation periods, including temperature, atmospheric humidity, light intensity, and CO_2 levels to ensure controlled environmental modulation.

Fig 1: Growth of Curly Leaf and Flat-Leaf (Italian) Parsley Varieties in a Greenhouse Using the Nutrient Film Technique (NFT) System

2.3 Data Collection and Analysis

At the end of 30 days, key parameters—including plant height (cm), number of leaves per plant, fresh weight (g/plant), and nitrate content (mg/kg) in leaves—were recorded. The study was conducted using a randomized complete design, and data were collected within the 30-day period from three plants randomly selected from each of three rows (total 9 plants) at each observation. Measurements were taken at 5, 10, 15, 20, 25, and 30 days to assess growth dynamics. Data were analyzed for varietal and seasonal differences, and figures were used to illustrate trends in plant height, leaf formation, average fresh mass, and nitrate content across seasons and cultivars.

3. Results

The average monthly data for green-house microclimate parameters, during autumn-Winter (October–November) periods, were recorded as follows: temperatures around 19–

22 °C, CO_2 levels near 390–460 ppm, and light intensity in the range of 100–250 W/m². Spring (March–April) transitions, March data indicated warmer averages close to 24–26 °C, with CO_2 around 460–480 ppm and light intensity approximately 150–260 W/m. Analyzing the Ory variety, it was found that during the spring season, parsley plants showed a constant and sustained increase in height, from 12.73 cm after 5 days to 25.67 cm after 25–30 days. The growth rate is more pronounced in the first 15–20 days, followed by a slight stagnation towards the end of the period, suggesting the approach of a vegetative maturity phase (Fig 2). In the autumn-winter season, growth was lower compared to spring, with the values recorded being consistently lower at each time of determination. After 30 days, the plants reached 24.67 cm, approximately 1 cm less than in spring. This difference can be attributed to less favorable climatic conditions (lower temperatures, reduced light intensity), which slow down the physiological processes of the plants.

In the case of the Grüne Perle variety, it was found that it presented, in the spring season, a higher growth capacity than the Ory variety. The height of the plants increased from 12.53 cm after 5 days to 28.33 cm after 30 days, indicating a higher vegetative potential. The growth rate remains sustained even in the interval of 20–30 days, without any obvious stagnation. In the autumn-winter season, Grüne Perle started from significantly lower initial values (7.67 cm after 5 days), but gradually recovered the difference, reaching 26.67 cm at the end of the period (Fig 3). Although the unfavorable season negatively influenced the initial growth, the variety demonstrates good adaptability and a capacity for recovery over time. Analyzing the comparison between seasons, the spring season favored height growth for both varieties, the differences being more evident in the early stages of vegetation. Comparing between varieties, Grüne Perle outperforms the Ory variety both in spring and autumn–winter, which suggests a superior genetic potential for vegetative growth. Dynamics of leaf number formation in parsley in the NFT system, depending on the variety and the growing season.

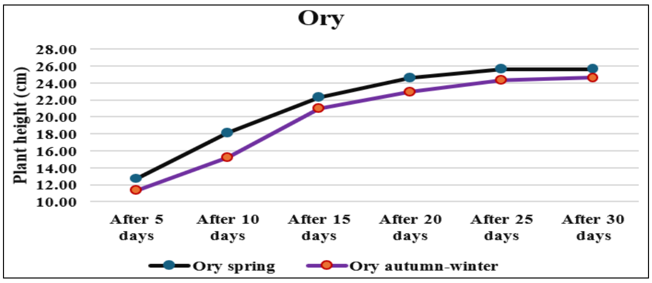

Fig 2: Height development pattern of the cultivar Ory in both season

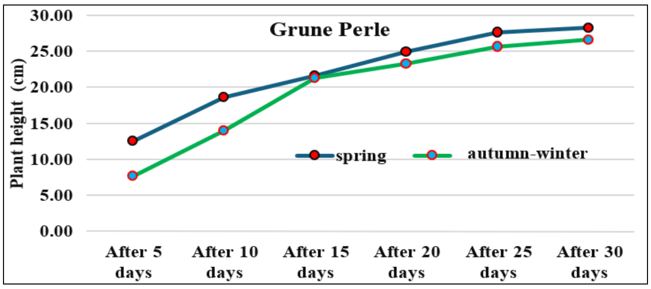

Fig 3: Height development pattern of the cultivar Grune Perle in both season

The analysis of data on the dynamics of leaf number formation highlights significant differences between the two parsley varieties analyzed, as well as between growing seasons, under the conditions of cultivation in the NFT hydroponic system (Figure 4 and 5). In the Ory variety (normal-leaf parsley), the number of leaves increased progressively throughout the observation period, both in the spring and autumn-winter crops. In the spring season, the plants showed a higher growth rate, reaching an average of 12.67 leaves per 30 days, compared to 10.67 leaves recorded in the autumn-winter season. The observed differences indicate a favorable influence of the environmental conditions specific to spring, especially light intensity and higher temperatures, on the vegetative growth processes. The relatively uniform evolution of the number of leaves suggests a stable behavior of the Ory variety in the NFT system, with a moderate capacity for foliar regeneration.

In the case of the Grüne Perle variety (curly-leaf parsley), the dynamics of leaf formation was significantly higher compared to the Ory variety, regardless of the season. In the spring crop, the average number of leaves increased from 5.00 leaves at 5 days to 27.00 leaves after 30 days, highlighting a pronounced acceleration of growth after the first 15 days of cultivation. In the autumn-winter season, although the rate of leaf formation was lower, the values obtained remained superior to those recorded for the Ory variety, reaching 21.33 leaves at the end of the analyzed period. This behavior can be correlated with the morphological peculiarities of the Grüne Perle variety, characterized by a greater capacity for leaf emission, specific to curly-leaf parsley.

Comparing the varieties, the differences in leaf number are reduced in the early stages of vegetation, but become more pronounced after 15–20 days from planting, especially in the spring crop. At 30 days, the Grüne Perle variety recorded a leaf number almost double that of the Ory variety in the spring season, respectively with approximately 10 leaves more in the autumn–winter season, highlighting a superior utilization of the NFT cultivation conditions.

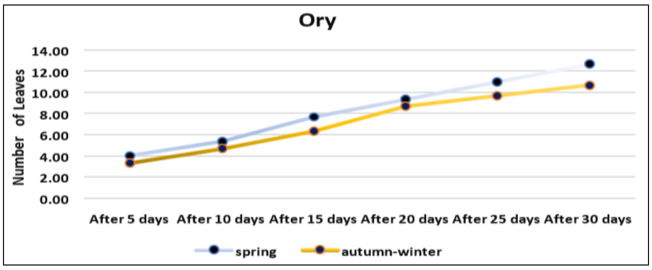

Fig 4: Leaf number formed in Ory parsley plants over the two growing seasons

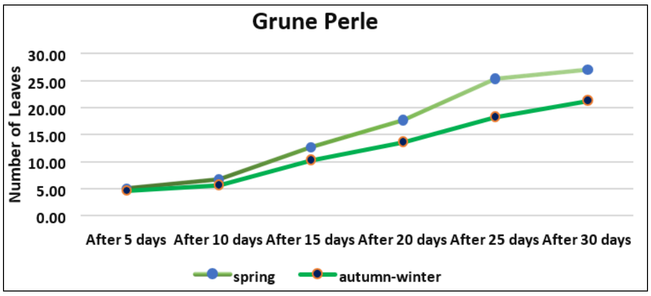

Fig 5: Number of leaves formed on Grüne Perle parsley plants in the two seasons

The analysis of the plant mass of leaf parsley highlights significant differences depending on both the season and the cultivated variety (Fig 6). In both experimental variants, the values recorded in the spring season are higher than those obtained in the autumn–winter period, which indicates a favorable influence of the environmental conditions specific to the spring season on vegetative growth. In the Ory variety, the plant mass reached the value of 98.70 g/plant in spring, while in the autumn–winter season a decrease was recorded to 78.60 g/plant. A similar behavior was observed in the Grüne Perle variety, where the plant mass was 118.00 g/plant in spring and 97.50 g/plant in the cold season. The reduction in vegetative mass in the autumn–winter period can be attributed to lower temperatures and reduced light intensity, factors that limit the physiological processes involved in growth. Compared between varieties, Grüne Perle consistently presented higher plant mass values than Ory, regardless of the season, which reflects a superior biological and productive potential. These differences suggest a more pronounced vegetative vigor and a better adaptability of the Grüne Perle variety to seasonal variations.

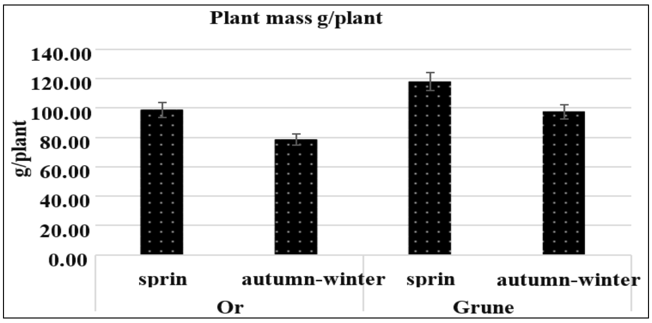

Fig 6: Mean plant mass of both varieties: Ory and Grune Perle

Nitrate content was higher in autumn-winter for Ory (71 vs. 47 mg/kg in spring), and slightly higher in Grüne Perle than Ory under spring conditions (53 vs. 47 mg/kg). Autumn-winter likely promotes greater nitrate accumulation due to reduced light and/or temperature. The nitrate content of leaf parsley varied depending on both the season and the cultivated variety. For both analyzed varieties, the values determined in the autumn-winter season were higher compared to those in the spring, highlighting the influence of environmental conditions on the accumulation of nitrates in plant tissues (Fig 7). In the Ory variety, the nitrate content was 47.00 mg/kg in the spring, increasing to 71.00 mg/kg in the autumn-winter season. Similarly, the Grüne Perle variety recorded values of 53.00 mg/kg in the spring and 76.00 mg/kg in the cold period. The increase in nitrate content in the autumn-winter season can be explained by the reduced light intensity and lower temperatures, which limit the processes of nitrate reduction and metabolism in the plant. Compared between varieties, Grüne Perle showed slightly higher nitrate content than Ory in both seasons, suggesting genetic differences in the capacity to absorb and accumulate nitric nitrogen (Table 1). However, the values recorded remain relatively low and indicate a moderate level of accumulation.

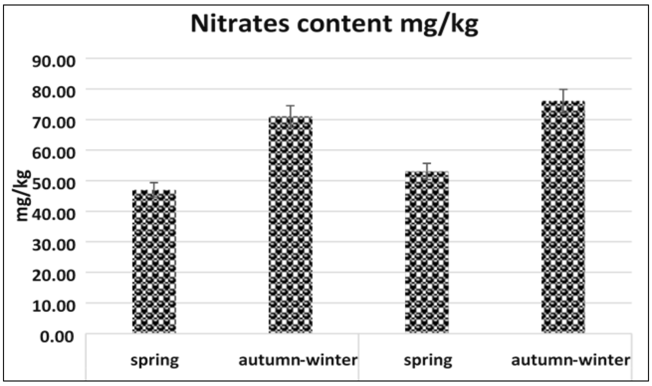

Fig 7: Nitrate Contents in both Varieties

Table 1: Mean Values (± SD) of Growth Parameters, Plant Mass, and Nitrate Content in Two Parsley ultivars (Ory and Grüne Perle) Across Spring and Autumn-Winter Growing Seasons

Parameter	Ory Spring (Mean ± SD)	Ory Autumn-Winter (Mean ± SD)	Grüne Perle Spring (Mean ± SD)	Grüne Perle Autumn-Winter (Mean ± SD)
Final Height (cm)	25.67 ± 1.15	24.67 ± 0.58	28.33 ± 0.58	26.67 ± 0.58
Final Number of Leaves	12.67 ± 1.15	10.67 ± 1.15	27.00 ± 1.00	21.33 ± 1.53
Plant Mass (g/plant)	98.70 ± 1.45	78.60 ± 1.14	118.00 ± 2.61	97.50 ± 1.41
Nitrates Content (mg/kg)	47.00 ± 1.10	71.00 ± 1.83	53.00 ± 1.13	76.00 ± 1.59

Table 2: Pairwise Statistical Comparisons (Welch's t-test) of Final Height and Number of Leaves Between Seasons and Between Cultivars in Parsley (Ory and Grüne Perle)

Comparison	Final Height t-value (p-value)	Final Leaves t-value (p-value)
Ory Spring vs. Autumn-Winter	1.34, $p < 0.272$	2.12, $p < 0.101$
Grüne Perle Spring vs. Autumn-Winter	3.54, $p < 0.024$	5.38, $p < 0.011$
Spring: Ory vs. Grüne Perle	-3.58, $p < 0.030$	-16.25, $p < 0.000$
Autumn-Winter: Ory vs. Grüne Perle	-4.24, $p < 0.013$	-9.64, $p < 0.001$

Statistical analysis revealed that Spring conditions generally improved final height, leaf production, and plant mass in both parsley cultivars compared to autumn-winter, though the differences were statistically significant ($p < 0.05$) only for Grüne Perle (Table 2). Ory showed no significant seasonal variation ($p > 0.05$), indicating greater resilience to seasonal changes. Grüne Perle consistently outperformed Ory in both seasons, with significantly greater final height ($p \leq 0.05$) and much higher leaf number ($p < 0.001$), demonstrating superior vegetative growth and leaf yield overall. Plant mass followed similar trends (higher in spring and for Grüne Perle), but lacked replicates for statistical testing.

4. Discussion

The observed variations in parsley growth attributes—plant height, leaf number, and fresh biomass—across the two growing seasons underscore the interplay between environmental cues and intrinsic physiological processes in Petroselinum crispum. In spring, both the Ory (normalleaf) and Grüne Perle (curly-leaf) varieties exhibited accelerated height increments, sustained leaf formation, and higher biomass accumulation, reaching up to 25.67 cm, 12.67 leaves, and 98.70 g plant^{-1} (Ory) or 28.33 cm, 27.00 leaves, and 118.00 g plant^{-1} (Grüne Perle) after 30 days (Fig 8). These responses reflect enhanced photosynthetic carbon assimilation and meristematic activity under higher temperatures and light intensity typical of spring (Sage, & Kubien 2007) [19]. Elevated daily light integral (DLI) and mean daily temperature (MDT) drive greater carbohydrate synthesis, fueling cell elongation and division in the shoot apical meristem, while optimal thermal regimes accelerate enzymatic kinetics in gibberellin-mediated stem extension (Zhong *et al*., 2026) [20]. In contrast, the autumn–winter season imposed cooler temperatures and reduced light intensity, resulting in slower initial growth (e.g., only 24.67 cm and 10.67 leaves for Ory; 26.67 cm and 21.33 leaves for Grüne Perle), with biomass declining by approximately 20% in both varieties. This retardation arises from limited photosynthate availability, which constrains sink strength and delays vegetative phase progression toward maturity. Supporting these patterns, Walters *et al*. (2021) [21] demonstrated through hydroponic modeling that increasing MDT from ~10 °C to 22.4 °C linearly boosted parsley fresh mass and height, while DLI positively interacted with temperature to enhance biomass when above suboptimal thresholds. Similarly, Currey *et al*. (2019) [22] reported 120% higher fresh mass in NFT-grown parsley under high DLI (~18 mol m^{-2} d^{-1}) versus low DLI (~7 mol m^{-2} d^{-1}), attributing the effect to amplified net photosynthesis and resource allocation to foliar expansion.

Varietal differences further highlight genetic modulation of these processes. Grüne Perle consistently outperformed Ory, displaying greater leaf emission capacity (nearly double in spring) and superior biomass recovery in autumn–winter, indicative of enhanced meristematic plasticity and higher photosynthetic efficiency inherent to curly-leaf morphology. The pronounced acceleration in leaf formation after 15 days in Grüne Perle aligns with genotypic variations in leaf primordia initiation rates, where curly types exhibit prolonged vegetative vigor. Genetic background is a primary determinant of such differential responses, as low-light stress disproportionately limits normal-leaf types through reduced chloroplast development and Rubisco activity (Ma *et al*., 2025) [23].

Fig 8: Side-by-Side Comparison of both varieties: Foliage and Root Morphology

Nitrate accumulation exhibited an inverse seasonal pattern, with higher contents in autumn–winter (71.00 mg kg^{-1} in Ory; 76.00 mg kg^{-1} in Grüne Perle) compared to spring (47.00–53.00 mg kg^{-1}). This stems from impaired nitrate assimilation under reduced irradiance: nitrate reductase (NR) enzyme activity, which catalyzes the conversion of NO_3^- to NO_2^- in the cytosol, is light-inducible and reliant on photosynthetically generated reductants (NADH) and carbon skeletons (αketoglutarate via TCA cycle). Low light diminishes NR gene expression, enzyme activation, and carbohydrate supply, leading to vacuolar NO_3^- storage as an osmoticum. Milder spring conditions promote NR upregulation and rapid metabolism into amino acids for protein synthesis, lowering tissue nitrates. These mechanisms are corroborated by Bian *et al*. (2020) [24], who identified low light intensity as the predominant factor elevating nitrate in controlled-environment leafy vegetables through suppressed NR activity and photosynthetic limitation. Petropoulos *et al*. (2012) specifically in parsley foliage confirmed that increasing light intensity, day length, and temperature enhance NR activity, thereby reducing nitrate accumulation, with diurnal peaks occurring under low-irradiance periods.

The NFT system under controlled greenhouse conditions played a pivotal role in buffering seasonal constraints while enabling precise nutrient delivery. By maintaining a continuous, shallow film of oxygenated nutrient solution over roots, NFT ensures aerobic respiration, prevents hypoxia-induced ethylene buildup, and facilitates rapid mass flow of NO_3^- and other ions to root surfaces without substrate impedance (Stoica *et al*., 2022) [26]. This enhances uptake efficiency via high root–solution contact and allows real-time adjustment of electrical conductivity (EC) and pH, mitigating temperature- or light-induced nutrient imbalances. Despite greenhouse climate control, residual seasonal variations in ambient DLI and MDT persisted, yet NFT sustained uniform rootzone conditions that supported recovery in Grüne Perle and moderate performance in Ory. Currey *et al*. (2019) [22] validated NFT's efficacy for parsley, cilantro, and dill, showing stable growth across DLI regimes without EC interactions, while Lennard (2019) demonstrated comparable or superior herb biomass (including parsley) in NFT hydroponics versus aquaponics across spring–winter cycles, underscoring its role in year-round stability.

In conclusion, the integration of NFT hydroponics with season-specific variety selection offers a robust platform for consistent parsley production, yet opportunities remain for optimization. Future directions should prioritize supplemental LED lighting to elevate winter DLI to spring-equivalent levels (targeting 15–18 mol m^{-2} d^{-1}), coupled with spectral tuning (e.g., red–blue ratios) to further suppress nitrate via enhanced NR activity and test interactions with curly- versus normal-leaf genotypes. Long-term trials evaluating NFT flow rates, root-zone temperature modulation, and economic viability under varying CO_2 enrichment will refine protocols. Horticulturally, these advancements enable reliable year-round supply of low-nitrate, high-biomass parsley in controlled environments, reducing reliance on seasonal imports, minimizing water and land footprints, and supporting urban vertical farming systems while ensuring compliance with nitrate safety thresholds—ultimately advancing sustainable, climate-resilient herb production.

5. Conclusion

The study demonstrates that spring cultivation in NFT hydroponic systems maximizes growth parameters, biomass yield, and nitrogen use efficiency in leaf parsley, while minimizing nitrate accumulation compared to autumn-winter seasons. The Grüne Perle variety outperforms Ory across metrics, highlighting its suitability for year-round sustainable production. These insights advocate for environmental modulation strategies, such as supplemental lighting in off-seasons, to enable consistent, high-quality output and reduce fertilizer dependency in hydroponic farming.

6. Author Contributions

Conceptualization, E.C. and E.M.D.; methodology, E.M.D, and A.A; software, E.C.; validation, E.M.D., A.A, and I.O.J.; formal analysis, E.M.D., and A.A; investigation, E.C.; resources, E.M.D., and I.O.J; data curation, E.C.; writing—original draft preparation, E.C. and A.A.; writing—review and editing, E.M.D, A.A., and. I.O.J; visualization, A.A.; supervision, E.M.D and I.O.J.; project administration, E.C.; funding acquisition, E.M.D and I.O.J. All authors have read and agreed to the published version of the manuscript.

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8. Data Availability Statement

Data sharing is not applicable to this article.

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10. Conflicts of Interest

The authors declare no conflicts of interest.

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