



Spatial productivity and water use in hydroponic and soil-based *Lactuca sativa* L. systems*

Productividad espacial y uso del agua en sistemas hidropónicos y en suelo de *Lactuca sativa* L.

Germán Darío Aguado¹, Gabriel Enrique Pisi¹, Jorge Esteban Perez Peña¹, Federico Sebastián de Biazzi¹, Carla Vanina Dagatti¹, Ernesto Martín Uliarte¹

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¹ Instituto Nacional de Tecnología Agropecuaria, Mendoza Research Station. Mendoza, Argentina. aguado.german@inta.gob.ar (corresponding author; <https://orcid.org/0000-0003-0779-7297>); pisi.gabriel@inta.gob.ar (<https://orcid.org/0009-0005-5713-3861>); perezpena.jorge@inta.gob.ar (<https://orcid.org/0000-0002-9942-1037>); debiazzi.federico@inta.gob.ar (<https://orcid.org/0000-0002-5939-3596>); dagatti.carla@inta.gob.ar (<https://orcid.org/0000-0003-4380-1708>); uliarte.ernesto@inta.gob.ar (<https://orcid.org/0000-0002-9657-2753>).

Abstract

Introduction. A comprehensive evaluation of hydroponic production systems relative to conventional approaches is essential for understanding their performance, particularly regarding resource-use efficiency and spatial intensification. **Objective.** To compare the spatial productivity and water use efficiency of hydroponic and soil-based *Lactuca sativa* L. production systems. **Materials and methods.** The experiment was conducted at the Instituto Nacional de Tecnología Agropecuaria, Mendoza Research Station, Luján de Cuyo, Argentina, from August to October 2025. Four production systems were compared: indoor hydroponic vertical farming with artificial lighting (A), greenhouse hydroponic vertical farming with supplemental artificial lighting (B), conventional horizontal hydroponic cultivation in a greenhouse without artificial lighting (C), and soil-based cultivation in a greenhouse (D). Each system consisted of three independent experimental units, and the data were analyzed using a linear mixed-effects model. Yield, water consumption, water productivity, water consumption per unit of horizontal area, and lettuce nutritional status were evaluated. **Results.** Vertical systems (A and B) achieved higher yields per unit of horizontal area than C and D, while D produced greater individual plant biomass. System A showed the highest daily productivity and the lowest water consumption per production cycle. Hydroponic systems required significantly less water per plant and per cycle than D. For water consumption per unit of surface area, A showed the lowest value, B and C showed similar intermediate values, and D the highest. Foliar nutrient concentrations and chlorophyll index differed among systems. **Conclusions.** Vertical systems achieved greater spatial productivity, while hydroponic systems showed lower water consumption than soil-based cultivation.

Keywords: controlled environments, vertical farming, indoor cultivation, artificial lighting, soilless culture, water productivity, plant nutrition, crop cycle.



Resumen

Introducción. La evaluación de los sistemas de producción hidropónica frente a sistemas convencionales es importante para valorar su rendimiento, en particular respecto de la eficiencia en el uso de los recursos y la intensificación espacial. **Objetivo.** Comparar la productividad espacial y la eficiencia en el uso del agua de sistemas de producción de *Lactuca sativa* L. en hidroponía y en suelo. **Materiales y métodos.** El experimento se desarrolló en el Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Mendoza, Luján de Cuyo, Argentina, de agosto a octubre de 2025. Se compararon cuatro sistemas de producción: agricultura vertical hidropónica en interior con iluminación artificial (A), agricultura vertical hidropónica en invernadero con iluminación artificial suplementaria (B), hidroponía horizontal convencional en invernadero sin iluminación artificial (C) y cultivo en suelo en invernadero (D). Cada sistema contó con tres unidades experimentales independientes y los datos se analizaron mediante un modelo lineal de efectos mixtos. Se evaluaron el rendimiento, el consumo de agua, la productividad hídrica, el consumo de agua por unidad de superficie horizontal y el estado nutricional de la lechuga. **Resultados.** Los sistemas A y B lograron mayores rendimientos por unidad de área horizontal que C y D, mientras que D produjo mayor biomasa individual por planta. El sistema A presentó la mayor productividad diaria y el menor consumo de agua por ciclo de producción. Los sistemas hidropónicos requirieron significativamente menos agua por planta y por ciclo que D. En el consumo de agua por unidad de superficie, A presentó el menor valor, B y C mostraron valores intermedios similares y D el mayor. Las concentraciones foliares de nutrientes y el índice de clorofila difirieron entre sistemas. **Conclusiones.** Los sistemas verticales alcanzaron mayor productividad espacial, mientras que los sistemas hidropónicos mostraron menor consumo de agua que el cultivo en suelo.

Palabras clave: ambientes controlados, agricultura vertical, cultivo en ambiente protegido, iluminación artificial, cultivo sin suelo, productividad del agua, nutrición vegetal, ciclo del cultivo.

Introduction

The sustained growth of the world's population and the expansion of urban areas have intensified the demand for fresh food produced through resource-efficient and environmentally sustainable systems (Benke & Tomkins, 2017). The progressive reduction of peri-urban cultivated land and increasing pressure on water resources have driven the development of intensive production systems in controlled environments, which aim to decouple horticultural productivity from traditional soil and climate constraints. Although modern hydroponics was established nearly 90 years ago through the pioneering work of William Frederick Gericke (Gericke, 1937), hydroponic and vertical farming systems are still emerging technologies in the semi-arid agricultural areas of Mendoza, Argentina. These systems have been proposed as promising alternatives to conventional soil-based cultivation owing to their potential to increase water-use efficiency, reduce the land footprint of production, and improve yield stability (Graamans et al., 2018; Pennisi et al., 2025).

Lettuce (*Lactuca sativa* L.) is one of the most extensively studied model crops in controlled production systems due to its short growth cycle, high responsiveness to environmental manipulation, and widespread commercial adoption. Studies have shown that precise control of environmental variables such as photosynthetically active radiation, light spectral quality, temperature, and mineral nutrition increases photosynthetic rate, water-use efficiency, and biomass accumulation in this crop (Pennisi et al., 2020; Vitoshkin et al., 2021). Recirculating hydroponic systems in protected environments have shown substantial improvements in growth predictability and resource-use efficiency compared to traditional soil-based cultivation (Barbosa et al., 2015; Graamans et al., 2018).

Vertical farming has emerged as one of the most promising innovations due to its ability to maximize productivity per unit of floor area through multi-tier stacking and the use of spectrum-controlled artificial lighting within fully controlled-environment systems known as plant factories (Kozai, 2018; Pennisi et al., 2020). This configuration allows for spatial intensification of production and, in many cases, has demonstrated increases in yield and water use efficiency, particularly in leafy greens and herbs, associated with strict regulation of the microenvironment and optimized planting density (Kaiser, Kusuma et al., 2024; Pennisi et al., 2020). However, the literature remains limited regarding integrated and controlled comparisons between different hydroponic farming systems.

Numerous studies have investigated the use and performance of hydroponic and vertical farming systems for indoor crop production (Al-Kodmany, 2018; Benke & Tomkins, 2017; Lovat et al., 2025; Pennisi et al., 2025). These studies have examined crop yield, environmental variables, resource-use efficiency, and energy consumption; however, these factors are often evaluated independently rather than through integrated comparative analyses. Consequently, the literature remains limited regarding comprehensive assessments that simultaneously compare the agronomic, environmental, and energy performance of different controlled-environment production systems (Barbosa et al., 2015; Gan et al., 2023). Further comparative research is therefore needed to provide a more holistic understanding of the sustainability and production efficiency of these systems (Al-Kodmany, 2018; Vastitas et al., 2022).

Studies have reported classic indicators such as yield per unit area (kg m^{-2}) and water productivity (L kg^{-1}), particularly in leafy crops grown in hydroponic systems and protected environments (Barbosa et al., 2015; Graamans et al., 2018; Pennisi et al., 2025). However, evidence that simultaneously integrates total water consumption with the horizontal area effectively occupied by the production system remains limited, restricting comparisons among systems with contrasting spatial configurations. Integrating water consumption with occupied ground area enables a more comprehensive evaluation of system performance by accounting for both productivity and spatial efficiency, which is especially relevant for vertically structured systems.

In addition to absolute yield and crop-level water productivity, evaluating water use in relation to the effective horizontal footprint of each system provides a more comprehensive basis for comparing vertical and horizontal production platforms, particularly in urban or space-constrained contexts. The objective of this study was to compare the spatial productivity and water use efficiency of hydroponic and soil-based *Lactuca sativa* L. production systems.

Materials and methods

Study site and experimental design

The study was conducted from August 20, 2025, to October 1, 2025, at the Instituto Nacional de Tecnología Agropecuaria (INTA), Mendoza Research Station (Luján de Cuyo, Argentina; 33°00'20" S, 68°51'54" W; 929 m a.s.l.), using a controlled-environment growth chamber and a polyethylene greenhouse with passive temperature control. The experiment was structured as a comparative trial among four lettuce (*Lactuca sativa* L.) production systems: indoor hydroponic vertical farming (A), greenhouse hydroponic vertical farming (B), conventional horizontal hydroponic cultivation in a greenhouse (C), and soil-based cultivation in a greenhouse (D). Conventional horizontal hydroponic cultivation refers to a traditional hydroponic growing system in which plants are arranged horizontally in a single layer, usually on benches, channels, pipes, or gutters positioned parallel to the ground. In contrast to vertical farming systems, where plants are stacked in multiple layers, conventional horizontal hydroponic systems use the available floor area only once.

Each treatment consisted of three independent experimental units. Experimental units corresponded to hydroponic vertical racks in Systems A and B, hydroponic modules in System C, and soil plots in System D (Figure 1). Treatment comparisons represented the overall performance of each production system as an integrated production package rather than the isolated effect of individual environmental or management variables.



Figure 1. Images of the different cultivation systems studied in lettuce: indoor vertical farming (A), greenhouse vertical farming (B), conventional horizontal hydroponics in a greenhouse (C), and soil-based cultivation (D). Instituto Nacional de Tecnología Agropecuaria, Mendoza Research Station, Luján de Cuyo, Argentina, 2025.

Figura 1. Imágenes de los diferentes sistemas de cultivo estudiados en lechuga: agricultura vertical en interior (A), agricultura vertical en invernadero (B), hidroponía horizontal convencional en invernadero (C) y cultivo en suelo (D). Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Mendoza, Luján de Cuyo, Argentina, 2025.

Waldman's Green curly lettuce seedlings supplied by a local nursery were grown for 35 days in trays containing 200 cells of 15 cm³ each before transplanting. At the start of the experiment, composite soil samples from System D and initial nutrient solution samples from Systems A, B, and C were characterized at the Soil, Water, and Plant Material Laboratory of the INTA Mendoza Research Station (Table 1).

Table 1. Physicochemical properties of the soil in System D (soil-based cultivation) and the initial nutrient solution used in the three hydroponic systems. Instituto Nacional de Tecnología Agropecuaria, Mendoza Research Station, Luján de Cuyo, Argentina, 2025.**Cuadro 1.** Propiedades fisicoquímicas del suelo del sistema D (cultivo en suelo) y de la solución nutritiva inicial utilizada en los tres sistemas hidropónicos. Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Mendoza, Luján de Cuyo, Argentina, 2025.

Soil analysis (0–0.3 m)		Nutrient solution analysis	
Variable	Value	Variable	Value
Sedimentation volume (cm ³ 100 g ⁻¹)	90	AEC (dS m ⁻¹)	1.66
ECse (dS m ⁻¹)	6.15	pH	6.28
Saturation moisture (%)	27.96	Na (mg L ⁻¹)	43.20
pH	7.09	K (mg L ⁻¹)	83.44
Cl ⁻ (mEq L ⁻¹)	1016.00	Ca (mg L ⁻¹)	134.5
CO ₃ ²⁻ (mEq L ⁻¹)	0.00	Mg (mg L ⁻¹)	30.50
HCO ₃ ⁻ (mEq L ⁻¹)	176.96	Cu (mg L ⁻¹)	0.04
SO ₄ ²⁻ (mEq L ⁻¹)	2375.56	Fe (mg L ⁻¹)	0.35
Ca ²⁺ (mEq L ⁻¹)	1028.85	Mn (mg L ⁻¹)	0.5
Mg ²⁺ (mEq L ⁻¹)	166.21	Zn (mg L ⁻¹)	0.26
Na ⁺ (mEq L ⁻¹)	367.84	P (mg L ⁻¹)	7.69
Sodium adsorption ratio	2.81	NH ₄ -N (mg L ⁻¹)	23.70
Total N (mg kg ⁻¹)	2129.64	NO ₃ -N (mg L ⁻¹)	58.30
Available P (H ₂ CO ₃ 1:10) (mg kg ⁻¹)	12.09		
Exchangeable K (NH ₄ OAc, pH 7) (mg kg ⁻¹)	637.00		
Organic matter (%)	3.74		
C/N Ratio	10.17		

ECse: Electrical conductivity of the saturated extract. **AEC:** Actual electrical conductivity. / **ECse:** Conductividad eléctrica del extracto de saturación. **AEC:** Conductividad eléctrica actual.

Treatment A: Indoor hydroponic vertical farming

The indoor vertical farming system was maintained under controlled conditions using a heating and cooling air-conditioning system. Mean air temperature during the production cycle was 22.1 ± 0.3 °C, and relative humidity averaged 78.7 ± 10.1 %. Three vertical modules were installed. Each module measured 2.27 m in height, 1.20 m in width, and 0.70 m in depth. Each module contained four shelves spaced 0.5 m apart vertically. Each shelf accommodated four NFT channels (80 × 42 mm), resulting in a planting density of 22.8 plants m⁻².

All four shelves were equipped with LED lighting fixtures providing a photosynthetic photon flux density (PPFD) of 250.3 ± 0.5 μmol m⁻² s⁻¹. A photoperiod of 16 h of light and 8 h of darkness was applied, resulting in a daily light integral (DLI) of 13.81 mol m⁻² d⁻¹. Artificial lighting consisted of four tubular LED fixtures per shelf. The spectral distribution of the radiation emitted by the LED fixtures was composed of 1.69 % UV-A (350–400 nm), 21.64 % blue (400–500 nm), 38.45 % green (500–600 nm), 34.27 % red (600–700 nm), and 3.97 % far-red (700–800 nm).

Spectral composition and PPFD values were established according to Aguado et al. (2024). PPFD was measured using a quantum sensor connected to a light meter. DLI was calculated from continuous PAR measurements obtained with a quantum sensor connected to a two-channel data logger.

In the hydroponic systems, nutrient solution recirculation was achieved using submersible pumps (60 W, 2500 L h⁻¹, 2.5 m head). Recirculation was programmed in intermittent cycles of 30 min on and 60 min off during the day (5:30 a.m. to 10:30 p.m.) and 30 min on and 120 min off during the night (10:30 p.m. to 5:30 a.m.). These schedules were maintained throughout the experiment to ensure consistent nutrient solution circulation and root-zone conditions.

The system was fertilized using a combination of macro- and micronutrients applied at an initial concentration of 1.5 mL L⁻¹. Nutrient solution pH was adjusted using 85 % phosphoric acid. Electrical conductivity (EC), pH, solution temperature, and dissolved oxygen concentration were monitored periodically throughout the production cycle using calibrated multiparameter probes (Table 2).

Table 2. Physicochemical parameters of the nutrient solution (mean $\pm$ standard error) during the hydroponic lettuce growing cycle. Instituto Nacional de Tecnología Agropecuaria, Mendoza Research Station, Luján de Cuyo, Argentina, 2025.

Cuadro 2. Parámetros físicoquímicos de la solución nutritiva (media $\pm$ error estándar) durante el ciclo de cultivo hidropónico de lechuga. Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Mendoza, Luján de Cuyo, Argentina, 2025.

System	Electrical conductivity (dS m ⁻¹)	pH	Temperature (°C)	O ₂ (mg L ⁻¹)
A	1.523 $\pm$ 0.019	6.07 $\pm$ 0.13	18.74 $\pm$ 0.25	8.21 $\pm$ 0.05
B	1.588 $\pm$ 0.024	6.03 $\pm$ 0.13	13.99 $\pm$ 0.43	8.70 $\pm$ 0.10
C	1.622 $\pm$ 0.020	6.03 $\pm$ 0.14	14.92 $\pm$ 0.41	8.75 $\pm$ 0.07

O₂: Dissolved oxygen. **A:** Indoor vertical farming. **B:** Greenhouse vertical farming. **C:** Conventional horizontal hydroponics in a greenhouse. / **O₂:** Oxígeno disuelto. **A:** Agricultura vertical en interiores. **B:** Agricultura vertical en invernadero. **C:** Hidroponía horizontal convencional en invernadero.

Treatment B: Greenhouse hydroponic vertical farming

This treatment was located inside the greenhouse, where the mean temperature was 14.8 $\pm$ 2.9 °C and relative humidity averaged 59.2 $\pm$ 9.1 %. The system consisted of three vertical modules identical to those used in Treatment A. The vertical modules were equipped with LED fixtures providing supplemental lighting in addition to natural sunlight. PPFD was maintained at 250.9 $\pm$ 1.0 μ mol m⁻² s⁻¹, with a photoperiod of 16 h of light and 8 h of darkness, resulting in a DLI of 10.38 mol m⁻² d⁻¹.

Four tubular LED fixtures were installed on each shelf. The spectral distribution of the radiation emitted by the LED fixtures was the same as that used in Treatment A and followed the specifications proposed by Aguado et al. (2024). PPFD and DLI were determined using the same instrumentation and procedures described above.

Nutrient solution recirculation was identical to that used in Treatment A. Macronutrients and micronutrients were applied at an initial concentration of 1.5 mL L⁻¹. Nutrient solution pH was adjusted with 85 % phosphoric acid, while EC, pH, temperature, and dissolved oxygen were monitored regularly during crop growth (Table 2).

Treatment C: Conventional horizontal hydroponic cultivation in a greenhouse

The conventional hydroponic system was established inside the greenhouse under the same environmental conditions described for Treatment B. Three hydroponic modules were installed. Each module consisted of eight NFT channels distributed over 1.75 m² (1.00 m $\times$ 1.75 m), with a planting density of 18.3 plants m⁻². No supplemental lighting was provided. Plants received only natural solar radiation, resulting in a DLI of 10.73 mol m⁻² d⁻¹. PPFD was measured using a quantum sensor connected to a light meter, and DLI was calculated from continuous PAR records.

Nutrient solution recirculation was identical to that used in Treatments A and B. The nutrient solution contained macro- and micronutrients applied at an initial concentration of 1.5 mL L⁻¹. The pH was adjusted with 85 % phosphoric acid, and the physicochemical characteristics of the solution were monitored periodically throughout the crop cycle (Table 2).

Treatment D: Soil-based greenhouse cultivation

This treatment was conducted inside the greenhouse under the same temperature and relative humidity conditions reported for Treatments B and C. The treatment consisted of experimental soil plots measuring 1.00 m × 0.90 m and planted at a density of 17.8 plants m⁻². No supplemental lighting was provided. Plants were grown exclusively under natural greenhouse radiation. The recorded DLI was 10.73 mol m⁻² d⁻¹.

For the soil-grown treatment, irrigation scheduling was initially established according to crop water requirements estimated from reference evapotranspiration (ET_o) and crop coefficients reported for lettuce under greenhouse conditions (Allen et al., 1998). Irrigation was supplied through a drip irrigation system equipped with emitters delivering 1.8 L h⁻¹ per emitter. Water was applied daily for 10 min, resulting in a cumulative irrigation depth of 128.7 mm during the 42-day production cycle.

The total volume of water applied was subsequently expressed on a per-plant basis, allowing water consumption to be calculated as cm³ plant⁻¹ day⁻¹ and cm³ plant⁻¹ per crop cycle. The irrigation system was pressurized using a 0.5 HP centrifugal pump. Drip lines for each experimental unit were independently isolated and regulated with 0.5-inch ball valves, ensuring constant hydraulic conditions throughout the experiment. Nutrients were supplied through fertigation twice weekly using a commercial root biostimulant (Rootex 8-46-5.5, Cosmocel, Mexico) and a plant initiator fertilizer (Plant-Prod 10-52-10 Iniciador, Master Plant-Prod Inc., Canada), applied at a rate of 2 g m⁻².

Measurements and evaluated variables

Crop harvest was performed when marketable size was reached, resulting in different crop cycle durations among treatments. Harvest was performed at 28 days after transplanting (DAT) in Treatment A, 35 DAT in Treatments B and C, and 42 DAT in Treatment D. Each treatment was evaluated according to its commercial production cycle. Yield comparisons were complemented with time-normalized indicators, including daily productivity per unit of horizontal area.

Five plants were sampled from each experimental unit. Fresh biomass per plant was recorded immediately after harvest. For hydroponic treatments (A, B, and C), the entire plant, including roots, was collected, whereas only shoot biomass was harvested in Treatment D. This difference reflected the commercial harvest practices of each production system: hydroponically grown lettuce is commonly marketed with roots attached, whereas soil-grown lettuce is harvested and marketed as shoot biomass only.

Samples were then dried at 65 °C in a forced-air oven until constant weight to determine dry biomass. Fresh and dry biomass values were recorded individually. Plant height was measured at harvest in the same sampled plants and recorded as the distance from the stem base to the highest point of the canopy using a graduated ruler.

Ground area yield (kg m⁻²) was calculated according to Equation 1:

$$Yg = Mf / Ag \quad (1)$$

Where Yg is ground area yield, Mf is total fresh mass harvested per production cycle (kg), and Ag is the ground footprint occupied by the cultivation module (m²).

Water consumption per cycle was expressed as liters per square meter of occupied ground surface ($L\ m^{-2}\ cycle^{-1}$), calculated from total water consumed divided by the ground footprint of each production system. Relative chlorophyll content was measured at 25 DAT using a chlorophyll meter operating in Chlorophyll Content Index (CCI) mode. Ten readings were recorded from each experimental unit.

Thirty leaves were collected from each experimental unit and dried at 65 °C to constant weight. Samples were ground and passed through a 1 mm sieve. Nitrogen was determined by the Kjeldahl method. Potassium, calcium, magnesium, iron, copper, manganese, and zinc concentrations were quantified by atomic absorption spectrophotometry. Phosphorus concentration was determined spectrophotometrically.

Statistical analysis

The physical arrangement of the experimental units within each system was fixed and determined by the structural characteristics of the growing environments, with no spatial randomization. Consequently, and considering the hierarchical structure of the experiment, the data were analyzed using a linear mixed-effects model (LMM) (Kuznetsova et al., 2017). In the statistical model, the production system was considered a fixed effect, while the experimental unit (rack, module, or growing bed) was included as a random effect nested within each system to model between-unit variability and avoid pseudoreplication. Within each experimental unit, five individual plants were selected as subsamples from central positions of the channels or growing beds, avoiding edges and ends.

The plants were not considered independent experimental replicates, but rather observational subunits incorporated into the model residual error term. Each production system was evaluated under its intended operational conditions. The indoor and greenhouse environments were represented by a single facility each and therefore did not constitute independently replicated experimental factors. Consequently, environmental effects could not be statistically separated from production system effects.

Comparisons among treatments should therefore be interpreted as comparisons among production platforms operating under their respective management environments rather than as a factorial test of cultivation environment. Differences between the indoor vertical farming system and the greenhouse-based systems reflect the combined influence of production system design and environmental conditions. Replication was achieved at the level of experimental units within each system (racks, modules, or growing beds), allowing statistical inference regarding the relative performance of the evaluated production platforms under the specific conditions of this study.

Prior to analysis, model assumptions were evaluated through residual diagnostics, including graphical inspection, the Shapiro-Wilk test for normality, and Levene's test for homogeneity of variances. Variables that did not satisfy the normality assumption were transformed prior to model fitting. Specifically, phosphorus (P), iron (Fe), and zinc (Zn) concentrations were natural-log-transformed [$\ln(x)$] before analysis. The remaining response variables met model assumptions and were analyzed on their original scale. Linear mixed-effects models were fitted using the transformed or untransformed data as appropriate, and statistical inference and multiple comparisons were conducted on the corresponding analysis scale. For transformed variables, estimated marginal means were back-transformed using the exponential function and are presented throughout the manuscript in their original units to facilitate biological interpretation.

Data were analyzed using mixed linear models fitted by restricted maximum likelihood (REML), with production system included as a fixed effect and experimental unit as a random effect. Comparisons among systems were performed using estimated marginal means, and pairwise differences were evaluated using Tukey adjustment for multiple comparisons ($\alpha = 0.05$). The analyses were conducted using R software, version 4.4.0, employing the *lme4*, *lmerTest*, and *emmeans* packages for model fitting, estimation of marginal means, and multiple comparisons.

Given that each configuration operates under distinct cultivation environments and exhibits different resource demands, plant growth conditions and resource inputs were intentionally not equalized among treatments. Instead, these differences were maintained to enable a realistic assessment of each system as a functional production unit operating under specific protected-environment conditions. This approach provides a more representative comparison of the agronomic performance and resource requirements associated with each cultivation system.

Results

Plant growth and yield

The production system significantly affected all evaluated growth and yield variables. Fresh biomass per plant differed among treatments (Table 3). Soil cultivation (D) had the highest value, exceeding A, B, and C by 61.6 %, 73.2 %, and 44.6 %, respectively. No differences were found among the three hydroponic systems. Dry biomass per plant also varied significantly, with D recording the highest value, exceeding B by 22.6 %, while A and C showed intermediate values that did not differ statistically from the soil system. When yield was expressed per horizontal area occupied by the system (kg m^{-2}), clear differences among production systems were observed.

Table 3. Effect of the production system on lettuce growth and yield variables for production cycles of 28 days after transplanting (DAT) (A), 35 DAT (B and C), and 42 DAT (D). Instituto Nacional de Tecnología Agropecuaria, Mendoza Research Station, Luján de Cuyo, Argentina, 2025.

Cuadro 3. Efecto del sistema de producción sobre las variables de crecimiento y rendimiento de la lechuga en ciclos de cultivo de 28 días después del trasplante (DDT) (A), 35 DDT (B y C) y 42 DDT (D). Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Mendoza, Luján de Cuyo, Argentina, 2025.

System	Fresh weight (g plant^{-1})	Dry weight (g plant^{-1})	Yield per unit area (kg m^{-2})	Height (cm)
A	158.29 $\pm$ 10.33 b	10.99 $\pm$ 0.35 ab	14.47 $\pm$ 0.94 a	29.67 $\pm$ 0.88 a
B	147.65 $\pm$ 13.01 b	9.97 $\pm$ 0.76 b	13.50 $\pm$ 1.24 a	19.88 $\pm$ 0.47 bc
C	176.92 $\pm$ 7.16 b	11.91 $\pm$ 0.32 ab	3.23 $\pm$ 0.13 b	18.33 $\pm$ 0.22 c
D	255.78 $\pm$ 24.20 a	12.22 $\pm$ 0.58 a	4.55 $\pm$ 0.43 b	24.11 $\pm$ 2.43 b
F _{3,8}	16.9	7.4	86.3	39.8
p	<0.001	0.011	<0.001	<0.001

Values are expressed as adjusted means $\pm$ standard error (linear mixed-effects model, restricted maximum likelihood estimation). Different letters within a column indicate significant differences based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$). **A:** Indoor vertical farming. **B:** Greenhouse vertical farming. **C:** Conventional horizontal hydroponics in a greenhouse. **D:** Soil-based cultivation. / Los valores se expresan como medias ajustadas $\pm$ error estándar (modelo lineal de efectos mixtos, estimación por máxima verosimilitud restringida). Letras diferentes dentro de una misma columna indican diferencias significativas según comparaciones por pares ajustadas mediante el método de Tukey ($\alpha = 0,05$). **A:** Agricultura vertical en interiores. **B:** Agricultura vertical en invernadero. **C:** Hidroponía horizontal convencional en invernadero. **D:** Cultivo en suelo.

The indoor environment (A) and the vertical greenhouse system (B) achieved the highest yields, with no significant differences between them. These values far exceeded those of horizontal hydroponics and soil cultivation. Compared to D, A and B increased production per unit area by 218 % and 197 %, respectively. Plants were tallest in A and shortest in C, while B and D showed intermediate values.

Analysis of temporal metrics revealed additional contrasts. Daily productivity per unit area was higher in A, followed by B, and considerably lower in D and C. Consistently, fresh biomass accumulation rate per plant, calculated from final fresh biomass and growth cycle length, was higher in D, followed by A, C, and B. Overall, the vertical systems (A and B) achieved the highest production per unit area and time, whereas D resulted in higher individual plant biomass.

Water consumption and water productivity

The production system significantly affected daily water consumption per plant, total consumption per cycle, and specific water consumption (Table 4). No significant differences in daily water consumption were observed between A and B, both of which recorded the lowest consumption rates. These were followed by C, while D exhibited the highest daily water demand among all treatments. These differences were amplified when considering total water consumption per cycle. System A had the lowest total water consumption, followed by B and C, while D reached markedly higher values than the hydroponic systems.

Table 4. Effect of the production system on water consumption and water productivity in lettuce for production cycles of 28 days after transplanting (DAT) (A), 35 DAT (B and C), and 42 DAT (D). Instituto Nacional de Tecnología Agropecuaria, Mendoza Research Station, Luján de Cuyo, Argentina, 2025.

Cuadro 4. Efecto del sistema de producción sobre el consumo de agua y la productividad del agua en lechuga para ciclos de cultivo de 28 días después del trasplante (DDT) (A), 35 DDT (B y C) y 42 DDT (D). Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Mendoza, Luján de Cuyo, Argentina, 2025.

System	Daily water use ($\text{cm}^3 \text{ plant}^{-1} \text{ d}^{-1}$)	Water use per cycle ($\text{cm}^3 \text{ plant}^{-1} \text{ cycle}^{-1}$)	Water productivity ($\text{cm}^3 \text{ g}^{-1}$)
A	$85.6 \pm 3.3 \text{ a}$	$2396 \pm 92 \text{ a}$	$15.2 \pm 0.5 \text{ a}$
B	$88.4 \pm 3.6 \text{ a}$	$3094 \pm 97 \text{ b}$	$19.9 \pm 0.7 \text{ a}$
C	$110.1 \pm 3.0 \text{ b}$	$3854 \pm 98 \text{ c}$	$20.9 \pm 0.7 \text{ a}$
D	$192.5 \pm 0.4 \text{ c}$	$8086 \pm 3.7 \text{ d}$	$32.3 \pm 3.4 \text{ b}$
$F_{3,8}$	590.1	1284.7	53.4
p	<0.001	<0.001	<0.001

Values are expressed as adjusted means $\pm$ standard error (linear mixed-effects model, restricted maximum likelihood estimation). Different letters within a column indicate significant differences based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$). **A:** Indoor vertical farming. **B:** Greenhouse vertical farming. **C:** Conventional horizontal hydroponics in a greenhouse. **D:** Soil-based cultivation. / Los valores se expresan como medias ajustadas $\pm$ error estándar (modelo lineal de efectos mixtos, estimación por máxima verosimilitud restringida). Letras diferentes dentro de una misma columna indican diferencias significativas según comparaciones por pares ajustadas mediante el método de Tukey ($\alpha = 0.05$). **A:** Agricultura vertical en interiores. **B:** Agricultura vertical en invernadero. **C:** Hidroponía horizontal convencional en invernadero. **D:** Cultivo en suelo.

Specific water consumption per unit of fresh biomass was similar across all hydroponic systems, whereas System D required significantly more water, demonstrating lower water-use efficiency in soil-based cultivation. Overall, hydroponic systems reduced water consumption per plant by 43–55 % and per cycle by 52–70 % compared to soil-based cultivation, with similar efficiencies observed between vertical and horizontal configurations within the protected environment.

Water consumption per unit of horizontal area

When water use was analyzed on a horizontal footprint basis, clear differences emerged among production systems. The indoor vertical system (A) recorded the lowest value and differed significantly from all other systems. The greenhouse vertical system (B) and the conventional horizontal hydroponic system (C) showed similar consumption rates and did not differ from each other, whereas D exhibited the highest consumption rate and was statistically higher than all hydroponic systems. In relative terms, A reduced water consumption per unit area by 64.7 % compared to soil-based cultivation, while B and C showed reductions of approximately 49–50 % (Table 5).

Table 5. Integrated water consumption per unit of horizontal surface area of the system ($L\ m^{-2}\ cycle^{-1}$) and relative reduction in consumption compared to soil-based cultivation (D). Instituto Nacional de Tecnología Agropecuaria, Mendoza Research Station, Luján de Cuyo, Argentina, 2025.

Cuadro 5. Consumo de agua integrado por unidad de superficie horizontal del sistema ($L\ m^{-2}\ ciclo^{-1}$) y reducción relativa del consumo en comparación con el cultivo en suelo (D). Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Mendoza, Luján de Cuyo, Argentina, 2025.

System	Water consumption ($L\ m^{-2}\ cycle^{-1}$)	Reduction vs System D (%)
A	$49.3 \pm 1.9\ a$	64.7
B	$70.7 \pm 2.2\ b$	49.4
C	$70.4 \pm 1.8\ b$	49.6
D	$139.6 \pm 0.9\ c$	—

Values are expressed as adjusted means $\pm$ standard error (linear mixed-effects model, restricted maximum likelihood estimation). Different letters within a column indicate significant differences based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$). **A:** Indoor vertical farming. **B:** Greenhouse vertical farming. **C:** Conventional horizontal hydroponics in a greenhouse. **D:** Soil-based cultivation. / Los valores se expresan como medias ajustadas $\pm$ error estándar (modelo lineal de efectos mixtos, estimación por máxima verosimilitud restringida). Letras diferentes dentro de una misma columna indican diferencias significativas según comparaciones por pares ajustadas mediante el método de Tukey ($\alpha = 0.05$). **A:** Agricultura vertical en interiores. **B:** Agricultura vertical en invernadero. **C:** Hidroponía horizontal convencional en invernadero. **D:** Cultivo en suelo.

Foliar nutritional status

The chlorophyll index (CCI) varied among systems. The vertical greenhouse system (B) showed the highest values, followed by horizontal hydroponics (C) and soil cultivation (D), while the indoor system (A) had the lowest. Foliar nitrogen differed, being highest in D, intermediate in C, and lowest in A and B. Foliar phosphorus concentration also differed among systems. Systems B and D showed the highest phosphorus concentrations, whereas system A exhibited the lowest values. System C presented intermediate concentrations and did not differ significantly from either group. Potassium showed the greatest contrast, with much higher levels in D than in the hydroponic systems. Calcium and magnesium also varied, with higher values in D and B, respectively. For micronutrients, iron concentration was highest in D, although it did not differ significantly from B. Manganese concentration was highest in D, while C showed an intermediate value that did not differ significantly from D or A; B had the lowest concentration. Zinc peaked in B, while copper showed no significant differences among systems (Table 6).

Table 6. Effect of the production system on foliar nutrient concentration and chlorophyll index (CCI) in lettuce. Instituto Nacional de Tecnología Agropecuaria, Mendoza Research Station, Luján de Cuyo, Argentina, 2025.**Cuadro 6.** Efecto del sistema de producción sobre la concentración foliar de nutrientes y el índice de clorofila (CCI) en lechuga. Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Mendoza, Luján de Cuyo, Argentina, 2025.

Variable	System				$F_{3,8}$	p
	A	B	C	D		
CCI	9.2 ± 0.3 c	14.4 ± 0.3 a	13.5 ± 0.5 ab	11.7 ± 0.4 b	52.4	<0.001
N (%)	1.95 ± 0.08 b	1.96 ± 0.08 b	2.84 ± 0.22 ab	3.92 ± 0.15 a	31.7	<0.001
P (%)	0.52 ± 0.02 b	0.70 ± 0.06 a	0.57 ± 0.02 ab	0.72 ± 0.01 a	5.6	0.023
K (%)	1.56 ± 0.05 b	0.72 ± 0.02 c	2.02 ± 0.11 b	10.25 ± 0.32 a	412.5	<0.001
Ca (%)	0.84 ± 0.03 b	0.98 ± 0.06 ab	0.91 ± 0.07 ab	1.36 ± 0.12 a	8.6	0.007
Mg (%)	0.29 ± 0.02 b	0.54 ± 0.02 a	0.30 ± 0.05 b	0.30 ± 0.02 b	14.2	0.002
Fe (mg kg ⁻¹)	69.9 ± 4.1 b	314.7 ± 50.6 ab	186.4 ± 4.9 b	915.3 ± 286.3 a	9.8	0.004
Mn (mg kg ⁻¹)	66.9 ± 3.6 b	27.1 ± 3.0 c	93.2 ± 3.2 ab	98.6 ± 12.3 a	6.7	0.014
Zn (mg kg ⁻¹)	51.6 ± 2.1 b	213.5 ± 18.2 a	50.3 ± 1.9 b	44.8 ± 3.5 b	49.3	<0.001
Cu (mg kg ⁻¹)	6.4 ± 1.7 a	13.2 ± 0.9 a	6.5 ± 0.7 a	13.4 ± 1.0 a	1.9	0.19

Values are expressed as adjusted means ± standard error (linear mixed-effects model, restricted maximum likelihood estimation). Different letters within each row indicate significant differences based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$). **A:** Indoor vertical farming. **B:** Greenhouse vertical farming. **C:** Conventional horizontal hydroponics in a greenhouse. **D:** Soil-based cultivation. / Los valores se expresan como medias ajustadas ± error estándar (modelo lineal de efectos mixtos, estimación por máxima verosimilitud restringida). Letras diferentes dentro de cada fila indican diferencias significativas según comparaciones por pares ajustadas mediante el método de Tukey ($\alpha = 0.05$). **A:** Agricultura vertical en interiores. **B:** Agricultura vertical en invernadero. **C:** Hidroponía horizontal convencional en invernadero. **D:** Cultivo en suelo.

Discussion

Soil-based cultivation promoted greater individual plant biomass compared to hydroponic systems. This was likely due to the larger root volume available and the longer cycle, which favored leaf expansion and biomass accumulation, as reported by Wen et al. (2026). Similar responses were reported in soil-grown lettuce under favorable physical conditions and extended growing periods (Vendruscolo et al., 2021). However, soil-grown lettuce reduced annual turnover and limited spatial productivity. Wang et al. (2023) reported higher yields in hydroponic than in soil-based greenhouse systems under optimized irrigation and nutrient management. In the present study, the vertical hydroponic systems (A and B) achieved significantly greater yields per unit of occupied ground area than both horizontal hydroponic and soil-based cultivation. These results suggest that system architecture and cultivation density may have contributed more strongly to spatial productivity than the cultivation method alone.

Previous studies have indicated that production differences among hydroponic systems reflect the interaction between crop architecture, plant density, cycle duration, and the degree of environmental control (Heuvelink et al., 2025). Vertical hydroponic systems (A and B) showed lower individual plant weights but markedly greater spatial efficiency. Yield per unit area was approximately four times greater in the vertical systems than in the conventional horizontal hydroponic system and about three times greater than in soil-based cultivation. This increase was likely associated with the greater cultivation density achievable in the vertical configuration. Similar trends have been reported for controlled-environment agriculture systems, where vertical arrangements substantially increase productivity per unit area while individual plant performance remains unchanged or may decrease slightly due to density effects (Gargaro et al., 2023).

These differences were explained by the system architecture and effective crop density, given that the individual fresh biomass values in C and D were equal to or greater than those in A and B. Continuous water and nutrient availability, together with improved root oxygenation, may have enhanced carbon allocation and growth uniformity, allowing higher planting densities while maintaining crop performance (Barbosa et al., 2015). The yield advantages observed in vertical configurations were consistent with evidence showing that space stratification significantly increases production per unit of floor area compared to horizontal systems (Graamans et al., 2018).

The indoor vertical system exhibited the highest daily productivity, associated with shorter production cycles and a stable cultivation environment. Thermal and light homogeneity, together with the use of artificial lighting, may have contributed to faster crop development and reduced variability among plants, resulting in earlier harvests (Pennisi et al., 2019; 2020; Kaiser, Weerheim et al., 2024). While the greenhouse vertical system achieved comparable yields per unit area, its lower temporal productivity suggested that vertical stacking explained most of the spatial advantage, whereas full environmental control may have contributed to a higher growth rate observed in system A.

This pattern was consistent with recent studies indicating that combining hydroponics with climate control can maximize radiation-use efficiency and biomass production (Pennisi et al., 2025). Although soil-based cultivation favored individual plant size, vertical farming, especially under indoor conditions, optimized yield per unit area and time, supporting its role in intensive production systems. Systems with longer growth cycles and lower planting density favored greater daily accumulation of individual biomass, whereas vertical systems prioritized spatial productivity over plant size.

Differences in water use and efficiency reflected the combined effects of production system type and cultivation environment. Hydroponic systems reduced water consumption per plant and per cycle compared to soil cultivation, likely due to precise nutrient solution delivery and recirculation (Barbosa et al., 2015). The indoor system showed the lowest consumption among the evaluated systems. Previous studies have reported improved water-use efficiency in controlled-environment agriculture under lower evaporative demand conditions (Amitrano et al., 2021) and greater water productivity in indoor farming systems compared with conventional greenhouse production (Graamans et al., 2018; Pennisi et al., 2019), which is consistent with the pattern observed in the present study.

In greenhouse systems, higher ventilation and temperature variability may have increased atmospheric evaporative demand rather than carbon dioxide availability, resulting in higher transpiration and intermediate consumption levels, particularly in horizontal configurations where leaf exposure to air exchange was greater (Vitoshkin et al., 2021). In contrast, soil-based cultivation exhibited the highest water consumption due to structural losses, including evaporation, percolation, and limited recovery. However, when analyzed on a spatial basis, differences between hydroponic and soil systems were smaller than expected, as the soil treatment was conducted under protected conditions with controlled irrigation. This suggested that water savings depended not only on the cultivation system but also on irrigation management and production conditions. Indeed, protected soil systems may approach hydroponic efficiency when losses are minimized (Barbosa et al., 2015; Graamans et al., 2018).

The absence of major differences in water productivity among hydroponic systems suggested that, once soil-related losses were eliminated, efficiency was mainly governed by plant physiology and nutrient management rather than spatial arrangement (Regmi et al., 2024). Nevertheless, the indoor vertical system showed the greatest overall efficiency per unit of installation area, combining lower water consumption with higher yields per unit area. The superior performance of the indoor vertical system likely reflected the combined effect of recirculation, spatial intensification, and environmental stability, which could have improved the conversion of water into marketable biomass. Conversely, greenhouse systems, although protected, remained subject to microclimatic fluctuations that may have increased evaporative losses, as documented in comparative studies of controlled-environment agriculture (Pennisi et al., 2019).

Nutritional differences were primarily associated with the characteristics of the root environment. Soil-based cultivation resulted in higher foliar concentrations of N and K, consistent with the greater N and K contents and availability observed in the soil, as well as its buffering capacity and ionic reserves. For Fe and Mn, the highest mean concentrations were observed in the soil-grown system, although some hydroponic systems did not differ significantly from soil cultivation.

Foliar P concentration also differed among systems. The highest concentrations were observed in systems B and D, whereas system A exhibited the lowest values and system C showed intermediate concentrations. These differences suggest that P uptake varied among production environments despite the controlled nutrient supply provided in the hydroponic systems. In soil systems, nutrient supply was influenced by interactions with the relatively high organic matter content recorded in the soil, minerals, and microbial activity, leading to a slower but more diverse nutrient flow (Jacoby et al., 2017; Kuryntseva et al., 2025).

The higher foliar K concentration observed in soil-grown plants highlights the influence of the root environment on potassium nutrition. As a highly mobile macronutrient involved in osmotic regulation, stomatal function, and assimilate transport, K uptake depends not only on its concentration in solution but also on nutrient buffering capacity. Soil contains multiple K pools that can replenish the soil solution and sustain plant uptake, whereas hydroponic systems rely exclusively on the nutrient solution as the immediate source of K (Ragel et al., 2019). Consequently, the higher foliar K levels in soil-grown plants likely reflect both greater potassium availability and a more stable nutrient supply throughout the crop cycle.

In contrast, hydroponic systems showed more uniform and moderate nutrient concentrations, which likely reflected the controlled composition of the nutrient solution and a closer coupling between supply and plant demand (Barbosa et al., 2015). This nutritional pattern could have contributed to reduced variability and more efficient fertilizer use. Notably, the lower chlorophyll index observed in the indoor system did not translate into reduced productivity. Under controlled conditions, high photosynthetic efficiency may have been maintained despite moderate pigment levels due to reduced stress and greater physiological uniformity (Pennisi et al., 2019). Overall, hydroponic systems, both vertical and horizontal, tended to show a more balanced and predictable nutritional status, while soil-based cultivation promoted greater mineral accumulation due to higher availability.

From a production perspective, such stability may support crop uniformity and resource-use efficiency, key aspects of controlled-environment agriculture (Benke & Tomkins, 2017; Graamans et al., 2018; Pennisi et al., 2025). Finally, this study provided a comparative evaluation of contrasting lettuce production systems under specific operational conditions. Although direct extrapolation should be made with caution, the results provide evidence of the relative performance of the evaluated systems under these protected- and controlled-environment conditions.

Conclusions

The evaluation showed that vertical hydroponic systems using LED lighting (A and B) achieved the highest lettuce yield per unit of occupied ground area, whereas soil cultivation (D) produced the greatest individual plant biomass. The indoor vertical system (A) exhibited the highest daily productivity and the lowest water consumption per production cycle. Hydroponic systems required significantly less water than soil cultivation when evaluated on both plant and area bases. Hydroponic and soil-based systems exhibited distinct nutrient dynamics, evidenced by differences in foliar nutrient composition and chlorophyll index.

The evidence indicated that the combination of system design and cultivation environment influenced production efficiency under controlled conditions. The incorporation of metrics based on the spatial footprint constituted a methodological contribution that strengthened the comparison between contrasting production platforms. Future studies should integrate energy consumption, economic performance, and multi-season validation to provide a more comprehensive assessment of the sustainability of these systems at the commercial scale.

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Conflict of interest

The authors declare that there are no conflicts of interest related to this study.

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