

Article

Water Productivity and Seasonal Performance of Floating-Root Hydroponic Lettuce Under Coastal Desert Conditions in Northern Chile

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Abstract

Water scarcity increasingly constrains horticultural production in coastal desert regions. This study provides a site-specific characterization of the seasonal performance and water productivity of a pilot-scale floating-root hydroponic lettuce system under coastal desert conditions in northern Chile, where air temperatures ranged from 0.98 to 27.1 °C during the study period. Four seasonal production cycles were conducted using two commercial cultivars. Because all seasonal observations were obtained from a single hydroponic bench and shared nutrient-solution reservoir without independent system-level replication, seasonal comparisons were interpreted descriptively. Fresh weight ranged from 230 to 265 g plant^{−1}, marketable yield exceeded 93% in all production cycles, and water productivity ranged from 7.1 to 12.5 L kg^{−1} fresh biomass, with the highest value observed during autumn. Fractional canopy cover was strongly associated with cumulative system water use ($R^2 = 0.89$), suggesting the potential application of non-destructive imaging tools for irrigation monitoring. In a separate winter experiment with statistical analysis, a four-day pre-harvest nutrient flushing reduced nitrate concentration by 15% without affecting yield or total polyphenol content. Water utility descriptively varied among seasons, reaching a maximum of 401 CLP L^{−1} during summer. Overall, the study provides a preliminary characterization of the technical performance, water-use indicators, and economic potential of a floating-root hydroponic system under coastal desert conditions, while highlighting the need for independent multi-bench and multi-location experiments to validate seasonal responses.

Keywords: floating hydroponics; water productivity; *Lactuca sativa*; coastal desert agriculture; digital phenotyping; nitrate reduction



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1. Introduction

Water scarcity has become one of the most critical constraints for agricultural production in Mediterranean and semi-arid regions worldwide. In central and northern Chile, the so-called “Mega-Drought” (2010–2018) marked an unprecedented reduction in precipitation, increased interannual variability, and greater frequency of extreme climatic events, severely affecting agricultural water security [1]. In the Coquimbo Region, prolonged precipitation deficits combined with high evaporative demand have intensified pressure on irrigation-dependent cropping systems, highlighting the urgent need for water-efficient production strategies.

Hydroponic systems represent a promising alternative under water-limited conditions because they allow precise control of nutrient and water supply, minimize soil evaporation losses, and enable recirculation of nutrient solutions [2]. Among hydroponic production systems, deep water culture (DWC), also known as floating-root systems, presents several characteristics that may be particularly advantageous under arid and coastal desert conditions. The relatively large volume of nutrient solution acts as a thermal buffer, reducing short-term fluctuations in root-zone temperature and helping maintain more stable growing conditions. In addition, the continuous availability of water and nutrients may contribute to crop resilience under environments characterized by high radiation, low precipitation, and elevated evaporative demand. Consequently, DWC systems have gained increasing attention for leafy vegetable production due to their simplicity, scalability, and potential for high water use efficiency (WUE). Previous studies have demonstrated that environmental conditions and nutrient management significantly influence hydroponic lettuce yield, quality, and phytonutrient accumulation [3]. Moreover, cultivar selection plays a critical role in performance under suboptimal temperature conditions, particularly in warm environments [4]. Comparisons among hydroponic production systems have shown that crop performance depends not only on cultivar but also on system configuration and management strategy [5]. Nutrient film technique (NFT) systems provide high oxygen availability but are generally more sensitive to interruptions in water flow and temperature fluctuations because of their low nutrient-solution volume. In contrast, substrate-based systems offer greater buffering capacity but require more complex irrigation scheduling and substrate management. Deep water culture (DWC), also known as floating-root hydroponics, provides a relatively large nutrient-solution volume that can buffer short-term fluctuations in water availability and temperature; however, it requires appropriate aeration to avoid oxygen limitations in the root zone.

Water use efficiency and nutrient use efficiency in DWC systems are influenced by multiple interacting factors, including solution characteristics and genotype [6]. In addition, seasonal variation has been shown to significantly affect growth dynamics, phytochemical concentration, nutrient uptake, and total system water use in butterhead lettuce cultivated under different hydroponic configurations [7]. However, most studies have been conducted under controlled environments or temperate conditions, and limited information is available regarding the site-specific performance of floating-root hydroponic systems under coastal desert climates characterized by high radiation, low rainfall, and strong evaporative demand.

Beyond productivity, nitrate accumulation remains a major concern in hydroponically grown leafy vegetables. Strategies such as pre-harvest nutrient solution flushing have been shown to reduce nitrate content without compromising postharvest quality [8]. More recently, innovative cultivation practices in vertical farming systems have demonstrated additional approaches to nitrate reduction in baby leaf lettuce [9]. Nevertheless, site-specific information describing the technical performance, water-use indicators, and quality-related responses of floating-root hydroponic systems under coastal desert conditions remains limited, particularly under pilot-scale production systems.

Recent advances in image-based phenotyping offer new opportunities to monitor crop growth non-destructively. The Canopeo application has been validated as an image-based tool for estimating canopy cover under controlled environments [10], providing a potential proxy for biomass accumulation and, indirectly, crop water demand. Similar approaches have been successfully applied in lettuce, where digital image-derived canopy cover showed strong correlations with destructively measured biomass and leaf area, supporting its use as a rapid and non-destructive indicator of crop growth and development [11]. The integration of canopy cover measurements with total system water use data may

contribute to developing simplified models for estimating crop water productivity in hydroponic systems.

Recent evidence indicates that nitrate accumulation in leafy vegetables is governed by the interaction between nitrogen uptake, nitrate assimilation, and environmental conditions, including light, temperature, humidity, irrigation, and greenhouse climate, all of which influence nitrate reductase activity and carbon availability [12]. Consequently, pre-harvest management strategies that reduce nitrate uptake while maintaining plant performance are of increasing interest for improving both nutritional quality and marketability of hydroponically grown lettuce.

Although previous studies have examined individual aspects of hydroponic lettuce production, such as crop productivity, water use efficiency, or pre-harvest nitrate management, site-specific information describing the technical performance of floating-root hydroponic systems under coastal desert conditions in northern Chile remains limited. Such information is relevant for understanding the operational behavior of these systems in water-scarce environments and for identifying priorities for future replicated studies.

The present manuscript comprises two complementary study components with different objectives and levels of inference. The first component provides a descriptive characterization of the seasonal performance of a pilot-scale floating-root hydroponic system under coastal desert conditions, focusing on crop growth, total system water use, water productivity, and economic indicators across four seasonal production cycles. Because only one production cycle was evaluated per season, this component was designed to provide site-specific baseline information, characterize system performance under the evaluated environmental conditions, and generate hypotheses for future research, rather than to statistically test seasonal effects. The second component consists of an independently replicated winter experiment designed to evaluate the effect of a four-day pre-harvest nutrient-flushing treatment on nitrate concentration, fresh yield, and total polyphenol content under controlled experimental conditions.

Therefore, the objectives of this study were (i) to provide a descriptive, site-specific characterization of the seasonal operation of a pilot-scale floating-root hydroponic lettuce system under coastal desert conditions, quantify total system water use and water productivity across production cycles, and assess the relationship between canopy cover, biomass accumulation, and cumulative total system water use as baseline information for future research; and (ii) to evaluate, through an independently replicated winter experiment, the effect of a short-term pre-harvest nutrient-flushing treatment on nitrate concentration, fresh yield, and total polyphenol content.

2. Materials and Methods

This study comprises two complementary methodological components that address different scientific questions and therefore require different experimental approaches. The first component consisted of a descriptive seasonal characterization of a pilot-scale floating-root hydroponic system conducted over four production cycles under coastal desert conditions. Because only one production cycle was available for each season, this component was intended to provide site-specific baseline information on system performance and to generate hypotheses for future research rather than to statistically evaluate seasonal effects. The second component consisted of an independently replicated winter experiment designed to evaluate the effect of a four-day pre-harvest nutrient-flushing treatment on nitrate concentration, fresh yield, and total polyphenol content. Accordingly, these two study components are presented, analyzed, and interpreted separately throughout the manuscript because they address different scientific questions and differ in their experimental design and inferential scope.

2.1. Study Site and Environmental Conditions

The study was conducted at the Pan de Azúcar Experimental Station of INIA Intihuasi, located in Coquimbo, Coquimbo Region, Chile (29°58'19.1" S; 71°15'55.7" W). The area is classified as a coastal desert climate with frequent cloud cover (BWn, Köppen classification), characterized by marked aridity, annual precipitation below 100 mm, high solar radiation, and low thermal amplitude due to maritime influence. Mean annual temperatures range between 13 and 16 °C, with mild summers and temperate winters influenced by maritime conditions. These conditions may influence crop growth, evapotranspiration, and water-use dynamics differently from those observed in temperate or continental climates. Consequently, evaluating hydroponic production systems under coastal desert conditions provides an opportunity to assess their performance in an environment where water scarcity coexists with comparatively stable atmospheric conditions and reduced thermal stress.

The experiment was carried out in a 48 m² hydroponic module equipped with a floating-root system (deep water culture, DWC). The system consisted of elevated wooden or PVC-supported benches containing nutrient solution reservoirs. Expanded polystyrene floating rafts were placed over the nutrient solution, with equidistant planting holes allowing roots to remain suspended directly in the solution. The hydroponic benches were equipped with a recirculation system operating daily between 08:00 and 19:00 h. The return flow of the nutrient solution generated turbulence within the reservoirs, promoting passive aeration and oxygenation of the solution. Dissolved oxygen concentration was not measured during the study. The system was designed as a low-water-consumption, low-cost technology adaptable to small-scale farmers under arid conditions [2].

2.2. Experimental Design and Crop Management

Lettuce (*Lactuca sativa* L.) was grown during four seasonal production cycles. Cultivar 'Milena' was used during the summer cycle, whereas cultivar 'Jade' was used during autumn, winter, and spring. Both cultivars are commonly grown commercially in the study area, and their use reflected cultivar availability and standard production practices during the respective growing periods. Because a different commercial cultivar was used during the summer production cycle, the observed summer responses reflect the combined influence of cultivar and seasonal environmental conditions. Consequently, cultivar effects cannot be separated from seasonal effects in descriptive comparisons involving the summer cycle. Plants were established at a density of 20 plants m⁻².

Each seasonal production cycle was conducted using six independent floating-root hydroponic units, each consisting of an elevated cultivation bench functioning as an individual nutrient solution reservoir. Each bench measured 307 × 107 × 80 cm (external dimensions) and 302 × 101 × 15 cm (internal dimensions), with an approximate nutrient solution capacity of 300 L. Expanded polystyrene floating rafts covered approximately 99.9% of the nutrient solution surface, supporting the plants while allowing direct root contact with the nutrient solution. Each hydroponic unit had its own independent aeration system, ensuring continuous oxygenation of the nutrient solution throughout the production cycle. Dissolved oxygen concentration was not monitored during the experiment; therefore, any discussion regarding oxygen availability is presented only as a possible explanation based on previous studies of floating-root hydroponic systems. The general configuration of the experimental hydroponic facility is presented in Supplementary Figure S1.

Seedlings were obtained from a commercial nursery and transplanted at approximately 35–40 days of age, when they had developed at least four true leaves. Transplant dates, harvest dates, crop duration, and cultivar used for each production cycle are summarized in Supplementary Table S1. All plants were harvested at the same commercial maturity stage,

defined as fully developed marketable heads with commercial size and appearance suitable for fresh-market sale, following the standard commercial criterion used by local producers.

Each hydroponic unit contained 60 plants. Border plants were excluded from all evaluations to minimize edge effects. Fresh weight, plant height, stem diameter, and root length were measured individually on 15 randomly selected plants from the central area of each hydroponic unit. Dry matter was determined from two composite samples per hydroponic unit, each prepared from pooled tissue of the sampled plants. Nitrate concentration and total polyphenol content were determined using one composite sample per hydroponic unit, following the same sampling procedure.

The six independent hydroponic units were used to estimate seasonal means and variability parameters within each production cycle. However, because only one production cycle was conducted in each season, seasonal comparisons represent descriptive observations and were not used for inferential statistical comparisons among seasons.

The nutrient solution was prepared and maintained according to standard hydroponic lettuce production recommendations [2], and water levels were replenished as needed to maintain stable solution depth. Three concentrated stock solutions were used: Solution A contained Ultrasol Desarrollo[®], magnesium sulfate (MgSO_4), potassium sulfate (K_2SO_4), and iron chelate (EDDHA); Solution B contained calcium nitrate [$\text{Ca}(\text{NO}_3)_2$] and potassium nitrate (KNO_3); and Solution C contained phosphoric acid (H_3PO_4), which was used for pH adjustment and phosphorus supplementation. The target electrical conductivity (EC) ranged between 1.0 and 2.0 dS m^{-1} , while pH was maintained between 6.0 and 7.0 throughout the production cycles. Both EC and pH were monitored weekly, and pH was adjusted when necessary to remain within the target range. A fresh nutrient solution was prepared at the beginning of each seasonal production cycle, whereas during crop growth, nutrient solution management was based on periodic replenishment of water and routine monitoring of EC and pH. Nutrient concentrations were not determined through routine chemical analyses during the experiment; instead, solution management relied on EC and pH measurements, as previous experiments conducted under the same hydroponic system and management conditions had confirmed nutrient solution stability through chemical analyses.

2.2.1. Non-Destructive Growth Monitoring

Plant growth was monitored weekly through estimation of fractional canopy cover (FCC). Digital images were acquired using a smartphone positioned approximately 1 m above the cultivation bench and oriented perpendicular (90°) to the crop surface. Three images were obtained from each hydroponic unit during every evaluation, always photographing the same area of each cultivation bench throughout the production cycle.

Images were collected under natural light conditions between 12:00 and 13:00 h, when illumination was relatively stable. Because the nutrient solution surface remained almost completely covered (approximately 99.9%) by the expanded polystyrene floating rafts, water reflections were negligible. In addition, photographs were acquired under lighting conditions that avoided shadows on the crop canopy.

Images were processed using the Canopeo mobile application for Android, version 1.1.7 (Oklahoma State University, USA) and COB CAL software (version 2.1; INTA, Argentina) to quantify green canopy cover as a percentage of the total image area. Default Canopeo threshold settings were used without additional calibration, as image acquisition was performed under standardized and consistent lighting conditions throughout the experiment. No post-acquisition light correction was applied prior to image analysis. FCC was used as a non-destructive indicator of vegetative biomass development.

2.2.2. Harvest and Morphometric Measurements

At commercial maturity, 15 plants were randomly selected from the central area of each hydroponic unit, excluding border plants. The same 15 plants were used for all morphometric measurements. The following variables were determined individually:

Fresh shoot weight (g)

Fresh root weight (g)

Total fresh biomass

Shoot height (measured from collar base to leaf apex)

Root length (from collar to root tip)

Stem diameter at collar (measured using a digital caliper, ± 0.1 mm)

Fresh biomass was determined using a precision digital balance (± 0.01 g). Leaf area was determined for the same 15 sampled plants by scanning representative leaves and analyzing the images using ImageJ software 1.54t (National Institutes of Health, Bethesda, MD, USA).

2.2.3. Dry Matter Determination

Dry matter was determined using two composite samples per hydroponic unit, prepared from the 15 harvested plants (plants 1–8 and plants 9–15, respectively). Approximately 100 g of fresh tissue per composite sample was dried in a forced-air convection oven at 60 °C for 48 h until constant weight. Dry matter percentage was calculated as the ratio of dry to fresh weight.

2.3. Nitrate and Total Polyphenol Content

Leaf nitrate concentration was determined by spectrophotometry using extracts obtained from fresh leaf maceration. Results were expressed as parts per million (ppm).

Total polyphenol content was quantified using the Folin–Ciocalteu colorimetric method. Results were expressed as mg gallic acid equivalents per 100 g fresh matter (mg GAE 100 g^{−1} FM). Nitrate concentration and total polyphenol content were determined from one composite sample per hydroponic unit prepared from the same harvested plants used for the destructive morphometric evaluations.

2.4. Total System Water Use and Water Use Indicators

Total system water use was monitored daily by measuring nutrient solution depth using a graduated ruler inserted vertically at three fixed positions within each hydroponic unit. Each 1 cm decrease in solution depth corresponded to approximately 30 L of water, based on the reservoir surface area and solution depth. Changes in nutrient solution depth were used to estimate total system water use rather than plant transpiration alone, integrating both plant water uptake and any residual evaporation from the nutrient solution surface. Because expanded polystyrene floating rafts covered approximately 99.9% of the reservoir surface, direct evaporation was expected to be minimal, although it was not quantified separately.

Cumulative total system water use per cycle was calculated from these measurements. The following water-use indicators were calculated:

Water Productivity (WP): liters of water per kilogram of fresh biomass (L kg^{−1} FM).

Total Biomass Water Productivity (TWP): liters per kilogram of total biomass (shoot + root).

Commercial Biomass Water Productivity (CWP): liters per kilogram of marketable shoot biomass.

Water Utility (WU): Was calculated as the gross economic return generated per liter of total system water use (CLP L^{−1}), using the seasonal farm-gate price received by the

producer for marketable lettuce at harvest. The indicator considered only gross income derived from commercial yield and total system water use. Production costs, including labor, infrastructure depreciation, energy, fertilizers, and other operating expenses, were not incorporated. Therefore, Water Utility should be interpreted as a gross indicator of the economic value of water use rather than as a measure of net profitability.

Correlations between cumulative total system water use and non-destructive morphometric variables (shoot height, fractional canopy cover, and stem diameter) were analyzed to identify potential indirect predictors of water use.

2.5. Economic Analysis

Direct production costs were recorded for each cycle, including seedling acquisition, nutrient solution preparation and replenishment, electricity consumption (pumping and aeration), minor supplies, and labor. Labor was calculated based on actual working time and valued according to the current Chilean agricultural minimum wage.

Total income was estimated from the number of marketable plants and their seasonally adjusted local market price.

The following economic indicators were calculated:

Gross Margin (GM): income minus direct costs (CLP m⁻²).

Water Utility (WU): gross margin divided by total system water use (CLP L⁻¹).

Economic analyses were performed independently for each season.

2.6. Winter Pre-Harvest Nutrient Flushing Experiment

During the winter production cycle, an independent experiment was conducted to evaluate the effect of pre-harvest nutrient suspension (flushing) on nitrate concentration, yield, and total polyphenol content.

The experiment followed a completely randomized design with two treatments: (i) control plants maintained in the standard nutrient solution until harvest and (ii) a flushing treatment in which the nutrient solution was replaced with potable water during the final four days before harvest. Each treatment consisted of four independent hydroponic units ($n = 4$). Each hydroponic unit functioned as an individual floating-root cultivation bench with its own nutrient solution reservoir; therefore, no nutrient solution was shared among experimental units or treatments.

Each hydroponic unit contained 60 plants managed under the same cultivation conditions described previously. For nitrate concentration and total polyphenol determination, one composite sample was prepared from each experimental unit using the harvested plants selected for destructive sampling, resulting in four independent composite samples per treatment.

The flushing treatment was designed to determine whether short-term nutrient withdrawal before harvest could reduce leaf nitrate concentration without negatively affecting commercial yield or total polyphenol content.

2.7. Statistical Analysis

2.7.1. Seasonal Descriptive Evaluation

Data obtained from the six independent hydroponic units within each production cycle were used to calculate descriptive statistics (mean $\pm$ standard deviation) for all measured variables. The reported standard deviations describe the variability among the independent hydroponic units within each production cycle and are presented to characterize system variability rather than to support inferential comparisons among seasons. Although each hydroponic unit consisted of an independent cultivation bench with its own nutrient solution reservoir and aeration system, only one production cycle was conducted per season. Consequently, the seasonal component of the study was designed

to provide a descriptive characterization of floating-root hydroponic system performance under contrasting environmental conditions rather than to test seasonal effects statistically.

The seasonal evaluation aimed to characterize crop performance, total system water use, and water productivity across four production cycles conducted under naturally different environmental conditions. Because the summer production cycle was conducted using a different commercial cultivar than the remaining seasons and only one production cycle was available for each season, seasonal observations were not considered suitable for inferential statistical comparisons. Therefore, seasonal results are presented descriptively and interpreted as indicators of system performance under the environmental conditions evaluated.

The relationships between cumulative total system water use and fractional canopy cover, fresh biomass, and leaf area were evaluated using regression analysis. The goodness-of-fit of the regression models was assessed using the coefficient of determination (R^2).

2.7.2. Statistical Analysis of the Winter Pre-Harvest Nutrient Flushing Experiment

The winter pre-harvest nutrient flushing experiment was analyzed independently because it followed a separate experimental design. Treatment effects on fresh yield, nitrate concentration, and total polyphenol content were evaluated by analysis of variance (ANOVA), considering the four independent hydroponic units per treatment ($n = 4$) as the experimental units. Treatment means were compared using Tukey's honestly significant difference (HSD) test at $p \leq 0.05$.

All statistical analyses were performed using XLSTAT Statistical and Data Analysis Solution (version 2024.3, Addinsoft, Paris, France, 2024).

2.8. Generative AI Statement

The authors used generative artificial intelligence (ChatGPT, OpenAI) to assist in translating the manuscript from Spanish to English and to improve scientific writing clarity and structure. The AI tool was not used to generate data, perform analyses, or interpret results. All experimental design, data collection, statistical analysis, and scientific interpretation were conducted exclusively by the authors. The authors take full responsibility for the content of the manuscript.

3. Results

The results from the four production cycles are presented descriptively to characterize system performance under the evaluated growing conditions. Because the study included only one production cycle per season, and the summer cycle was conducted using a different commercial cultivar than the remaining seasons, the data should not be interpreted as statistically validated seasonal comparisons or as evidence of seasonal effects.

3.1. Crop Growth Dynamics

Canopy cover increased progressively during the crop cycle in all evaluated production cycles (Figure 1). The highest final canopy cover was descriptively observed during the autumn production cycle, whereas the summer and spring production cycles reached slightly lower but comparable values. The winter production cycle exhibited the lowest final canopy development.

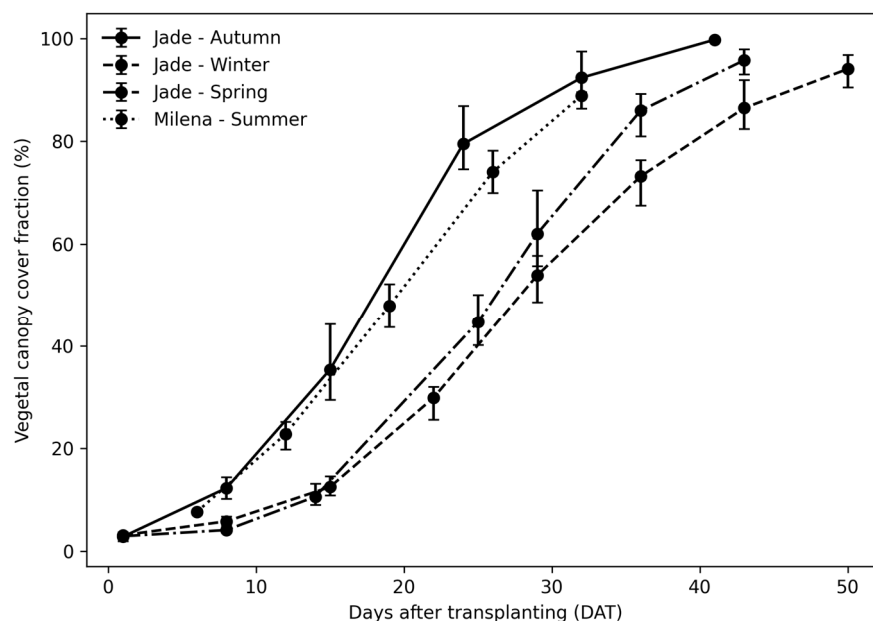


Figure 1. Seasonal dynamics of fractional canopy cover (%) over time (days after transplanting, DAT) in a floating-root hydroponic system.

Shoot height also increased progressively throughout the crop cycle in all production cycles (Figure 2). The greatest final shoot height was observed during the autumn production cycle, whereas the winter, spring, and summer production cycles exhibited similar final values.

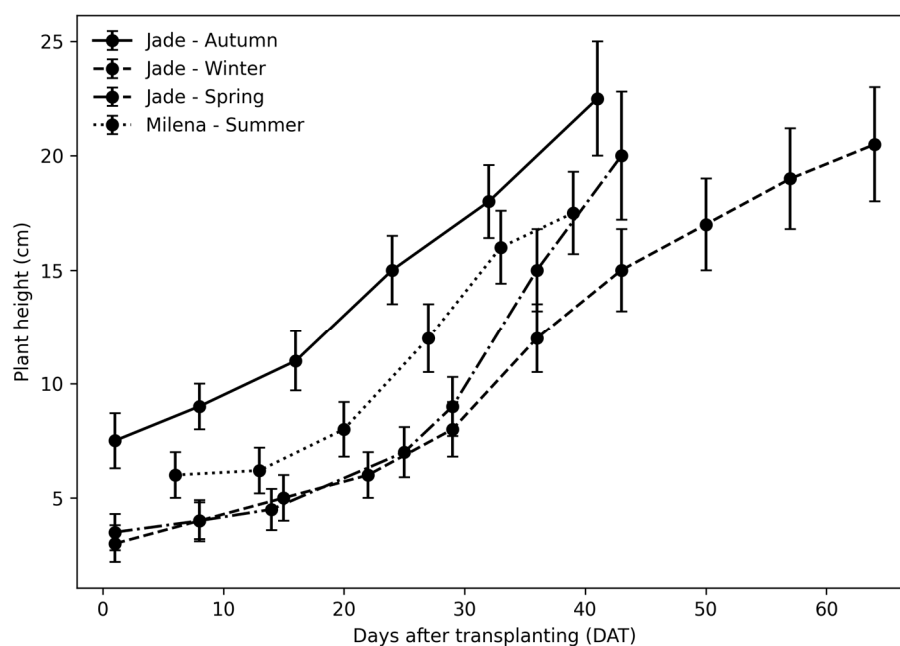


Figure 2. Seasonal evolution of shoot height (cm plant⁻¹) over time (days after transplanting, DAT) in a floating-root hydroponic system.

Root length increased consistently throughout the crop cycle in all production cycles (Figure 3). The greatest final root length was observed during the autumn and spring production cycles, whereas the shortest final root length was observed during the summer production cycle.

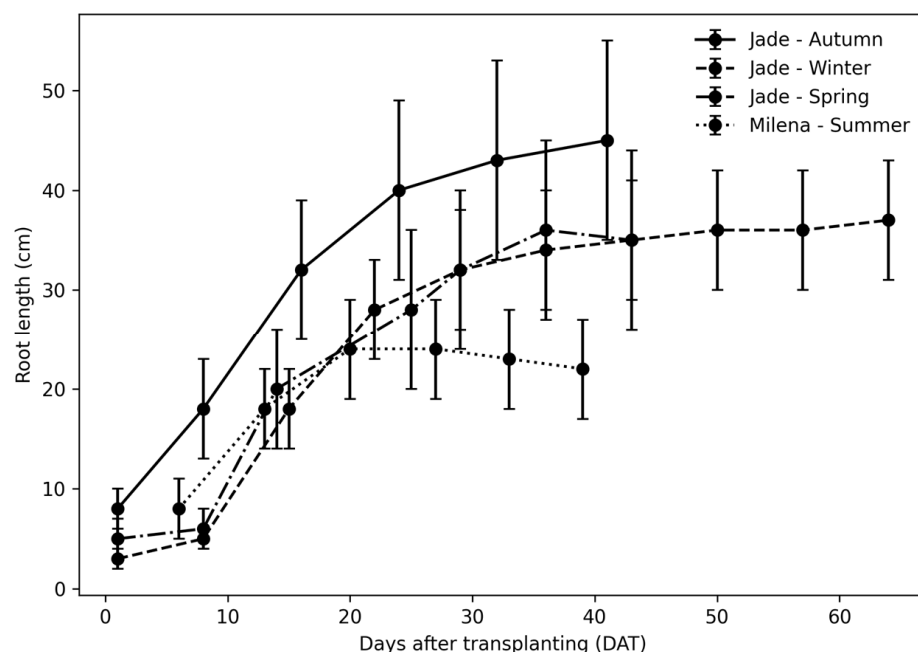


Figure 3. Seasonal evolution of root length (cm plant^{−1}) over time (days after transplanting, DAT) in a floating-root hydroponic system.

3.2. Morphological and Commercial Performance at Harvest

Morphological and commercial parameters at harvest are summarized in Table 1. During the autumn, winter, and spring production cycles (cv. Jade), shoot height ranged from 20.8 to 22.5 cm and fresh weight ranged from 230 to 245 g plant^{−1}. During the summer production cycle (cv. Milena), plants exhibited lower shoot height (17.9 cm) but greater fresh weight (265 g plant^{−1}) and stem diameter (20.1 mm). Because a different commercial cultivar was used during the summer production cycle, these observations reflect the combined influence of cultivar and environmental conditions and should therefore be interpreted descriptively. Dry matter content varied among production cycles, ranging from 4.9% during the winter production cycle to 7.4% during the summer production cycle, with intermediate values observed during the autumn and spring production cycles.

Table 1. Morphological and commercial characteristics of lettuce at harvest by season (mean ± SD, n = 6).

Season	Cultivar	Plant Height (cm)	Stem Diameter (mm)	Root Length (cm)	FW ¹ (g Plant ^{−1})	Dry Matter (%)	Marketable Yield ² (%)
Autumn	Jade	22.5 ± 2.5	19.2 ± 1.1	17.2 ± 1.5	240 ± 12	7.0	96
Winter	Jade	21.8 ± 2.8	18.7 ± 1.0	16.3 ± 1.4	245 ± 15	4.9	95
Spring	Jade	20.8 ± 3.2	18.4 ± 1.2	16.7 ± 1.6	230 ± 18	5.5	93
Summer ³	Milena	17.9 ± 1.9	20.1 ± 1.3	15.2 ± 1.3	265 ± 20	7.4	94

¹ FW = fresh weight per plant. ² Marketable yield corresponds to the percentage of plants meeting commercial quality standards. ³ The summer production cycle was conducted using the commercial cultivar ‘Milena’, whereas the autumn, winter, and spring production cycles used the commercial cultivar ‘Jade’. Consequently, summer observations reflect the combined influence of cultivar and seasonal environmental conditions and should not be interpreted as direct seasonal comparisons with the other production cycles.

Final root length ranged from 15.2 to 17.2 cm, with the greatest values observed during the autumn and spring production cycles (Table 1). The proportion of marketable lettuce exceeded 93% in all production cycles (Table 1).

3.3. Total System Water Use

Total system water use differed among the evaluated production cycles (Figure 4). The highest cumulative total system water use was observed during the summer production cycle (208 L per 3 m²), whereas the lowest value was observed during the winter production cycle (101 L per 3 m²). The autumn and spring production cycles exhibited intermediate total system water use.

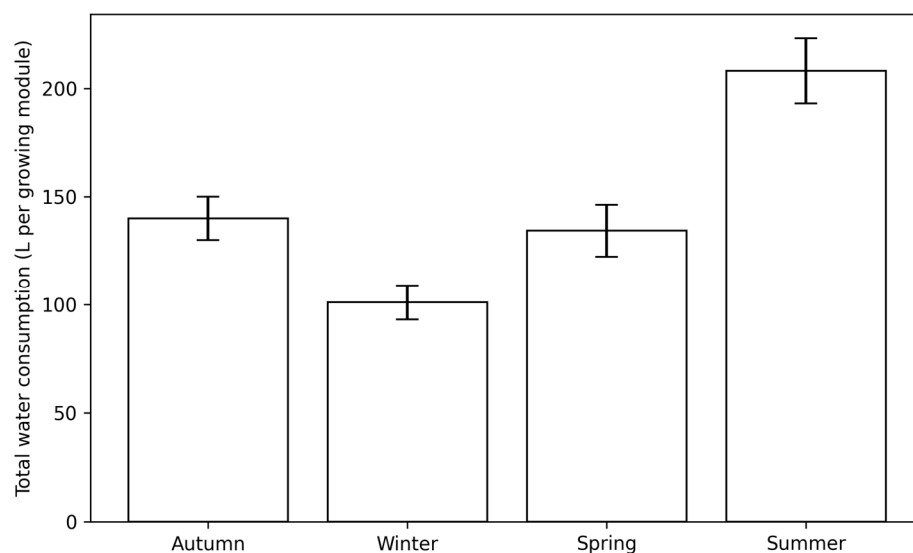


Figure 4. Total system water use per cultivation bench (3 m² growing area) during each seasonal production cycle. Values are expressed at the hydroponic system level and not on a per-plant basis.

3.4. Water Productivity Indicators

Water productivity expressed as liters per kilogram of fresh biomass (L kg⁻¹ FW) differed among the evaluated production cycles (Figure 5). The lowest water requirement per unit of fresh biomass was observed during the autumn production cycle (7.1 L kg⁻¹ FW), whereas the highest water requirement was observed during the summer production cycle (12.5 L kg⁻¹ FW). Accordingly, the autumn production cycle exhibited the greatest descriptive water productivity, while the summer production cycle exhibited the lowest.

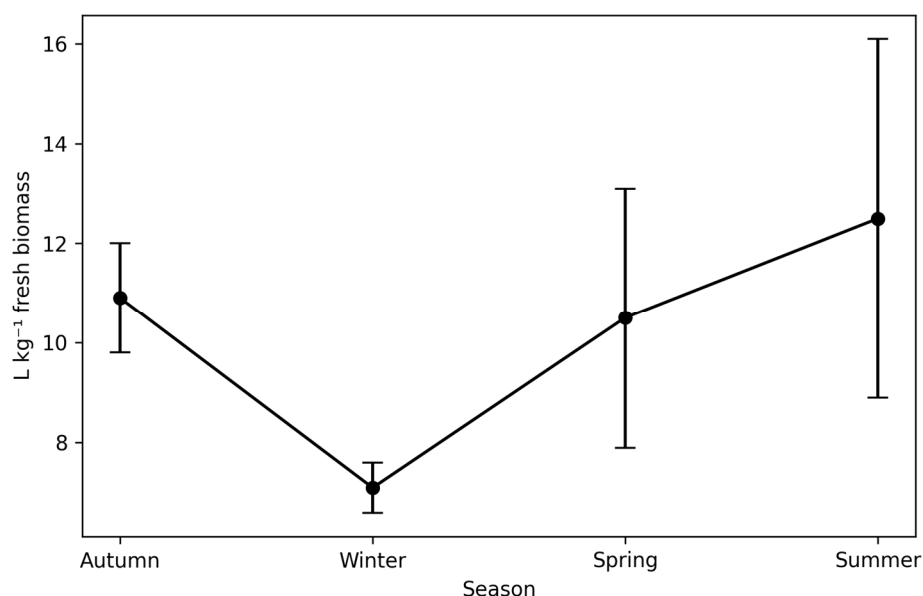


Figure 5. Seasonal water productivity expressed as liters per kilogram of fresh biomass (L kg⁻¹ FW).

Complementary water productivity indicators are presented in Table 2. Although total system water use and basic water productivity are shown graphically in Figures 4 and 5, Table 2 provides additional indicators not presented in the figures, including total water productivity (TWP), commercial water productivity (CWP), and water utility (WU). Total water productivity ranged from 6.2 to 11.3 L kg^{−1}, while commercial water productivity ranged from 6.8 to 11.9 L kg^{−1}. The lowest L kg^{−1} values across all water productivity indicators were observed during the autumn production cycle, whereas the highest values were observed during the summer production cycle. Water productivity exhibited relatively low variability among hydroponic units within each production cycle, with coefficients of variation below 10% across all evaluated production cycles.

Table 2. Complementary seasonal water-use indicators of the floating-root hydroponic system, including water productivity (WP), total water productivity (TWP), and commercial water productivity (CWP) (mean ± SD, *n* = 6).

Season	Total System Water Use (L per 3 m ²)	¹ WP (L kg ^{−1} ⁵ FW)	² TWP (L kg ^{−1})	³ CWP (L kg ^{−1})	⁴ WU (CLP L ^{−1})
Autumn	140 ± 11.2	7.1 ± 0.6	6.2 ± 0.5	6.8 ± 0.4	365
Winter	101 ± 9	8.2 ± 0.7	7.3 ± 0.6	7.9 ± 0.5	388
Spring	134.3 ± 29.3	9.3 ± 0.8	8.1 ± 0.7	9.0 ± 0.6	370
Summer ⁶	208 ± 4.2	12.5 ± 1.1	11.3 ± 1.0	11.9 ± 0.9	401

¹ WP = Water Productivity based on fresh weight. ² TWP = Total Water Productivity including shoot and root biomass. ³ CWP = Commercial Water Productivity (harvestable biomass). ⁴ WU = Water Utility (economic return per liter of water used). WU was calculated using the seasonal farm-gate price received by the producer for marketable lettuce. Production costs (labor, infrastructure depreciation, energy, fertilizers, and other operating costs) were not included; therefore, WU represents a gross water-value indicator rather than net economic profitability. ⁵ FW = Fresh Weight. ⁶ The summer production cycle was conducted using the commercial cultivar ‘Milena’, whereas the autumn, winter, and spring production cycles used the commercial cultivar ‘Jade’. Consequently, summer values reflect the combined influence of cultivar and seasonal environmental conditions and should not be interpreted as direct seasonal comparisons with the other production cycles.

3.5. Relationship Between Canopy Cover and Total System Water Use

A strong positive association was observed between canopy cover and cumulative total system water use (Figure 6), with an *R*² value of 0.89 (Figure 6). Under the evaluated conditions, canopy cover was closely associated with cumulative total system water use. However, because both variables increased progressively throughout crop development, part of this association may reflect their shared temporal progression rather than an independently validated predictive relationship.

3.6. Leaf Nutrient Composition and Nitrate Concentration Under Winter Conditions and Pre-Harvest Water Treatment

Leaf nutrient composition and nitrate concentration under winter conditions are presented in Table 3. Because the flushing treatment was evaluated exclusively during the winter production cycle, the following results should be interpreted within the context of winter environmental conditions. Plants transferred to water four days before harvest exhibited a significant reduction in leaf nitrate concentration, from 2262 to 1920 ppm (*p* = 0.0292), corresponding to a decrease of approximately 15.1% relative to plants maintained in nutrient solution until harvest. Both nitrate concentrations remained below the maximum threshold established by the European Commission for winter greenhouse lettuce.

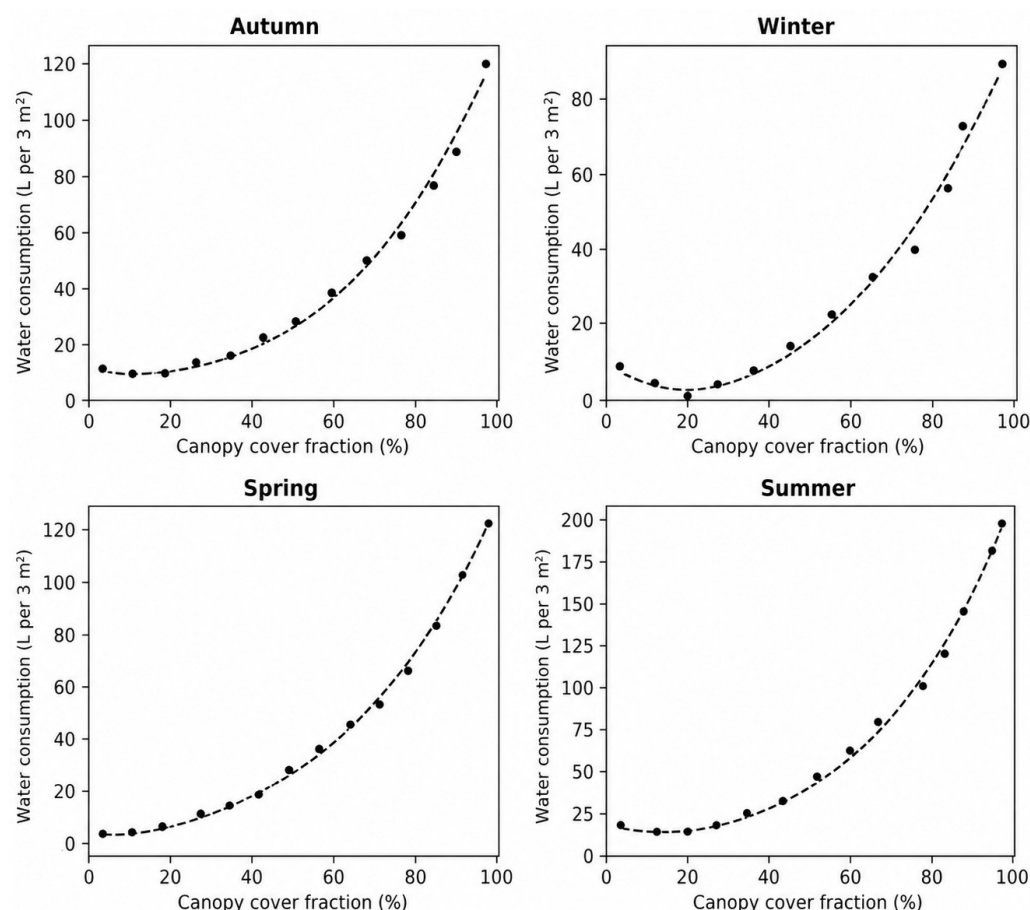


Figure 6. Relationship between fractional canopy cover (%) and cumulative system water use (L per 3 m²) across seasons. Strong positive associations were observed between canopy cover and cumulative water use in autumn ($R^2 = 0.8839$), winter ($R^2 = 0.8907$), spring ($R^2 = 0.8958$), and summer ($R^2 = 0.9596$). Water use values represent total system water use derived from changes in nutrient solution depth. Dots represent individual observations, and the dashed line represents the fitted regression line.

Table 3. Leaf nutrient composition and nitrate concentration under pre-harvest water treatment in winter-grown lettuce (mean).

Element	Unit	Water (4 Days Before Harvest) ²	Nutrient Solution Until Harvest	¹ Pr > F
Total Nitrogen (N)	%	3.44	3.9	0.0019
Nitrate (NO ₃)	ppm	1920	2262	0.0292
Phosphorus (P)	%	0.51	0.58	0.0224
Potassium (K)	%	4.02	4.52	0.0626
Calcium (Ca)	%	0.73	0.90	0.0394
Magnesium (Mg)	%	0.27	0.32	0.0710
Iron (Fe)	ppm	134.0	152.3	0.1693
Manganese (Mn)	ppm	16.0	18.0	0.2522
Zinc (Zn)	ppm	47.3	50.0	0.3279
Copper (Cu)	ppm	7.5	8.5	0.1817

¹ Pr > F corresponds to the probability value obtained from ANOVA. ² The flushing treatment was evaluated exclusively during the winter production cycle. Therefore, these results should not be generalized to other seasons without additional experimental validation.

Plants transferred to water four days before harvest also exhibited significantly lower total nitrogen (3.44% vs. 3.90%; $p = 0.0019$), phosphorus (0.51% vs. 0.58%; $p = 0.0224$), and

calcium (0.73% vs. 0.90%; $p = 0.0394$) concentrations than plants maintained in nutrient solution until harvest.

Potassium and magnesium concentrations were numerically lower in the flushing treatment but did not differ significantly between treatments ($p > 0.05$). Likewise, micronutrient concentrations (Fe, Mn, Zn, and Cu) were not significantly affected by the treatment ($p > 0.05$).

3.7. Total Phenolic Content and Dry Matter

Total phenolic content and dry matter parameters are presented in Table 4. No significant differences between treatments were observed for total phenolic content on either a fresh weight basis (38.77 vs. 30.99 mg GAE 100 g⁻¹ FW; $p = 0.3655$) or a dry weight basis ($p = 0.491$). Likewise, dry matter percentage was not significantly affected by the flushing treatment.

Table 4. Total phenolic content and dry matter percentage under pre-harvest water treatment (mean).

Treatment	¹ TPC (mg ² GAE 100 g ⁻¹ ³ DW)	Dry Matter (%)	TPC (mg GAE 100 g ⁻¹ ⁴ FW)
Water (4 Days before Harvest)	630.63	6.18	38.77
Nutrient Solution until Harvest	536.01	5.80	30.99
<i>p</i> -value (Student's <i>t</i> -test)	0.491	0.494	0.366

¹ TPC = Total Phenolic Content. ² GAE = Gallic Acid Equivalents. ³ DW = Dry Weight basis. ⁴ FW = Fresh Weight basis.

Dry matter percentage was not significantly affected by the pre-harvest water treatment (Table 4).

3.8. Economic Performance

Economic results are summarized in Table 5. Total production costs ranged from CLP 59,072 during the summer production cycle to CLP 73,743 during the winter production cycle. Labor represented the largest cost component in all evaluated production cycles.

Table 5. Seasonal economic analysis of the floating-root hydroponic system, including costs, gross income, gross margin, and water utility (CLP L⁻¹).

Production Cost						
Item	Unit	Unit Value (³ CLP)	Autumn (Total CLP)	Winter (Total CLP)	Spring (Total CLP)	Summer (Total CLP)
Labor						
Transplanting	Workday	35,000	17,500	17,500	17,500	17,500
Maintenance	Workday	35,000	35,000	42,000	42,000	28,000
Inputs						
Seedlings	Unit	15	5400	5400	5400	5400
Energy	kW	150	2952	4608	3312	2808
Nutrient Solution	Liters	352	4480	4235	4583	5365
Total costs (CLP)			65,332	73,743	72,795	59,072
Revenues and Profitability						
Item	Unit	Unit Value (CLP)	Autumn (Total CLP)	Winter (Total CLP)	Spring (Total CLP)	Summer (Total CLP)
Lettuce Sales	Unit	700	242,900	235,200	226,800	243,000
¹ Gross Margin (CLP)			177,568	161,457	154,005	183,928
² Water Utility (CLP L ⁻¹)			289	388	374	401

¹ Gross Margin = Total Revenue – Total Costs. ² Water Utility represents economic return per liter of water used (WU). ³ CLP = Chilean Peso. (1 USD = 870 CLP).

Gross income ranged from CLP 226,800 during the spring production cycle to CLP 243,000 during the autumn production cycle, resulting in gross margins ranging from CLP 154,005 to CLP 183,928 across the evaluated production cycles.

Water utility (gross economic return per liter of total system water use) differed among the evaluated production cycles. The highest value was observed during the summer production cycle (CLP 401 L⁻¹), followed by the winter (CLP 388 L⁻¹), spring (CLP 374 L⁻¹), and autumn (CLP 289 L⁻¹) production cycles (Table 5).

4. Discussion

4.1. Seasonal Performance and Morphological Stability

The floating-root hydroponic system exhibited relatively consistent morphological performance across the evaluated production cycles, with fresh weight values ranging between 230 and 265 g per plant. These observations are comparable to those reported for hydroponic lettuce grown in floating systems, where fresh weight values typically range between 200 and 300 g per plant under different environmental conditions [13]. Similar ranges of water productivity and biomass production have been reported in hydroponic lettuce systems, where crop performance is influenced by nutrient composition and cultivar selection [14]. Compared with values commonly reported for soil-based systems, the yields observed in the present study are consistent with the relatively stable production typically associated with controlled hydroponic environments. Likewise, commercial quality exceeded 93% in all evaluated production cycles, suggesting stable system performance under the evaluated coastal desert conditions.

Although the autumn and spring production cycles were conducted under relatively similar air temperatures, higher water productivity was descriptively observed during the autumn cycle. Water use and crop performance in hydroponic systems are influenced by multiple interacting factors, including canopy development, air temperature, solar radiation, vapor pressure deficit, crop duration, cultivar architecture, and root-zone conditions. Because several of these variables were not directly monitored, the differences observed among production cycles should be interpreted as the integrated response of the production system under the evaluated conditions rather than as evidence of seasonal effects.

Root length remained above 15 cm throughout all evaluated production cycles, although root elongation appeared to stabilize earlier during the summer production cycle. Reduced oxygen availability has frequently been proposed as one possible constraint in warm hydroponic systems because oxygen solubility decreases as nutrient solution temperature increases [15]. However, dissolved oxygen concentration, nutrient solution temperature, and nutrient uptake rates were not measured in the present study. Therefore, the observed root growth pattern should not be interpreted as evidence of oxygen limitation. Despite the earlier stabilization of root length, plants grown during the summer production cycle exhibited the highest fresh biomass and water utility values, suggesting that nutrient acquisition was sufficient to support commercial crop development under the evaluated conditions. This contrasting pattern of shorter root systems and greater shoot biomass may also reflect differences in biomass allocation between aboveground and belowground organs. Under deep water culture conditions, where water and nutrients are continuously available, extensive root elongation may be less critical for resource acquisition than in soil-based systems, potentially allowing proportionally greater assimilate allocation to shoot growth and marketable biomass production. However, because carbon partitioning, root architectural traits, and gas-exchange responses were not measured, these interpretations should be regarded as plausible hypotheses rather than demonstrated physiological mechanisms. Future studies incorporating dissolved oxygen monitoring, nutrient solution temperature, root architectural traits, biomass partitioning, gas-exchange

measurements, and nutrient uptake dynamics will be required to evaluate these proposed mechanisms. Nutrient management strategies in hydroponic systems play a key role in regulating nutrient uptake efficiency and overall plant physiological balance, particularly in relation to nitrate accumulation [9], reinforcing the importance of optimizing nutrient supply during the production cycle.

4.2. Water Use Efficiency and Canopy–Water Use Relationships

Water productivity values observed in this study ($6.2\text{--}12.5\text{ L kg}^{-1}$, depending on the indicator used) are within the range reported for highly water-efficient lettuce production systems. These values are substantially lower than those typically reported for soil-based systems, where higher evaporative losses and lower water-use efficiency are commonly observed [16,17]. Similar ranges of water productivity have been described in hydroponic and controlled-environment systems, highlighting the potential of these technologies to optimize water use under conditions of limited availability [7,16,17]. The water productivity values observed in the present study are consistent with the high water-use efficiency generally reported for closed hydroponic and deep water culture systems, which reduce water losses through recirculation and by minimizing soil evaporation. Although direct comparisons among studies are limited by differences in crop type, system design, environmental conditions, and the definition of water productivity, the values obtained here suggest that floating-root hydroponics may represent an efficient water-saving production strategy under the evaluated coastal desert conditions.

A strong positive association between fractional canopy cover and cumulative total system water use ($R^2 = 0.89$) was observed under the evaluated conditions. However, this association should be interpreted with caution because both variables increased progressively during crop development. Consequently, part of the observed association may reflect their shared temporal progression rather than a direct predictive relationship.

Recent advances in digital phenotyping and imaging techniques have demonstrated the applicability of image-based approaches for monitoring plant growth and estimating water use in controlled and semi-controlled production systems [18]. Accordingly, canopy cover measurements may provide a useful non-destructive approach for irrigation monitoring in floating-root hydroponic systems. However, independent validation, time-lagged analyses, and evaluation under additional production environments will be required before predictive applications can be generalized.

It should be noted that the reported water-use values represent total system water use rather than direct plant transpiration. Although evaporation from the nutrient solution was minimized by the floating raft design, a small evaporation component may have contributed to the measured water losses. Future studies incorporating direct measurements of evaporation, transpiration, dissolved oxygen concentration, nutrient solution temperature, and gas-exchange parameters would allow a more complete understanding of water-use dynamics and the physiological mechanisms underlying crop performance in floating-root hydroponic systems.

4.3. Pre-Harvest Nutrient Management and Nitrate Reduction

The substitution of nutrient solution with water four days prior to harvest reduced leaf nitrate concentration from 2262 to 1920 ppm (approximately 15%). Importantly, both values remained well below the maximum threshold established by the European Commission for winter greenhouse lettuce (4500 ppm fresh weight), supporting the effectiveness of short-term flushing as a practical strategy for nitrate management under the evaluated winter growing conditions. These concentrations are consistent with values previously reported for floating hydroponic systems [8].

The physiological interpretation of this response is consistent with current knowledge of nitrate metabolism in leafy vegetables. Nitrate accumulation reflects the balance between nitrogen uptake and nitrate assimilation, processes that are strongly influenced by environmental conditions such as light intensity, temperature, humidity, and carbon availability through their effects on nitrate reductase activity. Consequently, short-term reductions in external nitrogen supply are expected to promote the utilization of nitrate previously stored in leaf vacuoles while limiting further nitrate uptake, thereby decreasing leaf nitrate concentration without necessarily affecting biomass accumulation when applied shortly before harvest [12].

Although the reduction observed in the present study was smaller than that reported for more intensive or prolonged nutrient management strategies [9], no yield penalty was detected. This finding is particularly relevant because prolonged nutrient restriction may compromise biomass accumulation. Nutrient management strategies applied immediately before harvest are recognized as effective tools for controlling nitrate accumulation by temporarily modifying the balance between nitrate uptake and assimilation [19,20]. Accordingly, the present results support the technical feasibility of a short-duration flushing strategy for reducing leaf nitrate concentration without negatively affecting commercial productivity under the evaluated conditions. These findings are also consistent with modeling studies showing that abrupt reductions in nitrogen availability decrease nitrate accumulation in lettuce tissues while modifying biomass allocation and plant nitrogen dynamics [20]. Together, these studies support the physiological plausibility of pre-harvest nutrient flushing as a practical strategy for reducing nitrate concentrations without compromising marketable yield.

Because the flushing treatment was evaluated exclusively during the winter production cycle, caution is required when extrapolating these findings to other environmental conditions. Temperature, radiation, humidity, and evaporative demand are known to influence nitrate uptake and assimilation through their effects on plant carbon metabolism and nitrate reductase activity [12]. Consequently, the magnitude of the response to nutrient withdrawal may differ under contrasting environmental conditions. Future studies should evaluate the effectiveness of pre-harvest nutrient flushing across multiple production cycles, environmental conditions, and cultivars to determine the robustness and broader applicability of this management strategy.

4.4. Functional Quality Preservation

Total polyphenol content was not significantly affected by the flushing treatment. Environmental factors, particularly light quality and intensity, are known to influence phenolic metabolism and the accumulation of bioactive compounds in lettuce [21]; However, under the evaluated winter growing conditions, short-term nutrient withdrawal did not compromise antioxidant-related quality attributes. The ability to reduce nitrate concentration while maintaining functional quality suggests that short-term pre-harvest flushing may improve product quality without adversely affecting its antioxidant potential. Consequently, this management strategy may enhance the commercial value of hydroponically grown lettuce while contributing to compliance with nitrate quality standards.

4.5. Economic Implications and Regional Relevance

Water utility was highest during the summer production cycle, reflecting differences among the evaluated production cycles. Because this indicator was calculated using the farm-gate price received by the producer and did not include labor, infrastructure depreciation, energy, nutrient solution management, or other production costs, it should

be interpreted as a gross indicator of water-use value rather than a comprehensive economic assessment.

Previous studies have shown that the economic performance of hydroponic systems depends on production scale, infrastructure and operating costs, while their high water-use efficiency may improve overall economic competitiveness under water-limited conditions [22,23]. Likewise, the water productivity and gross economic indicators observed in the present study are consistent with the technical and economic advantages frequently reported for floating hydroponic systems relative to soil-based production, which generally exhibits higher total system water use and lower water productivity [15,16]. However, because the present economic analysis was conducted at pilot scale and did not include all production costs, these comparisons should be interpreted with appropriate caution.

In regions facing structural water scarcity, such as northern Chile, the combination of stable crop performance, relatively low total system water use, and positive gross economic margins observed under the evaluated conditions suggests that floating-root hydroponics may represent a resource-efficient production alternative. From a practical perspective, successful adoption of floating-root hydroponics depends not only on water-use efficiency but also on effective management of infrastructure, nutrient solution sanitation, dissolved oxygen, algae development, disease prevention, labor requirements, and market price fluctuations. These operational aspects were beyond the scope of the present study but should be incorporated into future techno-economic evaluations to better support commercial implementation.

The present results were obtained from a 48 m² pilot-scale hydroponic module under coastal desert conditions. Although the evaluated system exhibited stable agronomic performance under these conditions, larger commercial facilities may face additional challenges related to hydraulic uniformity, nutrient distribution, oxygenation, disease spread, labor efficiency, operational costs, and market variability. Consequently, the present findings should not be interpreted as evidence that system performance will scale linearly to larger commercial operations without further validation. Future research should evaluate floating-root hydroponic systems across larger commercial facilities, multiple production environments, additional lettuce cultivars, and repeated production cycles while incorporating more comprehensive techno-economic analyses that include infrastructure depreciation, labor efficiency, energy consumption, maintenance requirements, and market variability. Based on the evaluated production scale and management conditions, floating-root hydroponics appears particularly suitable for small- and medium-scale producers, protected cultivation systems, urban agriculture, and water-limited regions where efficient resource use is a priority.

4.6. Study Limitations

Despite the promising results, several limitations should be acknowledged. First, the seasonal component of this study should be interpreted as a pilot-scale characterization of floating-root hydroponic system performance under the evaluated coastal desert conditions rather than as a fully replicated seasonal experiment. However, each production cycle included six independent hydroponic units, each with its own cultivation bench, nutrient solution reservoir, and aeration system; only one production cycle was conducted per season. Consequently, the seasonal evaluation provides site-specific baseline information on system performance under the tested environmental conditions, and seasonal comparisons should therefore be interpreted as descriptive rather than confirmatory evidence of seasonal effects.

A second limitation relates to cultivar selection. Cultivar ‘Jade’ was evaluated during autumn, winter, and spring, whereas cultivar ‘Milena’ was evaluated during the summer

production cycle. Consequently, the summer observations reflect the combined influence of cultivar and environmental conditions, making it impossible to fully separate seasonal and genotypic effects.

Third, the winter nutrient-flushing experiment represents the only component of this study supported by an independently replicated experimental design. It was conducted exclusively under winter growing conditions and therefore provides statistically supported evidence for the effectiveness of a four-day pre-harvest nutrient-flushing treatment only under those environmental conditions. Accordingly, these findings should not be extrapolated directly to other seasons or cultivars, where differences in temperature, radiation, evaporative demand, transpiration, and nutrient uptake may modify crop responses.

Furthermore, the transferability of the present findings should be considered carefully. The study evaluated two commercial butterhead lettuce cultivars grown in a floating-root hydroponic system under coastal desert conditions in northern Chile. Therefore, direct extrapolation to other lettuce cultivars, leafy vegetable species, hydroponic production systems (e.g., nutrient film technique or substrate culture), climatic regions, or commercial production scales should be made with caution until additional validation studies become available.

The study was also conducted in a 48 m² pilot-scale hydroponic module, and larger commercial systems may face additional challenges related to hydraulic uniformity, nutrient distribution, dissolved oxygen management, disease spread, labor requirements, operational complexity, reservoir sanitation, algae development, and infrastructure costs. Likewise, the economic evaluation was based on the farm-gate price received by the producer and total system water use and did not include labor, infrastructure depreciation, energy consumption, or other production costs. Consequently, the economic indicators should be interpreted as gross measures of the economic value of water use rather than comprehensive assessments of production profitability.

Finally, future research should focus on validating the mechanisms proposed in this study and extending the applicability of the present findings. This will require repeated production cycles, multi-location experiments, and evaluations including additional lettuce cultivars to determine the robustness of the observed responses under different environmental conditions. Direct physiological measurements, including dissolved oxygen monitoring, nutrient solution temperature, root architectural traits, biomass partitioning, gas-exchange measurements, transpiration, and nutrient uptake, would be necessary to validate the proposed mechanisms underlying crop performance and water-use dynamics. In addition, more comprehensive techno-economic analyses incorporating infrastructure depreciation, labor efficiency, energy consumption, maintenance requirements, and market variability will be required to assess the scalability and broader commercial feasibility of floating-root hydroponic systems.

5. Conclusions

Under the evaluated coastal desert conditions, the floating-root hydroponic system exhibited stable agronomic performance across the evaluated production cycles, maintaining high commercial quality together with favorable water-use performance. However, because the seasonal component of the study included only one production cycle per season and the summer production cycle was conducted using a different commercial cultivar than the remaining production cycles, these observations should be interpreted as a pilot-scale characterization of system performance rather than as statistically validated evidence of seasonal effects.

From a practical perspective, the evaluated system exhibited high water productivity under the tested conditions. The winter production cycle showed the lowest water require-

ment per unit of fresh biomass, whereas the summer production cycle achieved the highest gross economic return per unit of total system water use under the evaluated market conditions. In addition, the independently replicated winter experiment demonstrated that a four-day pre-harvest nutrient-flushing treatment significantly reduced leaf nitrate concentration without affecting fresh yield or total phenolic content, suggesting that this management strategy may represent a practical option for reducing nitrate concentration while maintaining product quality under winter growing conditions. Likewise, the observed association between canopy cover and cumulative total system water use highlights the potential of image-based crop monitoring as a non-destructive management tool for floating-root hydroponic systems.

From a research perspective, the present findings should not be generalized beyond the evaluated conditions without further validation. Future research should include repeated production cycles, multi-location experiments, broader cultivar evaluations, and validation under larger commercial hydroponic systems to determine the robustness and transferability of the observed responses. In addition, direct physiological measurements—including dissolved oxygen monitoring, nutrient solution temperature, root architectural traits, biomass partitioning, gas-exchange measurements, transpiration, and nutrient uptake—will be necessary to validate the proposed mechanisms underlying crop performance and water-use dynamics. Finally, more comprehensive techno-economic analyses incorporating infrastructure depreciation, labor efficiency, energy consumption, maintenance requirements, and market variability will be required to assess the broader commercial applicability of floating-root hydroponic systems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/horticulturae12080972/s1>. Figure S1: Experimental setup of the floating-root hydroponic system; Supplementary Table S1: Crop management timeline and production cycle duration for the fourseasonal hydroponic lettuce experiments conducted under coastal desert conditions in northern Chile.

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Abbreviations

The following abbreviations are used in this manuscript:

WP	Water Productivity (L kg ⁻¹ fresh weight)
TWP	Total Water Productivity (including shoot and root biomass)
CWP	Commercial Water Productivity (harvestable biomass basis)
WU	Water Utility (CLP L ⁻¹)
FW	Fresh Weight
R ²	Coefficient of Determination
CLP	Chilean Peso
EU	European Union

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