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# Comparative analysis of closed hydroponic systems and planting seasons for lettuces

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**Abstract:** Hydroponic cultivation techniques offer innovative solutions to address challenges in conventional agriculture, such as soil infertility, disease outbreaks, and poor drainage. This study focuses on comparing the performance of different closed hydroponic systems for lettuce cultivation across distinct winter and summer planting seasons. Four closed hydroponic systems—deep water culture (DWC), nutrient film technique (NFT), media-bed system (MB), and sandponic (SP)—were evaluated for their impact on vegetative growth parameters, leaf nutrient content, chlorophyll and carotene levels, and water consumption. Our findings reveal that the DWC and NFT systems exhibited greater yield increases in winter (81.90% and 75.64%, respectively) and in summer (29.25% and 18.19%, respectively) compared to other systems. Notably, DWC lettuces consistently showed higher chlorophyll A, B, and carotene content, highlighting their potential for enhanced photosynthetic efficiency and nutritional value. The findings suggest that DWC is well-suited for achieving robust and vigorous lettuce growth and almost invariable water consumption in different seasons. NFT system also showed promising results, particularly effective water use per plant in both seasons. However, the water evaporation rate for this closed system was higher in summer. Moreover, our findings suggest that utilizing growth media in hydroponic systems can facilitate the retention of oxygen and nutrients. These findings can contribute to improving the selection of hydroponic systems and adapting them to seasonal variations in controlled greenhouse environments. They offer valuable insights and practical knowledge for precisely cultivating lettuce, promoting sustainable and efficient year-round production of leafy vegetables.

**Key words:** Deep water culture, growing season, hydroponic system, media, nutrient film technique, sandponic

## 1. Introduction

Hydroponics is a cultivation technique that employs nutrient solutions to provide plants with essential minerals for growth. Different media using organic materials, such as gravel, sand, rock wool, peat moss, coconut fibre, have been used as substrates to provide mechanical support for plants (Sharma et al., 2018). Hydroponic systems provide an innovative approach to growing plants in water solutions by eliminating the need for soil and enabling precise control over growing conditions such as maintaining pH and electrical conductivity (EC) values within the optimal range for efficient nutrient uptake by plants (Waiba et al., 2020). This cultivation method has gained significant attention in recent years as a promising solution to address the challenges of conventional agriculture due to several reasons including soil infertility, soil degradation, the outbreak of soil-borne plant diseases, and poor drainage. Various commercial and special crop species can be grown in these soilless techniques. For instance, tomatoes, strawberries, peppers, and leafy vegetables including lettuce (Lee and Lee, 2015; Sharma et al., 2018; Waiba et al., 2020; Gumisiriza et al., 2022).

Lettuce (*Lactuca sativa* L.) is one of the "easily" grown leafy vegetables in hydroponic cultivation systems due to its suitability for controlled environments and rapid growth. It belongs to the family Asteraceae, has been widely consumed, and is an economically important crop (Resh, 2013; Sharma et al., 2018). Generally, it is a good source of minerals and various beneficial bioactive compounds due to its antiinflammatory, sedative, cholesterol-lowering, and antidiabetic effects (Islam et al., 2021).

Various hydroponic systems have emerged, each offering unique advantages and limitations. Commonly used hydroponic systems are deep water culture (DWC), nutrient film technique (NFT), and media-bed systems which use substrates such as gravel, sand, and rock wool. The comparison of these systems is crucial to determine their suitability for lettuce cultivation in terms of growth rates, yield, and resource consumption (Gaikwad and Maitra, 2020). Previous studies have shown that

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hydroponic systems affect plant growth and nutrient uptake. Majid et al. (2021) reported higher yield and photosynthetic parameters (stomatal conductance and transpiration rate) in lettuce grown in DWC compared to NFT system and soil-based cultivation. Moreover, lettuces from DWC grow beds reached maturity 15 days earlier than those from other cultivation systems. Walters and Currey (2015) reported similar results in various basil (*Ocimum basilicum*) cultivars when comparing fresh weight between DWC and NFT hydroponic systems. In another study, Hamza et al. (2022) highlighted the DWC system's considerable capability for consistent nutrient supply and enhanced nutrient absorption through aerated water in optimal lettuce growth. Consequently, the lettuce yield and water use efficiency per unit of water in the DWC system surpassed those in soil-based cultivations utilizing drip irrigation in both open fields and greenhouses. Soares et al. (2020) tested lettuce growth in the NFT system with different cultivars in the winter and summer growing seasons and observed reduced stem growth in some cultivars at higher temperatures. Initially, it was known that sand and gravel were used in hydroponic studies due to lighter vessels and higher operability. Moreover, gravel provides better aeration (Caputo, 2022). However, the knowledge of the use of these substrates in leafy vegetable productions is very limited except for media use in the aquaponic context.

Similarly, comprehending the effect of planting seasons on lettuce growth plays a major role in efficient crop cultivation planning and optimizing nutrient and water use (Sublett et al., 2018). The hydroponic crops are mostly grown in closed greenhouses. These greenhouses provide precise control over environmental factors, including air temperature, relative humidity, light intensity, and photoperiod (Kang et al., 2013; Khan et al., 2020). By investigating the effects of different planting seasons, growers can strategically schedule lettuce cultivation to maximize the economic benefit of the most favourable conditions and achieve consistent crop growth throughout the year.

Lettuce is known as a cool-season vegetable that requires growth temperatures ranging from 7 to 24 °C, with an average of 18 °C (Maboko and Du Plooy, 2009; Sublett et al., 2018). A previous study by Fallovo et al. (2009) tested lettuce growth and quality in a floating raft growing system. They demonstrated that lettuces grown in spring had lower yield, vegetative growth (dry mass and leaf area index) and mineral composition than lettuces grown in the summer season but had the highest nutrition quality (higher content of glucose and fructose and lower nitrate content). Contrary to this result, Djidonou and Leskovar (2019) observed that the effect of the growing season on plant growth was higher than the effect of various N concentrations, and the dry weight of lettuces grown in spring was greater than those grown in fall and winter. In another study by Kosma et al. (2013), the effect of different light densities on lettuce growth and nutrient value using a shading net were tested in winter and spring growing seasons under Mediterranean climate conditions. They found that the low light intensity decreased fresh weight and ascorbic acid concentration, but leaf total chlorophyll and nitrate content were higher in both growing seasons.

The present study addresses the knowledge gap regarding the interaction between hydroponic systems and environmental variables in different seasons. Moreover, media bed systems for lettuce production have been tested for the first time. The main objective of the study is to evaluate the responses of lettuce in two growing seasons and grown in different hydroponics. This study aims to advance efficient and sustainable hydroponic leafy vegetable production as a viable alternative to conventional cultivation systems within closed greenhouse environments by supporting the development of controlled-environment agriculture practices.

## 2. Materials and methods

### 2.1. Study site, plant materials, experimental design, and growth conditions

Lettuce seeds (*Lactuca sativa* L., cv. *Batavia* F1) produced by Rijk Zwaan were purchased from the local distributor in Egypt. Batavia lettuce seeds were planted at a depth of 1–2 cm in trays measuring 70 × 40 cm, with 209 cells.

Two separate experiments were conducted in the summer and winter of 2021–2022 to examine the effects of the four hydroponic growing systems and different growing seasons on Batavia lettuce growth, mineral nutrients, and water consumption by plants under Mediterranean climate conditions. The experiments were performed in June and July, 2021 (summer), and in December, 2021 and January, 2022 (winter) under greenhouse conditions in Cairo, Egypt (30°2′41″ N, 31°14′44″ E, altitude 26 m a.s.l.). The research greenhouse measured 6.0 m in width and 30 m in length, with a height of 2.85 m. The experimental design was a randomized complete block with a hydroponic cultivation system during summer and winter growing seasons. The treatments consisted of three replications (units). Four cultivation system treatments comprised of (1) DWC, (2) NFT, (3) MB, and (4) SP, as Figure 1 shows.

The environmental parameters such as air temperature, relative humidity, and $CO_2$ were measured daily and data were collected using an online data logger (Tomatiki Smart Data Logger, Model: SDL320). The greenhouse was covered with polyethene plastic and cooled using a pad and fan evaporative cooling system and desired climate set points were maintained by an automatic climate control system. The shading net (73% shading rate) is used in

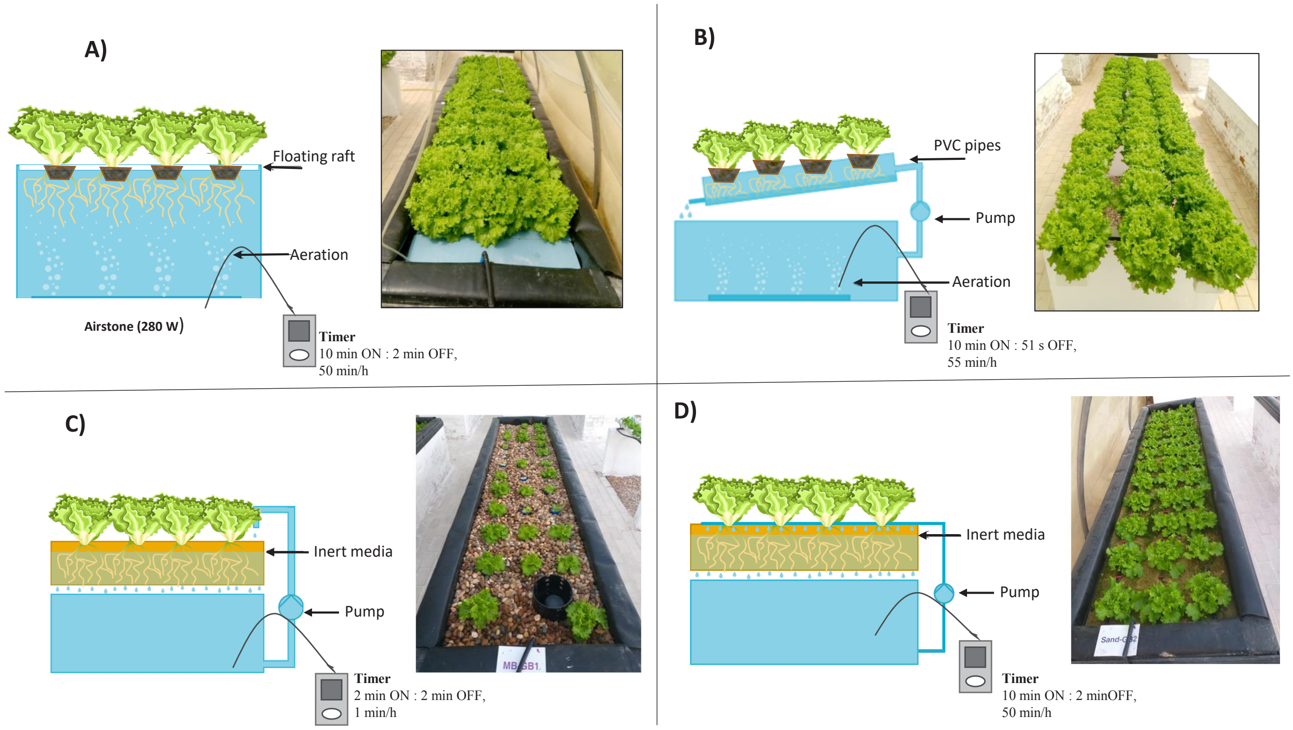


**Figure 1.** Various closed hydroponic subsystems were tested for lettuce growth under different growing seasons. These systems: (A)- DWC: deep water culture, (B)- NFT: nutrient film technique, (C)- MB: media-bed system and (D)- SP: sandponic

summer treatments to reduce solar radiation. Table 1 summarizes the environmental conditions for lettuce in growing beds and in the closed greenhouse during the experiments. The pH of the solution was maintained at a range of 5.5–6.5 with the addition of a base, potassium hydroxide (KOH) and nitric acid when it increased (Jones, 2016). Electrical conductivity (EC) is a measure of the dissolved salts in a solution, serving as a crucial factor for nutrient uptake in hydroponic systems. Typically, the EC value is maintained between 1.5 and 2.0 dS $m^{-1}$ in such systems (Wortman, 2015). Benoit and Ceustermans (1987, 1988) recommended maintaining the EC range between 2.0 and 2.5 dS $m^{-1}$ in their studies for hydroponics. Therefore, the EC range could be kept in a large range (1.5–2.5 dS $m^{-1}$) in experimental setups based on these two recommendations. When the EC value increased, it was diluted by adding water.

### 2.2. Crop and nutrient solution management

For seedling preparation, a mixture of 70% peat moss, 15% vermiculite, and 15% perlite as the growing media was used. At the time of media preparation, 8.5 g of (N-P-K, 19.19.19 + T.E) fertilizer was added to the growing media for each seedling tray. Once the cotyledons were fully expanded and the first true leaves began to emerge, the seedlings were sprayed with a dose of 0.5 g of NPK (19/19/19+ TE (Trace Elements)) fertilizer per 1 L of water with 3-day intervals. The pH and EC of the growing media were measured daily and maintained within a range of 5.4 to 6.0 and 1.5 to 2.0 dS $m^{-1}$, respectively. In the summer season, seedlings were irrigated 2 times a day, once with water only and once with the nutrient spray. After the seedlings reached a growth stage of true 5–7 leaves, along with root development, 23 ± 2-day-old seedlings were transplanted into the grow beds.

For hydroponic cultivation, each replicate of the experimental unit covered an area of 1.92 $m^2$. Plants were cultivated with a planting density of 20 × 25 cm. The NFT units consisted of 45 plants, a total of 135 lettuces, whereas other units consisted of 36 lettuces, a total of 108 plants for each cultivation system. The nutrient solution for hydroponic lettuce growth was formulated according to Hoagland's nutrient solution (Hoagland and Arnon, 1950). Each hydroponic subsystem was filled with a 500 L total volume of nutrient solution. The grow beds of DWC units had 324 L of water, and the water depth was 17 cm. The water flow rate in each grow bed across all systems is regulated by a water pump (85 W), which pumps at a rate of 7 L/min for 10 min, followed by a pause of 51 s. In the DWC system, plants were mechanically supported by a styrofoam board which floated on a bath of nutrient solution. The floating rafts (5 cm thick) had holes for supporting the plants, which also allowed the roots to be submerged in water and have constant contact with the

**Table 1.** The environmental conditions for lettuces in closed growing beds and closed greenhouse.

| Growing seasons | CS | EC (µS/cm) | pH | DO (ppm) | Water T (°C) | Air T (°C) | Air RH (%) | $CO_2$ (ppm) |
|---|---|---|---|---|---|---|---|---|
| Winter | DWC | 1.52 ±0.05 | 6.04 ±0.91 | 2.94 ±0.74 | 19.93 ±1.95 | 23.8±1.5 | 55±11 | 1900±710 |
| | NFT | 1.73±0.14 | 5.89±1.06 | 3.05±0.77 | 20.22±1.33 | | | |
| | MB | 1.88±0.16 | 6.34±0.44 | 3.11±0.71 | 20.7±1.33 | | | |
| | SP | 1.48±0.14 | 6.52±0.42 | 2.73±0.75 | 20.66±1.69 | | | |
| Summer | DWC | 1.81 ±0.06 | 5.84±0.62 | 5.32±0.25 | 27.12±1.08 | 27.4±1.9 | 65±4.6 | 1036 ±481 |
| | NFT | 1.86±0.09 | 5.85±0.62 | 5.10±0.31 | 27.46±1.06 | | | |
| | MB | 2.10 ±0.2 | 6.48±0.40 | 5.49±0.29 | 26.82±0.93 | | | |
| | SP | 2.44±0.22 | 6.71±0.25 | 4.06±0.45 | 26.89±1.16 | | | |

Data are expressed as means ± standard error (SE). Parameters: EC: electrical conductivity, DO: dissolved oxygen, T: temperature, RH: relative humidity. CS: cultivation systems, DWC: deep water culture NFT: nutrient film technique. MB: media-bed system and SP: sandponic.

nutrient solution. The reservoir in the DWC grow beds contained a submersible pump and air stone. Aeration in DWC was supplied via diffuser air stone to the root zone of plants, which was placed under a raft and connected to an air pump (280 W, ran 12 h/day). In the NFT system, only an air pump was used to constantly disturb high oxygen concentrations. DWC and NFT systems were performed with a continuous flow technique. In DWC, water was pumped with a submersible pump at a rate of 50 min per hour, whereas water in the NFT system was pumped at a rate of 55 min per hour. The NFT system was designed using pipes. In this system, the highly nutrient solution was recirculated continuously to the roots of lettuce plants through a set of channels; the solution ran off into the nutrient tank and was pumped back to the plants. Lettuces in the DWC and NFT grow beds were placed in plastic cups hung in pipes to support the plants, so they do not fall over during continuous streams of water.

The sand was washed out to remove salt composition for use in SP systems. As growth media, gravel was used in MB for supporting plants. In SP, irrigation was performed with drip irrigation and drainage (surface drainage). MB worked with continuous flow technique and drainage (a bell siphon system). Water was pumped with a submersible water pump with a flow rate of 7 L/min for 2 min in the SP system, followed by a 2-h pause. In the MB system, water was pumped at the same flow rate for 10 min, followed by a 2-min pause. This resulted in an irrigation rate of 1 min per hour in the SP system and 50 min per hour in the MB system.

### 2.3. Evaluated variables

Mature hydroponically grown lettuces were harvested on the 28th and 29th days after transplanting (DAT) over 2 days. The height of leaves, fresh shoot mass, fresh root mass, stem diameter, and head diameter were measured on-site at the harvesting time of the lettuces. A representative sample of 10 plants per replicate was taken to assess the vegetative growth parameters. Before starting measurements, substrates in the roots of the plants in the MB and SP systems were removed, whereas plastic cups were removed in the DWC and NFT systems. The plants were gently washed off. Then, the surface moisture on the lettuce was removed using a soft paper towel. Plant heights were measured from the base of the shoot to the terminal growing point. The root length of the lettuces was measured from the base of the shoot to the tip of the main root. The lettuces were weighed to determine the root and shoot weights. Lettuces were measured from the top of the plant and recorded in two orthogonal directions for head diameter. The lettuce was divided into two parts from the base of the shoot so that the stem diameters could be measured. For the dry mass, 6 randomly taken lettuce samples for each grow unit were sent to an external laboratory at the Agricultural Research Center, Giza, Egypt. Dry mass of lettuces was determined according to Horwitz and Latimer (2007). The leaf samples were dried in an oven at 100–110 °C until completely dry, and then repeatedly weighed until a constant weight was achieved. Subsequently, the moisture content percentage was calculated.

For nutrient content analysis, 12 lettuce leaves in each treatment were randomly taken from each unit on 26 ± 2 DAT. Nutrient content analysis was performed at the Agricultural Research Center, Giza, Egypt. Nitrogen (N) content was determined using the Micro-Kjeldahl method in the digestive solution as described by Plummer (1978). Five millilitres of digestive solution was distilled with 10 mL of sodium hydroxide (NaOH) for 10 min to obtain ammonia. Phosphorus (P) was determined colourimetrically as described by Jackson (1959). Potassium (K), calcium (Ca), and sodium (Na) contents were determined against a standard using a flame-photometer (JEN way flame photometer) according to the procedures described by Piper (1950). Magnesium (Mg), copper (Cu), manganese (Mn), zinc (Zn), and Iron (Fe) contents were determined by using atomic absorption spectrophotometer (Pyeunican SP1900) according to methods of Brandifeld and Spincer (1965). The contents of chlorophyll and carotenoids were determined spectrophotometrically according to the acetone method as described by Ritchie (2006).

To assess water consumption, the water tanks connected to hydroponic systems were filled with 500 L of water containing a nutrient solution for each unit in all systems at the beginning of the experiments. Additionally, 324 L of water were added to the grow beds in the DWC system, resulting in a total of 824 L of nutrient-rich water. Water discharge might have happened only through the following cases during experiments: (1) Evapotranspiration and (2) leakage. After mature lettuces were harvested from each grow bed for each treatment, the remaining water in the water tank was measured, allowing for the calculation of water consumption per square meter and per plant. Although detailed water losses were not calculated, the results indicate the effective water use for each system.

### 2.4. Statistical analysis

Data are presented as means ± SE. ANOVA (two-way ANOVA) was performed to detect significant differences in all the measured parameters after verifying homoscedasticity by Levene's test. All statistical analyses were conducted using SPSS Statistics 29 (IBM Software, Chicago, USA). Probabilities of significance among treatments and LSD ($p \leq 0.05$) were used to compare means among treatments.

## 3. Results

### 3.1. Vegetative growth parameters

Four hydroponic growing systems for lettuce growth were used, namely DWC, NFT, MB, and SP. In the experiment performed in the winter growing season, lettuces grown in the DWC and NFT systems had shoot fresh masses (SFM) of 159.81 and 165.89 g plant$^{-1}$, respectively, stem diameters (SD) of 1.50 and 1.51 cm, respectively, and head diameters (HD) of 23.85 and 23.61 cm, respectively, which are significantly higher compared to the MB and SP systems. Shoot height (SH, 17.71 cm) and root length (RL, 50.72 cm) of lettuces grown under the DWC system were significantly higher than those in other systems. Root fresh mass (RFM, 40.27 g) was higher in NFT hydroponics, while the lowest value of root dry mass (RDM, 0.93 g) was found in this system (Table 2).

During the summer growing season, lettuces grown in the NFT system exhibited higher SFM (169.97 g), SD (1.25 cm), RL (37.50 cm), and RFM (38.64 g) compared to other hydroponic systems. Lettuces grown in the DWC system exhibited significantly greater shoot height (SH, 17.93 cm). Furthermore, lettuces from both DWC and NFT systems demonstrated significantly larger head diameters (HD, 22.57 and 23.61 cm) compared to those from the MB and SP systems. In this growing season, there was no significant difference observed in the dry mass of lettuces among various hydroponic systems.

### 3.2. Lettuce leaf content analysis

In the winter growing season, the nutrient composition of lettuce leaves under various hydroponic systems showed no significant differences in macroelements, including nitrogen and potassium, as well as microelements such as sodium (Na) and zinc (Zn), as shown in Table 3. However, lettuce cultivated in media bed systems (MB and SP) exhibited significantly higher levels of calcium (Ca, 170.01 and 182.63 mg/100 g, respectively) and magnesium (Mg, 340.42 and 286.77 mg/100 g, respectively) compared to DWC and NFT hydroponic systems. MB lettuces in the winter term also showed the highest phosphorus (P) content at 1.08% and elevated levels of microelements

**Table 2**. Vegetative growth parameters.

| Cultivation seasons | Hydroponic systems | Shoot height (cm) | Shoot weight (g) | Stem diameter (cm) | Head diameter (cm) | Root length (cm) | Root weight (g) | Dry mass (g) |
|---|---|---|---|---|---|---|---|---|
| Winter | DWC | 17.71±1.14$^{a}$ | 159.81±23.73$^{a}$ | 1.50±0.13$^{a}$ | 23.85±0.97$^{a}$ | 50.72±8.15$^{a}$ | 31.46±4.86$^{b}$ | 1.15±0.15$^{a}$ |
| | NFT | 16.15±1.12$^{b}$ | 165.89±34.90$^{a}$ | 1.51±0.14$^{a}$ | 23.61±1.80$^{a}$ | 46.35±4. 18$^{b}$ | 40.27±8.23$^{a}$ | 0.93±0.04$^{b}$ |
| | MB | 11.60±1.09$^{c}$ | 57.60±12.39$^{b}$ | 1.00±0.08$^{b}$ | 14.07±1.52$^{b}$ | 21.68±2. 31$^{c}$ | 15.10±2.35$^{c}$ | 1.13±0.02$^{a}$ |
| | SP | 11.24±1.37$^{c}$ | 49.71±19.06$^{b}$ | 0.98±0.13$^{b}$ | 13.70±2.25$^{b}$ | 11.52±1. 91$^{d}$ | 16.77±7.13$^{c}$ | 1.20±0.14$^{a}$ |
| Summer | DWC | 17.93±1.16$^{a}$ | 155.40±17.38$^{b}$ | 1.16±0.06$^{b}$ | 22.57±0.80$^{a}$ | 32.17±5. 10$^{b}$ | 26.87±3.52$^{b}$ | 0.98±0.06$^{n}$ |
| | NFT | 16.23±0.92$^{b}$ | 169.97±18.35$^{a}$ | 1.25±0.07$^{a}$ | 23.63±1.27$^{a}$ | 37.50±4. 17$^{a}$ | 38.63±5.57$^{a}$ | 0.92±0.04 |
| | MB | 14.80±1.73$^{c}$ | 97.67±14.74$^{c}$ | 1.07±0.09$^{c}$ | 18.47±1.83$^{b}$ | 19.30±1. 93$^{c}$ | 20.00±4.74$^{c}$ | 0.98±0.09 |
| | SP | 14.77±0.75$^{c}$ | 101.07±14.25$^{c}$ | 1.06±0.12$^{c}$ | 19.40±1.18$^{b}$ | 12.40±1. 70$^{d}$ | 22.10±6.65$^{c}$ | 0.99±0.10 |

Data are expressed as means ± standard error (SE). Lowercase letters within each main treatment indicate significant differences after the least significant difference (LSD) post hoc test (significance level: $p < 0.05$ and $p < 0.01$; not significant at $p \geq 0.05$) for each parameter. DWC: deep water culture. NFT: nutrient film technique. MB: media-bed system, and SP: sandponic.

**Table 3.** The leaf nutrient compositions are expressed as percentages of dry mass for macroelements and Na content, and as mg/100g for microelements.

| Treatments | CS | N (%) | P (%) | K (%) | Na (%) | Ca (mg/100 g) | Mg (mg/100g) | Mn (mg/100g) | Zn (mg/100g) | Fe (mg/100g) | Cu (mg/100g) | B (mg/100g) | Mo (mg/100g) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Winter | DWC | $2.38 \pm 0.54^{n}$ | $1.03 \pm 0.07^{ab}$ | $2.17 \pm 0.21^{n}$ | $1.16 \pm 0.07^{n}$ | $117.16 \pm 13.60^{b}$ | $270.72 \pm 38.56^{b}$ | $17.94 \pm 1.97^{a}$ | $20.23 \pm 3.31^{n}$ | $110.48 \pm 1.29^{b}$ | $1.00 \pm 0.09^{c}$ | $8.54 \pm 0.77^{b}$ | $1.30 \pm 0.12^{b}$ |
| | NFT | 2.24±0.20 | $1.03 \pm 0.07^{ab}$ | 2.37±0.08 | 1.03±0.09 | $132.34 \pm 4.09^{b}$ | $216.38 \pm 30.47^{b}$ | $17.36 \pm 0.59^{a}$ | 21.42±1.66 | $114.84 \pm 6.74^{b}$ | $1.54 \pm 0.22^{b}$ | $13.23 \pm 1.85^{ab}$ | $1.69 \pm 0.24^{ab}$ |
| | MB | 2.03±0.65 | $1.08 \pm 0.15^{a}$ | 2.36±0.13 | 1.14±0.16 | $170.01 \pm 18.85^{a}$ | $340.42 \pm 7.17^{a}$ | $16.76 \pm 0.19^{a}$ | 21.06±1.93 | $138.71 \pm 16.63^{a}$ | $2.34 \pm 0.09^{a}$ | $17.68 \pm 5.54^{a}$ | $2.31 \pm 0.67^{a}$ |
| | SP | 1.91±0.24 | $0.79 \pm 0.18^{b}$ | 2.13±0.28 | 0.89±0.12 | $182.63 \pm 12.64^{a}$ | $286.77 \pm 25.81^{a}$ | $13.91 \pm 0.75^{b}$ | 19.30±2.55 | $124.47 \pm 2.23^{ab}$ | $1.47 \pm 0.33^{b}$ | $12.57 \pm 2.85^{b}$ | $1.61 \pm 0.37^{ab}$ |
| Summer | DWC | $2.37 \pm 0.34^{n}$ | $1.02 \pm 0.09^{ab}$ | $2.27 \pm 0.18^{n}$ | $1.93 \pm 0.56^{ab}$ | $94.23 \pm 23.03^{b}$ | $258.29 \pm 50.54^{a}$ | $15.14 \pm 1.82^{a}$ | $9.74 \pm 2.04^{b}$ | $211.50 \pm 3.43^{a}$ | $0.89 \pm 0.08^{c}$ | $10.09 \pm 1.21^{n}$ | $4.23 \pm 0.85^{n}$ |
| | NFT | 2.63±0.36 | $1.08 \pm 0.10^{ab}$ | 2.51±0.06 | $2.22 \pm 0.61^{a}$ | $78.30 \pm 23.94^{b}$ | $189.91 \pm 27.22^{b}$ | $16.52 \pm 0.97^{a}$ | $14.24 \pm 0.67^{a}$ | $189.11 \pm 9.45^{b}$ | $1.73 \pm 0.23^{a}$ | 11.02±0.65 | 3.78±0.72 |
| | MB | 2.26±0.26 | $0.88 \pm 0.14^{b}$ | 2.41±0.15 | $2.10 \pm 0.22^{ab}$ | $124.81 \pm 13.93^{a}$ | $293.84 \pm 61.41^{a}$ | $13.72 \pm 0.55^{b}$ | $15.75 \pm 1.78^{a}$ | $177.88 \pm 11.17^{b}$ | $1.28 \pm 0.26^{b}$ | 9.15±3.54 | 3.56±0.75 |
| | SP | 2.31±0.38 | $1.19 \pm 0.31^{a}$ | 2.33±0.15 | $1.50 \pm 0.09^{b}$ | $111.10 \pm 13.12^{a}$ | $293.33 \pm 26.00^{a}$ | $15.81 \pm 0.26^{a}$ | $17.72 \pm 2.47^{a}$ | $184.78 \pm 7.39^{b}$ | $1.14 \pm 0.19^{bc}$ | 10.54±1.86 | 3.70±0.15 |

Data are expressed as means ± standard error (SE). Lowercase letters indicate significant differences after the least significant difference (LSD) post hoc test (significance level: $p < 0.05$ and $p < 0.01$; not significant at $p \geq 0.05$) for each parameter. Different superscript letters within cultivation systems indicate a significant difference at $p < 0.05$ and $p < 0.01$ (not significant at $p \geq 0.05$) (LSD test). CS: cultivation systems: DWC: deep water culture. NFT: nutrient film technique. MB: media-bed system. SP: sandponic.

including iron (Fe, 138.71 mg/100 g), copper (Cu, 2.34 mg/100 g), boron (B, 17.68 mg/100 g) and molibden (Mo, 2.31 mg/100 g). Conversely, SP lettuces showed the lowest manganese (Mn) content at 13.91 mg/100 g.

During the summer growing season, lettuces cultivated under different hydroponic systems did not exhibit significant differences in the uptake of macroelements (N, K) and microelements (B, Mo). DWC lettuces displayed the highest Fe content at 211.50 mg/100 g, while the lowest Zn content (9.74 mg/100 g) was observed in DWC lettuces. Notably, NFT lettuces exhibited the highest levels of Na (124.81 mg/100 g) and Cu (1.73 mg/100 g) but the lowest Mg content (189.91 mg/100 g). MB and SP lettuces showed higher Ca content (124.81 mg/100 g and 111.10 mg/100 g, respectively) compared to DWC and NFT systems. Similarly, SP lettuces displayed the greatest P content at 1.19%. Finally, the lowest Mn content was measured at 13.72 mg/100 g in lettuces from the MB hydroponic system.

In both growing seasons, the DWC lettuce leaves exhibited the highest chlorophyll A, B and carotene content as illustrated in Figure 2. Moreover, chlorophyll b and carotene content levels were higher in the NFT lettuces compared to MB and SP, while there was no significant difference between the DWC and NFT lettuces.

### 3.3. Water consumption

The results revealed a significant impact of hydroponic cultivation systems on water consumption per unit, as illustrated in Figure 3. During the winter season, NFT lettuces exhibited the lowest water consumption at 2.02 L/plant. Conversely, in the summer growing season, DWC and NFT lettuces demonstrated higher water consumption, recorded at 4.49 L/plant and 4.01 L/plant, respectively.

Likewise, the water consumption per unit was influenced by hydroponic cultivation systems. In the winter season, NFT and SP systems required significantly less water per unit, measuring 47.43 L/$m^2$ and 57.88 L/$m^2$, respectively. Conversely, during the summer growing season, DWC (84.28 L/$m^2$) and NFT (93.90 L/$m^2$) systems exhibited significantly lower water consumption per unit compared to MB and SP systems (47.43 and 57.88 L/$m^2$, respectively). In the summer growing season, DWC (84.28 L/$m^2$) and NFT (93.90 L/$m^2$) systems needed significantly less water per unit compared to MB and SP systems.

## 4. Discussion

Our study documents the performance of different hydroponic systems for lettuce cultivation, focusing on vegetative growth parameters (Table 2), leaf nutrient content analysis (Table 3), and water consumption (Figure 3) during both the winter and summer growing seasons.

Our study provides compelling evidence that the NFT system outperformed other hydroponic systems in terms of shoot fresh mass (SFM), stem diameter (SD), head diameter (HD), and root growth parameters (RL and FRM) during the summer season. Conversely, the DWC subsystem performed better than other hydroponic systems in terms of vegetative growth parameters, except for root weight, during the winter season. Specifically, in terms of SFM in NFT and DWC systems, winter showed a remarkable increase of 81.90% and 75.64%, respectively. In contrast, MB and SP systems exhibited reductions of around 36.71% and 45.49%, respectively. In summer, NFT and DWC systems continued their superior performance with 29.25% and 18.19%, while MB and SP systems experienced reductions of approximately 26.28% and 23.10%, respectively. Our results demonstrate that in both cultivation seasons, the DWC and NFT systems exhibit comparable and superior shoot fresh mass productions. It can be argued that seasonal variations may affect the performance of selected hydroponic systems, resulting in different plant growth responses (Sublett et al., 2018). For instance, the observed EC value during days with higher solar radiation and air temperature leads to higher water uptake by plants and it directly increases the EC level (Cometti et al., 2013). Our results support this argument with evidence that water consumption in all other systems, except the DWC system, doubles in the summer compared

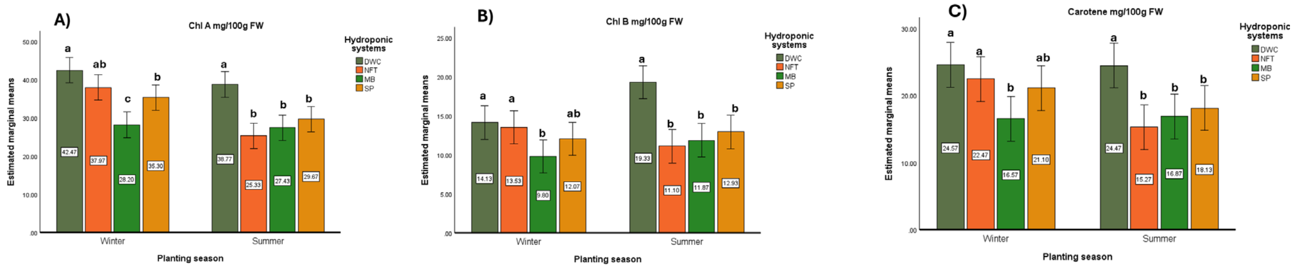


**Figure 2.** Chlorophyll and carotene contents of lettuces grown in closed hydroponic systems at different planting seasons. (A) chlorophyll a, (B) chlorophyll b, and (C) carotene content. Means with a different letter within each treatment and cultivation method are significantly different according to the LSD test at $p < 0.05$. DWC: deep water culture, NFT: nutrient film technique, MB: media-bed system, and SP: sandponic.

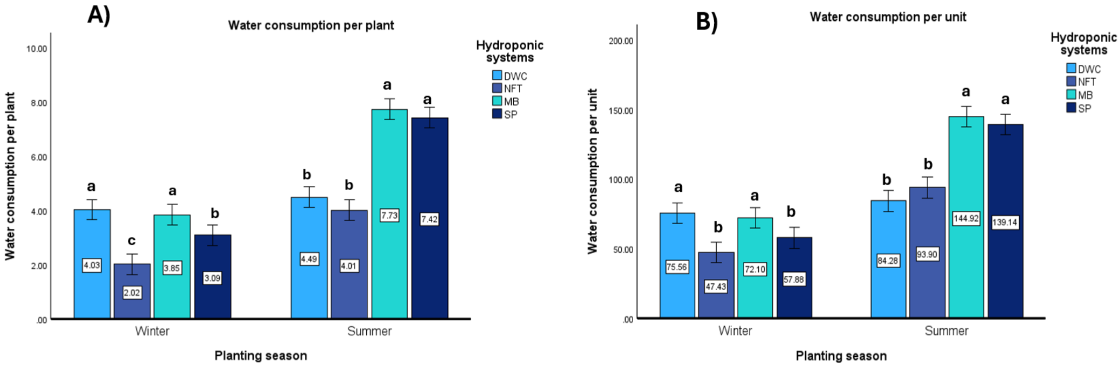


**Figure 3.** Water consumption per unit (L $m^{-2}$) (A) and per plant (L $plant^{-1}$) (B) in lettuce growth for different closed hydroponic systems in winter and summer. Means with a different letter within each treatment and cultivation method are significantly different according to the LSD test at $p < 0.05$. DWC: deep water culture, NFT: nutrient film technique, MB: media-bed system, and SP: sandponic.

to the winter growing season, even though the NFT system needed the least water for lettuce growth. Similarly, Assimakopoulou et al. (2013) found that the lettuce yield was twice as high and healthier in the DWC system than in hydroponic systems with solid substrates like pumice, perlite, and rockwool in late winter compared to the spring growing season. This suggests that DWC may promote plant precocity due to the large volume of the nutrient solution in the system that may buffer the temperature and provide more favourable conditions for the root development due to the more limited day-night temperature fluctuations. Moreover, we observed that the lettuce root lengths in the DWC and NFT systems were longer compared to the SP system. The suboptimal development of roots in the sand-based media system might be attributed to relatively lower dissolved oxygen levels in comparison to other cultivation methods (Blok et al., 2017; Schroeder and Lieth, 2004).

The leaf nutrient analysis revealed significant differences in nutrient content, potentially influenced by system characteristics. The higher pH of grow beds with medium might increase the Ca and P uptake in the MB and SP systems. Furthermore, the microelement levels in the MB lettuces were higher in the winter season than the lettuce grown in other systems. However, the higher Ca content led to less uptake of microelement Zn (Maucieri et al., 2019). Our results indicate that the growth mediums hold and store oxygen and nutrients for periods without water flowing and a steady supply until the recirculating water reaches the plants again (El-Kazzaz and El-Kazzaz, 2017).

Notably, the DWC lettuces consistently exhibited the highest chlorophyll A, B, and carotene content in both growing seasons. These essential pigments are involved in photosynthesis and antioxidant activity, suggesting that DWC lettuces may have superior photosynthetic efficiency and nutritional value compared to those grown in other systems. The higher chlorophyll and carotene readings in DWC lettuces could be attributed to precise control of nutrient availability management by effectively maintaining the optimum growth conditions for nutrient uptake compared to lettuces from the NFT system (Majid et al., 2021).

Overall, this study documents a comprehensive analysis of various hydroponic systems and their performance during different planting seasons for lettuce cultivation within closed greenhouse environments. Our results demonstrate that the DWC and NFT systems have greater shoot fresh mass in both growing seasons. Remarkably, DWC lettuces consistently showed higher chlorophyll A, B, and carotene content, suggesting heightened photosynthetic efficiency and nutritional value potential. These empirical findings underscore the suitability of the DWC system in fostering robust and vigorous lettuce growth, while concurrently maintaining a consistent water consumption pattern across diverse seasonal contexts. Likewise, the NFT system exhibits promising efficacy, particularly in terms of efficient per-plant water consumption during both seasonal regimes. However, the lettuces in the NFT system needed more water in the summer season. Based on our findings, we suggest strategic adjustments, such as targeted cooling in summer and controlled heating in winter, to optimize environmental conditions for year-round lettuce cultivation. Importantly, this thoughtful climate management not only enhances growth conditions but also mitigates water loss due to increased evaporation. These results reveal the importance of selecting the right hydroponic system and maximizing lettuce production in closed greenhouses, enhancing efficient and sustainable controlled-environment agriculture practices.

**Availability of data and materials**

All relevant data are provided within this manuscript.

**Conflict of interest**
The authors declare that there are no conflicts of interest.

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**Author contributions**
D.Ç., Mo.H., Ma.H., N.H, and R.L. conceived and designed the experiments; Mo.H and Ma.H performed the experiments; D.Ç. analysed the data; D.Ç. wrote the first version of the manuscript. H. S. supervised the study. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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