



Impact of Hydroponic Versus Soil Cultivation on Nutrient Uptake Efficiency, Morphological Traits, and Water Use Efficiency of Arugula plant (*Eruca sativa* Mill.)

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ARTICLE INFORMATION

RECEIVED: 25/05/2026

ACCEPTED: 01/06/2026

PUBLISHED: 02/06/2026

ABSTRACT

Plants are exposed to various soil-related stresses, including water scarcity, poor water quality, and limited nutrient availability, all of which can negatively affect growth and productivity. This study aimed to evaluate the effectiveness of hydroponic cultivation compared to soil cultivation. Seeds of (*Eruca sativa* Mill.) were sown in both cultivation systems. The experiment was conducted using a completely randomized design (CRD) with 24 replicates per treatment. Nutrient uptake, morphological traits, and water use efficiency of *Eruca sativa* grown in both systems were measured. The results showed highly significant differences ($P < 0.001$) between the treatments. Morphological traits including shoot and root length, stem diameter, and leaf area were greater under hydroponic cultivation. Additionally, water use efficiency in hydroponically grown arugula (*Eruca sativa* Mill.) was approximately four times higher than in soil-grown plants. These findings highlight the potential of hydroponics for improving plant growth, nutrient use, and water efficiency, and provide motivation for further research in this field.

Keywords: Hydroponics; Arugula (*Eruca sativa* Mill.); Nutrient Uptake; Morphological traits; Water Use Efficiency

1. Introduction

In recent years, traditional soil-based agriculture has faced escalating challenges that threaten global food security, as plants grown in open fields are increasingly subjected to severe abiotic stresses, most notably drought, soil salinity, and repellency-induced water stress [1]. Globally, soil salinization affects approximately 20% of all irrigated [2]. These environmental constraints significantly impair nutrient availability and root development, forcing plants to divert energy from growth toward survival mechanisms, which often results in stunted morphological development and reduced yields [3]. This situation is particularly critical in arid and semi-arid regions. In Libya, for instance, the agricultural sector struggles with chronic water scarcity and rapid soil degradation, the intensive use of groundwater in coastal agricultural belts has led to a significant drop in water tables and increased soil salinization, with levels often exceeding 8 dS/m [4]. The intensive use of groundwater has led to a drop in water tables and increased soil salinization, especially in coastal agricultural belts, making conventional farming increasingly unsustainable and necessitating a transition toward innovative cultivation technologies to preserve the country's limited resources [5].

To overcome these limitations, hydroponic systems (soilless culture) have emerged as a revolutionary solution. Studies indicate that hydroponics can reduce water consumption by 70-90% compared to traditional methods by recycling nutrient solutions and minimizing evaporation [6]. This precise control over the root zone significantly optimizes Water Use Efficiency (WUE), making it an ideal strategy for water-scarce regions like Libya [7]. Furthermore, hydroponic systems are known to substantially increase crop productivity 20% to 50% per unit area; by providing direct access to essential minerals, they accelerate growth cycles and allow for higher biomass accumulation [8]. The absence of soil-related stresses enables plants to reach their maximum genetic potential, contributing to a 20% to 50% increase in biomass and superior quality compared to soil-grown crops [9].

Among the leafy greens that thrive in these systems, Rocket (*Eruca sativa* Mill.), or Arugula, stands out as a crop of high economic and nutritional value, rich in health-promoting compounds such as glucosinolates, antioxidants, and essential vitamins [10]. Due to its fast growth cycle and high responsiveness to nutrient management, Rocket serves as an ideal model for studying resource utilization. The rationale of this study stems from the urgent need to find sustainable agricultural alternatives in regions like Libya, where traditional farming is hindered by saltwater intrusion and water scarcity. Therefore, the objective of this research is to evaluate the interaction between nutrient uptake efficiency, morphological characteristics, and water use efficiency in Rocket plants grown under hydroponic conditions. By analyzing root development, biomass accumulation, and mineral absorption rates, this study aims to establish effective protocols for high-quality production, providing a viable agricultural model for water-scarce and salt-affected regions.

2. Literature Review

The Impact of Hydroponic Cultivation on Nutrient Uptake Efficiency and Metabolite Formation. Previous studies have demonstrated that plants cultivated under hydroponic systems exhibit enhanced nutrient uptake rates compared with those grown in soil-based systems. In a study conducted on zucchini (*Cucurbita pepo*), nutrient absorption—including nitrogen, magnesium, sodium, iron, copper, zinc, and manganese—was significantly higher under hydroponic conditions than in conventional soil cultivation. This enhanced uptake was associated with increased concentrations of carbohydrates, such as glucose, fructose, sucrose, and starch [11].

Similarly, the studies conducted by [12] on soybean (*Glycine max*) revealed that soilless cultivation promoted the synthesis of several biochemical constituents compared with traditional agricultural practices. Specifically, lipid content increased from 17.37 to 21.94 g per 100 g dry weight, while total dietary fiber rose from 21.67 to 28.46 g per 100 g dry weight, resulting in an overall improvement in nutritional quality. Additionally, higher protein and vitamin contents have also been reported in hydroponically grown crops [13].

Beyond primary metabolic compounds, hydroponic systems have also been shown to stimulate the accumulation of secondary metabolites and antioxidant-related constituents. In lettuce (*Lactuca sativa*), hydroponic cultivation significantly increased chlorophyll content, phenolic compounds, flavonoids, enzymatic and non-enzymatic antioxidants, mineral composition, and dissolved oxygen levels compared with soil-grown plants [14]. Furthermore, studies conducted by [15] on tomato (*Solanum lycopersicum*) demonstrated elevated concentrations of key bioactive compounds, including lycopene and β -carotene,

under hydroponic conditions.

Furthermore, [16] reported consistent findings in chrysanthemum (*Chrysanthemum morifolium*), where chlorogenic acid and flavonoid concentrations reached 2.3 and 43.2 mg g⁻¹ dry weight, respectively, in hydroponically grown plants, compared with 1.7 and 36.7 mg g⁻¹ dry weight in soil-cultivated counterparts. Overall, these results indicate that the superior accumulation of primary and secondary metabolites under hydroponic conditions is closely linked to enhanced nutrient uptake efficiency.

2.1 The Impact of Hydroponic Cultivation on Plant Morphological Traits

Research has consistently shown that hydroponic cultivation significantly enhances the morphological traits of plants, which are observable visually without specialized instruments. For instance, a study on lettuce (*Lactuca sativa*) by [17] reported that roots in hydroponic systems were significantly longer ($p < 0.05$) than those in soil-grown plants. Additionally, hydroponically grown lettuce exhibited softer leaves and more rigid midribs, which was associated with a 24.18% increase in lignin content in the cell walls.

In other crops, [18] demonstrated that wheat (*Triticum aestivum*) seedlings grown hydroponically under various water treatments showed increases in shoot and root lengths by 35.2% and 84.1%, respectively, compared with soil-grown controls. Similarly, in chrysanthemum (*Chrysanthemum morifolium*), hydroponic cultivation resulted in higher flower numbers per plant and greater dry weight per flower (41.33 g and 20.25 g, respectively) compared with soil-grown counterparts (25.67 g and 12.58 g, respectively) [16].

Along with morphological traits, hydroponic systems have also been shown to enhance fresh biomass. In spinach (*Spinacia oleracea*), [19] observed a linear increase in both fresh and dry leaf weights under hydroponic cultivation across different salinity levels compared with soil-based systems. Similarly, [20] reported significantly higher fresh and dry weights of roots and leaves, as well as larger leaf areas, in hydroponically grown basil, lettuce, radish, dill, and coriander compared with soil-grown plants.

Furthermore, hydroponic cultivation improves plant responses to growth regulators and flowering. [21] found that *Matricaria recutita* (chamomile) grown hydroponically exhibited significantly greater fresh weight, flower number and diameter, stem diameter, leaf number and area, and root length compared with soil-grown plants under identical growth regulator treatments.

2.2 The Impact of Hydroponic Cultivation on Water Consumption

Studies have demonstrated that hydroponic cultivation significantly reduces water consumption while improving water use efficiency. For example, in tomato (*Solanum lycopersicum*), plants grown hydroponically exhibited lower transpiration rates relative to soil-grown plants, resulting in enhanced water use efficiency [15]. The water required for forage production in hydroponic systems constitutes only 2–3% of that needed under conventional soil cultivation [22]-[23], representing a water saving of 70–90% compared with traditional farming practices [24].

Moreover, studies on animal feed production have shown that producing one ton of green forage using hydroponics requires merely 2.83 m³ of water, compared with 117 m³ under open-field conditions. Consequently, water use efficiency per unit of fresh biomass is approximately 48 times higher in hydroponic systems than in conventional cultivation [25]. Similarly, [26] reported that cabbage, spinach,

and kidney bean plants consumed 82–92% less water when grown hydroponically compared with soil-based cultivation.

3. materials and methods

3.1 Experimental Models

Hydroponic System

The hydroponic unit was supplied by Hydrolibya Company (Al-Zawiya). It consisted of horizontally positioned PVC pipes (8–9 cm in diameter) sealed at both ends and supported by a fixed frame. Openings measuring approximately 6.5 cm in diameter were made along the pipes at intervals of 6–8 cm to accommodate perforated plastic pots (230 cm³) filled with perlite as a growing medium. The system was linked to a basin equipped with a pump that facilitated automated irrigation and drainage, as illustrated in [Figure 1](#).

Soil Cultivation System

The soil-based system was locally constructed to match the structural specifications of the hydroponic setup. The primary difference was that the pots were filled with soil instead of perlite, and irrigation was performed manually rather than automatically. This configuration is presented in [Figure 1](#). The soil used in this system possesses specific physical and chemical properties, as shown in [Table 1](#).



Figure 1: A model of a hydroponic farming system is on the right ,and a model of a soil-based farming system is on the left.

Table 1: The physical and chemical properties of the soil used for cultivation.

| Test | Results |
|------------------------------|----------------|
| Soil Texture | Sandy |
| pH | 9.22 |
| Electrical Conductivity (Ec) | 365 μ S/cm |
| Na ⁺ | 170 mg/kg |
| K ⁺ | 14.4 mg/Kg |
| Ca ⁺² | 50 mg/Kg |
| Mg ⁺² | 21 mg/Kg |
| P ⁺³ | 9.0 mg/Kg |
| NO ₃ ⁻ | 0.02mg/Kg |
| Organic matter (OM) | 369 mg/Kg |
| CaCO ₃ | 10.7 Wt.% |

3.2 Nutrients Solution and irrigation water

The nutrient solution used in the hydroponic system consisted of Hydrolibya formulations A and B, supplied by Hydrolibya Hydroponic Agriculture Company. The detailed chemical composition of both solutions is presented in [Tables 2](#) and [3](#). The water used for preparation had a total dissolved solids (TDS) concentration of 100 mg/L.

Table 2: Contents and concentration of the nutrient solution (hydrolibya), Class A of nutrients.

| Element | Concentration Range(mg/L) |
|-----------------------|---------------------------|
| Macro Elements | |
| Nitrogen(N) | 200 |

| | |
|-----------------------|-------------|
| Phosphorus(P) | 55- 60 |
| Potassium(K) | 280-310 |
| Magnesium(Mg) | 50 |
| Sulfur(S) | 60-80 |
| Micro Elements | |
| Copper(Cu) | 0.09 - 0.10 |
| Manganese(Mn) | 2 |
| Molybdenum(Mo) | 0.2 |

Table 3. Contents and concentration of the nutrient solution (hydrolibya), Class B of nutrients.

| Element | Concentration Range (mg/L) |
|-----------------------|---------------------------------------|
| Macro Elements | |
| Nitrogen(N) | 200 |
| Calcium(Ca) | 175-180 |
| Micro Elements | |
| Boron(B) | 0.2- 0.3 |
| Copper(Cu) | 0.09 - 0.10 |
| Iron(Fe) | 6 |

3.3 Plant Material

Seeds of local arugula (*Eruca sativa* Mill, family Brassicaceae) were utilized in this study.

3.4 Experimental procedure

Two cultivation methods, hydroponic and soil-based, were applied under open-field conditions at a farm located south of Zawiya, ensuring similar environmental conditions in terms of light exposure and temperature. The experimental layout followed a Completely Randomized Design (CRD), with 24 independent replicates for each model treatment.

In the hydroponic treatment, the reservoir and connected PVC pipes were supplied with irrigation water using a pump, with a total volume of 60 L. Planting containers were filled with perlite and inserted into the pipe openings, allowing the substrate to become fully saturated before seed sowing. For the soil treatment, 213 g of soil was weighed for each pot, thoroughly mixed with Organic fertilizer derived from sheep manure was applied at a rate of 1 g per 100 g of soil, and placed into the designated cultivation holes.

Arugula (*Eruca sativa* Mill.) seeds were sown on 23 June 2023 at a density of nine seeds per pot in both cultivation systems [27], and no thinning was performed; all seedlings were maintained until the end of the experiment.

Immediately after sowing, water circulation was activated in the hydroponic system. In contrast, soil-grown plants were irrigated manually three to four times daily, with a total daily water supply of 4.2 L per 24 pots.

Approximately seven days after sowing, equal proportions of nutrient solutions A and B were added to the hydroponic reservoir until the electrical conductivity (EC) reached 300–350 $\mu\text{S cm}^{-1}$. During the third week, the nutrient strength was further increased to 650–700 $\mu\text{S cm}^{-1}$ using the same nutrient solutions. Soil-grown plants were also supplemented with nutrient solutions A and B at a concentration of 1 mL L⁻¹ each, applied biweekly through irrigation.

Water levels in the hydroponic reservoir were regularly monitored and topped up as required. At the same time, irrigation of soil-grown arugula plants was observed daily. The amount of water applied was recorded for each system, with the total volume per pot being 8 L in the hydroponic system and 7L in the soil-based system.

Furthermore, the pH and electrical conductivity (EC) of the nutrient solution in the hydroponic system were regularly measured using a pH meter and an EC meter to ensure optimal nutrient availability. The pH range throughout the experiment was 6.5–8. Plant growth was continuously monitored in all experimental units until maturity. In the hydroponic system, plants reached maturity within 21 days, compared to 45 days in the soil system, while the plants in hydroponic are in the elongation stage, the plants in the soil are still in the germination stage, based on the morphological characteristics and marketability traits, the maturity stage was determined.

3.5 Measurements

Leaf Area and Shoot Length Measurements: Leaf area and shoot length were measured using the Image J software [28]. The total leaf area per plant and the shoot length of arugula (*Eruca sativa* Mill.) were recorded immediately at the conclusion of the experiment.

Root Length Measurement: The actual root length of each treatment was measured using a graduated ruler [29].

Stem Diameter Measurement: Stem diameter was measured using a digital micrometre calliper (digital mess-schieber). Arugula (*Eruca sativa* Mill.) plants were randomly selected from each experimental treatment, and the stem was positioned between the caliper jaws. Measurements were recorded for 24 samples per treatment [30].

Dry Weight Measurement: Arugula (*Eruca sativa* Mill.) samples were dried in an oven at 70 °C for 48 hours. The dry weight of the shoot biomass for each pot under both cultivation systems was then measured using a digital scale.

Determination of Macronutrient (NPK) Uptake Efficiency: Plant samples were collected and analyzed at the Delta Scientific Laboratory, Tripoli, to determine the uptake efficiency of major macronutrients (N, P, K) in arugula (*Eruca sativa* Mill.) grown under both hydroponic and soil cultivation systems.

Macronutrient Analysis Methods:

- **Nitrogen (N)** was determined using the Kjeldahl method [31].
- **Potassium (K)** was measured using a flame photometer [32].
- **Phosphorus (P)** was determined using a spectrophotometer [33].

Water Use Efficiency (WUE): The total volume of water consumed (in liters) was recorded throughout the growth period. The dry shoot biomass of arugula plants was measured in grams for 24 pots in both the hydroponic and soil cultivation systems. Water use efficiency for each pot was then calculated by dividing the dry shoot biomass by the total water consumed [34].

3.6 Statistical Analysis

The data were statistically analyzed using SPSS (version 28). Given that the experiment followed a Completely Randomized Design (CRD) comparing two independent cultivation systems (hydroponic and soil), an independent sample T-test was performed as the standard and most appropriate method to determine significant differences between the means at a 5% significance level ($p \leq 0.05$).

4. Results

Based on the statistical analysis, the studied traits of (*Eruca sativa* Mill.) exhibited significant differences between the two cultivation systems. Macronutrient (NPK) uptake efficiency, Morphological traits, and Water use efficiency were particularly influenced by the type of system. Table 4 summarises the P-values for these traits, indicating highly significant differences between the hydroponic and soil systems.

Table 4: The probability values(P-Value) for the effect of cultivation system (hydroponic and soil) on macronutrient (NPK) uptake efficiency, morphological traits, and water use efficiency of (*Eruca sativa* Mill.), based on SPSS statistical analysis.

| Studied Trait | P-value |
|---|----------|
| Nitrogen Uptake Efficiency (g/100 g Dry Weight) | (P<.001) |

| | |
|---|----------|
| Phosphorus Uptake Efficiency (g/100 g Dry Weight) | (P<.001) |
| Potassium Uptake Efficiency (g/100 g Dry Weight) | (P<.001) |
| Shoot Length (cm) | (P<.001) |
| Root Length (cm) | (P<.001) |
| Stem Diameter (cm) | (P<.001) |
| Leaf Area (cm ²) | (P<.001) |
| Number of Leaves per Plant | (P<.001) |
| Water Use Efficiency (g L ⁻¹) | (P<.001) |

4.1 Effect of Cultivation System on Nutrient Uptake Efficiency

The results indicate that the average uptake of nitrogen (N) and potassium (K) was higher in arugula (*Eruca sativa* Mill.) grown under the hydroponic system compared with soil cultivation system, with these differences being highly significant ($P < 0.001$). In contrast, the average phosphorus (P) content was higher in arugula grown in the soil system. Figure 2, illustrates these differences between the two cultivation systems.

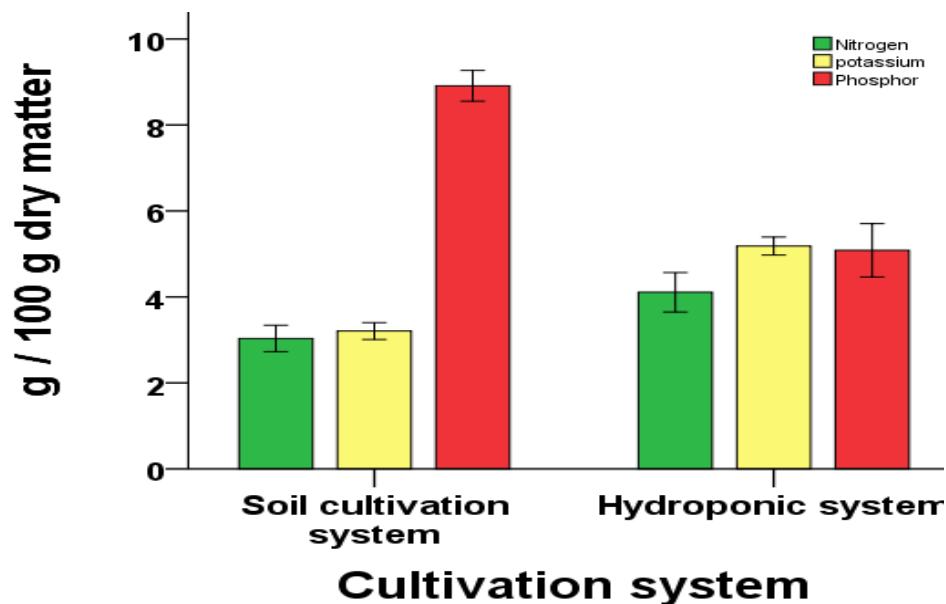


Figure2 :Average nutrient uptake efficiency in arugula (*Eruca sativa* Mill.) (g/100 g dry matter) under hydroponic and soil cultivation systems.

4.2 Effect of Cultivation System on Morphological Traits

The results obtained from the statistical analysis and comparison among the two cultivation systems revealed that arugula (*Eruca sativa* Mill.) grown under the hydroponic system exhibited the highest averages for shoot length, root length, stem diameter, and leaf area, as shown in Table 5. Additionally, the highest number of leaves per plant was recorded under the hydroponic system, as illustrated in Figures 3 and 4. All differences between the means were highly significant ($P < 0.001$).

Table 5: Morphological Traits of Arugula (*Eruca sativa* Mill.) in two Cultivation Systems.

| Cultivation System | Shoot Length (cm) | Root Length (cm) | Stem Diameter (cm) | Leaf Area per Plant (cm ²) |
|-------------------------|-------------------|------------------|--------------------|--|
| Soil cultivation System | 7.42 ± 0.22 | 6.88 ± 0.19 | 0.20 ± 0.02 | 38.38 ± 2.16 |
| Hydroponic System | 15.67 ± 0.50 | 13.38 ± 0.87 | 0.34 ± 0.019 | 167.46 ± 7.9 |

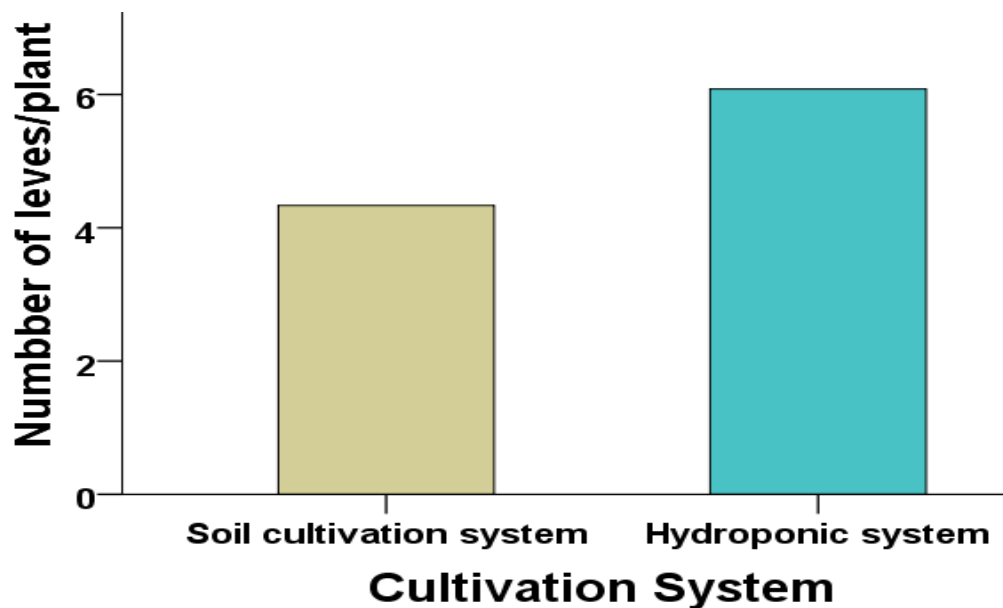


Figure 3: Average number of leaves per arugula plant(*Eruca sativa* Mill.) under hydroponic and soil cultivation systems.



Figure 4: The number of leaves per arugula plant(*Eruca sativa* Mill.) in each system was recorded as follows: hydroponic system (1) and soil cultivation system (2).

4.3 Effect of Cultivation System on Water Use Efficiency

The results indicate that the average water use efficiency (WUE) of arugula (*Eruca sativa* Mill.) grown under the hydroponic system was approximately four times higher than that of plants grown in the soil cultivation system. This difference between the means was highly significant ($P < 0.001$). Figure 5, illustrates these differences between the two cultivation systems.

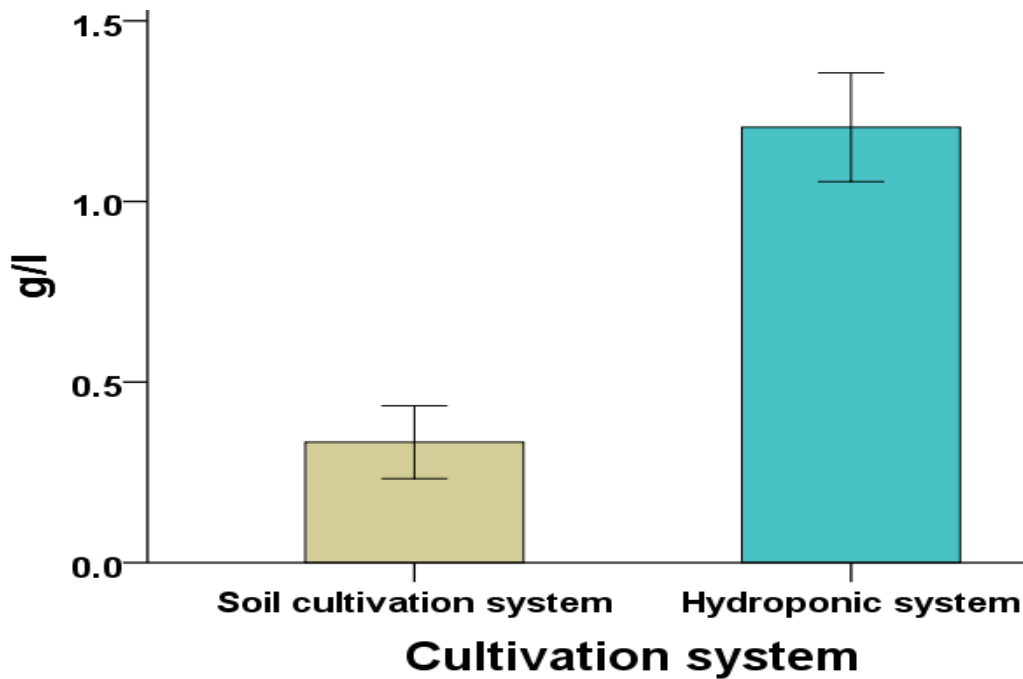


Figure 5: Effect of the cultivation system on the mean water use efficiency of arugula (*Eruca sativa* Mill.) under hydroponic and soil cultivation systems.

5. Discussion

Based on the results shown in Figure 2, the elevated concentrations of nitrogen (N) and potassium (K) observed in hydroponically grown arugula can be attributed to the elimination of the soil matrix resistance, which facilitates continuous mass flow and diffusion of ions (NO_3^- and K^+) directly to the root plasma membranes. In conventional soil systems, tortuous diffusion pathways and localized moisture depletion zones frequently govern nutrient availability. Conversely, the hydroponic system maintains a constant electrochemical gradient across the root zone, optimizing active transport kinetics. This luxury consumption of N and K directly stimulates downstream metabolic processes, such as chlorophyll synthesis and enzymatic activity. These findings are consistent with [11], who reported that soilless-grown plants exhibit higher uptake of essential nutrients such as nitrogen, magnesium, and iron. Increased nutrient uptake efficiency positively influences the synthesis of plant compounds, such as chlorophyll, which enhances nutritional value. This is supported by the findings of [12] on soybean (*Glycine max*). Lipid content increased from 17.37 to 21.94 g/100 g dry matter, and total dietary fiber increased from 21.67 to 28.46 g/100 g dry matter in hydroponic cultivation compared to soil-grown plants. Similarly, [16] reported that in chrysanthemum (*Chrysanthemum morifolium*), the concentrations of chlorogenic acid and flavonoids were higher in hydroponic cultivation than in soil-grown plants by 0.6 and 6.5 mg/g dry weight, respectively.

Conversely, the superior phosphorus (P) content in soil-grown arugula presents a distinct biochemical paradox. While P availability in closed hydroponic systems is often compromised by pH fluctuations that trigger chemical precipitation with divalent cations (Ca^{+2}) soil-grown plants possess specialized adaptive mechanisms. Under localized P-limitation, arugula roots actively modify their rhizosphere by exuding organic acids (such as malate and citrate) and acid phosphatases. These exudates effectively chelate bound cations and solubilize inorganic phosphorus complexes, rendering them highly bioavailable. This suggests that while hydroponics excels in delivering highly mobile ions, the biochemical complexity of the soil rhizosphere can be superior for the mobilization of highly immobile elements like phosphorus.

As shown in Table 5 and Figures 3 and 4, the comprehensive enhancement of all evaluated morphological traits—including shoot length, root length, and leaf area—in the hydroponic system reflects an optimized source-sink relationship. In the absence of mechanical impedance from soil compaction, the hydroponic root system expands with minimal physical resistance. Accompanied by high dissolved oxygen (DO) levels characteristic of closed systems, cellular elongation within the root apical meristem is maximized. This robust root architecture directly underpins shoot development. The enhanced nitrogen assimilation fuels the synthesis of Rubisco and photosynthetic pigments, resulting in the observed expansion of leaf area and leaf number. This creates a positive feedback loop: increased "source" capacity (leaf area) accelerates net carbon fixation, which is subsequently translocated to sustain growing "sinks" (stems and leaves). These results are in agreement with [35], who observed that cucumber plants grown hydroponically had higher average plant height and leaf length (68.5mm and 5mm, respectively) than soil-grown plants. Similarly, [18] reported increases in shoot and root length by 35.2% and 84.1%, respectively, in wheat under hydroponic cultivation. In chrysanthemums, [16] also reported an increase of 16 flowers per plant and an 8 g increase in dry weight per flower compared to soil-grown plants. Moreover, the study by [20] found that fresh and dry weights of roots and leaves, as well as leaf area in

green basil, lettuce, radish, dill, and coriander, were all significantly higher in hydroponic cultivation than in soil-based cultivation.

The fourfold increase in WUE within the hydroponic configuration represents a significant reduction in non-productive water loss Figures 5. Traditional soil cultivation is inherently inefficient due to substantial water loss via deep percolation and surface evaporation. By isolating the nutrient solution, the closed hydroponic system ensures that water consumption is strictly coupled to transpirational flow.

Furthermore, the luxury accumulation of potassium (K^+) in hydroponic arugula likely optimized stomatal kinetics. Adequate intracellular K^+ levels allow for rapid and precise stomatal regulation, enabling the plant to close its stomata during peak vapor pressure deficits (VPD) to prevent luxury transpiration without restricting internal CO_2 fixation. Consequently, these findings are consistent with [15], who reported similar improvements in water use efficiency in tomato cultivation. Similarly, [36] observed that water consumption for cucumber production decreased by 33% under a closed hydroponic system compared to conventional soil cultivation, attributing the reduction to the recirculation of irrigation water. Our results are further supported by [25], who reported that producing one ton of green fodder in a hydroponic system required 114 m^3 less water than in open-field production. Consequently, water use efficiency based on fresh biomass in hydroponic cultivation was 48 times higher than in conventional soil-based cultivation.

6. Conclusion

This study clearly demonstrates that hydroponic cultivation substantially improves nitrogen (N) and potassium (K) uptake efficiency, key morphological traits, and water use efficiency in arugula (*Eruca sativa* Mill.), despite a lower phosphorus (P) accumulation compared to soil-grown plants. These distinct physiological advantages highlight hydroponics as a highly promising and resilient strategy for crop production on marginal lands, including areas characterized by rocky or saline soils. Although hydroponic systems entail higher initial capital investment and require precise technical management, their profound environmental benefits—marked by minimized water waste and accelerated biomass accumulation—position this technology as a vital tool for achieving high-quality, sustainable crop yields in future agricultural frameworks.

Acknowledgments

We would like to express our sincere appreciation to Eng. Abdulraouf Al-Shatti, Executive Director of Hydrolibya for Hydroponic Agriculture, for his valuable scientific and practical cooperation, which significantly contributed to the successful completion of this study.

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