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# Growth Stimulation and Nutritional Health of Sorrel (*Rumex acetosa*) in Controlled Environment Using Supplemental LED lamps and new water resources

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Original Article

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## ABSTRACT

Sorrel (*Rumex acetosa*) is a nutritionally valuable leafy vegetable recognized for its high ascorbic acid, antioxidants, and bioactive compounds, making it suitable for controlled-environment production. This study examines the effects of water sources and light treatments on sorrel growth in a vertical hydroponic system using a factorial experiment with three replications. Water treatments included distilled water (DW), quantum water (QW) synthesized via diode laser irradiation, and hybrid water (HW) produced through cold plasma exposure and magnetization. Light treatments involved natural greenhouse light (AL) and supplemental LED light (SL). Results revealed that hybrid water combined with supplemental LED light (SL + HW) significantly enhanced vegetative parameters, including water use efficiency, chlorophyll index, and relative water content. The highest plant height (21 cm) was observed in the AL + HW treatment (27% more than the control), while SL + HW had the highest root fresh weight (6.7 g). vegetative yield peaked in SL + QW and AL + QW treatments (with a 40% increase compared to the control). Treatments SL + QW and SL + HW have the most Net photosynthesis rates (18.3 and 17.4 µmol $CO_2$ $m^{-2}$ $s^{-1}$, 47% increase compared to the control). Conversely, nitrate levels were highest in DW + AL treatments, while nitrate reductase activity was maximized in SL + HW. These findings highlight the importance of water quality and light conditions in optimizing sorrel growth and nutrient dynamics in hydroponic systems. The SL + HW combination demonstrated the strongest effects on growth and quality, while QW paired with supplemental light also showed significant benefits. This approach supports sustainable hydroponics in water-scarce regions, ensuring reliable food production.

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## 1.Introduction

As the global population continues to rise, the demand for sustainable food production methods has become increasingly urgent. Vertical hydroponic systems have emerged as a promising solution, allowing for the cultivation of vegetables in controlled environments without the need for soil. This innovative approach not only maximizes space utilization but also significantly reduces water usage compared to traditional farming methods, making it particularly suitable for urban settings where land is scarce (Dhandapani et al., 2025).

Recent advancements in hydroponic technology have highlighted the importance of optimizing growth conditions through the integration of hybridized water systems and supplemental lighting. Hybridized water, which is enriched with elevated levels of dissolved oxygen, has been shown to enhance nutrient uptake and promote healthier root systems, leading to improved plant growth and yield (Bakirov et al., 2025). Concurrently, the use of supplemental LED lighting allows for precise control over the light spectrum, which can be tailored to meet the specific needs of different crops. Research indicates that the strategic application of various light wavelengths can enhance photosynthesis, increase biomass, and improve the nutritional quality of produce (Budavári et al., 2024; Naresh et al., 2024). A recent study explored combining plasma discharge and nanocavitation to enhance hydroponic nutrient solutions. Testing individual and hybrid applications (3-15 min), results showed 9-min hybrid treatment boosted lettuce yield by 60%. The synergy improved nutrient stability, solubility, and antimicrobial effects while increasing flavonoids/potassium and reducing iron. The findings demonstrate plasma-nanobubble synergy's potential for optimizing hydroponic cultivation (Abbaszadeh and Bushehri, 2024). Cold plasma technology enhances hydroponic water treatment by improving nutrient availability and plant health. It generates nanobubbles, boosting dissolved oxygen levels up to ~30 ppm. Plasma-activated water (PAW) can replace synthetic nitrates, supporting sustainable agriculture. Studies show PAW boosts growth in leafy greens like green oak lettuce (Ruamrungsri et al., 2023). Other study combines microbubble technology with cold plasma to generate PAW, which has shown promising results in promoting plant growth and improving nutrient uptake in peanut, garlic and soybean sprouts (Han et al., 2025). Magnetic water treatment is an innovative technology that leverages the molecular structure of water and the interactions among its molecules. Water, being a dipolar molecule with a bent shape due to the repulsive forces from lone electron pairs on the oxygen atom, plays a crucial role in hydrogen bond formation (Mozafariyan et al., 2017). The positive effects on the biochemical and physiological characteristics of crops are attributed to the magnetic field's ability to modify water's surface tension and solubility, as well as its pH and electrical conductivity. Research on crops such as chicory, lettuce, and tomatoes has shown that using magnetized water in hydroponic systems results in increased nutrient uptake and enhanced growth parameters, including greater shoot height and leaf area (Alattar et al., 2022; Yao et al., 2024).

In recent years, advances in multispectral supplementary and LED lights have enabled precise control of light quality and spectrum, prompting extensive research on plant responses in fully artificial environments like plant factories. Light is a crucial environmental factor influencing plant growth and development. Recent advances in LED technology have made it an efficient supplemental light source. Light intensity and quality regulate photosynthesis and photoreceptor activity, affecting plant morphology, physiology, and metabolism (Martínez-Moreno et al., 2024; Wong et al., 2022). Optimizing light in these systems is key to enhancing growth, efficiency, and nutritional quality. Blue and red wavelengths are commonly used in controlled-environment plant production, as they closely align with the primary absorption peaks of chlorophyll pigments (Seif et al., 2021).

Specific wavelengths of light have distinct effects on plant growth. Blue light (400-525 nm) is particularly effective in promoting vegetative growth and enhancing chlorophyll production, which is vital for photosynthesis. Studies indicate that blue light can lead to increased leaf area and biomass in leafy vegetables such as lettuce and spinach (Martínez-Moreno et al., 2024). Conversely, red light (600-700 nm) is crucial for flowering and fruiting, influencing processes such as stem elongation and leaf expansion. The combination of red and blue light has been shown to optimize growth conditions, resulting in improved yield and nutritional quality (Trivellini et al., 2024; Wu et al., 2024).

Researchers found that an RB ratio of 3 maximized biomass production, chlorophyll content, and antioxidant activity in leafy vegetables like lettuce and basil, while also improving resource use efficiencies such as water, energy, and land surface (Pennisi et al., 2024). This indicates that spectral tuning, particularly adjusting the RB ratio, plays a crucial role in enhancing physiological and metabolic plant responses. For instance, a study found that a spectral ratio of red to blue light at 1.25:1 improved lettuce yield and antioxidant activity (Mohamed et al., 2021; Alrajhi et al., 2023).

Studies have shown that varying light intensities can affect the accumulation of essential nutrients in hydroponically grown crops, with higher intensities often resulting in greater biomass but not necessarily improved quality (Yang et al., 2024). In recent decades, Mediterranean vegetable production has grown in yield and cultivated area, despite a decline in the number of farms. This has led to higher output per grower, driven by technological advancements, greenhouse adoption, and export-oriented cultivation (Petropoulou et al., 2023).

Some research highlights the importance of light spectrum management, especially the red and blue (RB) ratio, in optimizing plant growth and resource use efficiency in indoor cultivation systems such as vertical farms and controlled environment chambers (Zhou et al., 2024). Further investigations into eco-efficiency from a life cycle perspective revealed that lower RB ratios are more energy-efficient but yield lower crop biomass, thus reducing overall eco-efficiency (Van Brenk et al., 2025). Conversely, higher RB ratios improve yield and physiological performance but at increased energy costs, primarily due to LED electricity consumption. This trade-off underscores the need for balancing spectral quality with energy sustainability in indoor farming (Dauchot et al., 2024), while light intensity (Pennisi, 2019) identified 250 µmol $m^{-2}$ $s^{-1}$ as the optimal photosynthetic photon flux density (PPFD) for maximizing biomass, stomatal conductance, and secondary metabolite activity in basil and lettuce. Increasing light intensity up to this level enhanced biomass accumulation and resource use efficiency, while further increases did not produce significant gains and could potentially lead to energy wastage (Palikrousis et al., 2024).

The photoperiod also influences plant growth, with responses varying among species. For example, basil and rocket showed no significant biomass differences across photoperiods of 16/8, 20/4, and 24/0 hours, whereas lettuce and chicory favored shorter photoperiods (16/8 hours) for optimal biomass and water use efficiency. These findings suggest that species-specific responses should guide photoperiod management in indoor cultivation (Pennisi et al., 2020). Overall, the literature underscores that optimal supplementary lighting for leafy vegetables involves a carefully calibrated combination of spectral quality, particularly an RB ratio around 3, light intensity near 250 µmol $m^{-2}$ $s^{-1}$, and a photoperiod of approximately 16 hours of light per day (Zha et al., 2018).

Future research should continue to explore multifactorial approaches integrating environmental variables with lighting strategies to further optimize indoor leafy vegetable production systems. The integration of supplementary lighting and optimized water resources plays a crucial role in enhancing the efficiency and productivity of hydroponic vegetable cultivation. Despite the individual benefits of these technologies, their synergistic effects in vertical hydroponic systems remain underexplored. Understanding how hybridized water and optimized lighting interact could unlock new potentials for vegetable production, enabling growers to achieve higher yields and better quality crops in a resource-efficient manner. This paper aims to investigate these synergistic effects, providing insights that could inform best practices for urban agriculture and contribute to global food security. Leafy vegetables such as sorrel (*Rumex acetosa*) have gained significant importance not only as salad vegetables in the food industry but also in the pharmaceutical and dietary product sectors due to their valuable nutrient composition, essential vitamins, and minerals. This study aims to investigate the main and interaction effects of different LED light regimes and three water sources on the growth and physiological parameters of sorrel as a leafy vegetable in hydroponic system.

## 2.Materials and Methods

### 2.1. Experimental Design

This study was conducted as a factorial experiment with two factors (water sources × light treatment) based on a completely randomized design with three replications using a vertical hydroponic system. Each experimental unit consisted of three cylindrical column features 12 flores of 4-hole modules with standard dimensions (2.8m height × 40cm width, purchased from Rahat_GIGAS Sepahan Co., Isfahan). Cooper's nutrient formulation was continuously supplied in two stock solutions: Stock A (containing calcium nitrate and micronutrients) and Stock B (containing potassium sulfate and ammonium phosphate) with EC=1.8 dS/m and pH=5.8.

### 2.1. Plant Preparation

Sorrel (*Rumex acetosa*) seeds with 99% genetic purity were obtained from Nazboo Company, Yazd. Seeds were surface-sterilized with 1% sodium hypochlorite for 3 minutes, then germinated in coco peat substrate (70% moisture) at 25°C in trays. Then Two-leaf seedlings were transferred to vertical aeroponic modules containing specific rockwool after 3 weeks.

### 2.2. Treatments

#### 2.2.1. Water Treatments (Factor 1)

**Distilled water (DW): Control with EC <0.5 µS/cm.**

Quantum water (QW): Quantum water (QW) was synthesized by irradiating deionized water with a diode laser operating at 632 nm wavelength and 50–100 mW output power for two hours. The irradiation process was conducted in a UV/IR-free quartz chamber to minimize external interference and ensure the purity of the treatment conditions. Throughout the procedure, the system temperature was strictly maintained between 25 and 30 °C using a circulating chiller, thereby preventing thermal fluctuations that could influence molecular reorganization. Following irradiation, the structural characteristics of the treated water were examined using Raman spectroscopy, focusing on the 3000–3500 $cm^{-1}$ region corresponding to O–H stretching vibrations. This analysis was performed to identify possible alterations in hydrogen bonding networks, which serve as a key indicator of quantum water formation (Prepared in the Optics and Laser Repair, Arman-teb Laboratory).

Hybrid water (HW) was prepared through a two-step physical modification process that combined cold plasma exposure and sequential magnetization. In the first stage, deionized water was subjected to a 10-minute treatment using direct-current (DC) cold plasma at atmospheric pressure, a method known to generate reactive species and induce modifications in the physicochemical properties of water without the need for chemical additives. Immediately following plasma treatment, the water underwent magnetization by exposure to a static magnetic field with an intensity of 0.5 Tesla for 14 minutes. This sequential process was designed to integrate the structural and energetic alterations induced by plasma with the molecular alignment and hydrogen bond reconfiguration promoted by magnetization, thereby producing hybrid water with potentially enhanced physicochemical characteristics suitable for experimental and applied investigations (Arman-teb Laboratory, Kerman, Iran). Throughout the experiment, the pH of hybrid water, which is a combination of plasma-activated water (PAW) and magnetic water, ranged from 1.7 to 2.4, while the pH of untreated water was approximately 5.8 to 6.3.

**Light Treatments (Factor 2)**

Natural greenhouse light (AL): 380-400 µmol/m²/s intensity for 9 hours (7 AM to 4 PM).

The supplemental LED light (SL) employs a wavelength ratio of 7:3 for red (660 nm) and blue (450 nm) light. The lighting duration is set for four hours, from 4 to 8 PM, strategically chosen to complement the diminishing natural light during this period, thereby maximizing photosynthetic activity. The lights are positioned about 50 cm above the canopy using adjustable hangers and legs to ensure even distribution and minimize shadowing. The AL + DW treatment serves as a control, and the specific LED lamps purchased from Iran Sunlight Company are designed for energy efficiency and low heat output.

**Table 1 Treatment Codes Description**

| Treatment code | |
|---|---|
| **SL+DW** | Supplemental LED + Distilled water (Control) |
| **SL+QW** | Supplemental LED + Quantum water |
| **SL+HW** | Supplemental LED + Hybrid water (Plasma + Magnetized) |
| **AL+DW** | Ambient greenhouse light + Distilled water |
| **AL+QW** | Ambient greenhouse light + Quantum water |
| AL+HW | Ambient greenhouse light + Hybrid water |

### 2.4. Measurements and analysis

#### 2.4.1. Measured Parameters and Methods

Vegetative growth traits were determined by measuring Head height using a digital caliper with 0.1 mm precision, while vegetative yield and root fresh weight were recorded by scaling with an analytical balance. Leaf dry weight was assessed after drying samples in a forced-air oven at 65 °C for 72 hours until constant weight was achieved. Photosynthetic performance, including net photosynthetic rate ($P_n$), intercellular $CO_2$ concentration, and water use efficiency (WUE), was measured using a portable photosynthesis meter (Korea Tech Inc.) under controlled conditions. Physiological parameters were evaluated by determining the chlorophyll index using a SPAD-502 chlorophyll meter (Minolta Camera Co., Japan) and calculating relative water content (RWC) using the standard formula: RWC (%) = [(fresh weight – dry weight) / (turgid weight – dry weight)] × 100. For chemical analysis, a microplate reader quantified leaf nitrate concentration by spectrophotometric determination (Epoch, BioTek Instruments, USA). The nitrate content was determined by ultraviolet spectrophotometry according to a published method[19] . Briefly, 1 g of fresh lettuce was heated in a boiling water bath with 10 mL of distilled water for 30 min. After cooling, the extract was filtered into a volumetric flask. A 0.1 mL aliquot of this solution was mixed with 0.4 mL of 5% salicylic acid in sulfuric acid, followed by 9.5 mL of 8% NaOH. The nitrate concentration of the resulting mixture was measured at 410 nm using a UV-VIS spectrophotometer (Epoch, BioTek Instruments, USA). To measure Nitrate Reductase Activity (NRA) using a modified method (Jaworski, 1971), prepare 50 mg of 2 mm cut lettuce leaves and incubate them in a dark vial with potassium phosphate buffer (0.05 M, pH 7.8) and KNO2 (0.4 M). Evacuate samples for 3 minutes, then incubate at 37 °C for 75 minutes, stopping the reaction by boiling for 5 minutes. Finally, add sulfanilamide (1%) and naphthyl (0.020%) to 200 µL of the extract, let stand for 30 minutes, and measure absorbance at 540 nm to quantify nitrite formed (µmol $NO_2^-$ $h^{-1}$ $g^{-1}$ FW) using a standard curve (Nieves-Silva et al., 2024).

#### 2.4.2. Statistical Analysis

Data were analyzed using SAS 9.4 with ANOVA at 5% significance level. Mean comparisons used Duncan's test. Each treatment had three replications with 48 plants in vertical multi-ponic greenhouse modules**.**

**Figure 1. Vertical aeroponic cultivation system for Sorrel plants in CAE**

**Table 2. Analysis of variance of sorrel characteristics**

| Source of Variation | df | Head height | Vegetative yield | Root fresh weight | Leaf dry weight | Net photosynthesis rate | Intercellular $CO_2$ |
|---|---|---|---|---|---|---|---|
| **Water source** | 2 | 1103$^{ns}$ | 183.7$^{*}$ | 45.1$^{*}$ | 239.8$^{*}$ | 95.7$^{**}$ | 179.5$^{**}$ |
| **Light type** | 1 | 256$^{*}$ | 937.2$^{**}$ | 23.12$^{ns}$ | 543.9$^{*}$ | 1.81$^{**}$ | 2.37$^{**}$ |
| **$Water_s \times Light_t$** | 2 | 671$^{**}$ | 812.6$^{*}$ | 4.2$^{*}$ | 24.37$^{**}$ | 1.74$^{**}$ | 0.58$^{**}$ |
| **Error** | 12 | 11 | 477.8 | 2.98 | 110/0 | 0.63 | 180.5 |
| **C.V. (%)** | - | 17.15 | 13.25 | 10.70 | 7.84 | 12.70 | 10.65 |

**Table 2 (continued)**

| Source of Variation | df | Chlorophyll index | Relative water content | nitrate level | Nitrate Reductase Activity | Water use efficiency |
|---|---|---|---|---|---|---|
| **Water source** | 2 | 73.5$^{*}$ | 35.7$^{**}$ | 0.09$^{*}$ | 0.045$^{*}$ | 25.62$^{**}$ |
| **Light type** | 1 | 0.42$^{**}$ | 18/0$^{*}$ | 0.03$^{**}$ | 0.051$^{**}$ | 237.76$^{*}$ |
| **$Water_s \times Light_t$** | 2 | 13.25$^{*}$ | 10.57$^{*}$ | 0.02$^{*}$ | 0.008$^{*}$ | 3453.11$^{**}$ |
| **Error** | 12 | 10.62 | 7.14 | 8.30 | 3.30 | 7.40 |
| **C.V. (%)** | - | 9.11 | 11.83 | 11.30 | 6.55 | 5.1 |

** = significant at $P \leq 0.01$; * = $P \leq 0.05$; ns = not significant

## 3. Results

### 3.1. Vegetative parameters

### 3.1. Head Height

Based on the results of this experiment, the highest plant height (21 cm) was observed in the AL + HW treatment, which involved the combined application of hybrid water + ambient greenhouse light. This value, however, was not significantly different from the results obtained under the other two treatments: (i) combined with quantum water, and (ii) greenhouse ambient lighting combined with sterile water (Figure 1a). Previous studies have demonstrated that red–blue LED lighting can enhance photosynthesis and promote vertical growth in plants.

### 3.2. Vegetative Yield

The highest edible vegetative yield of sorrel was measured in the two treatments of quantum water + 4 hours of supplemental LED light (SL + QW) and quantum water + greenhouse ambient light (AL + QW) (Figure 2, b).

### 3.3. Root Fresh Weight

As indicated by the results in Table 2, the highest fresh root weight in plants treated with a combination of hybrid water application and 4-hour supplemental LED light following greenhouse light (SL + HW) was measured at 6.7 grams.

### 3.4. Leaf Dry Weight

In this study, all three water sources, quantum, distilled, and hybrid, have the maximum leaf dry weight, especially combined with supplementary light followed by ambient light in the greenhouse, while the treatment of distilled water and ambient light without supplementary light has the minimum leaf dry weight.

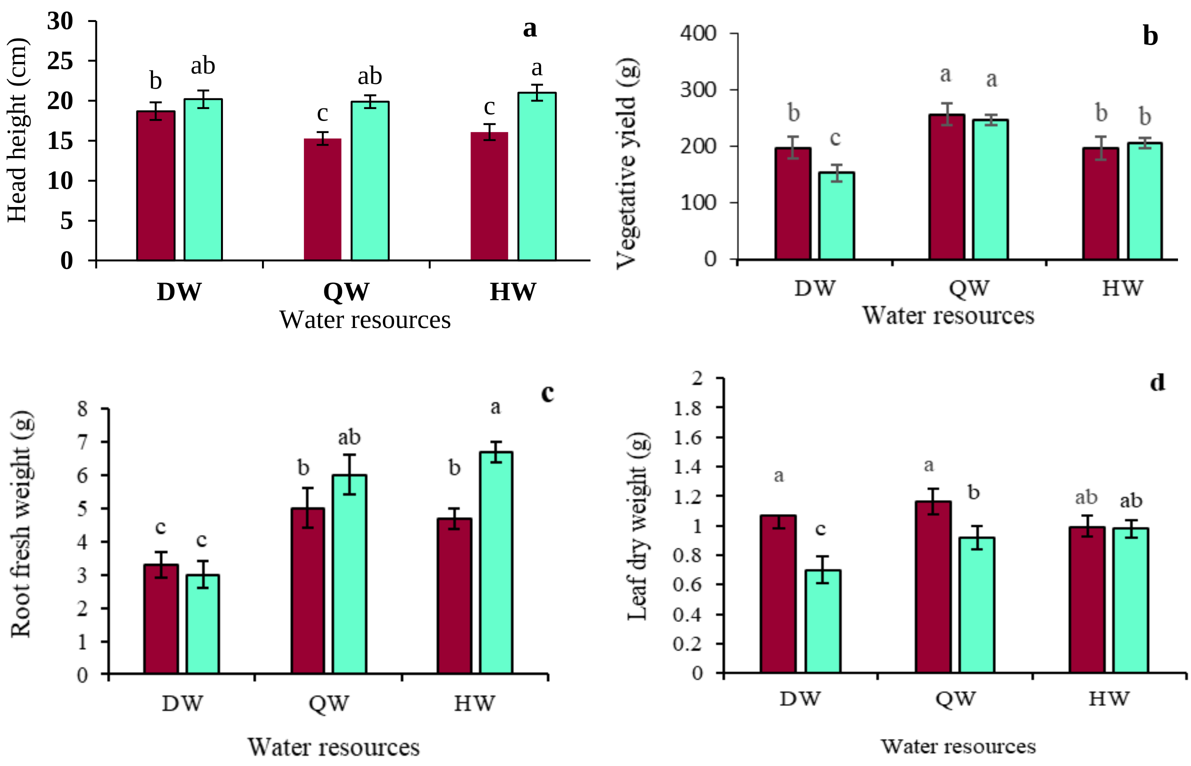


**Figure 1 Effects of different water sources and light types on head height (a), vegetative yield (b), root fresh weight (c), and leaf dry weight (d) of Sorrel in controlled environments. Values are means of three replicates ± SE.**

### 3.2.Gas Exchange and Physiological Parameters

#### 3.2.1. Net photosynthesis rate ($P_n$)

Gas exchange was strongly influenced by both water sources and light treatments (Figure 2a–c). Net photosynthesis ($P_n$) were highest in both treatments, including quantum water + supplementary LED light following ambient light and hybrid water + supplementary LED light following natural light ($P_n$: 18.3 and 17.4 µmol $CO_2$ $m^{-2}$ $s^{-1}$, respectively) and lowest in the control as distilled water with only ambient light ($P_n$: 9.68 µmol $CO_2$ $m^{-2}$ $s^{-1}$), while the lowest $P_n$ was measured under the conditions of greenhouse ambient light + quantum water and greenhouse light + sterile water, of course, it showed no significant difference with the quantum water + supplementary LED light treatment following ambient greenhouse light (Figure 1a).

#### 3.2.2. Inter Cellular $CO_2$

Intracellular $CO_2$ was higher in both treatments (SL + HW and SL + QW), including hybrid water + supplementary LED light following natural light, and then in quantum water +4 hours of supplementary LED light following natural light, without significant differences (Figure 2, b).

#### 3.2.3.Water Use Efficiency (WUE)

The highest water use efficiency in plants was obtained under treatment (SL + HW) with hybrid water + supplementary LED light following natural greenhouse light, while the lowest WUE was achieved in the quantum water + only natural light inside the greenhouse treatment.

#### 3.2.4.Chlorophyll Index

The highest chlorophyll index was obtained in the leaves of the vertical system nourished with quantum water + 4 hours of supplementary LED light following natural light, resulting in a net photosynthesis rate. The lowest value for this index was observed in plants affected by the greenhouse ambient light and both quantum and distilled water sources (AL +DW, AL + QW) (Figure 3, a).

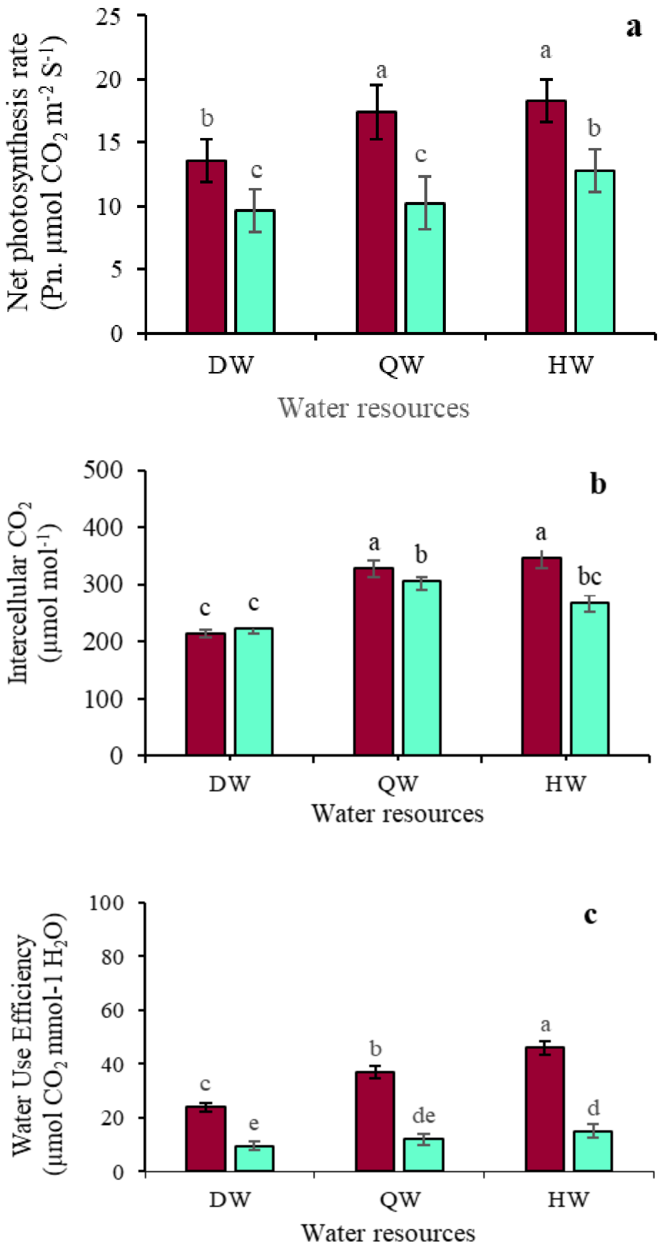


**Figure 2. Effects of water sources and light treatments on net photosynthesis rate (Pn) (a), intercellular CO2 (b), and water use efficiency (WUE) of Sorrel in controlled environments. Values are means of three replicates ± SE.**

#### 3.2.5. Relative Water Content (RWC)

Significant differences were observed among treatments in leaf relative water content. The RWC was highest in hybrid water + supplementary LED light following ambient light (SL + HW) (94%). The lowest leaf relative humidity was measured in control plants treated with distilled water + ambient greenhouse light (AL + DW).

### 3.3. Physicochemical parameters

#### 3.3.1. Leaf nitrate levels

According to the results of this study, the highest level of nitrate was observed in the leaves of heads grown in a system with a distilled water source and ambient light (AL + DW), without supplemental LED light. It appears that a hybrid water source and supplemental LED light resulted in the lowest level of nitrate ion accumulation in sorrel leaves (Figure 2, A).

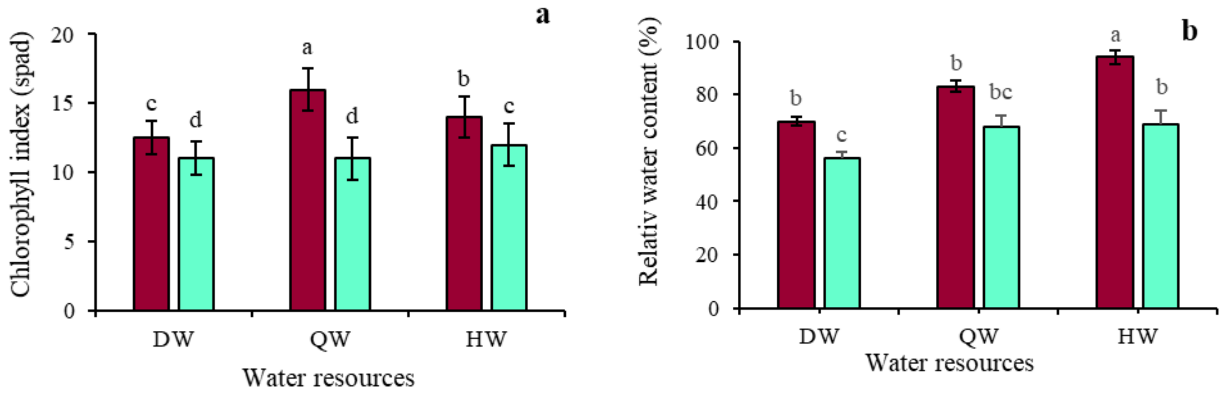


**Figure 3. Effects of water sources and light treatments on chlorophyll index ($P_n$) (a), and Relative water content (RWC) (b) of Sorrel in controlled environments. Values are means of three replicates ± SE.**

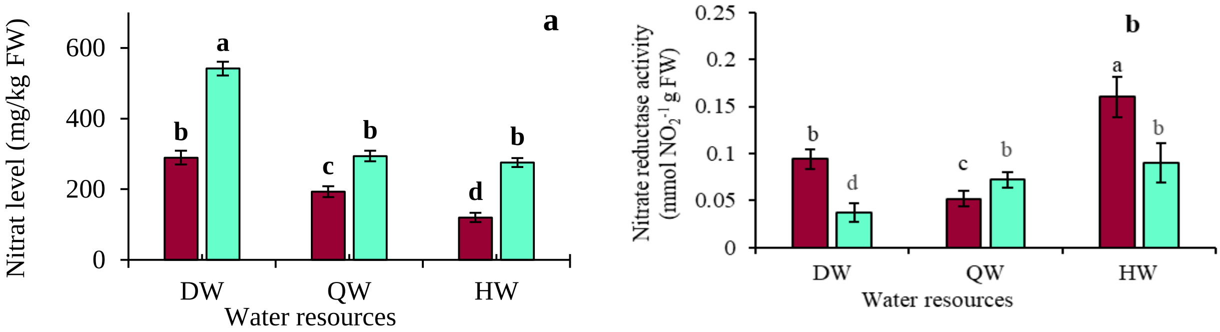


**Figure 4. Effects of water sources and light treatments on Nitrate levels (a), and Nitrate reductase activity (b) of Sorrel in controlled environments. Values are means of three replicates ± SE.**

### 3.3.2. Nitrate reductase activity

The highest activity of nitrate reductase enzyme in plants treated with hybrid water and 4-hour LED light following ambient greenhouse light was measured (SL + HW). In this treatment, the lowest amount of nitrate accumulation in the lettuce heads was also observed. Meanwhile, the lowest unit activity for this enzyme was obtained in heads grown in the system irrigated with distilled water and under natural greenhouse light (AL + DW).

## 4.Discussion

Based on this study's results, the highest plant height was recorded in the AL + HW treatment, indicating that hybrid water combined with natural light promotes vertical growth effectively. According to some reports, magnetized water prevents an increase in water electrical conductivity, a particularly important factor in hydroponic systems (Wu et al., 2020). In the present study, better stability of the nutrient solution's electrical conductivity was also observed under magnetized water application, which in this research was referred to as a hybrid water component. In our study, both hybrid and quantum water significantly enhance yield when paired with adequate light from a supplementary source. Recent research indicates that mixed red and blue light promotes tomato seedling growth by influencing leaf anatomy, photosynthesis, and $CO_2$ assimilation. The study emphasizes the importance of light quality in enhancing chlorophyll content and overall plant vigor (Arif et al., 2024). On the other hand, according to the results of this experiment, it can be analyzed that the selected and optimized LED light, used as a supplement following natural light in the greenhouse for the cultivation of sorrel, did not cause elongation of the petioles of this plant. In some cases, this elongation occurs in plants that are shaded by neighboring plants or exposed to infrared light, leading to increased height and non-standard growth of leafy plants. Another study highlighted that magnetically treated water positively affected the nutritional status and yield of lettuce plants. The findings suggested that this treatment could enhance the overall quality of the lettuce, making it more beneficial for consumers (Putti et al., 2023).

The improvement in the root weight of lettuce established in a hydroponic system is likely due to structural changes in the water (reduced surface tension and increased root membrane permeability), which facilitated ion absorption and the activation of growth signaling pathways such as cytokinins (Neypour Dizaj et al., 2019). A study highlighted that supplemental LED lighting, particularly with red light, had a pronounced effect on root fresh weight, especially under stress conditions such as salinity. This aligns with the idea that light quality can enhance root development and nutrient uptake efficiency in strawberry (Malekzadeh Shamsabad et al., 2022), while another study showed that LED Lights in lettuce can lead to improved root conditions. This is attributed to structural changes in water that enhance root membrane permeability, facilitating better ion absorption and signaling pathways related to growth, similar to the findings in our experiment (Qiao et al., 2025). The similar findings indicate that seeds treated with 10 min of PAW of the *Rayo* Marpha variety of tobacco exhibited maximum root and shoot lengths (Alkhatib et al., 2020). These findings suggest that PAW treatment, particularly for 15 min, enhances chlorophyll content in green leafy vegetables, contributing to improved plant quality and metabolic activity.

In another study, the application of magnetized water alone in the plant marjoram did not show a significant difference in the chlorophyll content of this plant (Neypour Dizaj et al., 2019). Research indicates that plasma-activated water can significantly increase chlorophyll content in green leafy plants. This enhancement is attributed to the water's altered chemical properties, which may improve nutrient availability and uptake by the plants (Wong et al., 2023). Magnetized water has been reported to enhance the biochemical composition of plants, including an increase in chlorophyll a and b, carotenoids, and overall photosynthetic pigments. This improvement is linked to better metabolic processes, including photosynthesis and respiration (Chalise et al., 2024). Studies have shown that plants irrigated with magnetized water exhibit increased photosynthetic activity, which correlates with higher chlorophyll content. This is likely due to improved leaf area and light absorption capabilities, allowing for more efficient photosynthesis in Turkish tobacco (Alkhatib et al., 2020). LED light with adaptive spectra (red to blue ratio of 3:1) can increase the quantum yield of photosystem II (PSII) and stimulate the production of ATP and NADPH. Ultimately, all these processes directly affect cell division and the development of plant leaves (Hernández-Adasme et al., 2024). Studies have demonstrated that combining red and blue light with white LEDs can enhance morphology and visual quality, particularly in leafy crops like lettuce (Farhangi et al., 2025). Based on this research, it appears that quantum water may increase the polarity of water by altering its molecular structure and improve root membrane permeability. This facilitates the uptake of ions such as nitrate and potassium, which are essential for chlorophyll synthesis and cell division. Additionally, the combination of quantum water and optimal light may regulate hormonal balance (such as increased cytokinin) and the activity of antioxidant enzymes (such as catalase), both of which play a role in reducing oxidative stress and enhancing growth (Zhang et al., 2022). Research has highlighted the significance of nuclear quantum effects (NQEs) in water, which influence the behavior of water molecules at a molecular level. These quantum effects can alter hydrogen bonding dynamics, enhancing the interaction of water with plant membranes and improving permeability. Additionally, external factors, such as the presence of nanoparticles, can modify the molecular structure of water, leading to changes in its polarity and ability to penetrate biological membranes. The concept of quantum tunneling further suggests that water molecules can break hydrogen bonds, facilitating better interactions with plant membranes and enhancing water's capacity to permeate through root membranes (Ceriotti et al., 2016; Geesink et al., 2020). Controlled environments that optimize these conditions can help manage nitrate levels effectively. For instance, providing adequate light can enhance photosynthesis and nutrient uptake, thereby reducing excess nitrate accumulation in plants (Bian et al., 2020). The use of magnetized or quantum water in hydroponics can enhance plant growth and nutrient uptake. These types of water are believed to improve the structural order of water molecules, which may facilitate better nutrient absorption and reduce stress on plants, potentially leading to lower nitrate accumulation (Li et al., 2023). Research has shown that environmental conditions, such as light duration and soil temperature, significantly affect nitrate accumulation. For instance, prolonged exposure to light can enhance nitrate assimilation, while high soil temperatures may lead to increased nitrate absorption, particularly in hydroponic systems (Calderón e al., 2025). It appears that all nutritional and irrigation structures in plants where molecular arrangements have been altered in novel ways - such as magnetized water, magnetized phosphorus solution, and quantum water - possess the ability to induce positive effects on plant growth through enhancement of the plant's metabolic energy. Recent studies showed that when basil plants were inoculated with arbuscular mycorrhizal fungi (*Divesispora versiformis*) and combined with magnetized $Ca(H_2PO_4)_2 \cdot H_2O$ solution, the P use efficiency further increased (by 23.5% compared to the control in sweet basil (Shabani et al., 2019). Integrating nitrogen-fixing plants, such as alfalfa, in hydroponic systems can enhance nutrient efficiency and reduce reliance on synthetic nitrogen sources. This approach not only improves resource use but also helps maintain lower nitrate levels in the primary crops, such as lettuce. An analysis of the nitrate measurement data from the plants in this experiment indicates that the hydroponic cultivation method significantly contributes to reducing the likelihood of nitrate accumulation in lettuce heads. This same phenomenon is also evident in the findings of other researchers regarding both lettuce and alfalfa in hydroponic systems. (Guffanti et al., 2022; D-Andrade et al., 2025). LED lighting, especially red light, is beneficial in controlling and reducing nitrate levels in leafy greens. One study noted that 100% red light treatment could significantly lower nitrate levels within 2-5 days before harvest (Nicole et al., 2018).

Plasma-activated water (PAW) has shown potential in producing various reactive species that can influence the concentration of bicarbonate, glyoxylate, malate, and carbonic anhydrase, although the direct production of these specific molecules may vary based on the conditions of PAW generation and application (Wartel et al., 2021; Hahn et al., 2024). The presence of the above molecules increases the concentration of carbon dioxide ($CO_2$) around the stomata, facilitating enhanced carbon fixation during photosynthesis and thereby boosting overall efficiency. This rise in intercellular $CO_2$ levels leads to increased photosynthetic rates, allowing plants to utilize more carbon for energy production. Overall, in our experiment, synergistic effects between different water sources and supplemental light were evident for most quantitative and qualitative growth traits of the sorrel plant. These synergistic effects between different water resources, especially between HW and supplementary light, contribute to improved measured parameters in sorrel, further supporting plant health and productivity.

## Conclusion

This study highlights the significant benefits of using hybrid and quantum water combined with affordable supplemental LED lighting in hydroponic systems for growing sorrel, demonstrating improved growth and water use efficiency. The low-cost techniques employed, such as utilizing quantum water created by laser irradiation of deionized water and hybrid water produced through cold plasma treatment, make these methods feasible for large-scale greenhouse applications and long-term use. These innovations not only enhance nutrient delivery and plant health but also optimize resource use, making them suitable for commercial environments and a large range of vegetables. As global demand for sustainable food production rises, the economic viability of these systems, including reduced energy consumption and increased crop yields, positions them as promising solutions for addressing food security challenges in a changing climate.

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## Conflicts of Interest

The author declares no conflict of interest

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