Effects of Different LED Light Spectra on the Shelf Life and Nutritional Quality of Hydroponically Grown Lettuce in a Plant Factory

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Abstract: A study was conducted to assess the shelf life of lettuce grown under three different LED light spectra using hydroponic techniques in a plant factory. The Batavia-type cultivar 'Capira' was used, and seedlings were transferred to an ebb-and-flow system 12 days after sowing. The plant factory was maintained at 25 °C (day), 20 °C (night), with a 12-hour photoperiod, ~400 ppm CO_2, and 60–70% relative humidity. Lettuce was grown under three LED spectra: LED1 = 70% red (610-720 nm) + 30% blue (450-495 nm), LED2 = Full PAR spectrum (400-700 nm), LED3 = 65% red (610-720 nm) + 25% blue (450-495 nm) + 5% white (400 475 nm) + 5% far red (700-760).. After 30 days of growth, the lettuce was harvested and stored at 8 °C and 60–70% humidity for 14 days. Post-storage evaluations included weight loss, chlorophyll degradation, phenolic and flavonoid contents, nitrate levels, and mineral composition. Weight loss ranged from 1.54% to 2.80%, chlorophyll degradation from 8.1% to 11.3%, phenolic decline from 20.2% to 23.2%, and flavonoid loss from 11.68% to 22.6%. Nitrate reduction varied from 26.0% to 47.3%. These results highlight how different LED light spectra influence the postharvest quality and shelf life of hydroponically grown lettuce.

1 INTRODUCTION

The increasing demand for minimally processed fruits and vegetables has drawn significant attention, especially regarding changes in their phytochemical properties during storage. Consumers, informed by scientific research, are becoming more selective, valuing not only sensory qualities like taste, aroma, and texture but also the nutritional content, including vitamins and minerals, when choosing fresh produce (Özgen & Tokbaş, 2007). A substantial body of research indicates that diets rich in fruits and vegetables reduce the risk of chronic diseases (Block et al., 1992). This protective effect is largely attributed to the abundance of antioxidants and flavonoids in these foods, which play a crucial role in promoting health (Hertog et al., 1993). Multiple studies have demonstrated an inverse relationship between fruit and vegetable intake and the incidence of certain cancers (Steinmetz & Potter, 1996; Kaur & Kapoor, 2001). Consequently, identifying phytochemical profiles and evaluating antioxidant capacities are essential steps in advancing clinical research on specific cancer types (Özgen & Scheerens, 2006). However, antioxidant levels in fruits and vegetables are sensitive to various factors, such as species differences, cultivation methods, storage conditions, and pre-treatment processes that affect bioactive compounds (Price et al., 1998; Del Caro et al., 2004). This variability has generated growing interest in assessing the antioxidant capacities of foods consumed regularly (Sağlam, 2007). In recent years, pre-processed fruits and vegetables have gained popularity among consumers due to their convenience in reducing preparation time. Maintaining high-quality standards throughout production and storage is crucial for these products (Martinez et al., 2008).

In this study, three types of LED lighting were used to grow lettuce, which was harvested after 30 days of cultivation. Following harvest, the lettuce was stored for 14 days, with chemical properties analyzed

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at three intervals: on the first, seventh, and fourteenth days of storage. These analyses aimed to assess the effects of storage duration and different lighting conditions on the lettuce's chemical composition. The study provides insight into how pre-harvest environmental conditions, such as light quality, and post-harvest treatments influence the nutritional and phytochemical stability of leafy greens during storage.

The quality of freshly cut fruits and vegetables depends on attributes such as texture, appearance, nutritional value, and flavor (Witkowska & Woltering, 2013). However, this quality degrades over time due to simultaneous biological processes (Witkowska & Woltering, 2014). These processes are influenced by the plant's morphological and physiological characteristics, which are shaped by pre-harvest environmental conditions (Watada et al., 1996; Zou et al., 2019). Therefore, optimizing the growth environment to preserve post-harvest quality is essential for the food industry (Watada et al., 1996; Fanourakis et al., 2016). Proper storage temperatures (0–5°C) are crucial for maintaining the quality of both whole and freshly cut produce (Tian et al., 2014; Tsaniklidis et al., 2014).

In many developing countries, maintaining the cold chain is challenging due to high costs and unreliable electrical infrastructure (Mercier et al., 2017). For example, only 15% of perishable food products in China are transported using refrigerated trucks (USDA, 2008), and India has only recently developed a fully refrigerated supply chain (Dharni & Sharma, 2015). Inadequate temperature control affects not only transportation but also storage at retail outlets and during commercial processing (Likar & Jevšnik, 2006; Tian et al., 2014; Mercier et al., 2017). Therefore, exploring ways to preserve product quality under near-ambient conditions remains a priority, especially in regions where cold chain infrastructure is limited.

The shelf life of fruits and vegetables containing chlorophyll is often constrained by the yellowing caused by chlorophyll degradation (Tay & Perera, 2004). Browning, another common issue, results from the oxidation of phenolic compounds (Fan & Mattheis, 2000; Degl'Innocenti et al., 2005). Phenylalanine ammonia-lyase (PAL) is the first key enzyme involved in the biosynthesis of phenolics and flavonoids via the phenylpropanoid pathway. PAL is induced by stress, and the resulting phenolic compounds offer antioxidant benefits for both plant defense and human health (Fan & Mattheis, 2000; Iakimova & Woltering, 2015; Tsaniklidis et al., 2017). However, excessive phenolic accumulation activates polyphenol oxidase (PPO), which catalyzes the oxidation of phenols into quinones, leading to undesirable browning. While PPO contributes to plant defense against biotic stress, it also accelerates post-harvest deterioration, affecting both the visual appearance and nutritional value of produce (Degl'Innocenti et al., 2005).

UVA radiation (320–400 nm), a primary component of solar UV light, lies outside the spectral range required for photosynthesis (Hogewoning et al., 2012). As a result, its use in indoor cultivation has been limited (Zhang et al., 2020). However, recent from our laboratory shows that supplementing indoor cultivation with UVA light (10 μmol m^{-2} s^{-1}) increases biomass and metabolite accumulation in lettuce plants (Chen et al., 2019). Before commercial application, it is essential to further evaluate the impact of UVA light on post-harvest processes, particularly its influence on shelf life.

The primary aim of this study is to investigate the effects of different LED light treatments on the quality, nutritional content, and shelf life of lettuce during a 14-day storage period. Specifically, the study seeks to evaluate key parameters such as weight loss, pH, electrical conductivity, titratable acidity, phenolic and flavonoid content, and nitrate levels under varying LED light conditions. The objective is to determine whether specific LED treatments can enhance the post-harvest stability of lettuce, preserving both its biochemical and sensory attributes. It is hypothesized that certain LED light treatments will be more effective in minimizing nutrient losses and maintaining product quality, thus extending the shelf life of lettuce. This research aims to provide valuable insights into how LED lighting can be optimized as part of post-harvest management strategies, aligning with the growing demand for high-quality, ready-to-eat produce in the modern food industry.

2 MATERIALS AND METHODS

The experiment was conducted in March 2024 at the Department of Horticulture, Faculty of Agriculture, Çukurova University. A climate-controlled plant growth chamber, measuring 5.0 m in length, 3.0 m in width, and 2.6 m in height, was designed to function as a plant factory for this study. The chamber was equipped to regulate environmental factors essential for optimal plant growth, including temperature, humidity, lighting, CO_2 levels, and air circulation.

These conditions were meticulously controlled to provide an ideal environment for plant development.

Lettuce plants were cultivated in a vertical farming system within the climate-controlled chamber. The system consisted of three stacked tiers made from galvanized steel, with 40 cm of space between each shelf, maximizing space efficiency. The plants were grown using the Ebb-Flow hydroponic technique, also known as the "Med-Cezir" technique in Turkish. This method periodically floods the plant roots with nutrient-enriched water, followed by drainage, ensuring the roots receive both optimal nutrition and aeration. The model plant selected for the study was green-leaf lettuce, a widely cultivated leafy vegetable, chosen for its suitability for indoor farming and sensitivity to controlled environmental conditions, making it ideal for hydroponic research. Twelve days after sowing, the lettuce seedlings were transferred to the Ebb-Flow hydroponic system (Figure 1). Environmental conditions in the plant factory were carefully managed to ensure optimal growth. Daytime temperatures were set at 25°C and nighttime temperatures at 20°C, with a 12-hour light/12-hour dark photoperiod. CO_2 levels were maintained at approximately 400 ppm, and relative humidity was kept between 60-70%. Lettuce plants were exposed to three distinct LED lighting configurations:

LED1 = 70% red (610-720 nm) + 30% blue (450-495 nm)

LED2 = Full PAR spectrum (400-700 nm)

LED3 = 65% red (610-720 nm) + 25% blue (450-495 nm) + 5% white (400 475 nm) + 5% far red (700-760).

The lettuce plants were cultivated under these controlled conditions using hydroponic techniques for 30 days before being harvested. After harvest, the plants were stored in a cold storage facility at 8°C with 60-70% humidity for 14 days. At the end of the storage period, various parameters were measured, including weight loss, chlorophyll content, phenol and flavonoid concentrations, nitrate levels, and mineral nutrient content. This approach enabled a comprehensive evaluation of the effects of different lighting conditions and storage durations on the post-harvest quality of lettuce.

Measurements and Analyses Conducted in the Experiment

Weight Loss: The fresh weight of the lettuce plants was measured on days 1, 7, and 14 using a precision scale. Based on these measurements, the percentage of weight loss was calculated to assess moisture loss over time.

Dry Matter (%): Dry matter content was determined by measuring both the fresh and dry weights of the plants. This analysis evaluated how much dry matter was produced per 100 g of fresh lettuce under different treatments.

Total Phenolic Content (mg GAE/100 g FW): The total phenolic content in lettuce leaves was measured using a modified version of the spectrophotometric method described by Spanos and Wrolstad (1990). Absorbance was recorded at 765 nm using a spectrophotometer (Perkin Elmer Lambda EZ201 UV/VIS). Phenolic content was calculated from a calibration curve prepared with gallic acid (Dasgan et al., 2022; Ikiz et al., 2024).

Figure 1: Lettuce plants grown in a plant factory using a hydroponic system under three different LED light spectra.

Total Flavonol Content (mg RUT/g FW): Flavonol content in the lettuce leaves was measured according to the method developed by Quettier-Deleu et al. (2000). Absorbance readings were taken at 415 nm using a spectrophotometer (Perkin Elmer Lambda EZ201 UV/VIS), with flavonol content calculated based on a calibration curve using rutin (Ikiz et al., 2024).

Nitrate Content (ppm): A quarter of each lettuce plant was used to determine nitrate levels using a colorimetric method based on the salicylic acid nitration procedure (Cataldo et al., 1975; Dasgan et al., 2023a; Balik et al., 2025).

Total Soluble Solids (TSS) (%): The lettuce plants were divided into four sections, and juice was extracted from one-quarter of each plant using a juicer. The soluble solid content (SSC) was measured using a digital refractometer (Keskin et al., 2025).

EC and pH Measurements: To measure electrical conductivity (EC) and pH, 100 ml of lettuce leaf juice was extracted. The EC and pH values were recorded using a combined pH and EC meter to evaluate the effects of treatments on leaf nutrient balance (Keskin et al., 2025).

Titratable Acidity (%): Titratable acidity was measured by adding 50 ml of distilled water to 1 ml of lettuce juice and titrating the mixture with 0.1 N NaOH until the pH reached 8.1. The amount of NaOH used was recorded to quantify acidity.

L, a, b Color Measurement: Lettuce color was assessed using a digital colorimeter to measure Hunter color parameters (L*, a*, b*). The colorimeter was calibrated with a white ceramic plate (L = 96.96, a = 0.08, b = 1.83) before each measurement. L* represents brightness, a* measures red/green balance (+a* for red, -a* for green), and b* indicates yellow/blue balance (+b* for yellow, -b* for blue) (Gould, 1977).

Nutrient Element Analysis: Macro- and microelement content in lettuce leaves was analyzed to determine the impact of different treatments on plant nutrition (Dasgan et al., 2023b). Leaves were washed with 0.1% detergent and rinsed three times with distilled water to avoid contamination. The cleaned leaves were dried at 65°C for 48 hours and then ground. Samples were combusted at 550°C for 8 hours, and the resulting ash was dissolved in 3.3% HCl. Potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) were measured using emission mode, while iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) were analyzed using absorption mode with an atomic absorption spectrometer. Phosphorus (P) content was determined spectrophotometrically using the Barton method.

Statistical Analysis

All experiments were conducted with three replicates. Variance analysis (ANOVA) was performed using JMP statistical software (Version 7.0, 2007). Differences between treatments were assessed using the Least Significant Difference (LSD) test, with significance set at $p < 0.05$.

3 RESULTS AND DISCUSSION

The results of the analyses, including weight loss, soluble solid content (SSC), dry matter content, pH, titratable acidity, total chlorophyll, total flavonoid, total phenolic content, and macro- and microelement concentrations in the lettuce samples, measured at the beginning and on day 14 of storage, are summarized in Tables 1, 2, 3, 4, and 5.

Effects of Biofertilizers on Leaf Nutritional and Antioxidant Compounds

At the start of storage, SSC values ranged from 2.29 to 3.01 °Brix. The highest SSC value (3.01 °Brix) was recorded in the 1st LED treatment on the first day, while the lowest value (2.29 °Brix) was observed in the 2nd LED treatment on day 14 (Table 1). A significant decline in SSC values occurred over the 14-day storage period, likely due to the respiration process, during which sugars and organic acids degrade.

The pH values of lettuce samples, recorded both post-harvest and during storage, are also presented in Table 1. The pH ranged between 5.75 and 6.10, with the highest value (6.10) observed in the 1st LED treatment on day 14, and the lowest (5.75) recorded in the 3rd LED treatment on day 1. A significant increase in pH occurred by the end of the storage period, consistent with previous studies. Hassenberg and Idler (2005) reported that lettuce washed with tap water showed a pH increase from 6.11 to 6.39 within six days. King et al. (1991) observed a similar rise in pH in lettuce stored at 5°C. Additionally, Allende et al. (2004) and Martin-Diana et al. (2006) suggested that microbial activity and production methods contribute to pH increases during storage.

Electrical conductivity (EC) values, which reflect changes in the mineral balance during storage, ranged from 23.42 to 27.56 dS/m. On the first day, the lowest EC value (8.60 dS/m) was measured under the 3rd LED treatment, decreasing further to 6.56 dS/m by day 14. This suggests a deterioration in the water and mineral balance of the lettuce during storage. In contrast, the 1st and 2nd LED treatments exhibited higher EC values at the end of the storage period, with the highest EC (27.56 dS/m) recorded under the 1st LED treatment on day 14. These results indicate that the 1st LED treatment was more effective in preserving the mineral content and ion balance of the lettuce plants during storage.

3.1 Implications for Post-Harvest Quality Management

These findings underscore the importance of storage conditions and light sources in maintaining the mineral balance and overall quality of lettuce during storage (Table 1). The ability of specific LED treatments to manage EC fluctuations suggests that targeted lighting strategies could play a crucial role in maintaining post-harvest quality. The 1st LED treatment, in particular, demonstrated potential for preserving mineral content, highlighting the value of optimized light conditions during storage. Research like this contributes to improving storage practices, enhancing quality parameters, and minimizing post-harvest losses, thereby supporting more sustainable agricultural practices.

Table 1: The changes in pH, EC and TSS values of the lettuce samples during the storage period.

Treatment	pH			EC			TSS		
	Day 1	Day14	Loss %	Day 1	Day 14	Loss %	Day 1	Day 14	Loss %
LED_1	5,92	6,10	-3,03	8,43b	6,10b	27,56a	3,01a	2,83a	5,66bc
LED_2	5,88	6,13	-4,24	8,40b	6,14b	26,92a	2,90a	2,50b	13,79a
LED_3	5,75	6,01	-4,51	8,60a	6,58a	23,42b	2,50b	2,29b	8,41b
$LDS_{0,05}$	n.s	n.s	4,138	0,095	0,107	0,811	0,244	0,263	0,252
P	0,1193	0,2220	0,6971	0,0043*	<0.0001*	<0.000*	0,0055*	0,0074*	0,0061

TSS: Total soluble solids. There is no significant difference between means with the same letter in the same column; LSD: the least significant difference.

3.2 Titratable Acidity and Dry Matter in Lettuce During Storage

The titratable acidity of lettuce samples during storage ranged from 0.35 to 1.61 g/100g, with the highest value (1.61 g/100g) recorded in the 1st LED treatment on day 1 (Table 2). The lowest value (0.35 g/100g) was observed in the 2nd LED treatment on day 14. By the end of the 14-day storage period, the reduction in titratable acidity varied between 62.67% and 77.01%, with the highest loss (77.01%) occurring in the 1st LED treatment on day 1, while the lowest reduction (62.67%) was recorded in the 3rd LED treatment on day 14. These results suggest that the 3rd LED treatment may be more effective in preserving titratable acidity during storage. Scuderi et al. (2011) reported similar findings for Duende lettuce, where titratable acidity decreased from 1.01 g/L on day 1 to 0.42 g/L by day 9 during storage at 4°C.

At the start of storage, the total dry matter content of the lettuce samples ranged from 3.02 to 4.56 g/100g (Table 2), with the highest value (4.56 g/100g) recorded in the 1st LED treatment on day 1 and the lowest value (3.02 g/100g) observed in the 2nd LED treatment on day 14. Over the 14-day period, the dry matter content ranged between 12.85 and 27.20 g/100g, with the highest reduction (27.20 g/100g) observed in the 1st LED treatment and the lowest reduction (12.85 g/100g) in the 3rd LED treatment. These results align with those reported by Scuderi et al. (2011), who found that the dry matter content of Duende lettuce decreased from 3.78% on day 4 to 3.59% on day 9 during storage at 4°C. Similarly, Wagstaff et al. (2007) reported an increase in dry matter content from 3.2% to 4.3% in Cos lettuce and from 2.6% to 3.7% in Lolo Rossa lettuce over 10 days of storage.

The findings from this study indicate that while the reduction in dry matter content during storage was statistically significant, the extent of the reduction was moderate ($p < 0.0001$). These results highlight the importance of selecting appropriate lighting and storage conditions to minimize the degradation of key quality parameters, such as titratable acidity and dry matter content, during post-harvest storage.

Table 2. Changes in dry matter and titratable acidity in lettuce during storage.

Practice	Acidity			Dry Matter		
	Day 1	Day 14	Loss %	Day 1	Day 14	Loss %
LED1	1.61a	0.37b	77.01a	4.56a	3.32a	27.20a
LED2	1.35b	0.35b	73.34a	3.94b	3.02b	15.43b
LED3	1.31b	0.50a	62.67b	3.45c	3.35a	12.85c
$LDS_{0.05}$	0.068	0.053	4.660	0.043	0.036	0.854
P	<0.0001*	0.0009*	0.0007*	<0.0001*	<0.0001*	<0.0001*

3.3 Effects of LED Lighting on Lettuce Leaf Color Attributes

The statistical analysis revealed that the color attributes of lettuce leaves, specifically L* (lightness) and B* (yellow), were not significantly influenced by the different LED treatments. However, a significant difference was observed in the A* (red) parameter. These findings suggest that LED lighting affects the color characteristics of lettuce, as the lowest color loss (5.8) was recorded under the 1st LED treatment (Table 3).

For L* (lightness and brightness), the smallest loss occurred in the 3rd LED treatment, while the highest loss was observed in the 1st LED treatment. Regarding the green color (-a*), the lowest loss was also found in the 1st LED treatment, whereas the greatest loss of yellow color (+b*) was recorded under both the 2nd and 3rd LED treatments.

Kowalczyk et al. (2016) conducted a similar study comparing different growing media, including rock wool and cocopeat, within hydroponic systems (Nutrient Film Technique, NFT), to cultivate two types of head lettuce and one type of curly lettuce. In their study, the color parameters of the Aficion variety (Rijk Zwaan seed company) were measured. For lettuce grown in rock wool, the values were 55.4 for L*, -14.8 for a*, and 39.1 for b*. In cocopeat, the values were 63.2 for L*, -15.1 for a*, and 36.0 for b*. In the NFT system, the measurements were 57.2 for L*, -13.7 for a*, and 37.6 for b*.

In comparison, the L* values observed in this study were lower than those reported by Kowalczyk et al. (2016) in all three environments, indicating reduced brightness and lightness. However, the a* values recorded in this study were higher, while the b* values were similar. Additionally, in Kowalczyk et al.'s study, the tones of green in the Aficion variety were assessed using a Minolta SPAD chlorophyll meter, with values of 19.6 in rock wool, 24.2 in cocopeat, and 19.6 in NFT.

Table 3. Effects of LED lighting on leaf color characteristics of curly lettuce cultivated in a hydroponic system.

Treatment	L, a, b color measurements								
	L1	L14	Loss %	a1	a14	Loss %	b1	b14	Loss %
LED_1	50,7	45,3	15,0	-11,6b	-10,9b	5,8b	29,4	24,7	6,4
LED_2	49,9	44,6	10,8	-10,5ab	-8,8a	14,8a	26,4	25,9	11,2
LED_3	49,5	41,8	10,5	-9,5a	-8,2a	13,9ab	25,6	21,6	14,9
$LDS_{0,05}$	n.s	n.s	n.s	1,022	1,405	8,795	n.s	n.s	n.s
P	0,8723	0,4324	0,5529	0,0812	0,0026	0,0849	0,2690	0,1454	0,3514

L: Lightness (ranges from 0 [black] to 100 [white], **a**: Red/Green value (positive values indicate red, and negative values indicate green), **b**: Yellow/Blue value (positive values indicate yellow, and negative values indicate blue). There is no significant difference between means with the same letter in the same column; LSD: the least significant difference.

3.4 Changes in Phenolic, Flavonoid Compounds, and Nitrate Levels in Lettuce During Storage

At the beginning of storage, the total phenolic compound values in lettuce samples ranged from 61.70 to 63.96 µg GAE/g, showing no statistically significant differences. On the 14th day of storage, these values ranged from 49.11 to 49.28 µg GAE/g, with no significant changes observed (Table 4). The lowest loss of phenolic compounds (20.24 µg GAE/g) occurred under the 3rd LED treatment, while the highest loss (23.20 µg GAE/g) was observed under the 2nd LED treatment. Ke and Saltveit (1988) found similar results in their study on iceberg lettuce, attributing changes in phenolic content to physiological responses related to infections and tissue damage.

In this study, no significant differences in total phenolic content were detected in the early days of storage. It is likely that pre-treatment procedures caused physiological responses and biochemical reactions within the lettuce cells, contributing to variations in phenolic content. Additionally, enzymatic activity during storage may have contributed to further reductions in phenolic levels. Yamaguchi et al. (2003) observed that heat-treated lettuces maintained stable phenolic content, while untreated samples showed significant decreases over time. Similarly, Altunkaya et al. (2009) reported a decline in total phenolic content in lettuce during storage.

Flavonoid content also varied based on the LED treatments. On the first day of storage, the highest flavonoid content (28.63%) was recorded under the 1st LED treatment, while the lowest (23.28%) occurred under the 3rd LED treatment. After 14 days, flavonoid content declined, with the 1st LED treatment maintaining the highest level (22.24%) and the 3rd LED treatment showing a reduction to 20.57%. The lowest flavonoid loss (11.67%) was recorded under the 3rd LED treatment, while the highest loss (22.61%) also occurred under the same treatment. These findings highlight the role of different LED light sources in influencing flavonoid content, with the 1st LED treatment being particularly effective in preserving flavonoids during storage. The slower decline in flavonoid content under the 3rd LED treatment also underscores the importance of optimizing post-harvest storage conditions to retain beneficial phytochemicals.

Nitrate content in the lettuce leaves showed significant variation at the beginning of storage. The lowest nitrate level (684 mg/kg) was observed under the 2nd LED treatment, while the highest (978 mg/kg) was recorded under the 3rd LED treatment. On the 14th day, nitrate levels again showed a similar pattern, with the lowest value under the 1st LED treatment and the highest under the 3rd LED treatment (509 mg/kg). The most significant nitrate losses occurred under the 3rd LED treatment (47 mg/kg) and the 1st LED treatment (42 mg/kg), while the 2nd LED treatment showed the lowest nitrate loss (26 mg/kg).

According to the Turkish Food Codex (2008), the maximum allowable nitrate levels for lettuce vary depending on the growing season and production method. For lettuce harvested between October 1 and March 31, the maximum nitrate levels are 4500 mg/kg for indoor-grown lettuce and 4000 mg/kg for outdoor-grown lettuce. For the period between April 1 and September 30, the limits are 3500 mg/kg for indoor-grown and 2500 mg/kg for outdoor-grown lettuce. The nitrate levels recorded in this study remained well below these thresholds, posing no health risks to consumers. Zhang et al. (2018) explored nitrate levels in hydroponically grown lettuce using two lighting systems (fluorescent and LED) with varying light intensities (150, 200, 250, and 300 µmol/m²/s), red-to-blue light ratios (1:1 and 1:2), and lighting durations (12 and 16 hours). They found that increasing light intensity from 150 to 300 µmol/m²/s and extending lighting duration to 16 hours reduced nitrate levels from 783 mg/kg to 359 mg/kg. In their LED treatments, nitrate levels decreased as lighting duration increased, with nitrate concentrations of 667 and 506 mg/kg for the 1:1 ratio and 810 and 456 mg/kg for the 1:2 ratio.

In summary, the results from this study showed higher nitrate levels at the beginning of storage, which declined by the end of the 14-day period. These findings align with those of Konstantopoulou et al. (2010), who reported no significant changes in nitrate levels after 10 days of storage.

Table 4. Changes in phenolic compound levels during the storage of lettuce.

Treatment	Total phenols (mg GA 100g FW^{-1})			Total flavonoids (mg RU 100g FW^{-1})			Nitrate (mg kg FW^{-1})		
	Day 1	Day14	Loss %	Day 1	Day 14	Loss %	Day 1	Day 14	Loss %
LED_1	63,13	49,28	21,95	28,63a	22,24a	22,34a	800ab	454	42a
LED_2	63,96	49,11	23,20	27,16b	21,02ab	22,61a	684b	502	26b
LED_3	61,70	49,18	20,24	23,28c	20,57b	11,67b	978a	509	47a
$LDS_{0,05}$	n.s	n.s	n.s	1,41	1,56	3,05	224	n.s	13,34
P	0,1744	0,9077	0,2338	0,0002*	0,0964	0,0002	0,0491*	0,2021	0,0185*

FW: Fresh weigh, GA: Gallic acid, RU: Rutin There is no significant difference between means with the same letter in the same column; LSD: the least significant difference.

3.5 Weight Loss Ratio in Lettuce During Storage

In this study, the initial fresh weight of lettuce samples ranged from 197 g to 216 g, with no statistically significant differences observed among the treatments. By the 14th day of storage, the fresh weight values ranged between 194 g and 213 g, again showing no significant differences (Figure 2). The lowest weight loss (1.54%) was recorded in the samples stored under the 1st LED light treatment, while the highest loss (2.8%) occurred in the 2nd LED light treatment. These results indicate that different LED light treatments had a limited effect on fresh weight loss during storage.

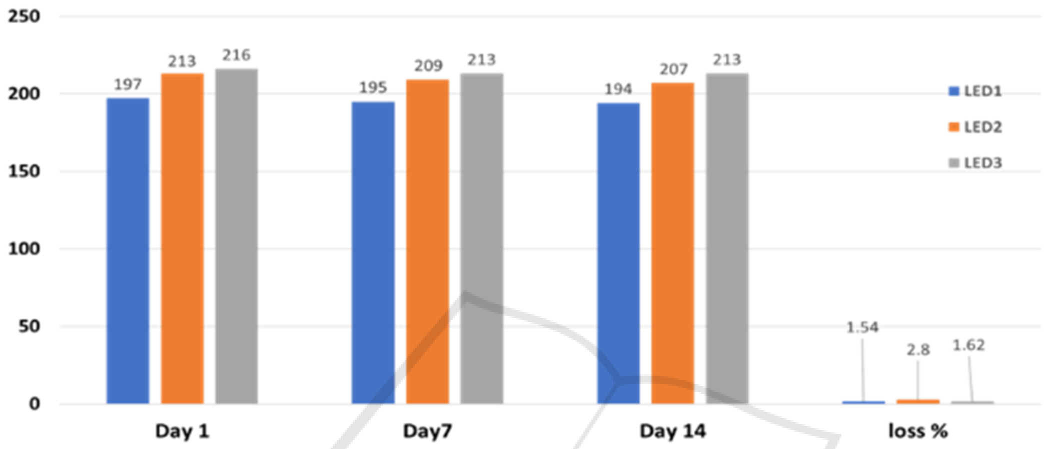

Figure 2. The effect of using different leds on the fresh weight loss of lettuce during storage.

From a scientific perspective, these findings suggest that LED light treatments did not significantly influence water loss, cellular respiration, or metabolic rates during storage. This highlights the idea that LED lights are more effective during the plant growth phase, rather than post-harvest. In storage, environmental factors such as temperature and humidity play a more critical role in preserving fresh weight. Although LEDs can provide various wavelengths to enhance plant growth, they do not appear to significantly impact the metabolic activities of lettuce during storage.

The absence of statistically significant differences in fresh weight between the beginning and end of the 14-day storage period supports the conclusion that LED treatments do not directly affect water loss.

Most of the water content in lettuce is stored within leaf tissues, and water loss is more closely related to environmental conditions, such as temperature and humidity, rather than the type of lighting used during storage. The fresh weight losses observed, ranging from 1.54% to 2.8%, further highlight the limited effect of different LED light treatments on storage performance. These low percentages suggest that LED lighting has a negligible impact on metabolic processes during storage. Instead, the findings emphasize the importance of optimizing storage conditions to maintain product quality.

These results align with the findings of Charles et al. (2018), who reported that lettuce stored under low light intensity (or in darkness) experienced less than 5% fresh weight loss, whereas high light intensity led to weight losses of up to 30%. Their study underscores the role of light intensity in influencing moisture loss and spoilage. Low light or dark conditions can effectively reduce water loss, while exposure to high light intensity accelerates dehydration and compromises product quality. In summary, while LED lighting may offer advantages for plant growth, its influence on post-harvest weight loss is minimal. This study demonstrates that environmental conditions, particularly temperature and humidity, are the primary determinants of lettuce quality during storage. Therefore, optimizing storage practices remains essential for extending the shelf life and maintaining the quality of lettuce.

3.6 Nutrient Loss in Lettuce Under Different LED Treatments

At the end of the 14-day storage period, nitrogen, calcium, and magnesium levels showed lower loss rates in the 3rd LED group compared to the 2nd LED group (Table 5). Specifically, the loss rates for the 3rd LED group were 1.72% for nitrogen, 12% for calcium, and 11% for magnesium, whereas the 2nd LED group exhibited higher losses of 8.22%, 14%, and 17%, respectively. Excluding potassium from the analysis, the lowest overall loss rate (2.17%) was recorded in the 2nd LED group. However, potassium loss rates varied, with the 1st and 3rd LED groups showing 13% and 3.51% loss, respectively. In terms of microelements, plants exposed to the 2nd LED treatment exhibited the highest nutrient loss rates after 14 days of storage compared to those under LED 1 and LED 3. However, when copper was excluded, the nutrient loss associated with the 2nd LED treatment remained significant. The copper loss rate for LED 2 was 15.48%, compared to 12.67% in LED 1 and LED 3.

For manganese, the highest loss rate (59.95%) was observed in the 2nd LED group, while the 1st and 3rd LED groups exhibited lower losses of 47.38% and 40.76%, respectively (Table 6). Similarly, iron losses were greatest in the 2nd LED group (59%), with LED 1 and LED 3 showing losses of 52% and 51%, respectively. In terms of zinc, the 2nd LED treatment resulted in the highest loss rate (9.27%), while LED 1 and LED 3 had slightly lower losses of 7.29% and 7.55%, respectively. These findings demonstrate that the type of LED treatment significantly influences the retention of essential nutrients in lettuce during storage, with the 3rd LED treatment generally yielding lower loss rates for most nutrients. This aligns with previous research highlighting the impact of light quality on the stability of nutrients in post-harvest produce (Zhang et al., 2018; Charles et al., 2018). Further research could focus on optimizing LED wavelengths and intensities to minimize nutrient loss during storage, thereby improving the quality and extending the shelf life of lettuce and similar crops.

Table 5. Changes in macroelement levels in lettuce during storage.

Treatment	**Macro Elements**											
	N1	**N 14**	**Los%**	**K 1**	**K 14**	**Loss %**	**Ca1**	**Ca 14**	**loss %**	**Mg 1**	**Mg 14**	**Loss %**
LED_1	5.42	5.33	1.59b	8.48a	7.38b	13a	3.72	2.63	29a	0.46c	0.46	-0.43b
LED_2	5.60	5.15	8.22a	8.49ab	8.30a	2.17b	3.18	2.72	14b	0.57a	0.47	17a
LED_3	5.06	4.98	1.72b	8.84a	8.53a	3.51b	3.02	2.65	12b	0.54b	0.47	11a
$LDS_{0.05}$	n.s	n.s	8.14	0.34	0.64	7.34	0.21	0.46	12.54	0.011	0.029	6.05
P	0.518	0.7618	0.0066	0.0776	0.0107*	0.0093*	0.0006*	0.8307	0.0313*	<0.0001*	0.5493	0.0009*

There is no significant difference between means with the same letter in the same column; LSD: the least significant difference.

Table 6. Changes in microelement levels in lettuce during storage.

Treatment	**Micro Elements**											
	Cu1	Cu 14	loss %	Mn 1	Mn 14	loss %	Fe 1	Fe 14	loss %	Zn 1	Zn 14	loss %
LED1	25.3	21.33a	15.48	86.33	45.33ab	47.38ab	95a	44a	52	68	62	7.29
LED2	22.6	22.0a	2.84	95.00	38.00b	59.95a	86ab	39b	59	65	60	9.27
LED3	20.6	17.3b	12.67	90.66	53.33a	40.76b	79b	34c	51	63	58	7.55
LDS0.05	n.s	2.732	n.s	9.126	10.09	14.99	12.32	3.36	n.s	6.39	n.s	n.s
P	0.4197	0.0120*	0.3679	0.1460	0.0278*	0.0519	0.0617	0.0011*	0.1310	0.2383	0.1985	0.5042

There is no significant difference between means with the same letter in the same column; LSD: the least significant difference.

4 CONCLUSIONS

This study demonstrated that different LED treatments had limited effects on parameters such as total phenolic content, L (lightness) and B (yellowness) color values, and weight loss during storage ($p > 0.05$). However, LED treatments significantly influenced key quality indicators, including pH, electrical conductivity, acidity, dry matter content, a (redness) color value, total soluble solids, flavonoid concentration, and nitrate levels.

These results highlight the selective impact of LED lighting on the biochemical and physical properties of lettuce during storage. The findings underscore the potential of specific LED treatments in preserving nutritional and sensory qualities, contributing to extended shelf life. This is particularly relevant for fresh-cut and pre-packaged lettuce products, which are increasingly favored by urban consumers seeking convenience. In conclusion, this study provides valuable insights into how LED lighting can be leveraged to improve post-harvest management strategies for lettuce. Future research should focus on optimizing LED wavelengths and integrating them with other preservation techniques to maximize both quality and shelf life, meeting the growing market demand for fresh, ready-to-eat produce.

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