



The effect of light-emitting diode (LED)-supported cold storage on some quality characteristics of parsley (*Petroselinum crispum*)

Alper Kuşçu¹ · Betül Altınay Özkan¹

Received: 6 February 2026 / Revised: 9 April 2026 / Accepted: 17 April 2026 / Published online: 11 June 2026
© The Author(s) 2026

Abstract

Postharvest green leafy vegetables are typically stored under cold conditions to preserve their quality during transportation, marketing, and consumption. This study examined the preservation of parsley in a cold chamber illuminated by light-emitting diodes (LEDs) and assessed its impact on quality attributes relative to storage in darkness (control). To do this, parsley was preserved for 25 days under consistent temperature and humidity settings, utilizing five distinct LED light colors (green, blue, yellow, red, and white) as well as a control compartment in darkness, by partitioning the cold chamber into six equal sections. An elevation in the significant constituents of parsley relative to the baseline values during storage was observed just on the fifth day, representing a key finding of the study. The maximum enhancements in ascorbic acid (AA), chlorophyll a, and chlorophyll b were recorded at 13.2, 6.32, and 6.31%, respectively, during blue LED application relative to the baseline measurement. The green LED samples had the greatest increase in antioxidant capacity at 34.97%, while the control samples demonstrated the biggest decrease at 26.9%. All applications exhibited a loss of phenolic substances relative to the starting value, with the lowest loss recorded at 0.87% in the green LED sample and the greatest at 40.33% in the control. LED application yielded superior outcomes compared to the control during the various storage periods and at the end of storage. LED applications influenced photochemical processes, affecting photosynthesis and causing changes in parsley components during cold storage. The findings indicate that blue and green LED light will aid in preserving the quality of parsley during postharvest cold storage.

Keyword Cold storage · Postharvest LED light · Parsley · Antioxidant capacity · Phenolic content · Chlorophyll

Introduction

Fresh fruits and vegetables (FFVs) are rich in carbohydrates, vitamins, minerals, amino acids, dietary fibers, organic acids, polyphenols, carotenoids, and other bioactive components, which are essential for human nutrition [1–3]. The loss rates of FFVs in the food supply chain are reported as follows: 10% in agricultural production, 9% in post-harvest transportation and storage, 25% in processing and packaging, 17% in distribution, and 5% in consumption [4]. Post-harvest, FFVs persist in their metabolic processes, leading to a rapid decline in freshness and potential spoilage [2, 5].

The objective of post-harvest activities is to extend the shelf life of fresh fruits and vegetables till consumption, while maintaining their physicochemical, nutritional, and sensory attributes at optimal levels. Both food waste and post-harvest losses can be reduced by efficient post-harvest management [6]. Methods employed to prolong the shelf life of post-harvest FFVs include modified and controlled atmospheres, ethylene biosynthesis suppression, antimicrobial nanoparticles, decay-preventing essential oils, intelligent packaging, and light-emitting diodes (LEDs) in conjunction with cold storage [7–11].

LED light applications in food are categorized into three distinct areas: food production, post-harvest storage, and food safety [12, 13]. Postharvest treatments effectively delay senescence, prolong shelf life, and preserve visual quality attributes in fresh produce [14]. Recently, the use of LED applications has become increasingly important due to their impact on the storage of post-harvest FFVs through various mechanisms. Agricultural products undergo photosynthesis

✉ Alper Kuşçu
alperkuscu@sdu.edu.tr

¹ Faculty of Engineering and Natural Sciences, Department of Food Engineering, Süleyman Demirel University, Isparta, Turkey

using natural light sources, such as the sun. In addition to these processes, plants produce signals and activate photo-receptors in response to various external factors, including light intensity, wavelength, ambient temperature, humidity, carbon dioxide levels, and the duration of exposure [14, 15]. LED sources, known for their high efficiency in photosynthetically active radiation, stimulate the metabolic pathways of phytochrome, cryptochrome, and phototropins [16]. This stimulation can lead to an increase in compounds such as flavonoids, quercetin glycosides, and kaempferol. In particular, light (red and blue) stimulates the absorption of chlorophyll a and b; blue light plays a significant role in the production of phenolic compounds by activating biosynthetic metabolic pathways [17, 18]. Furthermore, light helps increase gene expression such as MdMYB10 and MdUGT, resulting in an increase in the amounts of ascorbic acid, soluble sugars, organic acids, and anthocyanins. Additionally, enzymes like phenylalanine ammonia-lyase are also responsible for the production of secondary metabolites [19]. To mitigate losses due to senescence and infections in fresh tomatoes, red LED, red-blue-white LED, and UV LED were utilized in the study; it was shown that light application positively influences the firmness, size, mass, and total soluble solids of tomatoes. After 21 days of storage, tomatoes exposed to red LEDs had a higher ascorbic acid level than those subjected to the other two treatments and the control samples [9]. Pintos et al. [8] indicated that the most substantial weight loss occurred at 10 and 80 $\mu\text{mol m}^{-2} \text{s}^{-1}$ across three distinct doses of white light (10, 30, and 80 $\mu\text{mol m}^{-2} \text{s}^{-1}$) for broccoli and kale (green and red) stored under cold conditions, with a notable reduction in total color, hue angle, and lightness values at 30 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Chlorophyll values in broccoli, florets, and green kale are kept 30% more effectively at 30 $\mu\text{mol m}^{-2} \text{s}^{-1}$ than when stored in darkness. Xu et al. [15] reported that strawberries maintained at 5 °C for 12 days under 40 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of blue light exhibited enhanced color values, respiration rates, ethylene production, antioxidant capacity, total phenolic content, ascorbic acid, total sugar, and titration acidity. Mastropasqua et al. [20] reported minimal or negligible alterations in the parameters examined in the apical and basal regions of green asparagus maintained at 4 °C in darkness compared to treatments with white, blue, and red light. It was also discovered that vitamin C, chlorophylls (a and b), and carotenoids are diminished in both sections of asparagus preserved in light and darkness, however anthocyanins are only stimulated in the basal section upon exposure to blue light.

Parsley leaves are considered one of the most useful vegetables due to their biological properties [21]. It is commonly utilized as a green vegetable, garnish, flavoring agent, and fragrance, yet it also serves traditional and folkloric medicinal purposes due to its diverse compounds from

various phytochemical groups, including flavonoids, essential oils, furanocoumarins, carotenoids, minerals, and ascorbic acid [22–24]. It may be preserved for 6 to 28 days at temperatures ranging from 0 to 5 °C within a humidity level of 50–95% in cold storage. Chlorophyll in leaves degrades in prolonged storage and dark conditions, resulting in a color change from green to yellow or even white [25–28].

Despite numerous studies in the literature on LED applications for the cold storage of various fruits and vegetables, there are only a limited number of studies specifically focusing on cold storage using LED lighting for leafy green vegetables. This study aims to ascertain the impact of five different LED light treatments (green, blue, yellow, red, and white) and dark storage (control) on some quality properties of parsley during cold storage.

Materials and method

Material

The parsley (*Petroselinum crispum*) utilized in the study as a raw material was obtained from the Çünür region of Isparta province, Turkey. The harvested parsley was promptly transported to the laboratory, rinsed with tap water, and subsequently dried with a paper towel. Following the uniform cutting of the stems using a knife, parsley exhibiting bright green colors and similar leaf size was chosen. Subsequently, 500 g of parsley was allocated to each storage compartment and sealed with stretch film (Koroplast, Koroza Group, PVC Cling Film, Istanbul, Turkey) to mitigate excessive moisture loss. During the storage period, the first analysis of the parsley was performed on the 5th day, and then every 4 days thereafter.

Methods

Cold storage and LED applications

The storage temperature and relative humidity of vegetables in domestic refrigerators range from 0–14 °C and 20–100%, respectively [29]. The humidity levels in several brands of household refrigerators have been measured and found to range from 20–55% (10 distinct brands of residential refrigerators; unpublished data).

The literature indicates that the optimal temperature for cold storage of parsley is 0–3 °C, while the relative humidity in cold storage studies is reported to be 50% [30, 31]. Additionally, Kim et al. [32] measured the relative humidity in vegetable cold storage as ranging from 38–73%. Consequently, the cooling medium (Binder, KB 240, Germany) was maintained at a temperature of 0 ± 0.5 °C, and the

relative humidity of the medium, without external humidification, was assessed using a humidity indicator (eYc-Tech/Taiwan; THR 23) at $50 \pm 5\%$. The laboratory cooler utilized for cold storage is partitioned into six equal compartments, each measuring 48.5 cm in depth, 25.5 cm in height, and 32 cm in width, constructed with styrofoam. It features five distinct LED light applications and one control compartment devoid of light, ensuring isolation among the compartments.

In the LED application, two 50 cm strips of each hue are installed diagonally on the ceiling of the compartments. Calculations were conducted on two bars for emitted photons. The wavelengths and emitted photon flux (PF) intensities from LEDs are as follows: green LED (GL) at 520 nm emits $6.92 \mu\text{mol m}^{-2} \text{s}^{-1}$, red LED (RL) at 633 nm emits $10.22 \mu\text{mol m}^{-2} \text{s}^{-1}$, blue LED (BL) at 467 nm emits $11.64 \mu\text{mol m}^{-2} \text{s}^{-1}$, yellow LED (YL) at 599 nm emits $21.36 \mu\text{mol m}^{-2} \text{s}^{-1}$, and white LED (WL) at 448 nm emits $21.74 \mu\text{mol m}^{-2} \text{s}^{-1}$, respectively. The wavelengths and flux of radiated photons from LED strips were measured using HaasSuite (EVERFINE) by SiberLED Lighting Laboratories in Ankara, Turkey.

Analysis

Total dry matter The total dry matter (TDM) was assessed following the methodology of Kuscu and Uslu [33]. Five grams of parsley leaves were measured and placed in moisture containers, then dried in an oven at 105°C until a steady weight was achieved. The chemical analysis data are presented on a dry matter (DM) basis.

Ascorbic acid determination Analysis of ascorbic acid (AA) was conducted at a wavelength of 518 nm utilizing a Boeco S-20 (Germany) spectrophotometer, in accordance with the methodologies established by Kuscu and Uslu [33] and Demirdöven and Baysal [34]. The quantities of AA were quantified by the calibration curve (R^2 : 0.99) established at various concentrations, following the reaction between AA and 2,6-dichlorophenolindophenol (Sigma, D1878), utilizing AA (Sigma, 95,210) as the reference.

Total phenolic compounds The total concentration of phenolic compounds (TPCs) was determined using the Folin-Ciocalteu technique as outlined by Singleton and Rossi [35]. The idea of a redox reaction underlies the process, wherein phenolic chemicals reduce the Folin-Ciocalteu reagent (Merck, 1.09001, Germany) in an alkaline medium, resulting in their conversion to an oxidized form. The total concentration of TPCs was quantified by spectrophotometric measurements (Boeco S20, Germany) at 750 nm, based

on a calibration curve (R^2 : 0.94) established with the gallic acid standard (Sigma, G7384).

Antioxidant capacity Antioxidant capacity (AC) analysis was performed with some modifications to the method by Pokorny et al. [36]. A $1 \mu\text{M}$ solution of 2,2-diphenyl-1-picrylhydrazyl (DPPH; Sigma, D9132) was prepared in methanol. 0.5 g of parsley samples was weighed, combined with 50 mL of methanol, homogenized using an ultraturrax (T25-basic, IKA-Werke, Germany), then centrifuged (Hettich, Universal 16R) at 500 rpm for 5 min. The filtrate was subsequently passed through filter paper, and varying quantities of the material were introduced into tubes containing 600 μL of DPPH solution, with the total volume adjusted to 6 mL using methanol. It was subjected to a vortex (Biosan, V1 plus, Latvia) and incubated in the dark until a predetermined absorbance reading was attained. Following incubation, measurements were conducted using a spectrophotometer (Boeco S20, Germany) at a wavelength of 517 nm. A curve was generated for each sample, and percentage inhibition values were computed. The quantity of sample that diminished the DPPH concentration by fifty percent was measured in mg/mL, and EC_{50} values were derived from Eq. (1).

$$\%Inhibition = [(A_{DPPH} - A_s)/A_{DPPH}] \times 100 \quad (1)$$

A_{DPPH} represents the absorbance of the control, whereas A_s denotes the absorbance of the sample.

Chlorophyll a and b Chlorophyll quantification in the samples was conducted using the methodology of Nagata and Yamashita [37]. A 1 g sample of parsley leaves was obtained, and a mixture of acetone (Sigma, 24,201) and hexane (Sigma, 208,752) in a 4:6 volume ratio was added and homogenized using an ultraturrax (T25-basic, IKA-Werke, Germany). Following centrifugation at 4000 rpm for 10 min, absorbance readings at 663 and 645 nm were obtained from the supernatant, and the concentrations of chlorophyll a and b were determined by entering these values into the respective formulae (Eqs. 2 and 3).

$$\text{Chlorophyll a (mg/100 mL)} = 0.999 \times A_{663} - 0.0989 \times A_{645} \quad (2)$$

$$\text{Chlorophyll b (mg/100 mL)} = -0.328 \times A_{663} + 1.77 \times A_{645} \quad (3)$$

A_{663} denotes the absorbance of the extract at 663 nm, while A_{645} represents the absorbance at 645 nm.

Chroma The color values a^* , and b^* of parsley leaves during storage were assessed using a Minolta CR-400 (America) instrument. Chroma value was computed in accordance with McLellan et al. [38] using the equations provided below (Eq. 4).

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (4)$$

Statistical analysis Statistical analyses were performed on data collected from two independent biological replicates, each measured in triplicate. The two-way ANOVA technique was employed to analyze the data obtained regarding the characteristics that were the focus of the study. The study evaluated the storage performance of six levels of storage conditions (green, blue, yellow, red, white, and dark (control)) and seven levels of storage time (0, 5, 9, 13, 17, 21, and 25th days) factor. The differences between the averages of the LED light applications at each storage time point were compared separately, and the differences between storage time points were compared separately for each LED lighting, as the interaction was statistically significant. The multiple comparisons of the means between the samples stored under LEDs and the control were determined using Tukey's multiple ranges ($p < 0.05$). Statistical analyses were performed utilizing IBM SPSS Statistics version 29.0.2.0.

Results and discussion

Total dry matter

The influence of darkness and LED light treatments on the TDM variation during parsley cold storage is presented in Table 1. The TDM content was measured at 20.95% initially and reached its maximum at the end of storage, at 36.57%. The reduction in TDM content (excluding moisture loss) reached 20.91% with the green LED application and 20.88%

with the BL application on the fifth day of cold storage ($p > 0.05$). Subsequently, these values gradually increased throughout the storage period, and statistically significant differences were observed between storage days ($p < 0.05$). The TDM content exhibited a continuous increase from the beginning to the end of storage with YL, RL, and WL treatments and in the control, and these increases were statistically significant ($p < 0.05$). In the control group, the increase in TDM was greater than that in other LED applications on days 21 and 25 of storage. This indicates that dark storage (control) increases water loss, while LED applications decrease it ($p < 0.05$). There was no statistically significant difference in TDM change between the control group and LED light treatments on the 5th, 9th, 13th, and 17th days of storage ($p > 0.05$). It was concluded that parsley experienced a weight loss of 5–10% between the 13th and 21st days across all applications. The greatest moisture loss was observed in the control group on the 21st day of storage ($p < 0.05$). It has been observed that parsley preserved under these conditions experiences a decline in quality beginning on the 13th day due to moisture loss. At the conclusion of storage, the samples treated with BL exhibited the least moisture loss ($p < 0.05$). Contrary to our findings (based on the fifth day of storage), Perera et al. [39] reported that exposure to fluorescent light in spinach and Chinese cabbage resulted in moisture loss through stomatal opening. Ayala et al. [40] reported that the weight loss of leeks during dark storage is minimal, as the stem stomata remain closed under various light conditions, which aligns with our findings. According to Mahangade et al. [41], a weight loss of more than 10% in fresh fruits and vegetables can be indicative of diminished freshness and a withered appearance. Ouzounidou et al. [42] observed that parsley stored at 5 °C and 20 °C for a period of 23 days experienced weight losses of 6% and 7.5%, respectively. It would also be useful to evaluate the effects of using LEDs of different intensities on changes in the moisture contents of the samples. Although the BL application resulted in the least moisture loss at the end of storage ($p < 0.05$), the GL ($6.92 \mu\text{mol m}^{-2} \text{s}^{-1}$), which exhibited the most moisture loss in LED applications, had

Table 1 Changes in TDM values of parsley samples under green (GL), blue (BL), yellow (YL), red (RL), and white (WL) LED lights or in the darkness (control) stored for 25 days at 0 °C

Days	GL	BL	YL	RL	WL	Darkness
0	20.95 ± 1.00 ^{Ad}	20.95 ± 1.00 ^{Ac}	20.95 ± 1.00 ^{Af}	20.95 ± 1.00 ^{Ad}	20.95 ± 1.00 ^{Af}	20.95 ± 1.00 ^{Ac}
5	20.91 ± 1.10 ^{Ad}	20.88 ± 0.12 ^{Ac}	21.74 ± 0.26 ^{Af}	21.35 ± 1.20 ^{Ad}	21.60 ± 0.40 ^{Af}	21.74 ± 0.21 ^{Ac}
9	24.35 ± 1.34 ^{Ac}	24.51 ± 1.00 ^{Ad}	24.35 ± 0.22 ^{Ac}	23.11 ± 0.93 ^{Ac}	23.93 ± 0.03 ^{Ac}	24.20 ± 0.21 ^{Ad}
13	26.63 ± 0.63 ^{Ac}	26.68 ± 0.27 ^{Ac}	26.48 ± 0.60 ^{Ad}	25.17 ± 0.95 ^{Ac}	24.91 ± 1.13 ^{Ad}	26.83 ± 0.39 ^{Ac}
17	28.54 ± 1.07 ^{Ab}	29.81 ± 0.90 ^{Ab}	29.41 ± 0.91 ^{Ac}	27.73 ± 0.22 ^{Ab}	27.70 ± 1.12 ^{Ac}	28.36 ± 0.14 ^{Ac}
21	30.95 ± 0.82 ^{BCb}	30.91 ± 0.91 ^{BCb}	31.69 ± 0.11 ^{ABa}	30.04 ± 0.80 ^{Db}	30.24 ± 0.08 ^{BCb}	32.84 ± 0.05 ^{Ab}
25	36.30 ± 0.90 ^{ABa}	33.32 ± 0.65 ^{Ba}	36.21 ± 0.95 ^{Aa}	34.48 ± 0.06 ^{ABa}	35.22 ± 0.80 ^{ABa}	36.57 ± 0.99 ^{Aa}

Mean ± SD in the same row with different upper-case letters (A–D) indicate statistical differences between LED and darkness applications, and different lower-case letters (a–f) in the same column indicate statistical differences between storage days ($P < 0.05$). TDM: Total dry matter, LED: Light emitted diot

a lower intensity than the BL ($11.64 \mu\text{mol m}^{-2} \text{s}^{-1}$). Furthermore, the intensities of YL ($21.36 \mu\text{mol m}^{-2} \text{s}^{-1}$) and WL ($21.74 \mu\text{mol m}^{-2} \text{s}^{-1}$) LEDs were significantly higher than those of BL in applications with elevated moisture loss ($p < 0.05$). Accordingly, it was determined that moisture loss was not influenced by the intensities of various colored LEDs. Pintos et al. [8] stored broccoli and green-red kale at PF intensities of 10, 30, and $80 \mu\text{mol m}^{-2} \text{s}^{-1}$ and stated that there was more moisture loss at 10 and $80 \mu\text{mol m}^{-2} \text{s}^{-1}$.

Ascorbic acid (AA) content

Fresh vegetables are a vital source of AA, and their antioxidant properties additionally provide advantageous impacts in bolstering the immune system and addressing various health issues. Due to its sensitivity to various factors such as temperature and light, it is regarded as a sensitive indicator of nutrient integrity [43–46]. The AA content of parsley at the beginning and end of the storage was measured as 1046.7 and 298.6 mg/100 g in DM (Table 2), respectively. Karaca and Velioglu [47] reported that the AA content of fresh parsley was 1210 mg/100 g in DM. The increase in AA values relative to the initial measurement was observed to be 13.2% under BL and 10.52% under GL, exclusively on the fifth day of storage. Conversely, a decrease was noted in other LED applications, including the control. Once again, in the results on the fifth day, the percentage of AA was found to be 19.9 and 17.05% higher in BL and GL applications, respectively, compared to the control. On the ninth day of storage, the AA loss across all applications was found to be between 56.66 and 60.4% relative to the initial value. AA quantities exhibited a general decreasing trend in all applications from day 9 to the end of storage. The control group was found to have the highest AA loss among all LED lights on days 21 and 25, with values of 70.08% ($p < 0.05$) and 71.47% ($p > 0.05$), respectively, when the impact of storage time on the applications was analyzed. At the end of the storage period, the AA content was found to be slightly higher in LED applications compared to the control group, but this difference was insignificant

($p > 0.05$). It is important to evaluate the effect of different PF intensities on AA content. On the 5th day, when AA content increased compared to the beginning, the fact that YL and WL, which have higher PF intensities than GL, BL, and RL, which have intermediate PF intensities (in order of PF (light) intensity: $\text{GL} < \text{RL} < \text{BL}$), have lower AA content indicates that the differences in PF intensity have no effect on AA content. It has been reported that light helps increase gene expression such as MdMYB10 and MdUFGT, which in turn leads to an increase in the amounts of AA, soluble sugars, organic acids, and anthocyanins [19]. Lee et al. [48] indicate that after 18 days of storage in cabbage exposed to LED light, the AA content was greater in the LED-treated samples compared to those kept in darkness, with the maximum AA levels observed in the BL treatment. It was indicated that LED illumination enhances the synthesis of AA. Similarly, in our findings, the AA content of parsley treated with LED at the end of storage was observed to be higher than that of the samples stored in darkness. Noichinda et al. [49] reported that the AA content of Chinese kale, stored at a low light level of $21.8 \mu\text{mol m}^{-2} \text{s}^{-1}$ and 1°C (95% RH) in darkness, declined swiftly during storage in the dark, with the loss being approximately half of that observed during storage under illuminated conditions. Although AA exhibited a consistent decline during storage in this study, our results indicated an increase in AA on the fifth day of storage under LED exposure (specifically blue and green LEDs), followed by comparable decreases thereafter. Zhou et al. [50] reported that the levels of AA decreased across all LED and control treatments in pak choi stored for 30 days at $30 \mu\text{mol m}^{-2} \text{s}^{-1}$, and our findings were consistent with this trend during subsequent periods, except for an observed increase on the fifth day of storage.

Total phenolic compounds

Phenolics are significant due to their antioxidant properties; therefore, understanding their variability may be essential for the development of effective food storage and preservation strategies. The TPCs values decreased from

Table 2 Changes in AA (mg/100 g in DM) values of parsley samples under green (GL), blue (BL), yellow (YL), red (RL), and white (WL) LED lights or in the darkness (control) stored for 25 days at 0°C

Days	GL	BL	YL	RL	WL	Darkness
0	$1046.7 \pm 36.35^{\text{Ab}}$	$1046.7 \pm 36.35^{\text{Ab}}$	$1046.7 \pm 36.35^{\text{Aa}}$	$1046.7 \pm 36.35^{\text{Aa}}$	$1046.7 \pm 36.35^{\text{Aa}}$	$1046.7 \pm 36.35^{\text{Aa}}$
5	$1156.8 \pm 20.52^{\text{Aa}}$	$1184.9 \pm 15.86^{\text{Aa}}$	$715.0 \pm 23.18^{\text{Eb}}$	$933.6 \pm 7.17^{\text{Cb}}$	$870.2 \pm 11.63^{\text{Db}}$	$988.3 \pm 16.6^{\text{Bb}}$
9	$422.4 \pm 9.18^{\text{BCc}}$	$428.1 \pm 4.38^{\text{BCc}}$	$418.5 \pm 4.83^{\text{BCc}}$	$453.6 \pm 10.95^{\text{AcD}}$	$414.5 \pm 7.39^{\text{Cc}}$	$437.0 \pm 7.3^{\text{ABc}}$
13	$384.2 \pm 2.48^{\text{Dbcd}}$	$366.3 \pm 3.24^{\text{Ed}}$	$424.3 \pm 1.63^{\text{Bc}}$	$411.5 \pm 4.55^{\text{Cd}}$	$433.0 \pm 2.65^{\text{Ac}}$	$384.8 \pm 3.35^{\text{Dd}}$
17	$425.9 \pm 5.55^{\text{Bc}}$	$390.8 \pm 17.17^{\text{Cbcd}}$	$396.6 \pm 4.21^{\text{Cc}}$	$455.4 \pm 8.13^{\text{Ac}}$	$447.8 \pm 4.7^{\text{ABc}}$	$433.5 \pm 4.36^{\text{ABc}}$
21	$356.6 \pm 4.11^{\text{Ad}}$	$354.5 \pm 7.19^{\text{ABd}}$	$341.3 \pm 6.14^{\text{BCc}}$	$354.9 \pm 4.81^{\text{ABe}}$	$334.3 \pm 4.6^{\text{Cd}}$	$313.2 \pm 3.05^{\text{De}}$
25	$303.9 \pm 6.2^{\text{Ae}}$	$301.5 \pm 11.23^{\text{Ae}}$	$303.4 \pm 8.25^{\text{Ad}}$	$304.1 \pm 5.69^{\text{Af}}$	$303.4 \pm 13.16^{\text{Ad}}$	$298.6 \pm 7.38^{\text{Ae}}$

Mean $\pm$ SD in the same row with different upper-case letters (A–E) indicate statistical differences between LED and darkness applications, and different lower-case letters (a–f) in the same column indicate statistical differences between storage days ($P < 0.05$). AA: Ascorbic acid, DM: Dry matter basis, LED: Light emitted diot

824.3 mg/100 g to 407.7 mg/100 g on a DM basis during storage (Table 3). Although the rise in AA levels in GL and BL applications is notable only on the fifth day of storage, these applications also demonstrate the highest preservation of TPCs content. On the fifth day of storage, the minimal TPCs loss was observed in GL, BL, and RL light applications, whereas the maximum loss occurred in darkness. These values were recorded as 0.87, 3.62, 7.25, and 40.34%, respectively. TPCs losses were identified during the later phases of storage; however, it was concluded that these losses were significantly lower in LED light applications relative to the control. During the later phases of storage, the greatest TPCs loss was observed in darkness, whereas the minimal loss occurred under BL illumination on the 17 th, 21 st, and 25 th days of storage ($p < 0.05$). After a storage period of 25 days, the maximum TPCs loss was observed to be 50.54% under darkness, while the minimum losses were recorded as 28.53, 29.24, and 34.04% under BL, GL, and WL illumination, respectively ($p < 0.05$). When treated with BL, a significant ($p < 0.05$) TPCs preservation at each storage time was observed with respect to the control. In the long term, BL was the most stable application, maintaining the highest TPCs value. During the medium term (days 9–13), YL was advantageous, but its value tended to decrease toward the end. The factors that most rapidly reduced the TPCs value were determined as treated samples in darkness ($p < 0.05$).

The difference in TPCs levels at the end of storage was found to be significant ($p < 0.05$), and it was determined that LEDs with different PF intensities had no effect on TPCs. The BL had the highest TPCs value, while the YL and WL, which have higher PF intensities, had lower TPCs values. The GL, which has the lowest PF intensity, had a higher TPCs value than the YL and WL. In contrast to our findings, Loi et al. [51] reported that the increase in phenolic compounds in broccoli florets was due to the red LED PF level ($66 \mu\text{mol m}^{-2} \text{s}^{-1}$) being higher than the yellow LED PF level ($27 \mu\text{mol m}^{-2} \text{s}^{-1}$). Castillejo et al. [52] observed that the application of blue, red, and far-red LEDs

($35 \mu\text{mol m}^{-2} \text{s}^{-1}$, over 15 days at 5°C) enhanced the biosynthesis of total phenolic compounds in broccoli sprouts. Conversely, Mastropasqua et al. [53] reported that white, blue, and red LED illumination ($110 \mu\text{mol m}^{-2} \text{s}^{-1}$) maintained the phenolic content in radish, soybean, mung bean, and pumpkin sprouts. In the study conducted by Vitale et al. [54], which examined the development of germinated soybeans treated with a biostimulant and exposed to light, it was reported that the phenolic compound levels in samples subjected to blue-red LED illumination (which enhanced the expression of various genes) were higher than in those kept in darkness.

Antioxidant capacity

An increased EC_{50} value corresponds to a diminished AC [55]. Alterations (both increases and decreases) in the AC values of parsley were assessed under various storage conditions (LED illumination and darkness) (Table 4).

On the fifth day of parsley storage, the AC of samples exposed to BL, RL, and GL increased by 8.97, 18.52, and 25.91%, respectively, relative to the initial value. Conversely, the losses observed during storage under YL, WL, and darkness conditions were 13.00, 32.12, and 26.90%, respectively ($p < 0.05$). Loi et al. [51] reported that blue, red, and green LEDs have a direct positive impact on AC; similarly to our findings, this effect was observed as positive only on the fifth day of storage, with AC loss being lesser on other days relative to the control. The lowest AC values were observed in samples stored in darkness, with the exception of the fifth day.

Although decreases in AC values were observed across all applications after the fifth day of storage, it was found that these reductions were less pronounced in LED applications relative to the control. The level of AC loss observed during days 9 to 13 of darkness storage was attained on the 25 th day, marking the conclusion of the LED light application period. The AC of all groups decreases as the storage time increases. Nevertheless, it has been established

Table 3 Changes in TPCs (mg/100 g in DM) values of parsley samples under green (GL), blue (BL), yellow (YL), red (RL), and white (WL) LED lights or in the darkness (control) stored for 25 days at 0°C

Days	GL	BL	YL	RL	WL	Darkness
0	824.3 ± 9.76 ^{Aa}	824.3 ± 9.76 ^{Aa}	824.3 ± 9.76 ^{Aa}	824.3 ± 9.76 ^{Aa}	824.3 ± 9.76 ^{Aa}	824.3 ± 9.76 ^{Aa}
5	817.1 ± 26.11 ^{Aa}	794.5 ± 0.94 ^{Ab}	663.9 ± 1.81 ^{Cc}	764.5 ± 0.92 ^{Ab}	692.9 ± 5.67 ^{Cb}	491.8 ± 0.91 ^{Dc}
9	658.7 ± 2.15 ^{Bb}	654.6 ± 2.13 ^{Bd}	701.7 ± 3.56 ^{Ab}	713.8 ± 4.76 ^{Ac}	487.5 ± 5.96 ^{Ce}	486.3 ± 1.41 ^{Cc}
13	576.5 ± 1.48 ^{Dc}	652.3 ± 1.96 ^{Bd}	694.4 ± 1.39 ^{Ab}	602.2 ± 6.99 ^{Cd}	449.6 ± 4.41 ^{Ef}	458.7 ± 2.55 ^{Ed}
17	455.5 ± 5.93 ^{De}	726.7 ± 12.03 ^{Ac}	501.7 ± 5.34 ^{Cd}	498.9 ± 3.77 ^{Ce}	510.1 ± 1.23 ^{Cd}	576.1 ± 2.09 ^{Bb}
21	514.4 ± 0.63 ^{Dd}	657.3 ± 1.28 ^{Ad}	477.8 ± 2.25 ^{Ee}	602.9 ± 6.29 ^{Bd}	556.3 ± 5.35 ^{Cc}	412.7 ± 2.17 ^{Fe}
25	583.3 ± 1.09 ^{Bc}	589.1 ± 1.57 ^{Ae}	484.0 ± 2.38 ^{De}	436.9 ± 1.14 ^{Ef}	543.7 ± 0.56 ^{Cc}	407.7 ± 0.93 ^{Fe}

Mean ± SD in the same row with different upper-case letters (A–F) indicate statistical differences between LED and darkness applications, and different lower-case letters (a–f) in the same column indicate statistical differences between

storage days ($P < 0.05$). TPCs: Total phenolic compounds, DM: Dry matter basis, LED: Light emitted diot

Table 4 Changes in AC (mg/mL in DM) values of parsley samples under green (GL), blue (BL), yellow (YL), red (RL), and white (WL) LED lights or in the darkness (control) stored for 25 days at 0 °C

Days	GL	BL	YL	RL	WL	Darkness
0	10.15±0.03 ^{Ad}	10.15±0.03 ^{Ad}	10.15±0.03 ^{Ad}	10.15±0.03 ^{Ad}	10.15±0.03 ^{Ad}	10.15±0.03 ^{Ad}
5	7.52±0.02 ^{Ee}	9.24±0.34 ^{Ce}	11.47±0.06 ^{Be}	8.27±0.06 ^{Df}	13.41±0.32 ^{Ac}	12.88±0.11 ^{Ad}
9	13.79±0.65 ^{Bc}	11.02±0.07 ^{Cd}	12.26±0.11 ^{BCde}	11.95±0.23 ^{Cde}	15.77±1.36 ^{Abc}	17.35±0.30 ^{Ac}
13	14.28±0.32 ^{Cc}	12.97±0.62 ^{CDc}	12.88±0.33 ^{Dcd}	13.45±0.77 ^{CDcd}	16.49±0.44 ^{Bb}	18.11±0.22 ^{Ac}
17	15.65±0.59 ^{ABCb}	15.00±0.73 ^{BCb}	13.31±0.56 ^{Cc}	14.30±1.54 ^{BCcd}	16.45±1.45 ^{ABb}	18.40±0.75 ^{Ac}
21	16.55±0.23 ^{BCdab}	15.56±0.47 ^{Cb}	17.32±0.54 ^{Bb}	15.47±0.34 ^{Cbc}	16.95±0.09 ^{Bab}	20.28±0.61 ^{Ab}
25	17.45±0.32 ^{Ba}	17.70±0.35 ^{Ba}	18.67±0.28 ^{Ba}	17.62±1.36 ^{Ba}	18.91±0.91 ^{Ba}	21.98±0.85 ^{Aa}

Mean±SD in the same row with different upper-case letters (A-E) indicate statistical differences between LED and darkness applications, and different lower-case letters (a-f) in the same column indicate statistical differences between storage days ($P<0.05$). AC: Antioxidant capacity, DM: Dry matter basis, LED: Light emitted diot

Table 5 Changes in chlorophyll a (mg/100 g in DM) values of parsley samples under green (GL), blue (BL), yellow (YL), red (RL), and white (WL) LED lights or in the darkness (control) stored for 25 days at 0 °C

Days	GL	BL	YL	RL	WL	Darkness
0	363.8±2.97 ^{Aa}	363.8±2.97 ^{Ab}	363.8±2.97 ^{Ab}	363.8±2.97 ^{Aa}	363.8±2.97 ^{Aa}	363.8±2.97 ^{Aa}
5	365.7±0.39 ^{Ca}	386.8±0.74 ^{Aa}	371.2±0.19 ^{Ba}	303.1±0.72 ^{Fb}	359.0±1.38 ^{Db}	306.7±1.04 ^{Eb}
9	255.0±0.6 ^{Eb}	286.1±0.6 ^{Cc}	307.9±0.63 ^{Ac}	236.7±0.92 ^{Fd}	297.1±0.47 ^{Bc}	260.6±0.35 ^{Dc}
13	217.1±1.46 ^{Dc}	240.7±1.35 ^{Bd}	208.0±0.89 ^{Ed}	282.0±0.34 ^{Ac}	283.7±1.93 ^{Ad}	225.7±0.15 ^{Cd}
17	194.1±1.66 ^{Dd}	211.7±0.28 ^{Be}	179.5±0.81 ^{Ec}	213.2±0.26 ^{Be}	247.1±0.26 ^{Ac}	204.4±0.52 ^{Ce}
21	156.5±0.27 ^{Ee}	197.4±0.15 ^{Cf}	145.2±1.33 ^{Ff}	204.5±1.92 ^{Bf}	215.4±0.14 ^{Af}	162.6±0.22 ^{Df}
25	118.7±0.85 ^{Ef}	150.0±0.88 ^{Cg}	105.8±0.11 ^{Fg}	159.9±0.32 ^{Bg}	182.3±0.24 ^{Ag}	134.0±0.20 ^{Dg}

Mean±SD in the same row with different upper-case letters (A-F) indicate statistical differences between LED and darkness applications, and different lower-case letters (a-g) in the same column indicate statistical differences between storage days ($P<0.05$). DM: Dry matter basis, LED: Light emitted diot

that the rate of impact of LED color on this process varies ($p<0.05$). In particular, the quickest AC depletion occurs under WL and dark conditions. Conversely, the decrease in AC is more evenly distributed in BL applications, despite the initial advantage of GL, which ultimately results in increased losses. The lowest AC value at the end of storage was found in the dark application ($p<0.05$). A certain correlation (inverse relationship) between the PF intensity of the LEDs and the AC of the samples is noteworthy. When the fifth day ($p<0.05$) and the end of storage ($p>0.05$), which are particularly prominent in the study, are examined, the AC ranking of the LEDs in both cases is as follows: GL>RL>BL>YL>WL. The PF intensities of the LEDs behaved inversely proportionally during this process, and the LED photon flux intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ranking is as follows: GL (6.92)<RL (10.22)<BL (11.64)<YL (21.36)<WL (21.74). It was concluded that the application of LED lighting markedly decreased antioxidant depletion in stored parsley. Zhang et al. [56] reported that in pak choi subjected to LED lighting, DPPH free radical scavenging activity tends to increase during the initial stage of storage. As reported by Loi et al. [51], and similarly in our study, blue, red, and green LEDs were assessed and shown to positively influence the AC—exceeding the initial value—only on the fifth day of storage, suggesting a potential contribution to anti-aging effects.

Chlorophyll a and b content

The chlorophyll a content was observed to range from 105.8 to 363.8 mg/100 g in DM (Table 5). It was determined that the chlorophyll a content increased only on the fifth day of storage in comparison to the baseline under BL ($p<0.05$), YL ($p<0.05$), and GL ($p>0.05$) applications, while a decrease was observed under WL, RL and dark conditions ($p<0.05$). On the fifth day of BL, YL, and GL applications, the increase in chlorophyll a content relative to the initial value was measured as 6.32, 2.03, and 0.52%, respectively. These increases generally diminished by the end of the ninth day, and reductions were observed in all samples except on the thirteenth day of red LED exposure. The rise in chlorophyll a observed in the fifth-day results was interpreted as the enhancement of chlorophyll biosynthesis and the inhibition of enzymes responsible for chlorophyll degradation through the application of blue, yellow, and green LEDs [46, 51]. Dean Kopsell and Carl Sams [18] stated that light alters the absorption effect of chlorophyll, and that LED lights promote chlorophyll absorption, leading to an accumulation of chlorophyll levels. We believed that the observed differences in chlorophyll content among the samples are due to this effect. At the conclusion of storage, the chlorophyll a content in samples exposed to GL and YL was observed to be lower than that of the control. Conversely,

the chlorophyll a levels in samples treated with WL, RL, and BL were found to be 36.04, 19.33, and 11.94% higher than the control, respectively. Perera et al. [39] reported that during light storage, the respiration rate in broccoli elevates, accompanied by an increase in chlorophyll degradation. In a different study, Noichinda et al. [49] reported that the total chlorophyll content diminished in both light- and dark-treated Chinese cabbage samples, although the decline was more gradual when the samples were preserved in the light. Zhang et al. [46] observed a modest increase in chlorophylls content in pak choi stored for 30 days under two control conditions with three distinct LEDs combined with modified atmosphere across four applications on the tenth day, followed by subsequent declines, which aligned with our findings.

The applications of BL, YL, and GL were identified as advantageous owing to the positive contribution—an increase relative to the initial value—in short-term storage (5 days). In long-term storage, only samples treated with WL exhibited higher levels of chlorophyll b compared to the control ($p < 0.05$) (Table 6). The augmentation in chlorophyll b content within BL, YL, and GL applications relative to the initial measurement was observed solely on the fifth day of storage, with increases of 6.31, 2.04, and 0.53%, respectively. On the fifth day of storage under WL and RL and in darkness, reductions in chlorophyll b relative to the initial value were observed, with corresponding values of 1.3, 8.7, and 16.02%, respectively. Contrary to the findings of Ferrante et al. [56], who reported that chlorophyll degradation did not occur in darkness, our results showed an increase in chlorophyll b on the fifth day in certain LED treatments, while it decreased in the control. Starting from the 17th day of storage, the reduction in chlorophyll b content was greater in the GL and YL treatments compared to the control. Chlorophyll b content was found to be higher in BL, RL, and WL applications compared to the control group throughout all storage days.

Once more, beginning on the 13th day of storage, the highest levels of chlorophyll b were observed in the WL treatment. At the end of storage, WL application provided

the best chlorophyll b preservation, followed by RL, BL, control group and GL, while the greatest loss was observed in the YL application ($p < 0.05$). Zhou et al. [57] reported that the stored garland chrysanthemum exposed to white LED light more effectively suppressed chlorophyll degradation relative to the control, which is consistent with our results. Chlorophyll a and b levels were not affected by variations in LED PF intensity. Pintos et al. [8] found that the chlorophyll content of broccoli and green kale was higher at $30 \mu\text{mol m}^{-2} \text{s}^{-1}$ than at 10 and $80 \mu\text{mol m}^{-2} \text{s}^{-1}$ among the three distinct PF intensities they applied.

Chroma

Chroma refers to the level of color saturation, with zero indicating dullness and higher chroma values representing vivid and vibrant hues [58]. It was observed that the chroma values decreased in the control and RL applications compared to the initial measurement on the fifth day of storage, while an increase was noted in the other LED applications (Table 7) ($p < 0.05$). Chroma values exhibited fluctuations, with increases and decreases observed across all applications between the 9th and 17th days of storage. The chroma value of control samples remained below the initial value until the 21st day, although it rose above the initial value at the end of storage. Despite these results, the chroma value of the control samples was the lowest among the applications. By the end of the storage period, chroma values showed a significant increase in all applications ($p < 0.05$). The purity and intensity levels of the colors in the samples stored in darkness were observed to remain stable, while an increase was noted in other LED lighting applications. The samples' chroma values were highest in the BL application, followed by the GL and RL applications, respectively, at the conclusion of storage. The effect of PF intensity was observed at the end of storage. Here, GL, BL, and RL, which have low PF intensity values, were found to have higher chroma values than YL and WL, which have high values ($p < 0.05$). At this point, an inverse relationship is observed between chroma value and LED light PF intensities. Kibar and Kibar

Table 6 Changes in chlorophyll b (mg/100 g in DM) values of parsley samples under green (GL), blue (BL), yellow (YL), red (RL), and white (WL) LED lights or in the darkness (control) stored for 25 days at 0 °C

Days	GL	BL	YL	RL	WL	Darkness
0	190.33 ± 1.90 ^{Aa}	190.33 ± 1.90 ^{Ab}	190.33 ± 1.90 ^{Ab}	190.33 ± 1.90 ^{Aa}	190.33 ± 1.90 ^{Aa}	190.33 ± 1.90 ^{Aa}
5	191.34 ± 0.25 ^{Ca}	202.34 ± 0.47 ^{Aa}	194.21 ± 0.12 ^{Ba}	173.78 ± 0.25 ^{Eb}	187.84 ± 0.88 ^{Da}	159.83 ± 0.66 ^{Fb}
9	133.71 ± 1.88 ^{Cb}	137.0 ± 0.89 ^{Cc}	158.30 ± 2.17 ^{Ac}	145.76 ± 0.42 ^{Bc}	155.46 ± 0.30 ^{Ab}	136.32 ± 0.22 ^{Cc}
13	119.87 ± 2.18 ^{Cc}	125.79 ± 0.21 ^{Bd}	108.43 ± 0.57 ^{Dd}	125.53 ± 1.82 ^{Bd}	145.83 ± 3.54 ^{Ac}	118.09 ± 0.10 ^{Cd}
17	95.26 ± 0.25 ^{Dd}	107.15 ± 0.03 ^{Cf}	93.93 ± 0.51 ^{De}	111.52 ± 0.17 ^{Be}	124.89 ± 1.10 ^{Ad}	106.95 ± 0.33 ^{CE}
21	81.89 ± 0.17 ^{Ee}	118.65 ± 0.31 ^{Ac}	65.38 ± 0.23 ^{Ff}	97.09 ± 0.46 ^{Cf}	110.65 ± 1.18 ^{Be}	86.54 ± 1.14 ^{Df}
25	62.12 ± 0.54 ^{Df}	69.81 ± 0.84 ^{Cg}	56.30 ± 0.01 ^{Eg}	83.66 ± 0.21 ^{Bg}	101.91 ± 1.13 ^{Af}	68.87 ± 2.23 ^{Cg}

Mean ± SD in the same row with different upper-case letters (A-F) indicate statistical differences between LED and darkness applications, and different lower-case letters (a-g) in the same column indicate statistical differences between storage days ($P < 0.05$). DM: Dry matter basis, LED: Light emitted diot

Table 7 Changes in chroma values of parsley samples under green (GL), blue (BL), yellow (YL), red (RL), and white (WL) LED lights or in the darkness (control) stored for 25 days at 0 °C

Days	GL	BL	YL	RL	WL	Darkness
0	19.05 ± 0.7 ^{Ac}	19.05 ± 0.7 ^{Ab}	19.05 ± 0.7 ^{Aa}	19.05 ± 0.7 ^{Ac}	19.05 ± 0.7 ^{Ac}	19.05 ± 0.7 ^{Ab}
5	21.00 ± 1.51 ^{Ac}	19.94 ± 0.41 ^{ABb}	21.31 ± 1.24 ^{Aa}	18.47 ± 1.33 ^{BCc}	20.56 ± 0.41 ^{ABbc}	16.99 ± 0.15 ^{Cb}
9	23.13 ± 0.89 ^{Bbc}	21.58 ± 1.32 ^{Bb}	25.56 ± 1.15 ^{Aa}	17.27 ± 0.85 ^{Cc}	16.55 ± 1.22 ^{Cc}	18.51 ± 1.14 ^{Cb}
13	20.99 ± 0.07 ^{Bc}	20.76 ± 2.31 ^{ABb}	18.78 ± 2.15 ^{Ba}	20.06 ± 0.97 ^{Bc}	28.10 ± 1.39 ^{Aa}	18.16 ± 1.35 ^{Bb}
17	22.89 ± 1.91 ^{ABab}	17.78 ± 1.31 ^{Bb}	19.79 ± 2.03 ^{ABa}	18.94 ± 1.54 ^{Bc}	25.34 ± 2.47 ^{Abc}	18.51 ± 2.21 ^{Bb}
21	26.80 ± 0.93 ^{Ab}	23.78 ± 1.75 ^{ABb}	24.40 ± 2.35 ^{ABa}	24.10 ± 1.92 ^{ABb}	25.46 ± 1.44 ^{Abc}	18.40 ± 1.78 ^{Bb}
25	33.28 ± 1.74 ^{ABa}	34.65 ± 2.98 ^{Aa}	25.37 ± 2.60 ^{BCa}	32.32 ± 0.08 ^{ABa}	27.32 ± 2.45 ^{BCa}	23.67 ± 1.08 ^{Ca}

Mean ± SD in the same row with different upper-case letters (A–C) indicate statistical differences between LED and darkness applications, and different lower-case letters (a–c) in the same column indicate statistical differences between

storage days ($P < 0.05$). LED: Light emitted diot

[59] reported an increase in the chroma values of spinach following UV (A, B, and C) treatments over a 10-day storage period, and this observation was consistent with our findings.

Conclusion

This study identified notable benefits of LED illumination applications compared to the control group (darkness) in the cold storage of parsley. Among the LED lighting utilized, BL and GL were generally observed to be more effective than YL, RL, and WL concerning the nutritional and physicochemical properties examined. The greatest increases in AA, chlorophyll a, and b were observed under BL illumination, while the highest AC level was detected in GL conditions. The minimal TPCs loss occurred in GL applications, whereas the lowest values of these components were found in the control groups (darkness). The LED lights used in this study had varying levels of PF intensity. This difference had no effect on moisture loss, AA, TPCs, and chlorophyll a and b but showed an inverse relationship with the chroma and AC values.

Based on the widely accepted approach that parsley can retain its quality for up to 25–30 days in cold storage, it has been observed that, although no visual deterioration is evident in the control, there are substantial losses in nutritional content. These losses were less pronounced in storage conditions supported by LED lighting. Furthermore, it was observed that during short-term LED-supported storage (5–7 days), there were notable increases in the nutritional constituents of parsley (AA, AC, chlorophyll a and b) relative to the initial storage levels. Our results indicate that LED-supported cold storage is potentially an effective method for preserving the nutritional components of parsley, enhancing its quality and prolonging postharvest storage life compared to storage in darkness.

In future research, the scope of investigations, including the simultaneous or partial application of LED lighting and

the optimization of conditions, can be assessed from various perspectives.

Acknowledgements The authors acknowledge that AI tools were used to assist in improving the readability and style of the manuscript and to ensure that the text is free of errors in grammar, spelling, punctuation, and tone.

Author contributions Author contributions Alper Kuşçu: Conceptualization, Methodology, Validation, Investigation, Writing—original draft, Visualization. Betül Altınay Özkan: Formal analysis, Data curation.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Bulantekin Ö, Kuşçu A (2017) Elmada bulunan fitokimyasallar ve diğer zengin bileşenlerin insan sağlığına yararları. *Meyve Bilimi* 1:213–218

2. El-Beltagi HS, Parmar A, Chen T, El-Mogy MM (2023) Advances in pre-and postharvest applications to reduce qualitative and quantitative food loss and waste. *Front Plant Sci* 14:1149358
3. Huang Y, Zhang M, Mujumdar AS, Luo Z, Fang Z (2023) Dehydrated fruits and vegetables using low temperature drying technologies and their application in functional beverages: a review. *Dry Technol* 41(6):868–889
4. Hailu G, Derbew B (2015) Extent, causes and reduction strategies of postharvest losses of fresh fruits and vegetables—a review. *J Biol Agric Healthc* 5(5):49–64
5. Zhang W, Jiang Y, Zhang Z (2023) The role of different natural organic acids in postharvest fruit quality management and its mechanism. *Food Front* 4(3):1127–1143
6. Valenzuela JL (2023) Advances in postharvest preservation and quality of fruits and vegetables. *Foods* 12(9):1830
7. Ullah S, Hashmi M, Lee J, Youk JH, Kim IS (2022) Recent advances in pre-harvest, post-harvest, intelligent, smart, active, and multifunctional food packaging. *Fiber Polym* 23(8):2063–2074
8. Pintos F, Rodoni L, Patrignani M, Ixtaina P, Vicente A, Martínez G, Hasperué J (2023) Advances in the use of white light on broccoli and kale postharvest shelf life. *Innov Food Sci Emerg Technol* 86:103373
9. Meiramkulova K, Devrishov D, Adylbek Z, Kydyrbekova A, Zhagazin S, Ualiyeva R, Temirbekova A, Adilbektegi G, Mkilima T (2023) The impact of various LED light spectra on tomato preservation. *Sustainability* 15(2):1111
10. Osei-Kwarteng M, Mahunu GK, Abu M, Apaliya M. (2023) Minimally processed fruits and vegetables. *New Advances in Post-harvest Technology* 59
11. Pizzo JS, Visentainer JV, da Silva AL, Rodrigues C (2023) Application of essential oils as sanitizer alternatives on the postharvest washing of fresh produce. *Food Chem* 407:135101
12. D'Souza C, Yuk HG, Khoo GH, Zhou W (2015) Application of light-emitting diodes in food production, postharvest preservation, and microbiological food safety. *Compr Rev Food Sci Food Saf* 14(6):719–740
13. Shin YK, Lee JG (2025) Effects of light intensity and temperature on growth and secondary metabolite production of *Centella asiatica* in vertical farms. *Hortic Environ Biotechnol* 66(6):1437–1456
14. Nassarawa SS, Abdelshafy M, Xu Y, Li L, Luo Z (2021) Effect of light-emitting diodes (LEDs) on the quality of fruits and vegetables during postharvest period: a review. *Food Bioprocess Technol* 14(3):388–414
15. Xu F, Shi L, Chen W, Cao S, Su X, Yang Z (2014) Effect of blue light treatment on fruit quality, antioxidant enzymes and radical-scavenging activity in strawberry fruit. *Sci Hortic-Amsterdam* 175:181–186
16. Jones MA (2018) Using light to improve commercial value. *Hortic Res* 5:1. <https://doi.org/10.1038/s41438-0180049-7>
17. Wang SY, Chen CT, Wang CY (2009) The influence of light and maturity on fruit quality and flavonoid content of red raspberries. *Food Chem* 112(3):676–684. <https://doi.org/10.1016/j.foodchem.2008.06.032>
18. Kopsell DA, Sams CE (2013) Increases in shoot tissue pigments, glucosinolates, and mineral elements in sprouting broccoli after exposure to short-duration blue light from light emitting diodes. *J Am Soc Hortic Sci* 1(138):31–37
19. Hasan MM, Bashir T, Ghosh R, Lee SK, Bae H (2017) An overview of LEDs' effects on the production of bioactive compounds and crop quality. *Molecules* 22(9):1420
20. Mastropasqua L, Tanzarella P, Paciolla C (2016) Effects of postharvest light spectra on quality and health-related parameters in green *Asparagus officinalis* L. *Postharvest Biol Technol* 112:143–151
21. Lisiewska Z, Kmiecik W (1997) Effect of freezing and storage on quality factors in Hamburg and leafy parsley. *Food Chem* 60(4):633–637
22. Farzaei MH, Abbasabadi Z, Ardekani MRS, Rahimi R, Farzaei F (2013) Parsley: a review of ethnopharmacology, phytochemistry and biological activities. *J Tradit Chin Med* 33(6):815–826
23. Chauhan ES, Aishwarya J (2018) Nutraceuticals potential of *Petroselinum crispum*: a review. *J Complement Med Altern Healthc* 7:1–6
24. Liberal Â, Fernandes Â, Polyzos N, Petropoulos SA, Dias MI, Pinela J, Petrović J, Soković M, Ferreira ICFR, Barros L (2020) Bioactive properties and phenolic compound profiles of turnip-rooted, plain-leafed and curly-leafed parsley cultivars. *Molecules* 25:23:5606
25. Arıcı M, Yılmaz S (2006) Paketlenmiş taze sebzelerin bazı mikrobiyolojik özellikleri ve raf ömrünün belirlenmesi. *Gıda Teknolojileri Elektronik Dergisi* 1:9–21
26. Álvares VS, Finger FL, de ASantos RC, da Silva Negreiros JR, Casali VW (2007) Effect of pre-cooling on the postharvest of parsley leaves. *J Food Agric Environ* 5(2):31
27. Kaiser A, Jaksch AV, Mix K, Kammerer DR, Carle R (2014) Processing and storage of innovative pasty parsley (*Petroselinum crispum* (Mill.) Nym ex AW Hill) and celeriac (*Apium graveolens* L. var. *rapaceum* (Mill.) DC.) products. *J Appl Bot Food Qual* 87:139–146
28. Sitarek-Andrzejczyk M, Przybył J, Gajewski M (2017) The effect of post-harvest treatment and storage conditions on vitamin C content in two leafy parsley cultivars. *Proceedings of the 8th international scientific conference rural development*. <https://doi.org/10.15544/RD.2017.018>
29. Wucher H, Klingshirn A, Brugger L, Stamminger R, Kölzer B, Engstler A, Gindele T (2021) Evaluation of humidity retention in refrigerator storage systems by application of a food simulant. *Int J Refrig* 130:161–169
30. Rana MK, Chikkeri SS (2017) Parsley. In: Rana MK (ed) *Vegetable crop science*, 1st edn. CRC Press, Boca Raton, pp 967–974
31. Koşalay İ, Bingöl O, İlk HG, Yildirim M, Özkaya B (2017) The design of a novel and portable energy performance-measuring device for household refrigerators. *Turk J Electr Eng Comput Sci* 25(5):3776–3786
32. Kim H, Kim J, Park Y, Park SH (2023) Moisture evaporation prediction model for fresh storage of vegetables in refrigerator. *J Mech Sci Technol* 37(4):2043–2054
33. Kescu A, Uslu UH (2018) The effects of ultrasound pre-treatment in hot air and microwave drying of kumquat (*Fortunella margarita* Swingle) on the quality characteristics. *Adv Food Sci* 40(1):42–51
34. Demirdöven A, Baysal T (2014) Optimization of ohmic heating applications for pectin methylesterase inactivation in orange juice. *J Food Sci Technol* 51:1817–1826
35. Singleton VL, Rossi JA (1965) Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *Am J Enol Vitic* 16(3):144–158
36. Pokorny J, Yanishlieva N, Gordon M (2001) *Antioxidants in food: practical applications*. Woodhead Publishing Limited, Abington Hall, Abington, Cambridge, England
37. Nagata M, Yamashita I (1992) Simple method for simultaneous determination of chlorophyll and carotenoids in tomato fruit. *Nippon Shokuhin Kogyo Gakkaishi* 39(10):925–928
38. McLellan MR, Lind LR, Kime RW (1995) Hue angle determinations and statistical analysis for multiquadrant Hunter L, a, b data. *J Food Qual* 18(3):235–240
39. Perera WPTD, Navaratne SB, Wickramasinghe I (2022) Review on effect of postharvest illumination by fluorescent and ultraviolet light waves on the quality of vegetables. *J Food Process Eng* 45(2):e13960

40. Ayala F, Echávarri JF, Olarte C, Sanz S (2009) Quality characteristics of minimally processed leek packaged using different films and stored in lighting conditions. *Int J Food Sci Tech* 44(7):1333–1343
41. Mahangade PS, Mani I, Jagadale M, Jadhav M (2023) Design and development of a solar pv based evaporative cooled transit storage unit for horticultural products. *Int J Environ Clim Change* 13(9):644–657
42. Ouzounidou G, Papadopoulou KK, Asfi M, Mirtziou I, Gaitis F (2013) Efficacy of different chemicals on shelf life extension of parsley stored at two temperatures. *Int J Food Sci Tech* 48(8):1610–1617
43. Perrin PW, Gave MM (1986) Effects of simulated retail display and overnight storage treatments on quality maintenance in fresh broccoli. *J Food Sci* 51(1):146–149
44. Giannakourou MC, Taoukis PS (2003) Application of a TTI-based distribution management system for quality optimization of frozen vegetables at the consumer end. *J Food Sci* 68(1):201–209
45. Ansorena MR, Goñi MG, Agüero M, Roura SI, Di Scala KC (2009) Application of the general stability index method to assess the quality of butter lettuce during postharvest storage using a multi-quality indices analysis. *J Food Eng* 92(3):317–323
46. Zhang XJ, Zhang M, Chitrakar B, Devahastin S, Guo Z (2022) Novel combined use of red-white LED illumination and modified atmosphere packaging for maintaining storage quality of postharvest pakchoi. *Food Bioprocess Technol* 15(3):590–605
47. Karaca H, Velioglu YS (2020) Effects of ozone and chlorine washes and subsequent cold storage on microbiological quality and shelf life of fresh parsley leaves. *Food Sci Technol-Leban* 127:109421
48. Lee YJ, Ha JY, Oh JE, Cho MS (2014) The effect of LED irradiation on the quality of cabbage stored at a low temperature. *Food Sci Biotechnol* 23(4):1087–1093
49. Noichinda S, Bodhipadma K, Mahamontri C, Narongruk T, Ketsa S (2007) Light during storage prevents loss of ascorbic acid, and increases glucose and fructose levels in Chinese kale (*Brassica oleracea* var. *alboglabra*). *Postharvest Biol Technol*. <https://doi.org/10.1016/j.postharvbio.2006.12.006>
50. Zhou F, Zuo J, Gao L, Sui Y, Wang Q, Jiang A, Shi J (2019) An untargeted metabolomic approach reveals significant postharvest alterations in vitamin metabolism in response to LED irradiation in pak-choi (*Brassica campestris* L. ssp. *chinensis* (L.) Makino var. *communis* Tsen et Lee). *Metabolomics*. <https://doi.org/10.1007/s11306-019-1617-z>
51. Loi M, Villani A, Paciolla F, Mulè G, Paciolla C (2021) Challenges and opportunities of light-emitting diode (LED) as key to modulate antioxidant compounds in plants A Review. *Antioxidants*. <https://doi.org/10.3390/antiox10010042>
52. Castillejo N, Martínez-Zamora L, Gómez PA, Pennisi G, Crepaldi A, Fernández JA, Artés-Hernández F (2021) Postharvest LED lighting: effect of red, blue and far red on quality of minimally processed broccoli sprouts. *J Sci Food Agr* 101(1):44–53
53. Mastropasqua L, Dipierro N, Paciolla C (2020) Effects of darkness and light spectra on nutrients and pigments in radish, soybean, mung bean and pumpkin sprouts. *Antioxidants Basel* 9(6):558
54. Vitale E, Velikova V, Tsonev T, Ferrandino I, Capriello T, Arena C (2021) The interplay between light quality and biostimulant application affects the antioxidant capacity and photosynthetic traits of soybean (*Glycine max* L. Merrill). *Plants*. <https://doi.org/10.3390/plants10050861>
55. Cam M, Hisil Y, Kuscü A (2007) Organic acid, phenolic content, and antioxidant capacity of fruit flesh and seed of *Viburnum opulus*. *Chem Nat Compd* 43:4
56. Ferrante A, Incrocci L, Maggini R, Serra G, Tognoni F (2004) Colour changes of fresh-cut leafy vegetables during storage. *J Food Agric Environ* 2(3–4):40–44
57. Zhou F, Gu S, Zuo J, Gao L, Wang Q, Jiang A (2019) LED irradiation delays the postharvest senescence of garland chrysanthemum (*Chrysanthemum carinatum* Schousb.). *J Food Meas Charact* 13:3005–3014
58. Dhakal K, Ravi R, Nandwani D (2021) Comparative study of sensory attributes of leafy green vegetables grown under organic and conventional management. *Int J Food Agric Nat Resour* 2(3):29–45
59. Kibar H, Kibar B (2025) Comparison of ultraviolet A, B and C treatments in preserving the quality and nutritional integrity of fresh-cut spinach. *Foods Basel* 14(8):1374

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.