International Journal of Horticultural Science and Technology
Journal homepage: http://ijhst.ut.ac.ir

Impact of Different LED Lights on the Quality and Bioactive Compounds of Strawberry Fruits in Storage

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ARTICLE INFO

Article history:

Received: 23 Jun 2024,
Received in revised form: 11 August 2024,
Accepted: 14 August 2024

Article type:

Research paper

Keywords:

Anthocyanin,
Antioxidant activity,
Decay,
Firmness,
Light quality

ABSTRACT

Strawberry (*Fragaria × ananassa*) has a short postharvest life due to its sensitivity to water loss, relatively high metabolic activity, sensitivity to fungal decay, and mechanical damage. Among various preservation techniques, the use of LED light is considered an effective way to preserve quality and extend the storage life of fruits. This approach has attracted significant attention in recent years. Therefore, this study aimed to explore the effect of various LED light qualities (white, blue, red, blue + red, violet, and darkness as a control) on specific quality characteristics of strawberries stored in a cold room over four storage durations (0, 5, 10, and 15 d). The lowest weight loss (76% less than the control) and the highest fruit firmness were observed in the red light treatment. Also, after 15 d of storage, the violet light had caused the lowest total soluble solids and taste index (TSS TA-1) values, while the blue + red light had the highest acidity with a significant difference from the control ($p \leq 0.05$). Blue and white lights caused a significant increase in vitamin C, total phenols, and antioxidant activity percentage compared to the other lights and the control. However, the effects of violet light on fruit flavonoids and total anthocyanin concentrations were greater than in the other treatments. Violet and blue + red lights significantly reduced the percentage of fruit decay (73.91% more than the control). These findings suggest that different LED lights can maintain fruit quality and extend the storage life of strawberries before they are sold. Consequently, these LEDs could potentially replace fluorescent lights in fruit storage rooms.

Introduction

Strawberries are a highly nutritious fruit, abundant in various bioactive antioxidant compounds such as vitamin C, minerals, anthocyanins, phenolic compounds, and flavonoids (Giampieri et al., 2015). These compounds possess several beneficial biological properties, including anticancer, antioxidant, and anti-inflammatory activities (Guiamba et al., 2022). However, the postharvest handling and storage of fresh strawberries present significant challenges due to their high sensitivity to mechanical damage, water loss, microbial decay, physiological deterioration, and elevated respiration rates (Yan et al., 2019). While the use of synthetic chemicals is a straightforward and cost-effective method for postharvest quality control, it poses several issues, including negative

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environmental and human health impacts, as well as the development of fungal resistance to fungicides (Panou et al., 2021). Therefore, there is a critical need to develop environmentally conscious and sustainable alternatives to synthetic chemicals to reduce postharvest losses and extend the shelf life of fresh produce (Zhang et al., 2022a).

Recent research has explored various techniques to enhance the shelf life of fresh strawberries, including ozone treatment (Contigiani et al., 2018), modified atmosphere packaging (Kahramanoğlu, 2019), ultraviolet light treatment (Amiri et al., 2021), bioactive compounds (Liu et al., 2018), and edible coatings (De Bruno et al., 2023). Among these, the application of visible light-emitting diodes (LEDs) has garnered considerable attention in the postharvest handling of fruits and vegetables. LEDs, commonly used to manipulate the light environment, have emerged as an eco-friendly tool to enhance plant tolerance to various stresses and improve the shelf life while preserving the quality of horticultural products (Poonia et al., 2022; Zhang et al., 2022a). Compared to other light sources, LEDs offer numerous advantages, including monochromatic light emission, lower heat generation, longer lifespan, reduced production costs, lower energy consumption, higher energy efficiency, safety, and the ability to adjust light intensity and direction. These features make LED technology particularly suitable for the growth, storage, and preservation of fresh horticultural products (Loi et al., 2020).

The literature review reveals that while numerous studies have investigated the benefits of LEDs in enhancing the growth and nutritional value of horticultural crops, research on their impact on the quantity and quality of plant products postharvest is relatively recent and has focused on a limited range of fruits and vegetables (D'Souza et al., 2015; Nassarawa et al., 2021). Advances in LED technology have enabled a more nuanced understanding of the effects of visible light on fresh produce by allowing for the manipulation of light spectrum composition (Zhang et al., 2022a). The quality of light has shown considerable potential in improving the quality and extending the storage duration of fruits and vegetables postharvest. The response of these products to different light spectra (wavelengths) varies and is dependent on their ability to absorb specific wavelengths. The use of red and blue LEDs with a single wavelength has been observed to increase levels of bioactive compounds, phenols, flavonoids, and antioxidants in fresh fruits and vegetables, thus helping to maintain their nutritional value and overall quality (Hasan et al., 2017; Nassarawa et al., 2021). Studies have also demonstrated that short-term exposure to blue wavelength light can extend the postharvest life of tomatoes by delaying color change (Dhakal and Baek, 2014), and the use of blue LED light in strawberries can accelerate ripening by increasing respiration and ethylene production (Xu et al., 2014a). Additionally, the use of green, blue, and red LEDs has been shown to enhance anthocyanin content in strawberries compared to storage in the dark, while also maintaining vitamin C levels and increasing total phenol content (Kim et al., 2011; D'Souza et al., 2015).

Recent research has also explored the effects of other wavelengths. For instance, Xie et al. (2022) found that exposing broccoli florets to purple LED light at an intensity of 40 μmol m^{-2} s^{-1} can enhance levels of ascorbic acid and carotenoids. Similarly, Zhou et al. (2020) demonstrated that irradiation with white LED light at an intensity of 10 μmol m^{-2} s^{-1} effectively preserves postharvest quality and prolongs the freshness of pak choi during storage. Moreover, different light spectrum ratios, particularly blue in varying proportions, have been shown to enhance the efficiency of LED lighting (Hasan et al., 2017; Nassarawa et al., 2021). LED lighting also has the potential to alter carotenoid accumulation and prevent fungal decay, a major cause of postharvest losses, potentially reducing the need for chemical treatments (D'Souza et al., 2015). The application of LEDs in the postharvest stage can extend the shelf life of products, delay senescence (Ma et al., 2014), and thereby contribute to the reduction of food waste.

To date, only a limited number of studies have examined the impact of LED lighting on the postharvest quality of strawberry fruit, using a narrow range of LED light types and quality-related parameters (Xu et al., 2014a, 2014b; Chong et al., 2022; Zhang et al., 2022b). Therefore, to provide a more comprehensive assessment of the potential application of LED technology in the postharvest handling of strawberries, the present study investigated the effects of five distinct LED light qualities (blue, red, blue + red, violet, and white) on various quality attributes and the percentage of fruit decay in the strawberry cultivar 'Paros' during a 15-d storage period at 4 ± 1 °C. The findings of this research are expected to enhance our understanding of the role of different LED light qualities in the postharvest storage and preservation of strawberries.

Material and Methods

Plant materials

Fresh, uniform strawberry fruits of the 'Paros' cultivar, harvested at commercial maturity (defined as 80% red surface color), were collected in early October 2022 from a farm in Hassanabad, Sanandaj, Kurdistan, Iran. The strawberries were then transported to the laboratory of the Department of Horticultural Sciences at Bu-Ali Sina University, Iran. The selected fruits were carefully chosen to ensure they were free from both mechanical damage and fungal decay. Initially, the strawberries were washed with distilled water, then allowed to dry and cool to remove surface moisture. Subsequently, the strawberries were placed in small containers (24 × 14 × 5 cm).

The experiment was structured as a factorial design based on a completely randomized design with three replications. The first factor was the light treatment, which included six different conditions: blue light (peak at 449 nm), red light (peak at 632 nm), a combination of blue and red light (50% red, peak at 630 nm, and 50% blue, peak at 450 nm), violet light (peak at 400 nm), white light (peaks at 437 nm and 493 nm), and darkness as the control (Fig. 1). The second factor was the storage duration, with measurements taken at 0, 5, 10, and 15 d.

Light treatments and storage conditions

We constructed specialized chambers using metal frames (60 × 50 × 100 cm) to facilitate the application of the various light treatments. LED lamps were installed on each frame to deliver the specific light conditions, with the distance between the strawberry fruits and the lamps set at 40 cm. The light intensity of the lamps was carefully adjusted to a range of 112.5 to 150 μmol m-2 s-1. To ensure the integrity of the light treatments, the chambers were surrounded with aluminum foil to prevent the intrusion of external light sources and to isolate the intended light conditions effectively.

The strawberry fruits were placed in disposable plastic containers and exposed to the light treatments for 6 h per d, from 6 AM to 12 PM, while maintaining a temperature of 4 ± 1 °C and a relative humidity above 85% within the chambers. The control group, corresponding to the darkness treatment, was housed in a chamber similarly covered with aluminum foil and devoid of any light source during the storage period. A digital timer regulated the light exposure for the duration of up to 15 d. At specific intervals—d 0 (time of harvest), d 5, d 10, and d 15 of the storage period—15 fruits from each treatment were removed for various evaluations.

Fruit weight loss

The samples selected for this experiment were meticulously labeled and stored separately in appropriately marked containers. From each treatment, three strawberry fruits were chosen for analysis. On the first day, immediately after the application of the treatments, the initial weight of the samples was measured with high precision (Soto-Zamora et al., 2005). Subsequently, on d 5, 10, and 15, the samples were weighed again, and the difference between the weight on these days and the initial weight was used to calculate the percentage of weight loss using the following equation:

$$\text{Weight loss (\%)} = \left[\frac{W2-W1}{W1}\right] \times 100$$

where W1 and W2 are the initial fruit weight and the fruit weight after a special storage period, respectively.

Fruit firmness

Fruit firmness was measured using a penetrometer and a texture analyzer device (Zwick/Roell, Model bt1-fr0 .5th. d14. Xforce hp, Germany). The device was equipped with a stainless flat probe that had a diameter of 4.6 mm, a crosshead speed of 10 mm s^{-1}, and a penetration depth of 3 mm. During each evaluation period (0, 5, 10, and 15 d), three strawberries of similar size and shape were selected from each treatment and placed on the fixed plate of the texture analysis device at the equatorial region. The firmness of the fruit tissue was expressed in Newtons (N).

Total soluble solids

A handheld refractometer (model N1, Atago, Japan) was employed to measure the total soluble solids (TSS) content at room temperature (20 °C), which was expressed in degrees Brix (°Brix).

Titratable acidity

The titratable acidity (TA) of the strawberry juice was measured by titrating with 0.1 N NaOH until a pH of 8.2 was reached. The TA percentage was expressed in terms of citric acid, the main acid found in strawberries.

Taste index (TSS TA^{-1})

The taste index was calculated by determining the ratio of total soluble solids to titratable acidity (TSS TA^{-1}).

pH

The pH level of the fruit juice was assessed using a digital pH meter (model 827, Metrohm, Switzerland).

Vitamin C

The vitamin C content in strawberry fruits was determined using a method adapted from Petriccione et al. (2015). Strawberry samples (0.0025 kg) were homogenized with a solution containing 16% metaphosphoric acid and 0.18% EDTA, then centrifuged to collect the supernatant. The assay mixture was prepared by combining the extract with 3% metaphosphoric acid and 20% Folin-Ciocalteu reagent, and the absorbance was measured at 760 nm using a spectrophotometer (UV-1280, Shimadzu, Japan). The vitamin C content was expressed as mg of ascorbic acid equivalent 100 g^{-1} of fresh weight.

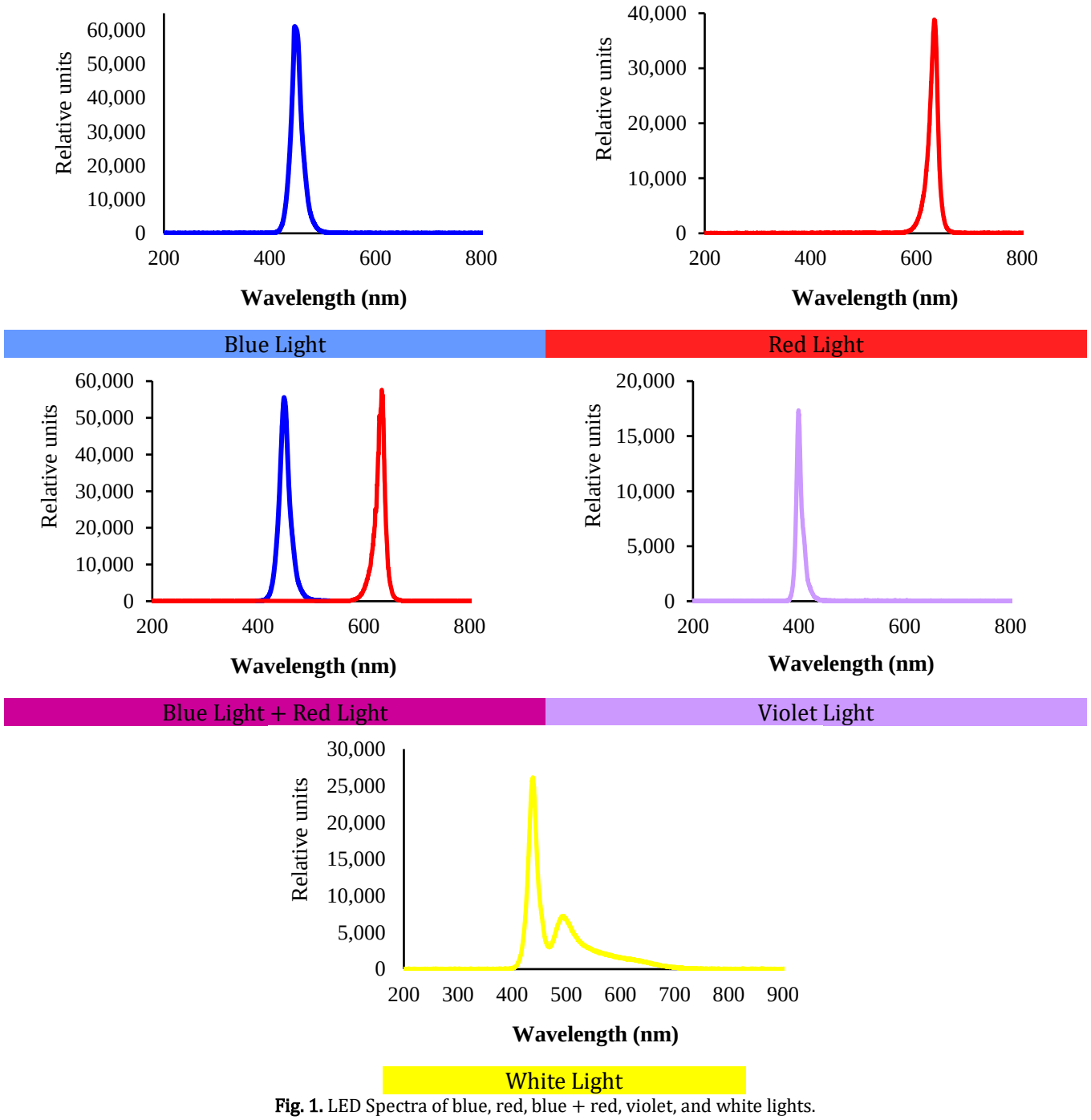

Fig. 1. LED Spectra of blue, red, blue + red, violet, and white lights.

Total phenols
The total phenols content of strawberry fruit extracts was measured using the Folin–Ciocalteu method (Singelton and Rossi, 1965). The results were reported as mg of gallic acid equivalent 100 g^{-1} of fresh weight.

Total flavonoids
The total flavonoids level was determined using the aluminum chloride colorimetric method (Chang et al., 2002). The total flavonoid content was expressed as mg of quercetin equivalent 100 g^{-1} of fresh weight.

Total anthocyanins
The total anthocyanin content of the extracts was measured using the pH differential method with some modifications (Ali et al., 2022). To extract the anthocyanins, 4 g of strawberry puree were mixed with 40 mL of a methanol-hydrochloric acid mixture in a 99:1 ratio and subjected to ultrasound for 10 min. The resulting extract was then centrifuged at 3500 rpm for 15 min. Subsequently, 1 mL of the sample extract was combined with 9 mL of potassium chloride buffer solution and sodium acetate buffer solution. The absorbance was measured at 520 and 700 nm using a spectrophotometer. The total anthocyanin concentration was expressed as mg of pelargonidin-3-glucoside equivalent 100 g^{-1} of fresh weight.

Antioxidant activity
The determination of antioxidant activity was carried out using the DPPH assay according to a method described by Brand-Williams (Brand-Williams et al., 1995). The percentage of inhibition was calculated using the following equation:

$$\%\text{Inhibition} = \left(\frac{\text{A515 Con} - \text{A515 Sam}}{\text{A515 Con}}\right) \times 100$$

Where %Inhibition is the DPPH-scavenging percentage, A515 Con is the control's absorbance, and A515 Sam is the sample's absorbance.

Decay incidence
The rate of decay was assessed through visual inspection and by counting the number of decayed fruits in each experimental group. Any fruit displaying minor indications of fungal growth was classified as a decayed fruit. The percentage of decayed fruit for each storage period was determined using the following equation:

$$\text{Decay Incidence}(\%) = \frac{\text{DF}}{\text{TF}} \times 100$$

Where 'DF' represents the number of decayed fruits and 'TF' represents the total number of fruits (Hernandez-Munoz et al., 2008).

Statistical analysis
Statistical analysis was conducted using SAS software (SAS Institute Inc., USA), version 9.1, based on a factorial experiment within a completely randomized design. The primary and secondary factors analyzed were postharvest light treatments and time, respectively. To compare significant differences between mean values, Duncan's multiple range test was applied ($P \leq 0.05$). Graphical representations were generated using Microsoft Excel 2016.

Results
Weight loss
Over the storage period, the weight loss of the fruits increased. However, the various light quality treatments significantly reduced this weight loss ($P \leq 0.05$). At the end of the storage duration, the weight loss decreased by 36, 50, 76, 67, and 59% in response to white, blue, red, blue + red, and violet lights, respectively, as compared to the control. The highest weight loss (12.96%) was observed in the control fruits on day 15. By the end of the storage period, the red light treatment exhibited the least weight loss (3.11%) compared to the control and other light treatments. Additionally, the blue + red and violet light treatments effectively mitigated weight loss throughout the entire storage period (Fig. 2A, Table 1).

Table 1. Mean square (MS) values from analysis of variance (ANOVA) of data for weight loss and firmness of strawberries treated by different light qualities during storage duration.

Source	df	Weight loss	Fruit firmness
Light Treatment (LT)	5	68.191**	3.133**
Storage Duration (SD)	3	153.270**	6.808**
LT×SD	15	8.324**	0.400**
Error	48	0.076	0.017
Total	71		

**$P \leq 0.01$

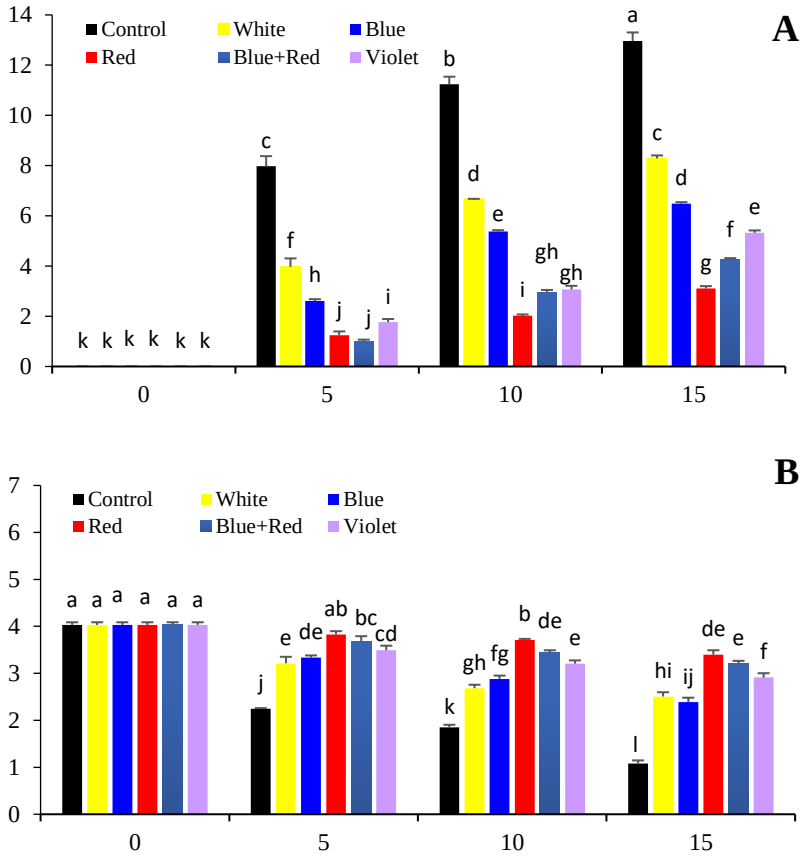

Fig. 2. Impact of light quality and storage duration on weight loss (A) and firmness (B) of strawberry fruit cv. Paros, stored at 4 ± 1 °C for a period of up to 15 d. The values are expressed as means ± standard error (SE). Error bars represent the standard error (n = 3). No significant differences (P≤0.05) between columns with the same letters, based on Duncan's multiple range test.

Fruit firmness

The fruit firmness decreased with the passing of the storage duration. The initial fruit firmness was 4.03 N, but it decreased to 1.08 N during storage. However, this reduction in firmness was delayed by the application of different light quality treatments. The red light treatment preserved the firmness by 215% compared to the control at the beginning of storage. The highest and lowest fruit firmness on day 15 of storage was observed in the control treatment (1.08 N) and the red light treatment (3.40 N), respectively. Furthermore, the white and blue light treatments did not exhibit a significant difference in fruit firmness throughout the storage period (Fig. 2B; Table 1).

Total soluble solids (TSS)

Changes in the TSS content of the control and light quality-treated fruits during storage are shown in Figure 3. The interaction of light quality and storage duration exhibited that at the end of the storage duration, the lowest TSS (7.4 °Brix) was observed in the violet light treatment, which was statistically different from the other treatments; in fact, the violet light was able to maintain the TSS at the initial level (7.1 °Brix) at the beginning of storage, compared to other light qualities. The violet light caused a 4% increase in TSS, whereas the red and blue + red lights increased the TSS by 13 and 16%, respectively. The violet light prevented the TSS level from increasing further. The maximum TSS was observed in the control treatment. There was no statistically significant difference (P≤0.05) between the blue and white lights, and the red and blue + red lights on day 15 of storage, and the increase in soluble solids in these treatment groups was also less compared to the control (Fig. 3, Table 2).

Titratable acidity (TA)

TA decreased during the storage in both the control and the light-treated fruits, however, the decrease was less pronounced under different light qualities. The light treatments were able to maintain the TA level compared to the control; nevertheless, the extent of TA decrease in the different light treatments did not follow a specific pattern during storage. The highest TA (0.84%

citric acid) was observed in the blue + red light treatment on day 15, which did not exhibit a significant difference compared to the red and combined light treatments on that day. The blue + red and red treatments maintained TA levels 83 and 66% higher than the control at the end of the storage duration (Fig. 4 and Table 2).

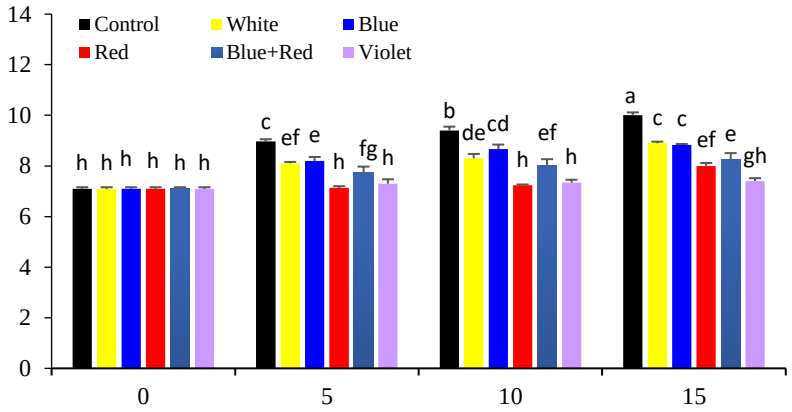

Fig. 3. Impact of light quality and storage duration on total soluble solids (TSS) of strawberry fruit cv. 'Paros', stored at 4 ± 1 °C for a period of up to 15 d. The values are expressed as means ± standard error (SE). Error bars represent the standard error (n = 3). No significant differences (P≤0.05) between columns with the same letters, based on Duncan's multiple range test.

Table 2. Mean square (MS) values from analysis of variance (ANOVA) of data for Total soluble solids, Titratable acidity, TSS TA^{-1} and pH of strawberries treated by different light qualities during storage duration.

Source	df	Total soluble solids (TSS)	Titratable acidity (TA)	TSS TA^{-1}	pH
Light Treatment (LT)	5	4.167**	0.111**	62.987**	0.002*
Storage Duration (SD)	3	6.889**	0.990**	196.916**	0.119**
LT×SD	15	0.536**	0.021**	12.930**	0.001^{ns}
Error	48	0.050	0.003	0.402	0.001
Total	71				

^{ns}, *, ** = non-significant, $P \leq 0.05$, $P \leq 0.01$, respectively.

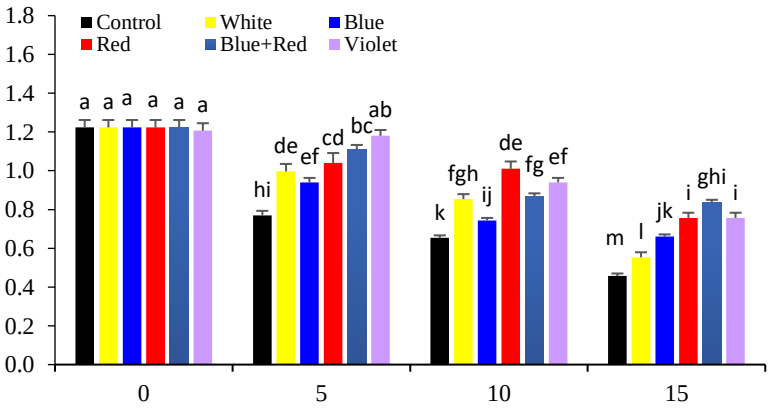

Fig. 4. Impact of light quality and storage duration on titratable acidity (TA) of strawberry fruit cv. 'Paros', stored at 4 ± 1 °C for a period of up to 15 d. The values are expressed as means ± standard error (SE). Error bars represent the standard error (n = 3). No significant differences (P≤0.05) between columns with the same letters, based on Duncan's multiple range test

Taste index (TSS TA^{-1})

Similar to the TSS, the taste index also increased through storage time. The extent of increase in the fruits under different light qualities was

significantly lower compared to the control fruits. At the end of the storage duration, the taste index in the red, blue + red, and violet light-treated fruits did not exhibit a statistically significant difference (P≤0.05). A reduction of 52-55% was observed in the taste index of the red, blue + red, and violet light-treated fruits in comparison to the control. The enhancement in the taste index at the end of the storage period for these treatments, compared to day zero, was 83, 69, and 67%, respectively, while the increase in the control group was 279% (Fig. 5 and Table 2).

pH

Through storage from day zero to day 15, the pH level increased in all treatment groups. However, the pH increased from 3.35 to 3.56 in the control group. On day 15 of storage, there were no significant differences in pH levels between the various light treatments and the control group (Fig. 6 and Table 2).

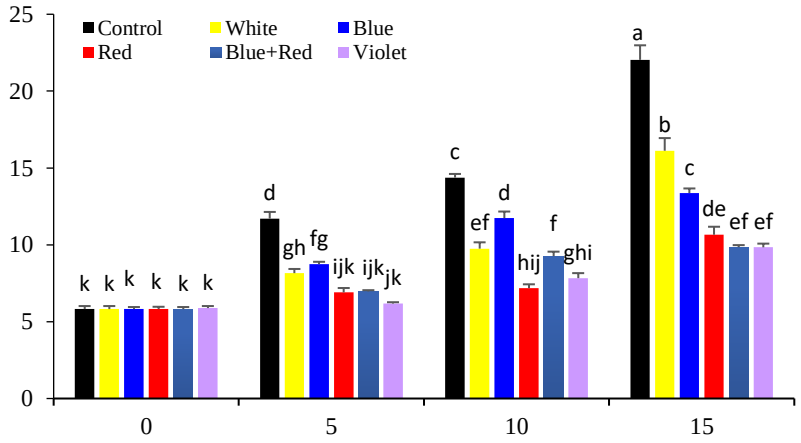

Fig. 5. Impact of light quality and storage duration on taste index (TSS TA^{-1}) of strawberry fruit cv. 'Paros', stored at 4 ± 1 °C for a period of up to 15 d. The values are expressed as means ± standard error (SE). Error bars represent the standard error (n = 3). No significant differences (P≤0.05) between columns with the same letters, based on Duncan's multiple range test.

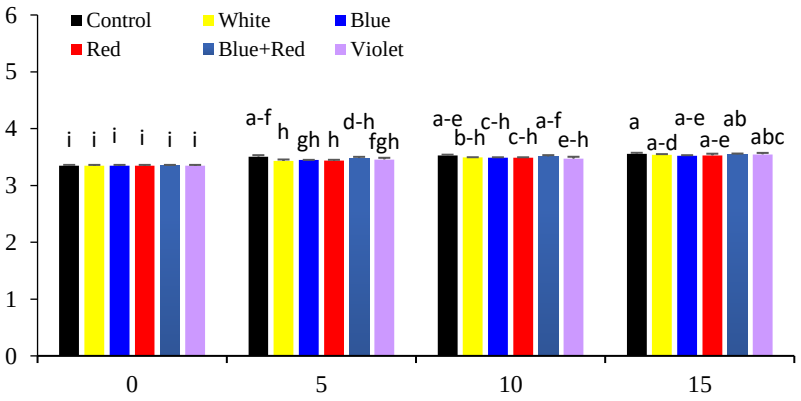

Fig. 6. Impact of light quality and storage duration on pH of strawberry fruit cv. Paros, stored at 4 ± 1 °C for a period of up to 15 d. The values are expressed as means ± standard error (SE). Error bars represent the standard error (n = 3). No significant differences (P≤0.05) between columns with the same letters, based on Duncan's multiple range test.

Vitamin C

Changes in the vitamin C concentration under different light treatments during storage are illustrated in Figure 7. Throughout the storage duration, all treatment groups showed a rising trend in vitamin C content, compared to the control treatment. At the beginning of storage, the vitamin C content was 49.51 mg ascorbic acid 100 g^{-1} fresh weight, and by the end of storage, it changed to 35.11, 79.73, 83.79, 62.87, 66.92, and 72.55 mg ascorbic acid 100 g^{-1} fresh weight in the control, white, blue, red, blue + red, and violet light treatments, respectively. On day 15 of storage, the blue light treatment enhanced the

fruit's vitamin C content by 101%. The lowest increase in vitamin C concentration was noted in the red light treatment, with only a 51% increase compared to the other light treatments (Fig. 7 and Table 3).

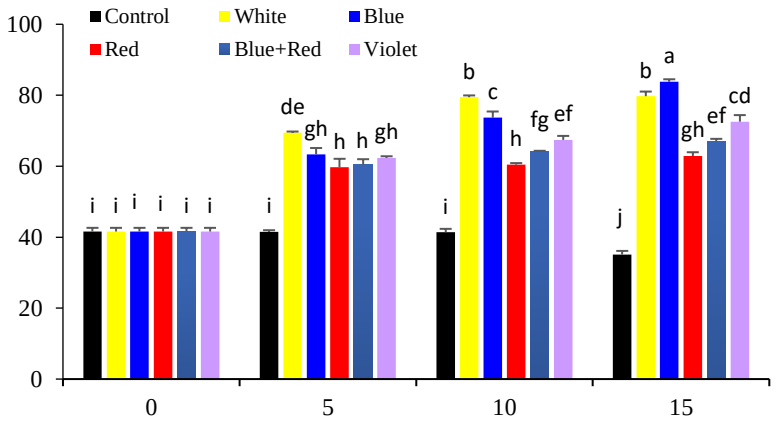

Fig. 7. Impact of light quality and storage duration on vitamin C of strawberry fruit cv. Paros, stored at 4 ± 1 °C for a period of up to 15 d. The values are expressed as means ± standard error (SE). Error bars represent the standard error (n = 3). No significant differences (P≤0.05) between columns with the same letters, based on Duncan's multiple range test.

Table 3. Mean square (MS) values from analysis of variance (ANOVA) of data for vitamin C, total phenols, total flavonoids, total anthocyanins, antioxidant activity, and decay incidence of strawberries treated by different light qualities in storage.

Source	df	Vitamin C	Total phenols	Total flavonoids	Total anthocyanins	Antioxidant activity	Decay incidence
Light Treatment (LT)	5	1174.259**	3731.382**	100.639**	101.981**	359.215**	270.080**
Storage Duration (SD)	3	2344.338**	5005.611**	423.964**	279.517**	335.837**	975.161**
LT×SD	15	173.165**	1008.076**	32.168**	13.377**	49.999**	58.916*
Error	48	4.047	9.009	3.165	1.853	0.684	25.304
Total	71						

*, ** = $P \leq 0.05$, $P \leq 0.01$, respectively.

Total phenols content

The total phenol concentration showed a decline until day 10 of storage. However, on day 15 of storage, all the light quality treatments enhanced the phenol concentration, except the red light treatment, which did not. The increase in total phenols ranged from 9-45%. The white light treatment had the greatest effect, resulting in a 45% increase in total phenols compared to day zero, which was significantly different from the other light treatments and the control. The total phenol concentration increased from 145.06 mg gallic acid 100 g^{-1} fresh weight on day zero to 209.88 mg gallic acid 100 g^{-1} fresh weight on day 15. Although the red light increased the total phenols after 15 d compared to 10 d, this increase was less than that observed at the beginning of storage. Thus, by the end of the storage period, the red light had reduced the total phenols by 10% (Fig. 8 and Table 3).

Total flavonoids content

Total flavonoids content in strawberry fruits was affected by different light quality treatments. All five light qualities used in the present study increased the total flavonoids concentration over the storage duration. The maximum total flavonoids content was recorded on day 15 of storage under the violet light treatment (58.83 mg quercetin 100 g^{-1} fresh weight), while the lowest was observed in the control treatment (43.0 mg quercetin 100 g^{-1} fresh weight). The violet light increased the flavonoids concentration by 37% compared to the control fruits. Furthermore, the different LED light quality treatments increased the total flavonoids content within a range of 19-46% at the end of storage, compared to the beginning. The red, blue + red, and white lights did not differ significantly in this regard (P≤0.05) on day 15 of storage (Fig. 9 and Table 3)

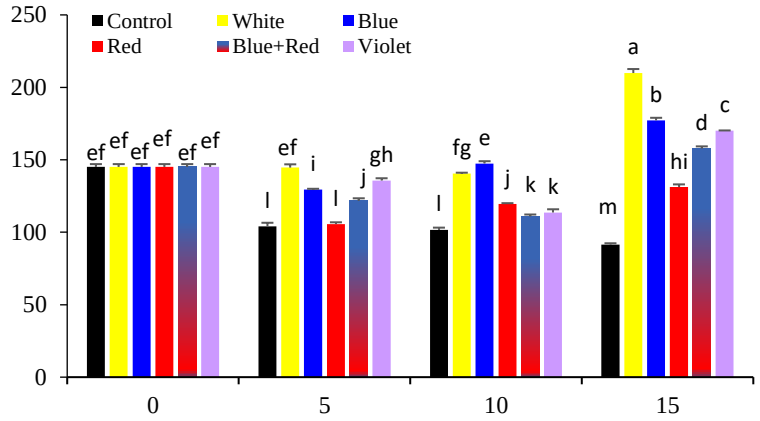

Fig. 8. Impact of light quality and storage duration on total phenols concentration of strawberry fruit cv. Paros, stored at 4 ± 1 °C for a period of up to 15 d. The values are expressed as means ± standard error (SE). Error bars represent the standard error (n = 3). No significant differences (P≤0.05) between columns with the same letters, based on Duncan's multiple range test.

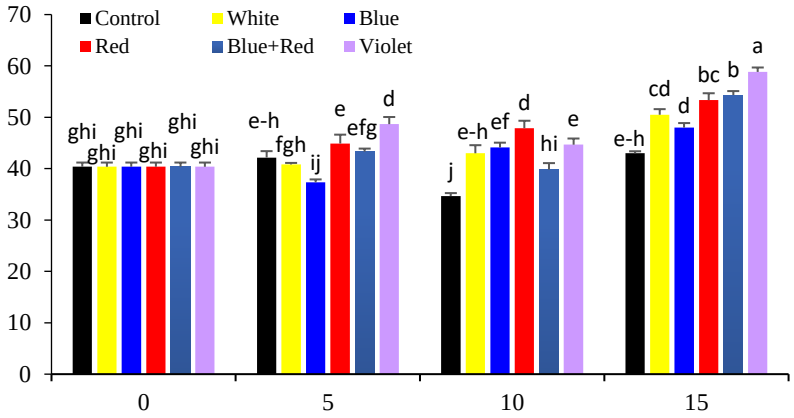

Fig. 9. Impact of light quality and storage duration on total flavonoids concentration of strawberry fruit cv. Paros, stored at 4 ± 1 °C for a period of up to 15 d. The values are expressed as means ± standard error (SE). Error bars represent the standard error (n = 3). No significant differences (P≤0.05) between columns with the same letters, based on Duncan's multiple range test.

Total anthocyanins content

The average total anthocyanins level of the untreated strawberry fruits on d zero (at harvest) and after 15 d of storage was 9.41 and 11.60 mg pelargonidin-3-glucoside 100 g^{-1} fresh weight, respectively. The total anthocyanin concentration increased in both the control and light-treated fruits, but this increase was more pronounced in the light-treated fruits compared to the control group. The highest total anthocyanins concentration, 15 d after treatment, was observed in the violet light treatment (24.93 mg pelargonidin-3-glucoside 100 g^{-1} fresh weight), which exhibited a significant difference (P≤0.05) compared to the other treatments. This treatment increased the total anthocyanins content by 165% in comparison to the beginning of storage. Following the violet light treatment, the red, blue + red, white, and blue light treatments also increased the total anthocyanin concentration of the fruit by 134, 109, 90, and 72% respectively, but the anthocyanins content in the control fruits remained constant (Fig. 10 and Table 3).

Antioxidant activity

The antioxidant activity (%) in strawberry fruits increased in storage under different light quality treatments, but it decreased in the control fruits. On the last day of storage, the blue light had caused the maximum antioxidant activity (95.22%). In comparison to the beginning of storage, the control fruits exhibited a 5% reduction in antioxidant activity after 15 d of storage. The blue, white, and violet light treatments had increased the percentage of antioxidant activity after 15 d of storage by 28, 22,

and 17%, respectively, compared to the beginning of storage. The red and blue + red light treatments caused increases of 12 and 7%, respectively (Fig. 11 and Table 3).

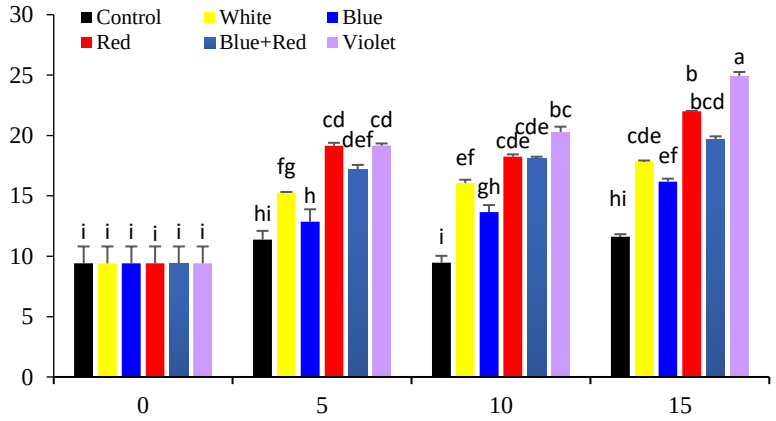

Fig. 10. Impact of light quality and storage duration on total anthocyanins concentration of strawberry fruit cv. Paros, stored at 4 ± 1 °C for a period of up to 15 d. The values are expressed as means ± standard error (SE). Error bars represent the standard error (n = 3). No significant differences (P≤0.05) between columns with the same letters, based on Duncan's multiple range test.

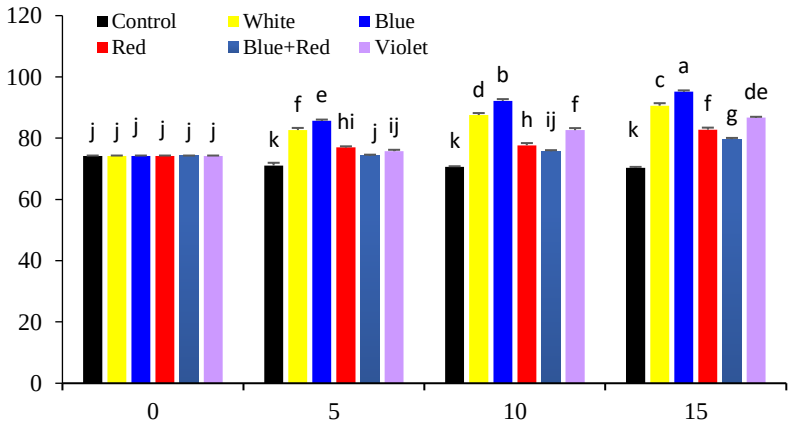

Fig. 11. Impact of light quality and storage duration on antioxidant activity of strawberry fruit cv. Paros, stored at 4 ± 1 °C for a period of up to 15 d. The values are expressed as means ± standard error (SE). Error bars represent the standard error (n = 3). No significant differences (P≤0.05) between columns with the same letters, based on Duncan's multiple range test.

Fruit decay incidence

Through the storage time, the percentage of decay increased gradually and significantly in all treatment groups. Fruit decay in the control began on day 5, while decay in the light-treated fruits began on day 10 of storage. The violet light treatment caused 0% decay on day 10 of storage. The different light quality treatments reduced the percentage of decay compared to the control fruits over the storage period. After 15 d of storage, the lowest percentage of decay was observed in response to the blue + red (8.33%) and violet (8.33%) light treatments, which did not differ significantly from the other light treatments, except for the white light. The percentage of decay in the control fruits at the end of storage was 31.94%, the highest among all treatment groups (Fig. 12 and Table 3).

Discussion

In the present study, weight loss consistently increased over the storage duration across all treatments. This weight loss is primarily attributed to water loss through transpiration and the depletion of carbon reserves due to respiration (Sogvar et al., 2016; Asgareyan et al., 2019). Strawberries, in particular, are highly susceptible to rapid water loss owing to their very thin skin structure (Hernández-Muñoz et al., 2008). Consequently, reducing fruit weight loss is crucial in optimizing control strategies to extend the storage life of strawberries. At the end of the

storage period, red light treatment demonstrated the greatest effect in mitigating weight loss compared to the control and other light treatments (Fig. 2A). Exposure to red light helps reduce weight loss during the postharvest period by enhancing sugar and phenol metabolism, preserving fruit quality, and extending storage life, particularly when compared to blue light (Nassarawa and Luo, 2022). Generally, the quality of LED light during postharvest storage of fruits significantly influences their weight loss by delaying senescence and reducing microbial decay, which consequently extends storage life and maintains fruit quality (Nassarawa et al., 2021).

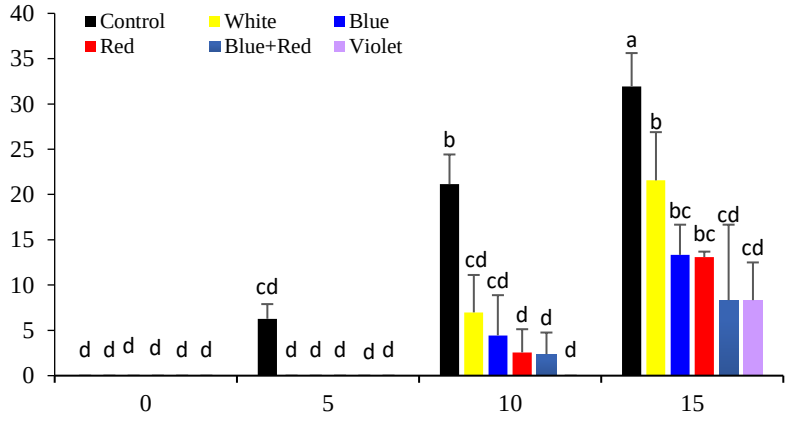

Fig. 12. Impact of light quality and storage duration on decay incidence of strawberry fruit cv. Paros, stored at 4 ± 1 °C for a period of up to 15 d. The values are expressed as means ± standard error (SE). Error bars represent the standard error (n = 3). No significant differences (P≤0.05) between columns with the same letters, based on Duncan's multiple range test.

LED light treatments have been shown to effectively prevent strawberries from losing moisture by strengthening their skin and slowing the outward movement of moisture from the interior of the fruit to its surface. This process leads to decreased moisture loss and potentially a lower rate of respiration (Qi et al., 2011). The results indicate that red light treatment also resulted in the highest firmness, showing a 215% increase in firmness by the 15th day of storage compared to the control treatment (Fig. 2B). Firmness is a critical quality attribute that significantly influences consumer evaluation and acceptance of the fruit. Changes in fruit firmness during ripening and storage are largely due to the breakdown of protopectin into pectin by the enzyme polygalacturonase, the hydrolysis of methyl esters by pectin methylesterase, and the degradation of cellulose and hemicelluloses (Luo, 2006; Duan et al., 2008; Cheng et al., 2009). Previous studies have shown that strawberry texture softens during storage due to metabolic changes and moisture loss, which in turn reduce firmness (Ahmadi-Afzadi et al., 2013). Similar findings have been reported in tomatoes, where postharvest treatment with red and white lights better maintained fruit firmness compared to blue or green lights (Arslan et al., 2021).

Following a 4-day LED treatment at 5 °C on strawberry fruit, both ascorbic acid (vitamin C) content and sugar levels exhibited a significant increase during postharvest storage. However, the notable rise in the total soluble solids (TSS) content is likely due to the breakdown of cell wall components such as hemicelluloses and polyuronides, rather than the conversion of starch into sugars, as there is minimal glycogen accumulation during fruit growth (Kim et al., 2011). An enhancement in TSS has also been reported in Chinese bayberry (Myrica rubra Sieb) under blue LED (470 nm) treatment at 40 W m^{-2} for 8 days at 10 °C, along with increased amounts of fructose, glucose, and sucrose compared to untreated samples (Shi et al., 2016).

Titratable acidity (TA) reflects changes in the overall organic acid content, particularly citric acid, in fresh fruits, as citric acid is the predominant acid in strawberries. As the fruit ripens, TA decreases due to the comprehensive utilization of organic acids in the citric acid cycle and other decarboxylation reactions (Panou et al., 2021). Previous research has indicated that the greater loss of acidity in untreated fruits (control) may suggest the consumption of organic acids as substrates for respiratory metabolism during storage (Díaz-Mula et al., 2009, 2012). Grozeff et al. (2016) observed no changes in TA following exposure to pulsed white light. The preservation of TA under blue light treatment, compared to the control, during strawberry storage has been

documented by Xu et al. (2014b). This finding aligns with the results of the present study, where various light qualities, including blue light, maintained the fruit's acidity level (Fig. 4).

The TSS/TA ratio is a critical parameter for assessing strawberry quality, as it indicates the balance of fruit flavor and its appeal to consumers (Sturm et al., 2003). Fruits exposed to different light qualities (white, blue, red, blue + red, and violet) exhibited a smaller increase in the TSS/TA ratio compared to the control (dark) fruits during the 15-day storage period. This observation suggests reduced ripening and delayed senescence in the light-treated strawberries compared to the control fruits (Fig. 5). Furthermore, pH reflects alterations in organic acid content in fresh fruits during storage. Generally, pH increases during storage, which is attributed to fruit senescence and the growth of microorganisms in an acidic environment (Abu Salha and Gedanken, 2021). This leads to a less acidic environment with a higher pH value due to the metabolic activity of these microorganisms within the fruit. The changes in the pH of strawberries under different light qualities and in the control (darkness) over 15 days of storage at 4 °C are presented in Figure 6. Martínez-Zamora et al. (2023) reported that physicochemical quality parameters in cherry tomatoes, such as soluble solids content and pH, remained stable without significant differences under different light qualities, which is consistent with the results of the present study.

The results of this study demonstrate that different light qualities can be more effective in increasing vitamin C levels during storage compared to the control treatment (Fig. 7). Light can upregulate the expression of various metabolic pathways, thereby increasing the content of metabolites such as soluble sugars, ascorbic acid, organic acids, and anthocyanins. Furthermore, light can activate the enzyme phenylalanine ammonia-lyase or function as a signal through light receptors (Nassarawa et al., 2021). The level of vitamin C is influenced by the activities of enzymes involved in its biosynthesis and oxidation, both of which have been reported to be affected by LEDs (Tabata et al., 2002; Massot et al., 2012). Blue and red LEDs are the most commonly used types for enhancing vitamin C levels in various fruits and vegetables. However, less research has been conducted on other LED types, such as green or yellow, or on other light qualities (Loi et al., 2020). Blue light has been found to be more effective than red light in increasing the vitamin C content, as well as ascorbate peroxidase activity and the activity of other antioxidant enzymes during strawberry storage (Xu et al., 2014b). This finding is consistent with the present study, which showed higher vitamin C content under blue light compared to other light qualities. In agreement with the current study on the application of LEDs, an increase in vitamin C content has been reported with blue light irradiation in various horticultural products, including green-harvested tomatoes (Ntagkas et al., 2019), raspberry fruit (Ganganelli et al., 2023), citrus fruit juices (Zhang et al., 2015), and leafy vegetables (Ohashi-Kaneko et al., 2007).

The increased levels of phenolic compounds observed in the treatments may be associated with the percentage of weight loss. Notably, the white and blue light treatments, which exhibited the highest weight loss percentage on day 15 of storage compared to other light sources, also demonstrated higher total phenol concentrations than the other light treatments. In contrast, the red light treatment, which had the lowest weight loss percentage, showed a 9% decrease in total phenol levels compared to day 0 of storage (Fig. 8). The impact of various LED wavelengths on fresh horticultural products varies because these lights influence specific receptors in fruits and vegetables (Samuoliene et al., 2013). In the current study, we observed an increase in the total phenolic and anthocyanin concentrations in the fruits when exposed to various light qualities during storage (Figs. 8 and 10), which aligns with previous reports (Hassanpour, 2015). This enhancement may occur because these compounds continue to be synthesized after harvest (Sogvar et al., 2016). Moreover, the finding that blue light treatment significantly enhanced total phenol levels in our study may be related to the cumulative effect of blue light induction on the enzyme phenylalanine ammonia-lyase (PAL) (Xu et al., 2014b). García-Pastor et al. (2020) also noted that blue light plays a beneficial role in increasing the concentration of total phenols. An increase in total phenol levels under blue and purple lights has been documented (Xie et al., 2022), consistent with the results of the present study. Conversely, total phenol levels in control fruits diminished throughout the storage period. Cold storage of fruits and vegetables has been found to lead to a decrease in total phenolic content, with reductions of up to 50% observed in tomatoes (Galani et al., 2017). The authors suggested that this decline in total phenolic compounds might result from degradation processes, which occur following changes in the activity patterns of associated enzymes, such as reduced PAL activity or increased polyphenol oxidase activity during cold storage.

The findings also indicate that the total flavonoid and anthocyanin levels in the fruits increased during storage. Notably, the violet light treatment resulted in a 37% increase in flavonoids and a 115% increase in total anthocyanins on the 15th day of storage, both compared to the control (Figs. 9 and 10). Previous studies have indicated that blue light can enhance the production of phenolic compounds, particularly flavonoids, which are known for their antioxidant properties, their ability to absorb UV radiation, and their function as UV filters (Agati and Tattini, 2010). Furthermore, the synthesis of phenolic compounds is linked to an increase in the production of the amino acid phenylalanine, rather than tryptophan. This suggests that the regulation of total phenol and flavonoid levels by LED lighting may occur directly through the induction of key enzyme expression and indirectly through the increase of precursor molecules (Wang et al., 2020). Our findings are consistent with other studies that have reported the effect of different light quality applications on increasing total flavonoid concentration in table grapes (Nassarawa and Luo, 2022), raspberries and blackberries (Ganganelli et al., 2023), and tomatoes (Martínez-Zamora et al., 2023).

The present study also suggests that the increase in anthocyanins could be related to the ongoing biosynthesis of phenolic compounds throughout the storage period, a process associated with fruit ripening (Fig. 10). It has been demonstrated that LED treatments can enhance the postharvest life of various fruit and vegetable species by modifying certain quality attributes. These attributes include delaying senescence, boosting nutritional content, slowing down ripening, minimizing microbial decay, increasing phenolic and anthocyanin levels, and improving antioxidant activity (Nassarawa et al., 2021). Various LED spectra, including red, blue, green, and even white lights, have been shown to enhance the nutritional quality of harvested fruits and vegetables. For example, increased levels of vitamin C, anthocyanins, and total phenols have been observed in cabbage exposed to LED light (Lee et al., 2014; Hasan et al., 2017). The present study (Fig. 11) suggests that the enhanced antioxidant activity in strawberries under various light-quality treatments may be due to the stimulated positive regulation of metabolites, such as ascorbate (Ntagkas et al., 2019), and the increased activity of PAL, an enzyme involved in the production of phenolic compounds, including flavonoids and coumarins (Xu et al., 2014b).

Irradiation with blue light has been demonstrated to increase total sugars, TA, ascorbic acid, total phenolic content, and DPPH radical scavenging activity in strawberries during storage (Xu et al., 2014b). Therefore, utilizing this light during the postharvest phase can effectively preserve the quality attributes and enhance the nutritional value of strawberries by bolstering the antioxidant system and increasing the capacity to neutralize free radicals (Ahmadi et al., 2020). The positive and significant impact of LED lights on preserving antioxidant capacity is consistent with results reported in bell pepper (Martínez-Zamora et al., 2021), tomato (Baenas et al., 2021), and banana (Huang et al., 2018). Jin et al. (2023) observed that purple LED light reduces the browning index in fresh-cut apples and delays browning compared to a dark control. This effect is attributed to the purple light's role in inducing the synthesis of phenols in apple fresh cuts via the upregulation of the MdHY5 and MdHY5S genes. These findings align with the current study (Fig. 12), which also noted a significant decrease in decay percentage in strawberries exposed to violet LED light treatment compared to other light treatments. Furthermore, a reduction in the microbial community and reproduction of specific spoilage organisms was observed in fresh-cut pak choi (Zhang and Xie, 2021). They reported that violet light has an effective antibacterial impact on bacteria that cause rot. Overall, various LED light qualities may have potential usefulness across diverse applications, such as storage, long-distance transportation, and even integration with refrigeration systems. However, further research is required to evaluate the quality characteristics of fruits and to investigate the effectiveness of each light quality on the appearance, quality, antifungal, and antibacterial properties of different fruit varieties. Additionally, scale-up studies under real-world commercial conditions are necessary.

Conclusions

The findings of the present study demonstrate that LED illumination with specific wavelengths within the visible spectrum during storage can significantly enhance the postharvest life of strawberry fruits. This enhancement is achieved by improving or delaying the degradation of key quality attributes such as total soluble solids, titratable acidity, fruit firmness, vitamin C content, anthocyanin levels, total phenolic content, and antioxidant activity. Additionally, LED treatments were effective in preventing weight loss and reducing the percentage of decay in the fruits. Among the treatments, violet, red, and blue + red light treatments were particularly effective in improving the physicochemical properties of the strawberries, increasing the

levels of total flavonoids and anthocyanins, and reducing both the percentage of decay and weight loss. On the other hand, blue and white lights were more influential in increasing the bioactive compounds in the fruit, including total phenols, vitamin C, and antioxidant activity, compared to the other light treatments.

Furthermore, the study observed that the different LED light qualities did not have a significant effect on the fruit's pH. Therefore, postharvest treatment with various LED light qualities can be proposed as an environmentally friendly, highly effective, and economically beneficial technology for extending the storage life of strawberry fruits. This is achieved through enhanced disease resistance and increased nutritional value, attributes that are currently in high demand due to strawberries' rich vitamin C content and unique antioxidant properties. Nonetheless, further research is necessary to elucidate the underlying molecular mechanisms responsible for the accumulation of these bioactive compounds. Additionally, more investigations into the effects of other LED light qualities are required to fully understand their potential benefits.

Acknowledgements

We would like to express our sincere gratitude to the Department of Horticultural Science at Bu-Ali Sina University in Hamedan for their invaluable support of this research.

Conflict of Interest

The authors indicate no conflict of interest in this work.

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