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Red LED light affects the physicochemical responses of strawberries during storage

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ABSTRACT

This study aimed to evaluate the effect of the storage of strawberries under LED lights on 'Albion' strawberry quality. The treatments were applied as follows; (1) storage under continuous blue, red, and ultraviolet-A (UVA) LED light, (2) storage in the dark conditions (control), and (3) storage in the dark conditions after 1 h UVA (UVAh) LED lighting. Strawberries were stored at a temperature of 4±1°C with 85-90% relative humidity for 10 days. In the study, analyses were conducted on the total anthocyanin content, color (L*, hue angle, redness index), total soluble solids (TSS), fructose, glucose, total sugar content, titratable acidity (TA), fruit firmness (N), and weight loss at the start of the experiment and at 2-day intervals during storage. According to the results, the storage of strawberries under continuous red-LED light was successful in improving the anthocyanin and TSS contents, while preserving fruit firmness and reducing weight loss. Moreover, UVA treatment was effective in maintaining the L*, a*, and b* color values, whereas UVAh was effective on the hue angle and redness index. Furthermore, UVAh treatment caused a decrease in the glucose, fructose, and total sugar content and, in the titratable acidity of the strawberries.

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1. Introduction

Strawberry (*Fragaria x ananassa* (Weston) Dushesne ex crozier (pro sp.)) belongs to the *Fragaria* L. species in the Rosaceae family and Rosales order (USDA, 2024). Strawberry production in Türkiye amounted to 669.195 tons across 186.761 decares as of 2021 (TUIK, 2023). Strawberry is defined as a berry-like fruit. It is also named aggregate fruit because it comprises many individual tiny fruits embedded in a fleshy receptacle (Oğuz et al., 2022). It is a perishable fruit; therefore, it is important to ensure a cold chain process from harvest to consumer to maintain its quality. Losses are thus caused by water loss, fungal attacks, undesirable metabolic changes, and senescence, softening, structural changes, and color changes (Kuchi and Sharavani, 2019). Therefore, several studies have investigated the effects of modified atmosphere storage, gamma irradiation, ultraviolet irradiation, heat treatments, edible coating application, and recently light-emitting diode (LED) treatments for maintaining the postharvest quality of strawberries (Nassawara et al., 2021).

Previous studies have determined that LEDs affect secondary metabolites during postharvest storage of horticultural crops, the blue LED improves antioxidant enzyme activity in strawberries (Xu et al., 2014) and the white LED delays the breakdown of carotenoids in lettuces (Kasım and Kasım, 2017). Similarly, it was found that the red LED leads to an increase in the total carotenoids of Satsuma mandarins (Ma et al., 2012) and in the ascorbic acid of broccoli (Ma et al., 2014), whereas blue LEDs are more effective in increasing the vitamin C content of cabbages (Lee et al., 2014). LEDs improved the yield and biochemical quality of crops in both the pre-and postharvest periods and, increased the storage duration of horticultural crops via surface disinfection (Kasım and Kasım, 2017).

LED lights at 385, 470, 525, and 630 nm wavelengths increased the content of total soluble solids from 9.87% (both at harvest and during storage) to 12.77%. In addition, the vitamin C content (78.70 mg/100g), anthocyanin content (12.48 mg/100g), and total phenol content (172.75 mg/100 g) of strawberries treated with LED irradiation were higher than those in the control group (54.28 mg/100 g, 6.89 mg/100g, and 129.5 mg/100g, respectively) (Kim et al., 2011). Similarly, blue LED light treatment at a dose of 40 μmol/m2s increased in the total anthocyanin content of strawberries (Xu et al., 2014). However, it was stated that the white LED (300 $\mu mol/m^2s$) and blue LED (200 $\mu mol/m^2s$ and 100 $\mu mol/m^2s$) treatments did not affect the vitamin C content, and the 100 $\mu mol/m^2s$ white and blue light treatments caused weight loss in strawberries by increasing the transpiration of calyx (Li, 2016).

Ultraviolet A, B, and C irradiation have been commonly used in surface sterilization for years, and the effects of UV light on the quality of fresh produce have been well investigated and are currently being studied. However, studies on the effect of UVA-LED on the quality of fresh fruit and vegetables are limited. In a study investigating the use of UVA-LED for surface sterilization of fresh produce, it was concluded that UVA-LED treatment caused weight loss in cabbage, but no differences between UVA-LED and control were not found (Aihara et al., 2014). Therefore, the authors declared that UVA-LED treatment has great potential for surface sterilization of fresh produce (Aihara et al., 2014). Another study using red leaf lettuce detected that the different LEDs such as red and blue, blue and UVA LEDs, or white LEDs that were treated on lettuce three days before harvest did not affect leaf thickness and greenness, antioxidant capacity, and phytonutrient concentrations (Hooks et al., 2022). Lante et al. (2016) stated that UVA-LED (390 nm) is a technological alternative to the traditional approach for reducing the browning of fresh-cut apples and pears.

There is limited information on LED lighting applications for strawberry postharvest storage. To this end, there is a need to determine the effects of different LED light treatments such as continuous red, blue, and UVA and dark storage after one hour UVA (UVAh) light treatment on postharvest biochemical changes and the quality of strawberries during storage at a temperature of 4 ± 1°C.

2. Materials and methods

2.1. Plant material

In this study, the 'Albion' strawberry variety was used, which was grown under open field conditions in the town of Karamürsel located at coordinates 40.613365 north latitude and, 29.644316 east longitude in Kocaeli, as shown in Figure 1.

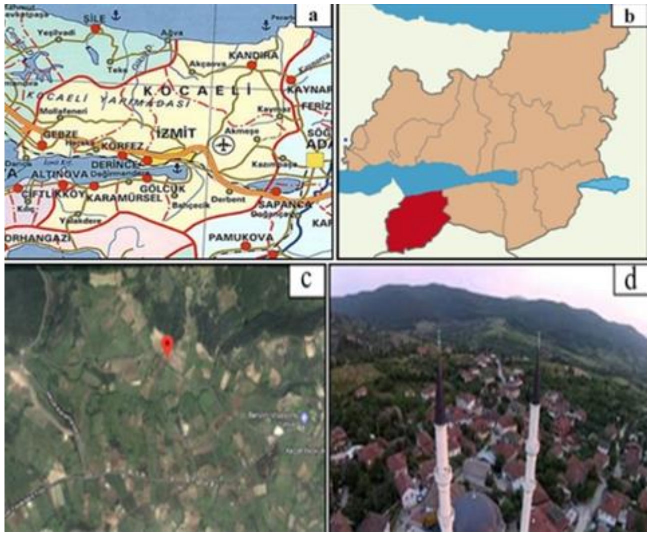


Figure 1. The location (a), region map (b), location (c) and visual status (d) of the field at which the strawberries are grown

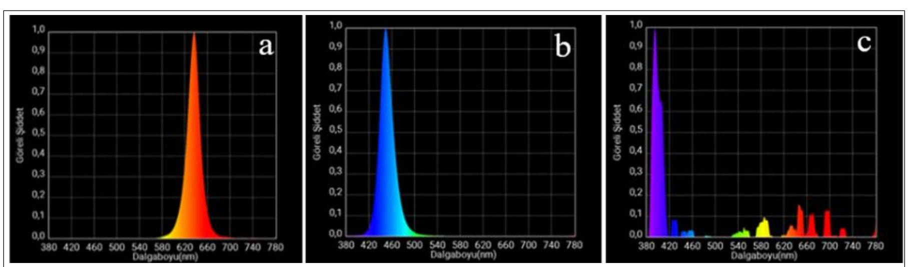
The strawberries were harvested at the 90% coloring stage, which was used as a commercial harvest stage, on July 15, 2017. They were immediately transported to the Postharvest Physiology Laboratory in the Arslanbey Vocational School of Kocaeli University within 1 h of harvest. The fruits were examined for uniformity and vigor, and those that were bruised, injured, etc., were separated. Only good looking fruits were used in the study.

2.2. LED light application apparatus

Three LED experiments were set up, which included red, blue, and ultraviolet-A (UVA) lights. These were set up using 1 m -1 m - 80 cm wooden frames on which a 5 m strip of LEDs was mounted for each light color. Strawberries were placed under LED lights, and the distance between the fruit and the light was 40 cm. The surroundings of the apparatus were covered with black polyethylene to inhibit light penetration into the strawberries from outside (Kasım and Kasım, 2017).

2.3. LED light treatments

The strawberries were divided into five groups. The first, second, and third groups of fruits were stored under continuous red (R), blue (B), and ultraviolet-A (UVA) LEDs, whereas the fourth control (C) group was stored in dark conditions. The fifth group was kept under dark storage conditions after 1 h of UVA-LED (UVAh) treatment. The wavelengths and properties of the LED lights were detected using the Asensetek Lighting Passport Essence and are given in Figure 2.



Red LED: 600-700 nm	Blue LED: 400-499 nm	UVA LED: 380-399 nm
PPFD: 2,0256 μmol/m²s	PPFD: 6,8933 μmol/m²s	PPFD: 0,0018 μmol/m²s
YPFD: 1,9631 μmol/m²s	YPFD: 5,0702 μmol/m²s	YPFD: 0,0011 μmol/m²s

Figure 2. The wavelengths and properties of the LED lights

2.4. Packaging and storage conditions

In the experiment, the strawberries were packaged into 15 x 25 x 5 cm transparent polyethylene boxes that included 350-400 g fruit. The packaged strawberries were stored at a temperature of 4 ± 1°C with 85-90% relative humidity for 10 days.

2.5. Total anthocyanin content (TAC)

For the calculation of the total anthocyanin content, 1 g of fruit sample was placed in a beaker, a 10 mL first buffer pH=1 (125 mL 0.2 M KCl + 375 mL 0.2 M HCl) was added to it, and the content was homogenized. The same process was repeated for the second buffer (pH=4.5) (400 mL 1 M sodium acetate + 240 mL 1 M HCl + 360 mL water). After homogenization, the samples for each buffer were centrifuged for 15 min at 5000 rpm, and the supernatant was collected and measured at 510 nm. The total anthocyanin content was calculated using the following formula by Şahin et al. (2021):

TAC (mg/kg TA) = (ABSpH:1,0 – ABSpH:4,5) x 484,82 x 1000 / 24825 x DF

In the formula: ABS expresses absorbance and DF: Dilution factor.

2.6. Color measurements

The color of the samples was measured using a colorimeter (Minolta CR 400 Chroma; Minolta Co., Osaka, Japan) at three different points on 10 strawberries. The L*, a*, and b* color values (CIELAB) were used in the expression of fruit color. From these values, the hue angle was calculated according to (Kasım and Kasım, 2016), and the redness index was calculated according to (Hobson, 1987).

2.7. Total soluble solids (TSS) content

The TSS was measured using a digital refractometer (Atago DR-A1) and expressed as a percentage.

2.8. Titratable acidity (TA)

Twenty milliliters of distilled water were added to 10 mL of filtered strawberry juice, and the pH was measured using a pH meter against 0.1 N NaOH. The TA content of the fruit was calculated from the NaOH amount used during titration as described by Karaçalı (2006), and the results were expressed as citric acid %.

2.9. TSS/TA values

It was calculated by the division of TSS values by TA values.

2.10. Sugar content

Three grams of strawberry fruit were placed in a beaker, and 10 mL distilled water was added, which was then homogenized and filtered. The filtrate was filtered from the injection filter (Nylon 66.25 µm) and, then injected into HPLC (Agilent, HP 1260 Hewlett Packard, CA/USA). The glucose, fructose, and total sugar content of the strawberries were calculated according to (Kasım and Kasım, 2015).

2.11. Fruit firmness

Fruit firmness was measured at three points on each strawberry using a digital penetrometer with a 7.9 mm plunger.

2.12. Weight loss

The three-box fruit samples were separated to measure weight loss, and the same samples were used during storage. The boxes were weighed at the start of the study and at 2-day intervals during storage. Weight loss was calculated using the following formula: WL (%) = (initial weight-final weight) x 100/initial weight.

2.13. Experimental design

The experiment was established, conducted, and evaluated using a Completely Randomized Design in three replicates, with three boxes of fruit (150 g fruit/box) for each replicate.

The data obtained were analyzed using the SPSS 16 software program, and the differences among the treatments were compared using Duncan's multiple range's test at 95% confidence interval.

3. Results and discussion

3.1. Anthocyanin content

The anthocyanin content of the strawberries was calculated as 18.2 mg/kg FW (fresh weight) before storage (Figure 3). It increased after 2 days of storage in all treatments and varied from 23.10 mg/kg FW in UVA to 31.90 mg/kg FW in B. This increase in anthocyanin content was attributed to the response of strawberries to low temperatures, which caused abiotic stress. The anthocyanin content of the strawberries in the R treatment was high compared with the other treatments during storage. The differences between the R treatment and the other treatments were found to be statistically significant ($p<0.05$). Anthocyanins are the most important phenolic compounds in colorful fruits and vegetables and are mostly found in their skin. It is also found in strawberries and account for up to 40% of total phenol (Warner et al., 2021). Besides, anthocyanin is important for human health because of its anticarcinogenic feature. Therefore, the maintenance of anthocyanin content or reduced losses with various applications is significant during postharvest storage of strawberries. The quality of light plays an important role in the accumulation of anthocyanins by plants.

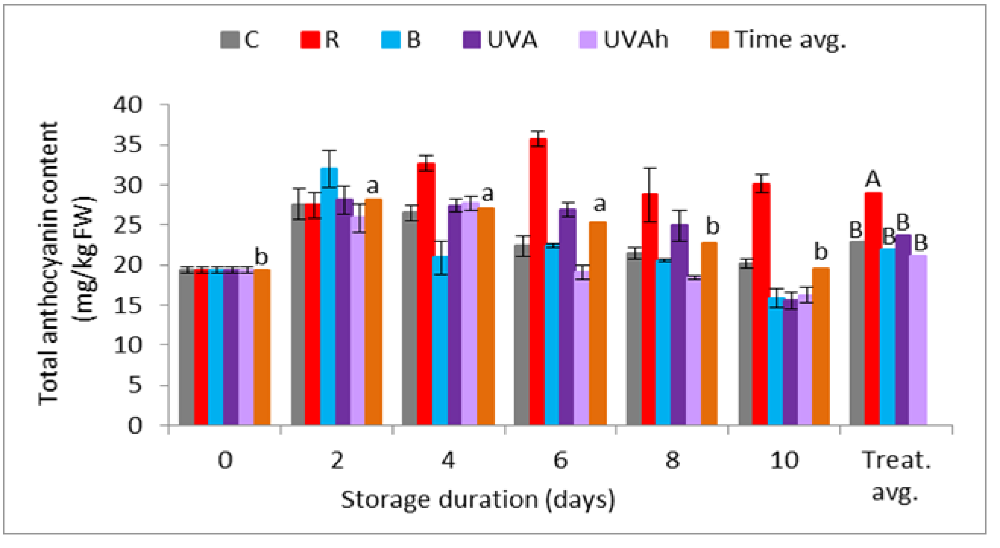


Figure 3. The changes in total anthocyanin content of the strawberries during 10 days storage at a temperature of 4±1oC. C: Control, R: Red LED, B: Blue LED, UVA: Storage under continuous UV LED, UVAh: Storage in dark conditions after one hour of UV LED treatment. Lower cases letters are shown differences among the storage time. Capital letters are shown differences among the treatments

Hobson (1987) also concluded that the total phenol and anthocyanin contents of strawberries were increased by 405-nm LED treatments. With LEDs of different colors, the color in which the plant is used more in the light spectrum is applied directly to the plant. Thus, the plant receives the required wavelength. In addition, because LED lamps are cold light emitters, long-term illumination can be provided without harmful effects on the plant. Nowadays, red and blue LEDs are also widely used to improve the postharvest quality of fruits and vegetables. In a study, it was shown that the content of total anthocyanins (TA), pelargonidin 3-glucoside (Pg3G), and pelargonidin 3-malonylglucoside (Pg3MG) significantly increased after blue and red light treatment. In addition, in a comparative transcriptome analysis that was conducted using six cDNA libraries from the treated strawberries, photoreceptors and light transduction components remained dynamic to upregulate the expression of regulatory factors and structural genes related to anthocyanin biosynthesis under red and white light, whereas most genes had low expression levels that were not consistent with the highest total anthocyanin content under blue light.

Therefore, the authors declared that light was an essential environmental factor for anthocyanin biosynthesis before the anthocyanin concentration reached saturation in strawberry fruits, and that blue light could quickly stimulate the accumulation of anthocyanin in the fruit. Moreover, it was suggested that red light not only elevated the anthocyanin content but also contributed to the synthesis of proanthocyanidin by inducing leucoanthocyanidin reductase and anthocyanidin reductase (Zhang et al., 2018). Thus, the total anthocynanin content increased by red light in this study was thought to be due to this proposed mechanism. In another study, blue LED and salicylic acid (2 mM) treatment increased the amount of anthocyanin in strawberries during storage at a temperature of 8 °C (Zhang et al., 2022). The blue LED light also increased the anthocyanin content of the strawberries, but it was not as effective as the red LED light in this study, contrary to the results of the study by (Zhang et al., 2022). (Wang, et al., 2022) found in their study that red LED light promotes the accumulation of pelargonidin-based anthocyanins in strawberries and that the expression of genes associated with anthocyanin biosynthesis is also upregulated by the red LED light.

3.2. Color values

The L* values of the strawberries declined after 2 days of storage in all treatments, then increased in UVA and C, and continued to decrease in R; however, a sharp decrease-increase in B and UVAh treatments was found after 8 days. There were, however, no significant differences among the treatments ($p<0.05$). Furthermore, in general, it can be said that UVAh promoted the brightness of the strawberries after the fourth day of storage because, the lowest decrease in the L* values occurred in UVAh (Table 1). The hue angle values of strawberries decreased on the second day of storage in all treatments. The lowest reduction was observed in R (32.19), whereas the highest reduction was observed in C (30.64). After this decrease, the hue angle values increased after the fourth day of storage in all treatments, and then changed to decrease-increase in all treatments except for C. The effect of the UVAh treatment was prominent in terms of raising the hue angle, but this increase was not significant (Table 1).

Table 1. The L*, hue angle and RI values of the strawberries treated with different wavelengths of LEDs

		Treatments					
	Storage duration (days)	C	R	B	UVA	UVAh	*Time average*
L*	0	37.67±2.83	37.67±2.83	37.67±2.83	37.67±2.83	37.67±2.83	**37.67 a**
	2	33.05±2.68	35.14±2.91	35.08±1.62	33.63±0.25	35.05±2.59	**34.39 b**
	4	34.05±2.58	34.82±1.81	35.08±0.17	34.40±0.09	37.22±1.16	**35.11 b**
	6	34.32±2.34	34.98±2.73	32.26±1.00	34.78±0.92	33.14±2.63	**33.90 b**
	8	33.85±2.62	33.27±1.48	34.16±0.37	33.92±0.74	35.15±1.06	**34.07 b**
	10	31.79±0.67	32.40±0.44	31.43±0.73	31.39±0.93	31.58±0.77	**31.72 c**
	Treatment average	**34.12**	**34.71**	**34.28**	**34.30**	**34.97**	
Hue	0	39.84±2.85	39.84±2.85	39.84±2.85	39.84±2.85	39.84±2.85	**39.84 a**
	2	30.64±1.29	32.19±0.49	30.97±0.37	31.22±1.91	31.46±1.92	**31.30 c**
	4	31.78±1.89	35.11±3.34	35.83±1.80	36.57±2.64	33.26±3.61	**34.51 b**
	6	33.12±2.01	34.99±3.79	31.94±1.40	33.85±3.01	32.11±2.82	**33.20 b**
	8	34.79±3.03	34.29±2.00	34.38±0.60	34.20±1.11	37.42±2.19	**35.02 b**
	10	34.32±2.32	33.83±2.58	33.87±2.41	34.86±1.22	36.66±4.30	**34.71 b**
	Treatment average	**34.08**	**35.04**	**34.47**	**35.09**	**35.12**	
RI	0	250.60±19.40	250.60±19.40	250.60±19.40	250.60±19.40	250.60±19.40	**250.60 d**
	2	299.69±8.42	286.02±13.10	289.69±7.44	294.84±6.84	288.44±10.92	**291.74 a**
	4	291.55±6.54	277.32±17.88	273.69±6.08	273.66±9.20	273.85±12.70	**278.01 c**
	6	286.16±11.93	277.11±17.78	298.85±7.14	281.38±8.51	294.48±14.60	**287.60 ab**
	8	282.72±21.27	286.62±13.29	282.40±1.96	283.99±3.04	267.87±10.29	**280.72 bc**
	10	292.82±6.83	291.62±6.92	296.05±8.34	292.95±8.05	284.91±13.40	**291.67 a**
	Treatment average	**283.92**	**278.22**	**281.88**	**279.57**	**276.69**	

RI: Redness index. C: Control, R: Red, B: Blue, UVA: Storage under continuous UV LED, UVAh: Storage in dark conditions after 1 h of UV LED treatment.

As shown in Table 1, the redness index (RI) values increased in all treatments on the second day of storage, and the RI values of the control group were the highest. From this result, it was thought that the strawberries in C started to senescence earlier than the other treatments, followed by UVA, B, UVAh, and R. Additionally, the RI values were also higher in C than in the other treatments on day four, but then decreased afterwards.

Furthermore, although the RI values in B and UVAh were higher on day six, the differences among the treatments were not statistically significant (p<0.05). The objective evaluation of fruit color was performed using Minolta colorimeter according to the color coordinate system developed by CIELAB. In this system, colors can be expressed closer to human perception, and all colors are shown with three vertical axes. According to this system, a* color values represent colors from green to red, and b* color values represent colors from blue to yellow. The hue angle value calculated from these values represents the true color of the fruit, and the redness index indicates the intensity of the red. In the CIELAB color coordinate plane, L* values vary between 0 and 100, while the L* value approaches zero indicates a decrease in brightness, while an increase toward 100 indicates an increase in brightness (Mcguire, 1992). Generally, the LED treatments did not have any significant differences in color values considered, as stated by (Chong et al., 2022). There are limited numerous studies showing LED light's effect on fresh produce, and in these studies, the authors focused on the antimicrobial effect of LED lights. In one of these studies, the authors stated that the LED lights including UVA did not affect the biochemical quality of red leaf lettuce, whereas the other said that UVA-LED reduced browning in fresh-cut apples and pears. The color of strawberries in UVAh is lighter than in the other treatments, which means the L* values of these fruits are higher, whereas the RI values are lower. An increase in RI values can indicate that the color becomes darker, and therefore the fruits mature more. The fruits treated with UVAh responded to this abiotic stress by delaying ripening. Thus, it can be concluded that UVAh treatment retards the senescence of fruit compared with other treatments.

3.3. TSS

The TSS content was measured as 7.06% at the start of the study (Table 2).

Table 2. TSS, fructose, glucose, and total sugar contents of strawberries treated with different wavelengths of LEDs

		Treatments					
	Storage duration (days)	C	R	B	UVA	UVAh	*Time average*
TSS (%)	0	7.06±0.26	7.06±0.26	7.06±0.26	7.06±0.26	7.06±0.26	**7.06 ab**
	2	7.12±0.43	8.54±0.63	7.47±0.98	8.22±0.70	6.54±0.45	**7.58 a**
	4	7.03±0.12	8.13±0.58	6.75±0.59	8.63±0.65	6.80±1.02	**7.40 ab**
	6	7.06±1.01	6.88±0.61	7.06±0.31	6.69±0.24	6.98±0.23	**6.93 b**
	8	6.32±0.69	6.96±0.78	7.06±0.31	5.01±0.54	5.76±0.38	**6.22 c**
	10	5.82±0.36	5.91±0.27	4.22±0.40	4.77±0.24	4.78±0.25	**5.10 d**
	Treatment average	**6.74 b**	**7.25 a**	**6.60 b**	**6.68 b**	**6.32 b**	
Fructose content (%)	0	0.69±0.30	0.69±0.30	0.69±0.30	0.69±0.30	0.69±0.30	**0.69 c**
	2	1.34±0.51	1.25±0.08	0.92±0.15	1.20±0.19	0.97±0.12	**1.13 ab**
	4	1.29±0.11	1.00±0.04	1.20±0.14	1.08±0.11	1.11±0.21	**1.14 ab**
	6	1.11±0.23	1.01±0.45	1.11±0.25	1.14±0.10	0.79±0.01	**1.03 b**
	8	1.33±0.13	1.41±0.24	1.18±0.26	1.29±0.61	1.30±0.10	**1.30 a**
	10	0.75±0.11	0.82±0.14	0.99±0.10	0.77±0.27	0.86±0.07	**0.84 c**
	Treatment average	**1.084 a**	**1.028 a**	**1.014 a**	**1.026 a**	**0.954 a**	
Glucose content (%)	0	0.74±0.16	0.74±0.16	0.74±0.16	0.74±0.16	0.74±0.16	**0.74 b**
	2	2.30±1.03	1.64±0.18	0.74±0.15	1.00±0.23	0.79±0.20	**1.30 a**
	4	0.81±0.12	0.61±0.11	0.77±0.26	0.95±0.21	0.69±0.23	**0.77 b**
	6	0.81±0.56	0.66±0.21	0.57±044	0.29±0.19	0.29±0.20	**0.52 c**
	8	0.29±0.37	0.31±0.18	0.15±0.03	0.30±0.15	0.10±0.02	**0.23 d**
	10	0.18±0.03	0.19±0.11	0.22±0.12	0.14±0.09	0.19±0.09	**0.18 d**
	Treatment average	**0.86 a**	**0.69 ab**	**0.53 bc**	**0.57 bc**	**0.47 c**	
Total sugar content (%)	0	1.43±0.36	1.43±0.36	1.43±0.36	1.43±0.36	1.43±0.36	**1.43 c**
	2	3.64±1.02	2.89±0.25	1.66±0.28	2.20±0.42	1.76±0.32	**2.43 a**
	4	2.10±0.23	1.61±0.15	1.98±0.39	2.03±0.31	1.80±0.43	**1.90 b**
	6	1.92±0.79	1.66±0.63	1.68±0.52	1.42±0.24	1.09±0.19	**1.55 c**
	8	1.62±0.44	1.72±0.40	1.33±0.29	1.58±0.69	1.40±0.11	**1.53 c**
	10	0.94±0.13	1.01±0.24	1.21±0.21	0.91±0.36	1.04±0.11	**1.02 d**
	Treatment average	**1.94 a**	**1.72 ab**	**1.55 b**	**1.60 b**	**1.42 b**	

C: Control, R: Red LED, B: Blue LED, UVA: Storage under continuous UV LED, UVAh: Storage in dark conditions after one hour of UV LED treatment.

It then increased in all treatments except UVAh on day two of storage. The highest increase in the TSS content was measured in the R treatment, followed by UVA, B, C, and UVAh. After this time, the TSS content of the strawberries decreased during storage. Moreover, the average values given in Table 2 show that the highest TSS content was found in R (7.25%), and the differences between R and the other treatments were statistically significant ($p<0.05$).

Because TSS of strawberry fruit is changed according to the maturation stage of fruits and in harvest time, and the maturation stage is not homogenous among the fruits, there is no standard value of TSS as in kiwi fruits or grapes. In fact, in a study, it was determined that the amount of TSS of strawberry fruits harvested at six different stages varied between 5.19 and -9.19 °Brix (Basak et al., 2022). In addition, in another study conducted with the Albion variety, the TSS value was found to vary between 7.00 and -8.10% (Polat et al., 2016). In the present study, the initial TSS value of the Albion strawberry cultivar was within these limits, but after the fourth day of storage, it decreased in all treatments. On the other hand, it was also found that the amount of TSS in the fruits was higher in the R application than in the other treatments. Light treatments cause abiotic stress in horticultural crops. The plant or plant part activates a defense mechanism for responding to abiotic stress, resulting in an increase in the bioactive component of fruit and vegetables. In this study, the red LED light treatments were more effective on the TSS content than the other treatments, and the TSS content of the strawberries stored under the red LED light was the highest. Therefore, this result showed that the storage of strawberries under red light was successful in retarding TSS loss. In another study, it was found that the total soluble solids of strawberries stored under white, red, and blue light decreased over time (Noor et al., 2022). On the same line, a similar trend was detected in this study. On the other hand, the highest TSS content was measured in the R treatment, and differences among LEDs were also significant, as concluded by (Noor et al., 2022). Additionally, it could be said that the senescence of the strawberries was slowed by the R and UVAh treatments in this study.

3.4. TA

The titratable acidity (TA) of the strawberries in R decreased during the first 2 days of storage, whereas the acidity increased in the other treatments. The highest TA level was found in the K treatment on day four of storage, followed by B, R, UVAh, and UVA. Additionally, when the average of the treatments was considered, the highest TA level was detected in C, and the differences between C and the other treatments were statistically significant ($p<0.05$) (Figure 4).

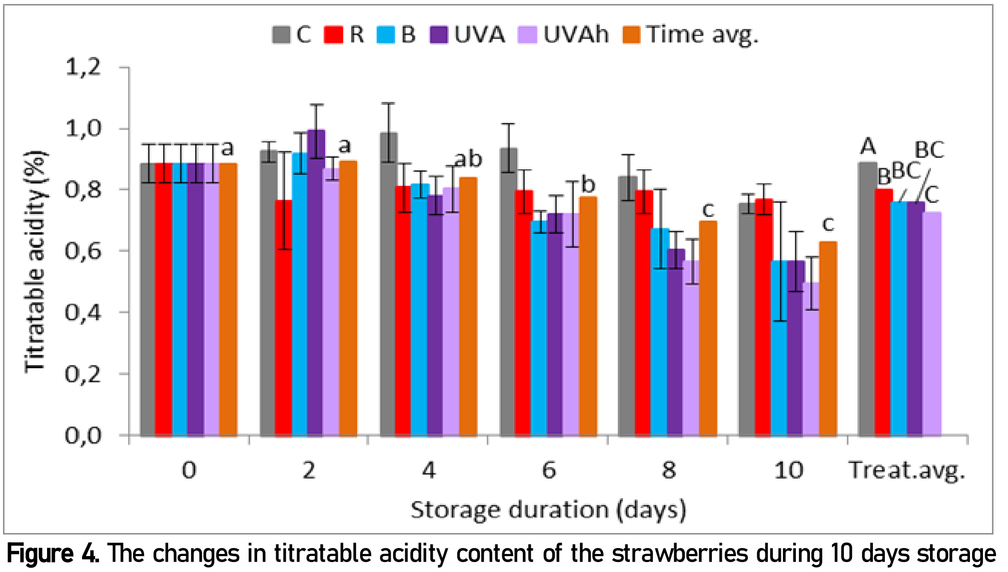


Figure 4. The changes in titratable acidity content of the strawberries during 10 days storage at a temperature of 4±1oC. C: Control, R: Red LED, B: Blue LED, UVA: Storage under continuous UV LED, UVAh: Storage in dark conditions after one hour of UV LED treatment. Lower cases letters are shown differences among the storage time. Capital letters are shown differences among the treatments.

LED treatments decreased TA levels after the second day of storage compared with the control group. This result was also supported by (Wang et al., 2022), who concluded that BL + SA treatment decreases titratable acidity contents. Among the treatments, however, the R treatment was more effective in retaining TA levels than the other LED treatments.

3.5. TSS/TA

The TSS/TA percentage of strawberries was lower in C than in all LED treatments (Figure 5). In addition, the differences between C and LED treatments were found to be crucial. According to the TSS and TA results, TA values were decreased by LED treatments, whereas TSS increased. Therefore, it could be concluded that LED treatments improve the taste of strawberries by reducing TA. Generally, studies on the TSS/TA content of strawberries treated with LED light were conducted during the growing period. Unlike our work results, only one study revealed that the TSS/TA ratio of strawberries treated with red, blue, and white light was decreased (Jiang et al., 2023). These contradictions could have originated because the PPFD of LED lights treated to strawberries is different.

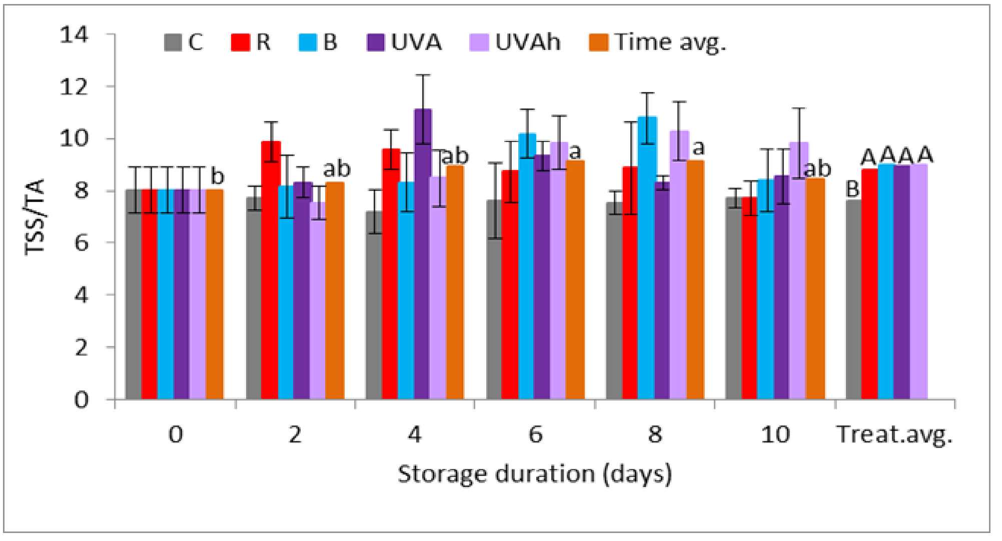


Figure 5. The changes in TSS/TA content of the strawberries during 10 days storage at a temperature of 4±1oC. C: Control, R: Red LED, B: Blue LED, UVA: Storage under continuous UV LED, UVAh: Storage in dark conditions after one hour of UV LED treatment. Lower cases letters are shown differences among the storage time. Capital letters are shown differences among the treatments.

3.6. Fructose, glucose, and total sugar content

Both glucose and fructose levels of strawberries increased sharply after two days of storage. While the glucose content decreased dramatically after this time and, continued to decline during storage, the fructose levels decreased more slowly. As seen in Table 2, when the treatment averages were examined during the storage period, the fructose content in C (1.08%) was higher than that in the other treatments, but it was not statistically significant. Nevertheles, a similar trend was obtained by glucose measurement, and the differences between C and the other treatments except for R were significant ($p<0.05$). The total amount of sugar changed as it did for glucose, and the highest total sugar content was found in C (1.94%), followed by R (1,72%), UVA (1,560%), B (1.55%), and UVAh (1,42%) treatments. Additionally, statistical differences were similar to those of the glucose content (Table 2). In the study, it was found that the fructose, glucose, and total sugar content of the strawberries in C were higher than those in the other treatments, followed by R. In this case, it could be concluded that the strawberries in C and R started to age earlier those in the other treatments. In contrast, the C, R, UVA, B, and UVAh treatments delayed senescence, and the most effective treatment was UVAh in this context. Moreover, the TSS content and color values of the strawberries in UVAh supported this result.

Jiang et al. (2023) concluded that blue and red LED light increased the soluble sugar content of strawberries compared with 0 days of storage. In this study, similar results were detected for fructose and total sugar, but glucose content first increased and then decreased during storage.

3.7. Fruit firmness

The fruit firmness was 5.38 N at the beginning of the study, which started to decrease in the C (4.70N) and UVA (5.23 N) treatments but increased in the other treatments (Figure 6) after the second day of storage. Additionally, the highest firmness was measured in B, whereas the lowest firmness was measured in C on the second and fourth days of storage. Generally, fruit firmness did not show pronounced changes in C and R and nearly retained the initial level of firmness at the end of storage. However, it changed to a slight decrease-increase after the sixth day of storage, and then sharply decreased in B, UVA, and UVAh. When Figure 6 is examined, it can be seen that the difference between R and UVA treatments is statistically significant ($p<0.05$). According to the results of firmness measurements, it can be concluded that all LED treatments were effective in terms of promoting fruit firmness after 4 days of storage. However, afterwards, the firmness of the strawberries decreased to a level below that of the control group in all LED treatments. Therefore, it seems that the LED treatments were successful in protecting fruit firmness after four days of storage. Additionally, the R LED treatment retained fruit firmness (5.37 N) longer than the other treatments. (Zhang et al., 2022) stated that 405 nm (blue) LED application did not affect the texture of strawberries. Similarly, in the present study, it was concluded that blue light had no effect on fruit firmness, and red light was more effective at the end of storage.

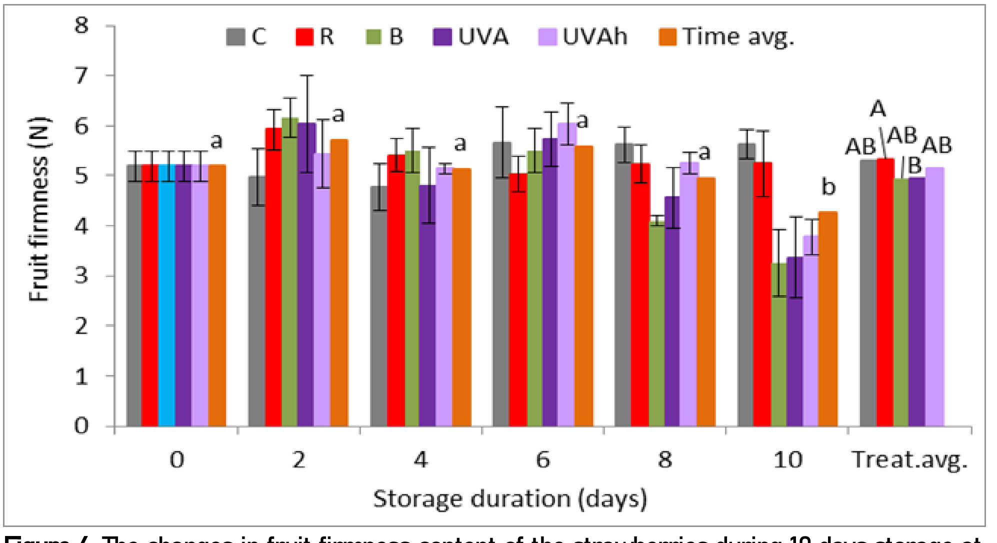


Figure 6. The changes in fruit firmness content of the strawberries during 10 days storage at a temperature of 4±1oC. C: Control, R: Red LED, B: Blue LED, UVA: Storage under continuous UV LED, UVAh: Storage in dark conditions after one hour of UV LED treatment. Lower cases letters are shown differences among the storage time. Capital letters are shown differences among the treatments.

3.8. Weight losses

The weight loss of strawberries in all treatments increased during storage (Figure 7). The highest weight loss occurred in the UVA and UVAh treatments (0.65% and 0.50%, respectively), followed by B (0.44%), C, and R (both 0.17%). Additionally, when the average of the treatments was examined, the differences between C, R, and B, UVA, and UVAh treatments were significant ($p<0.05$). In the study, the lowest weight losses were found in C; therefore, it, can be concluded that the all LED treatments lead to an increased loss of weight in strawberries. However, among the LED treatments, the UVA treatment caused the most weight loss compared with the other treatments. LED light treatment is an abiotic factor that affects fruit metabolism, thus causing weight loss during storage.

Thus, ultraviolet irradiation is also a strong abiotic factor for fruit and creates a stronger effect than the other LED treatments. Therefore, the weight loss of strawberries under UVA was higher than that of other LEDs. Meanwhile, the weight losses never exceeded the marketable limits, and the loss was not reflected in the appearance of the strawberries.

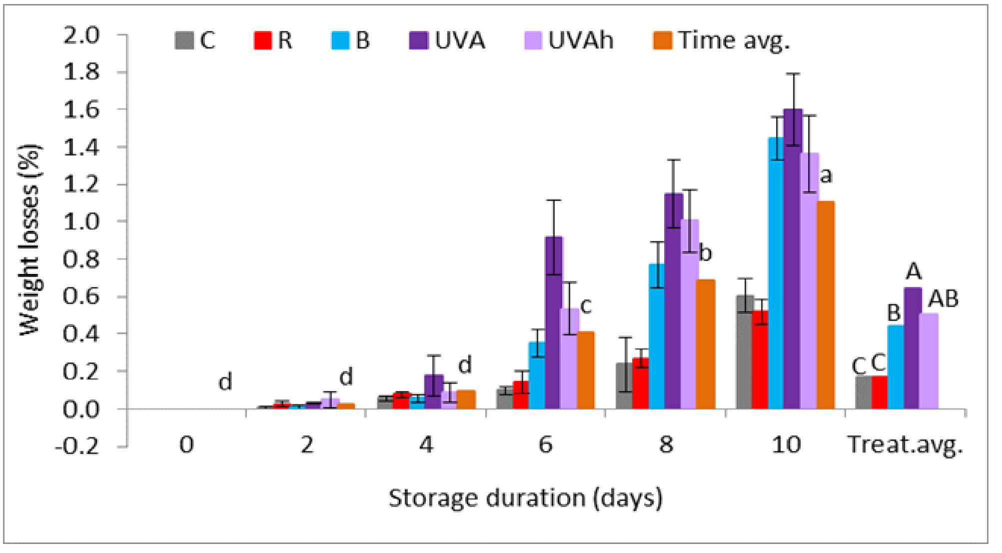


Figure 7. The changes in weight loss content of the strawberries during 10 days storage at a temperature of 4±1oC. C: Control, R: Red LED, B: Blue LED, UVA: Storage under continuous UV LED, UVAh: Storage in dark conditions after one hour of UV LED treatment. Lower cases letters are shown differences among the storage time. Capital letters are shown differences among the treatments.

4. Conclusions

This study aimed to investigate the effect of lighting during the storage of 'Albion' strawberries using LED lights with different wavelengths as well as dark storage and dark storage after 1 h ultraviolet LED lighting on the postharvest quality of the strawberries. In this study, the storage of strawberries under continuous red LEDs was effective in improving the anthocyanin content. A significant effect was detected on the TSS content and fruit firmness, and a reduction in weight loss was also observed. When evaluating the color values, it was observed that the UVA LED treatment was effective on L*, whereas UVAh was effective on the hue angle and redness index of the strawberries. Moreover, LED light irradiation did not affect the glucose, fructose, and total sugar content, whereas it reduced the TA levels of the strawberries. Consequently, red LED lighting during storage was successful in increasing the biochemical quality of the strawberries compared with the other treatments. However, more studies are needed to investigate the effect of continuous UVA and dark storage after 1 h UVA treatments on the quality of strawberries.

Compliance with Ethical Standards

Conflict of Interest

The authors declare that they have no conflict of interest.

Authors' Contributions

Onur YAVUZ: data collection, draft manuscript preparation. Rezzan KASIM: study conception and design, analysis and interpretation of results. **Mehmet Ufuk KASIM**: analysis and interpretation of results. All authors reviewed the results and approved the final version of the manuscript.

Ethical approval

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Data availability

Not applicable.

Consent for publication

Not applicable.

Acknowledgment

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