

Effect of Blue and Red Light-Emitting Diodes on Haskap (*Lonicera caerulea* L.) Postharvest Storage

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Abstract

Light-emitting diodes (LEDs) have been applied to many fruits and vegetables during postharvest storage; however, their effects on haskap storage remain unknown. This research aims to identify the impact of red and blue LEDs on haskap postharvest storage. By analyzing physical parameters (weight loss and firmness) as well as physicochemical factors (soluble solid content, pH, and acids), in addition to color parameters, microbial populations, total phenolic quantifications, and antioxidant capacity, the effects of red LED, blue LED, and darkness treatments were compared. The results indicated that red and blue LEDs significantly increased weight loss in haskap compared to the dark treatment. LEDs did not influence SSC, pH, or acids on any sampling day; however, pH showed significant changes throughout the storage period. Both red and blue LEDs affected color parameters, resulting in lower a^* and higher L^* , suggesting that LEDs may influence anthocyanin content in the fruit skins. With similar preservation effects, haskap treated by LEDs exhibited firmer berries during storage. The assessment of secondary metabolism indicated that total phenolics and flavonoids remained unchanged, while anthocyanins significantly increased throughout storage. Haskaps under both LEDs also displayed higher antioxidant capacities without significantly affecting microbial populations or ascorbic acid content during storage. This study demonstrated that red and blue LEDs positively affected the preservation of haskap, considering the assessment of firmness, color, anthocyanin content, and antioxidant capacities. However, the weight loss under LEDs needs to be addressed with adjustments of irradiation intensity or duration in the future.

Introduction

Haskap berries (*Lonicera caerulea* L.) were referred to as the “elixir of life” by Japanese aborigines. They contain more ascorbic acid and anthocyanins than other super berries, such as blueberries (Celli et al. 2014). All parts of the haskap plant, including fruits, stems, leaves, and flowers, are rich in nutrients and possess valuable bioactive properties. Consequently, haskap has been widely utilized in food, medicine, health products, cosmetics, and materials (Cheng et al. 2023). However, the market value of haskap fruit and its products does not reflect their potential, mainly because the fresh fruit market is significantly limited due to its short shelf life. Challenges in storing haskap include moisture loss, rapid shriveling, skin rupture, juice leakage, and mold growth (Leisso et al. 2021; Qiao et al. 2024b). In the field of haskap storage research, only a few publications serve as references. Leisso noted that the variety and maturity of haskap significantly influence its storage life and quality (Leisso et al. 2021, 2022a). Most haskap fruits need to be frozen to extend their storage duration.

One of the fundamental and urgent problems that needs to be solved is the storage conditions of haskap and extending the longevity of the fruits. Like some other fruits, haskap can be harvested premature if the postharvest conditions support maturation (Yamamoto et al. 2014). Meanwhile, harvest maturity influences the berry's polyphenol composition and health-beneficial properties (Silva and Hansanee 2020). Solutions for extending the shelf life of haskap include preharvest and postharvest treatments. Preharvest spraying of hexanal (an inhibitor of phospholipase) had slight benefits for haskap storage

and no effect on its quality (MacKenzie et al. 2018). Chitosan and aloe gel coatings have been applied to haskap storage under near-freezing conditions (-1°C). The results indicated that chitosan and aloe gel preserved haskap quality, including physicochemical properties and antioxidant capacities (Qiao et al. 2024b). However, applying coatings can be challenging at small scales, especially for soft berries. Light-emitting diodes (LEDs) have been used for postharvest storage of many fruits and vegetables, and many beneficial effects during postharvest storage were mentioned (Nassarawa et al. 2021). The positive influences of LEDs on post-storage include delaying senescence, enhancing nutritional content, improving the ripening process, reducing microbial spoilage, and extending the fruit or vegetable shelf life. Different types of LEDs have diverse effects on various fruits and vegetables. Continuous red light strongly accelerated changes in the tomato outer layer, such as color parameters and major secondary metabolite compounds (Panjai et al. 2021). Similarly, lycopene concentration in mature-green (breaker-stage) tomato exocarp was affected by red light treatment. Still, red radiation did not influence the β -carotene and the total soluble solids concentration (Liu et al. 2009). A postharvest red light could influence some fruit ripeness, such as oriental melon fruit and banana fruit (Gong et al. 2023; Guan et al. 2024). Pulses of red plus blue light could modify raspberries and blueberries' vitamin C and organic content during postharvest (Ganganelli et al. 2023).

The other type of LED, blue LED (400-500nm), was also studied in various fruit and vegetable postharvest storage. Depending on the fruit or vegetable, light intensity, fluence rate, and storage conditions, blue light had multiple effects on the fruit or vegetable ripening process. Blue light combined with salicylic acid could maintain strawberry quality in the refrigerator (Zhang et al. 2022). Blue (470nm) LEDs at a fluence rate of 40Wm^{-2} with the 10°C temperature enhanced the ripening process in peaches (Gong et al. 2015). On the other hand, blue light has also been reported to delay purple pepper fruit ripening (Liu et al. 2022b). An intensity of $40\text{ }\mu\text{mol m}^{-2}\text{s}^{-1}$ blue LEDs did not affect fruit quality or disease development on ripe blueberries (Wang et al. 2020). However, eight days of blue LEDs at 10°C increased Chinese bayberry sugar content (Shi et al. 2016). At $15\text{--}25^{\circ}\text{C}$, 80W m^{-2} Blue LED light enhanced the titratable acidity in grape berries (Azuma et al. 2019). Besides influencing the postharvest ripening process, blue LEDs also might inhibit fungal pathogenic microorganisms during postharvest (Alferez et al. 2012; Liao et al. 2013). Although red LEDs increased the content of anthocyanins in immature strawberries, the influence was less effective than blue LEDs in increasing anthocyanins and color intensity (Kim et al. 2011).

This study presents and discusses the typical intensity of LED applications on haskap refrigerated storage. Special emphasis is placed on the influence of red and blue LEDs on haskap physiochemical and nutritional changes. This work is the first time to report the LED lights have the potential to store haskap berries.

Material and Methods

Plant materials and light treatments

Haskap variety 'Aurora' fruits (~ 7.5kg) were hand harvested during July 2024 at the Western Agricultural Research Center of Montana State University and immediately moved into a cooler room (4°C, humidity 75%-90%) within 2 hours before postharvest treatment. Haskap fruits without physical damage were divided into three groups randomly for the different treatments (Fig. 1). Treatment one is 630 nm Red LED lights with 14 W/m² irradiation (HQR, US); Treatment two is Blue LED with a peak at 475nm and 14 W/m² irradiation (HQR, US); Treatment three is the control group, meaning haskap berries are stored without any light. All the treatments were conducted in a walk-in cooler at 0–4°C and ≥ 90% humidity. Thirty berries (weight from 39g to 50g) were randomly put into transparent clam shells and marked by number and treatments before storing them in a walk-in cooler until sampling points. The sampling time points (5 in total) were 0 days, 7 days, 14 days, 21 days, and 28 days. Six clam shells of each treatment were chosen for storage measurement at each sampling point. A total of 30 clam shells went through each treatment.

Weight loss

All the clam shells were weighted and marked by number and treatment as the Day 0 weight of each clam shell. Six clam shells under each treatment were picked randomly and weighed to calculate the weight loss on each sampling day. Weight loss percentage (%) is calculated as $\text{Weight loss percentage (\%)} = (W_1 - W_0) / W_0 \times 100\%$. W_1 is the weight on sampling time; W_0 is the weight on day 0.

Color Index

About sixty haskap berries were selected from each treatment at each sampling time to measure their surface color. The color values of the haskaps were determined using a Konica Minolta CR-400 colorimeter (Konica Minolta American Inc., NJ, USA) to evaluate both the absolute color values (L, a, b, C, h) using Spectra Magic NX2 software (Konica Minolta Inc., Tokyo, Japan). A standard whiteboard from Konica Minolta calibrated the colorimeter before each test. The L* value represents lightness (black (L*=0) to white (L*=100)). The a* value indicates the color range from green (-) to red (+), and the b* value indicates the color range from blue (-) to yellow (+).

Firmness

Thirty haskap berries from each treatment were picked for firmness measurement on each sampling day. The firmness of the haskap was measured using a Landtek FHT-05 Fruit Hardness Tester (Landtek, China). The firmness of each berry was tested through a puncture test on each berry's cheek midway between the top and the bottom. The results were expressed as N (N/cm²).

Physicochemical changes during storage

After measuring the firmness of the haskap berries, they were hand-crushed and juiced into 15 mL centrifuge tubes. Before conducting physicochemical testing, the tubes were briefly centrifuged for 15 seconds. The juice soluble solid content (SSC[°Brix]) was measured using an Atago 3810 (PAL-1) digital pocket refractometer (ATAGO, Japan), and the pH was measured with Atago PAL-pH meters (ATAGO, Japan). Titratable acidity, expressed as citric acid, was measured with an Atago Pocket Brix-Acidity meter (Citrus) PAL-BX|ACID1 Master Kit. Acidity was reported as % citric acid equivalent.

Ascorbic acid assay

The ascorbic acid in each haskap juice from crushed berries was measured by colorimetric method using Ascorbic Acid Assay Kit AB65346 (Abcam, USA). To prevent ascorbic acid degradation from light, the juice was stored at 4°C in 15 mL tubes wrapped in foil and tested after 48 hours. The results were expressed as µg/100mg of each sample.

Microbial population during storage

Haskap microbial populations were examined by placing 30 ± 0.1 g of haskap from each treatment into sterile BagPage paddle blender bags (Interscience, France) with 170 mL of distilled water (dH_2O) and homogenized using a Bagmixer 400 (Interscience, France) for 30 seconds. Serial dilutions (10^1 , 10^2 , and 10^3) were prepared after removing the blended liquid from the filter bags. Selective media, including 3M™ Petrifilm for yeast and mold (Carolia, US) and 3M™ Petrifilm for Aerobic Count plates for aerobic bacteria (Carolia, US), were utilized for the microbial population growth study. 1 mL of each serial dilution solution was spread on each selective plate. The yeast and mold study incubation conditions were set at 25°C for 4 days, while for the aerobic population, the conditions were at 37°C for 2 days. Results were calculated as log CFU/g (colony-forming unit per gram) and analyzed with two sample containers (technical replicates) along with two replicate counts of each treatment (biological replicates).

Polyphenols content, total flavonoids, and total anthocyanin content determination during storage

The total polyphenolic content of haskap juice was determined by the Folin-Cioaltea colorimetric method with BQC KB03006 polyphenol quantification assay kit (BQC Redox Technologies, Asturias, Spain). The total phenolic content was expressed as µg gallic acid equivalent (GAE) per mg of each sample. Flavonoid assay kits (MyBioSource, CA, USA) were used to measure the total flavonoids in haskap juice during storage. The results were expressed as µg/µL of haskap juice. The haskap was measured for total anthocyanin content using pH differential methods with Anthocyanins Assay Kits (BQC Redox Technologies, Asturias, Spain). Results were expressed as cyanidin-6-glucoside equivalent (mg C6GE/L).

Haskap antioxidant capacity changes during haskap storage

Two methods were used for haskap antioxidant capacity measurement during storage. The 2,2-Diphenyl-1-picrylhydrazyl DPPH-method with DPPH Antioxidant Capacity Kit (KF01007) (BQC Redox Technologies, Asturias, Spain) was used, and the results were expressed as Trolox Equivalent Antioxidant Capacity (TEAC) $\mu\text{M}/\mu\text{L}$. The other method, the Ferric Reducing Antioxidant Power (FRAP) assay, was conducted with FRAP assay kit (AB234626) from Abcam Biotechnology company (Cambridge, UK). The antioxidant capacity was tested based on the manufacturer's protocols. The results were expressed as FRAP μM Ferrous Equivalent/ μL .

Statistical Analysis

All assays for each treatment contained two replicates and were expressed as mean $\pm$ standard deviation (SD) of three replicates. Statistical analyses were performed by R-4.3.1 (R Core Team 2023) ([CSL STYLE ERROR: reference with no printed form.]). The ANOVA and normality assumption were performed using "doebioresearch" package in R studio (Popat and Banakara 2020). Package ggplot2 was used to generate the plots.

Results and discussion

Haskap Fruit Physiochemical Changes during Postharvest Treatments

Physiological water loss is one of the postharvest disorders that occur during fresh fruit storage, which can lead to further degradation of fruit quality (Lufu et al. 2020). Haskap shriveling is one of the phenomena researchers have observed during postharvest storage (Leisso et al. 2022b). In the first week of storage (Fig. 2), the treatments had no significant differences. Subsequently, the weight loss percentage increased in both Red and Blue LED treatments, resulting in substantial differences in weight loss. On the final sampling day (Day 28), the red and blue LEDs caused a weight loss of 7–9%, significantly higher than the 3–4% observed under dark treatment.

In summary, weight loss under all the treatments progressively increased throughout the cold storage conditions, but the light treatments resulted in more significant weight losses over the shelf-life period. One factor may be the slight temperature increase ($< 2^{\circ}\text{C}$) under LED lights, contributing to the minor warming of the haskap berries. Another reason might be the oxidative stress from the LEDs during the continuous treatment (Shao et al. 2020). Further research on monitoring LED illumination stress and haskap berry respiration is needed to determine the contributors to weight Loss.

During the postharvest storage (Table 1), although the average SSC under red, blue, and dark treatments on day 28 was higher than the SSC at the first beginning on Day 0, both the treatments on each sampling

day and storage days did not cause significant changes in the SSC. On average, the SSC values were from 15.55 to 18.00°Brix. Unlike SSC, the storage time caused substantial ($p < 0.05$) pH value changes. However, the treatment on each sampling day did not significantly impact the haskap pH values. The pH values of haskap ranged from 2.79 to 3.01 on average. Like SSC changes, acids did not change significantly within the sampling time, ranging from 1.34–1.63%.

Table 1
Haskap postharvest physicochemical characteristics.

Haskap Postharvest Treatment	Storage time (Day)				
	0	7	14	21	28
	SSC (°Brix)				
Red	15.70 ± 0.93	16.15 ± 0.65	15.9 ± 0.10	17.4 ± 0.60	17.25 ± 0.85
Blue		15.40 ± 1.10	17.95 ± 1.35	17.95 ± 1.45	17.95 ± 0.75
Dark		16.90 ± 0.20	15.95 ± 0.45	16.35 ± 0.15	16.10 ± 0.40
p-Value	1	0.46	0.28	0.53	0.3
	0.20				
	pH				
Red	2.82 ± 0.08	2.87 ± 0.01	2.94 ± 0.01	2.96 ± 0.03	2.99 ± 0.06
Blue		2.87 ± 0.01	2.94 ± 0.04	2.00 ± 0.09	3.01 ± 0.01
Dark		2.87 ± 0.01	2.88 ± 0.03	2.89 ± 0.02	2.96 ± 0.01
p-Value	1	0.49	0.35	0.43	0.62
	< 0.05				
	Acid (%)				
Red	1.58 ± 0.15	1.47 ± 0.03	1.45 ± 0.01	1.42 ± 0.10	1.34 ± 0.08
Blue		1.71 ± 0.26	1.48 ± 0.07	1.43 ± 0.03	1.36 ± 0.08
Dark		1.53 ± 0.02	1.44 ± 0.06	1.49 ± 0.06	1.44 ± 0.02
p-Value	1	0.57	0.84	0.74	0.61
	0.11				

Five sampling days (Day 0, Day 7, Day 14, Day 21, and Day 28) are chosen. *P* values show ANOVA statistical tests ($p < 0.05$) results. The data is shown as values ± SD. SD is the standard deviation.

LEDs on haskap color and the firmness texture

Fruit color levels are usually significantly related to fruit quality, directly affecting consumers' preferences and profitability (Lee et al. 2011). Haskap skin coloration is highly associated with anthocyanins and fruit ripening (Fujita et al. 2020). Haskap mature fruits are violet-blue, and skin color is a crucial physiological parameter in postharvest storage (Qiao et al. 2024b). Haskap fruit skin under LEDs had differential changes during storage. L^* index, representing the lightness, had slight changes during 28 days' storage, although variations were detected on each sampling day. On Day 28, red LEDs caused significant differences from the control under darkness (Fig. 3a). The lightness enhancement was not apparent by observing the naked eye; further research can be assisted by a higher technology, such as microscopy, to detect the tissue changes on the surface of haskap berries.

a^* , the red-green index, decreased under all the treatments, especially under the LEDs (Fig. 3b). On average, the a^* value changed from 1.75 to 0.5 and 0.25 with the red and blue LED treatments. Whether the red value reduction is correlated with haskap ripening needs further analysis, such as biochemical analysis.

Corresponding to the dark violet color of haskap, the b^* values were all negative (Fig. 3c). LEDs had specific influences on each sampling day, and no consistent changing patterns were observed over the 28 days. Meanwhile, the postharvest treatment results indicated that LEDs also affected the firmness of haskap fruits (Fig. 3d), which decreased during storage. On average, haskap fruits were firmer under red and blue LED treatments. Additionally, the results from D14 indicated that haskap berries were significantly firmer than the other treatments. Changes in the firmness of haskap berries were significant throughout the storage period.

LED effects on fruit or vegetable firmness can depend on the variety. It has been reported that red LEDs enhanced one pepper variety, while blue LEDs increased the firmness of another pepper variety (Liu et al. 2022a). Blue and red LEDs increased strawberry firmness by 1 to 2 N during storage (Free University of Bozen-Bolzano, Faculty of Science and Technology, 39100 Bolzano-Bozen, Italy et al. 2017). In this study, on average, the differences in haskap firmness between LEDs and darkness treatment can also be 1 to 2 N. Based on both color and firmness results, both red and blue LEDs positively impact firmness, which might benefit the preservation of haskap fruit.

Total phenolics, flavonoids, and anthocyanins in haskap fruit juice during storage

LEDs did not influence the polyphenol content in the stored haskap fruit juice (Table 2). Polyphenols are secondary metabolites in plants, playing a role in plant growth and human health (Fronsdal et al. 2019). The haskap berry contained 1.41 to 11.42 GAE/g of fresh weight (Khattab et al. 2016). In addition to variety and test variations, the difference in polyphenol amounts also resulted from the tested samples. In this study, only pressed haskap juice was used for testing instead of the whole fruit. This might partially

explain why different polyphenols (1.8–2.5 mg GAE/mL) were detected in the ‘Aurora’ samples during storage.

Haskap contains a substantial amount of flavonoids, about 1000–1500 mg QE/100g FW in the berries (Rupasinghe et al. 2015). During storage, red and blue LEDs did not cause significant differences in flavonoids from the dark treatment, and the quantity was about 1.3 to 3.0 mg QE/mL. Besides the plant protection functions under abiotic and biotic stresses, flavonoids are well-known for their health-beneficial effects (Panche et al. 2016). Within 28 days of storage, none of the treatments significantly impacted the total flavonoid contents. This indicated that storage won’t considerably influence the amounts of flavonoids in haskap.

Unlike the polyphenolics and flavonoids, the total anthocyanins from the treatments showed significant differences during storage but no notable differences on each sampling day. The total anthocyanins significantly increased ($p < 0.05$) from less than 70 mg/L to more than 70 mg/L during storage, suggesting that haskap berries might change their color attributes directly through anthocyanin content.

Haskap skin is red-purple, but fruit pulp has a yellow-green color. The imaging mass spectrometry showed that haskap anthocyanin distributions were primarily in the fruit’s inner and outer skins (Fujita et al. 2020). Therefore, the changes in the haskap anthocyanin in pressed juice in the study cannot completely represent the change in skin color. Compared to the skin surface changes (Fig. 2b) with decreased red color, the results of haskap juice color showed a reversed trend. This might indicate that haskap skin and pulp have different anthocyanin types and amounts.

Ascorbic acid levels in haskap were higher than in other vitamin C-rich sources, such as oranges and strawberries (Rupasinghe et al. 2018). During storage, the ascorbic acid content did not change significantly within each sampling day or across the storage period ($p < 0.05$). This indicated that the vitamin C content in haskap remained stable throughout the storage Period under the storage conditions.

Table 2

Total phenolics, total flavonoids, total anthocyanins, and ascorbic acids in haskap fruit juice during storage.

Treatment	Day	Polyphenols (mg GAE/mL)		Total Flavonoids (mg QE /mL)		Total Anthocyanins (mg/L)		Ascorbic Acids (µg/mL)	
		<i>p</i>		<i>p</i>		<i>p</i>		<i>p</i>	
Red	0	2.23 ± 0.22	1	2.04 ± 0.36	1	62.26 ± 12.23	1	55.78 ± 13.71	1
Blue									
Dark									
Red	7	2.25 ± 0.28	0.98	1.98 ± 0.40	0.63	63.88 ± 2.24	0.64	47.14 ± 11.28	0.82
Blue		2.20 ± 0.51		1.65 ± 0.35		64.96 ± 16.53		54.93 ± 20.06	
Dark		2.23 ± 0.14		1.97 ± 0.33		72.81 ± 0.59		55.17 ± 7.66	
Red	14	2.10 ± 0.01	0.32	2.04 ± 0.18	0.06	70.76 ± 6.08	0.06	56.27 ± 16.44	0.18
Blue		2.33 ± 0.48		2.08 ± 0.33		76.44 ± 2.54		79.04 ± 15.58	
Dark		1.80 ± 0.15		1.31 ± 0.06		54.65 ± 6.91		46.58 ± 3.79	
Red	21	2.38 ± 0.10	0.36	2.17 ± 0.08	0.35	84.92 ± 3.54	0.56	74.59 ± 6.89	0.86
Blue		2.29 ± 0.06		2.16 ± 0.25		79.53 ± 2.89		72.65 ± 10.33	
Dark		2.12 ± 0.25		1.90 ± 0.15		76.69 ± 11.4		64.73 ± 30.48	
Red	28	2.26 ± 0.03	0.72	2.19 ± 0.14	0.39	71.72 ± 5.67	0.56	76.24 ± 10.76	0.65
Blue		2.53 ± 0.32		2.94 ± 0.83		81.49 ± 5.19		83.61 ± 14.46	
Dark		2.24 ± 0.55		1.96 ± 0.73		74.48 ± 12.63		67.35 ± 21.61	
<i>p</i>	0.55			0.22		0.03*		0.06	

The data is presented as values ± SD, where SD represents the standard deviation. P values reflect the results of ANOVA statistical tests ($p < 0.05$). Asterisks (*) indicate statistically significant differences (p

< 0.05). Polyphenols are measured as mg Gallic Acid Equivalent (GAE)/mL, total flavonoids as Quercetin Equivalent (QE) mg/mL, and total anthocyanins as mg/L using pH differential methods. Ascorbic acids are quantified in µg/mL.

Antioxidant activity changes in haskap fruits

Antioxidant capacity assays of fruits are the methods to assess the nutritional quality of fruits during postharvest (Qiao et al. 2024b). A controlled atmosphere experiment indicated that reducing oxygen content during haskap postharvest storage had a detrimental effect on the antioxidant capacities (Qiao et al. 2024a). In this study (Table 3), DPPH and FARP indicated that red and blue postharvest treatment might enhance the antioxidants in haskap fruits. However, only FRAP showed significance among them on day 14, day 21, and day 28. On day 14, haskap antioxidant capacities under red and blue LEDs had more than 70 to 100 mM F(II) /10 µL antioxidant capacities compared to dark treatment. Similarly, red LEDs caused fruits to have more than 70 mM F(II) /10 µL antioxidant capacities, and blue LEDs caused fruits to have more than 40 mM F(II) /10 µL antioxidant capacities compared to 102 mM F(II) /10 µL in dark treatment on Day 21. The enhancement effects of LEDs were kept on the final day (day 28) with high significance ($p < 0.05$). The possible reasons might be because LEDs could activate the antioxidant enzymes, such as catalase and superoxide dismutase (Wang et al. 2023).

Table 3
Antioxidant capacities of haskap across postharvest storage.

Haskap Postharvest Treatment	Storage time (Day)				
	0	7	14	21	28
DPPH (TEAC mM/mg)					
Red	42.36 ± 0.04	38.60 ± 1.01	38.15 ± 0.86	41.25 ± 3.09	41.62 ± 2.44
Blue		38.70 ± 1.36	40.08 ± 4.16	38.34 ± 1.81	43.37 ± 0.19
Dark		39.28 ± 0.29	34.88 ± 0.29	37.59 ± 0.29	37.40 ± 1.26
<i>p</i> -Value	1	0.84	0.34	0.45	0.19
	0.45				
FRAP (mM Ferriious Equivalent (II) /10 µL)					
Red	166.17 ± 57.04	127.23 ± 44.48	146.25 ± 14.83	177.44 ± 23.64	195.66 ± 35.61
Blue		105.44 ± 26.94	172.12 ± 70.19	146.11 ± 5.05	250.73 ± 85.43
Dark		137.49 ± 18.55	71.02 ± 6.68	102.11 ± 9.73	120.99 ± 49.66
<i>p</i> -Value	1	0.39	0.02*	0.0002**	0.04*
	0.02*				

The data is shown as values ± SD. SD is the standard deviation. P values show ANOVA statistical test results. * and ** Indicate statistically different (p < 0.05 and p < 0.001).

Microbial population changes under postharvest treatments

Visual mold was not apparent during haskap postharvest treatments, but the total populations of haskap yeast and mold almost doubled during the 28 days of storage, increasing from 2.25 to 4.0 Log CFU/g. Research publications did not measure the microbial counts of the isolated haskap fruits. On haskap dried leaves, there were about 200 to 500 CFU/g mold and yeast populations (Sip et al. 2022). Yeast and molds are commonly enumerated in fruits as quality indicators except for food pathogens, such as *Salmonella* (Food 2003). LED postharvest storage did not cause significant changes in yeast and mold populations compared to the dark treatment (Fig. 4). Interestingly, aerobic populations were low, less than 1.0 Log CFU/g (data not shown), and there were no significant changes in haskap fruits during storage. Meanwhile, the aerobic bacteria were detected at more than 100 CFU/g on haskap dry leaves,

which might indicate various microbial populations from haskap different tissues, and food material processing might also contribute to population changes.

Conclusion

Haskap berries are rich in bioactive substances and are defined as a “homology of medicine and food.” Because of their short shelf life under typical storage conditions, fresh haskap fruits are barely utilized and transported long distances. LED technologies have been applied to various fruits and vegetables for postharvest storage, but no research has worked on the effects of LED on haskap berries. This research offers fundamental knowledge of the LED application on haskap postharvest storage.

The assessment of haskap fruit quality during storage includes physical, physiochemical, berry colors, total phenolics, total flavonoids, total anthocyanin content, ascorbic acid content, the quantities of microbial population, and antioxidant capacities. The results indicated that red and blue LEDs positively affected haskap preservation, except for weight loss. The positive effects included the maintenance of haskap berry color and berry firmness, as well as the enhancement of the anthocyanins and total antioxidant capacities. Further research is needed to improve weight loss control under LEDs during haskap postharvest storage. The strategies might include but are not limited to LED intensity or radiation length modifications. In conclusion, both red and blue LEDs have the potential to maintain haskap fruit qualities during postharvest storage, but for industry applications, the optimization of LEDs needs further studies.

Declarations

Author Contributions: Conceptualization, Z.W.; Methodology, Z.W.; Investigation, Z.W. and A.S.; Formal Analysis, Z.W., A.S., and Z.M.; Writing- Original Draft, Z.W.; Writing- Review and Editing, Z.W., A.S., and Z.M.; Funding Acquisition, Z.W., A.S., and Z.M.

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Data Availability The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare no competing interests.

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Figures

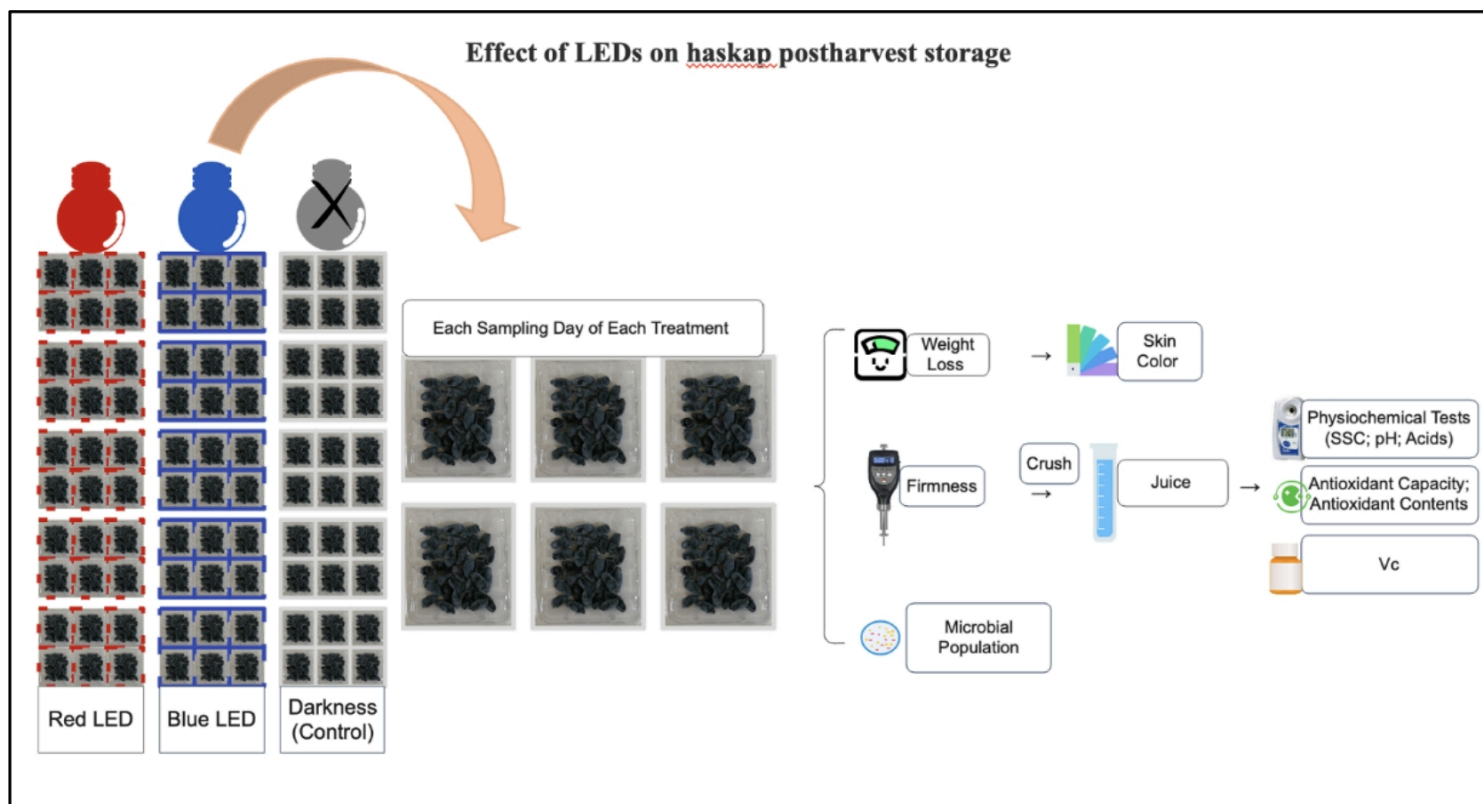


Figure 1

Graphical abstract of proposed work.

There are three treatments: red LED, blue LED, and darkness (control).

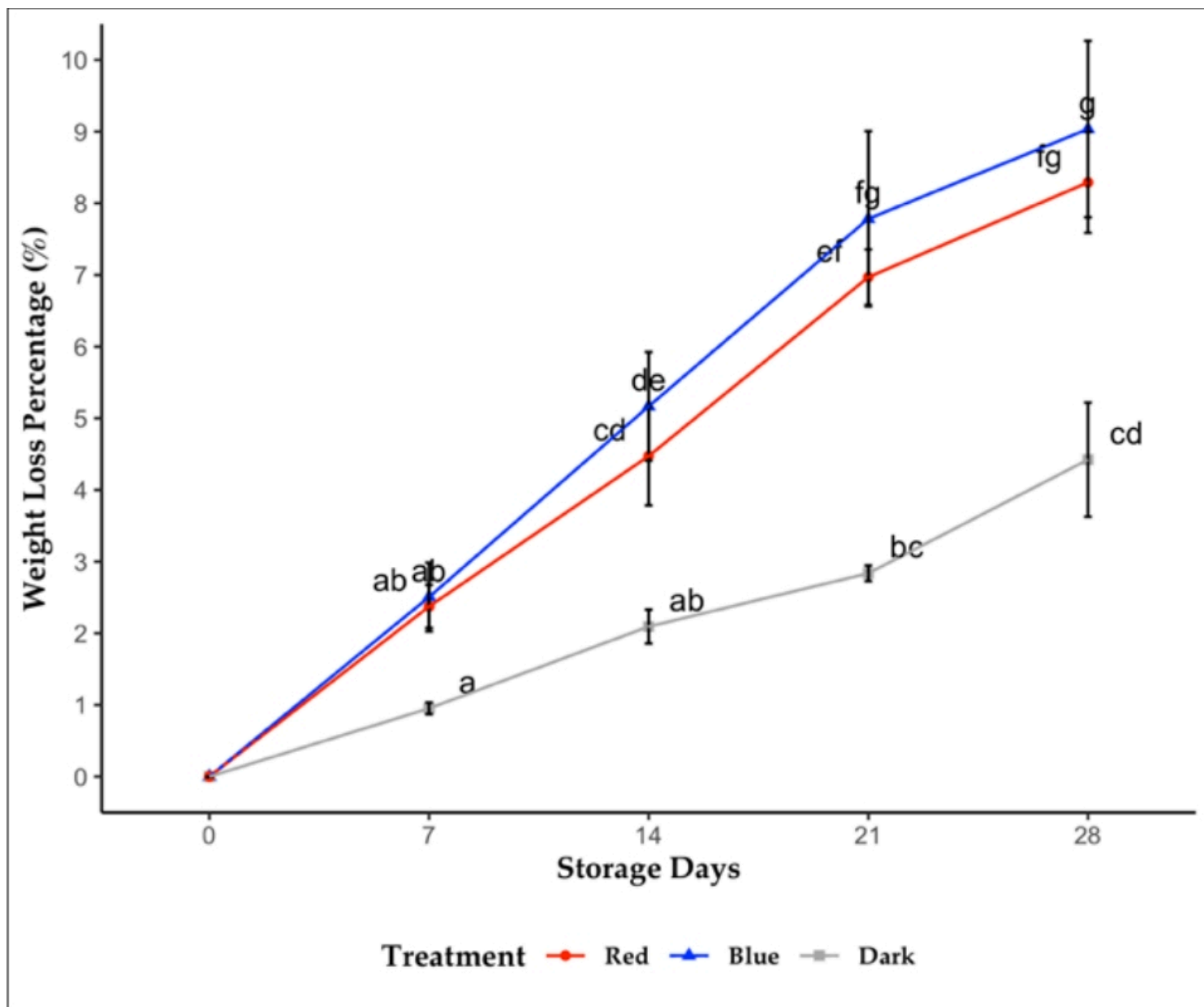


Figure 2

LEDs effect on haskap weight loss during postharvest.

Each treatment contains three replicates. Bars indicate values are mean $\pm$ standard deviations. Different letters correspond to mean values significantly different ($p < 0.05$) by analysis of variance (ANOVA).

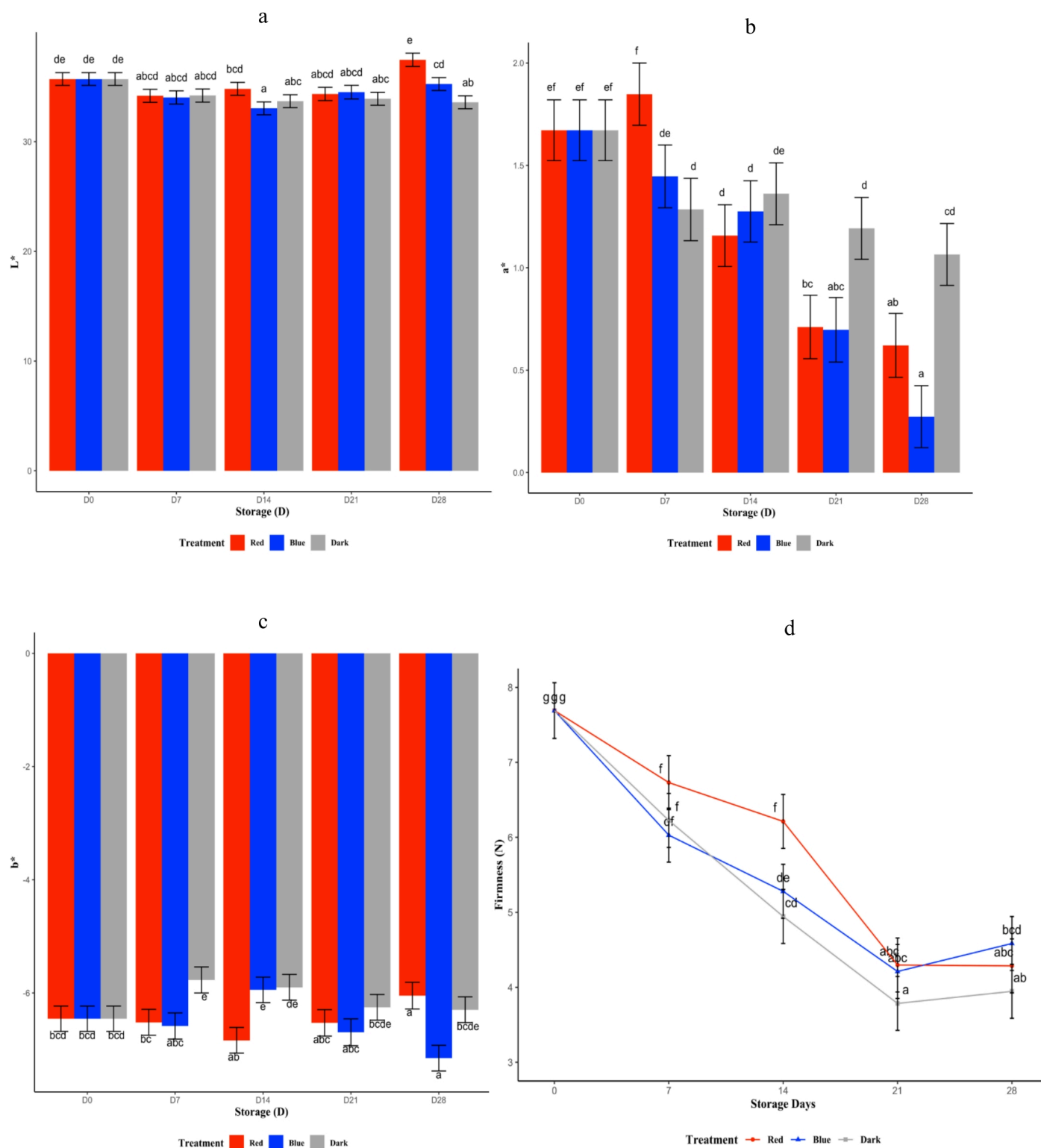


Figure 3

Postharvest treatments on haskap fruit skin color index L^* (a), a^* (b), b^* (c), and haskap berry firmness (d).

Bars represent mean values $\pm$ standard deviations. Different letters indicate mean values that are significantly different ($p < 0.05$) according to analysis of variance (ANOVA) and Tukey post hoc test.

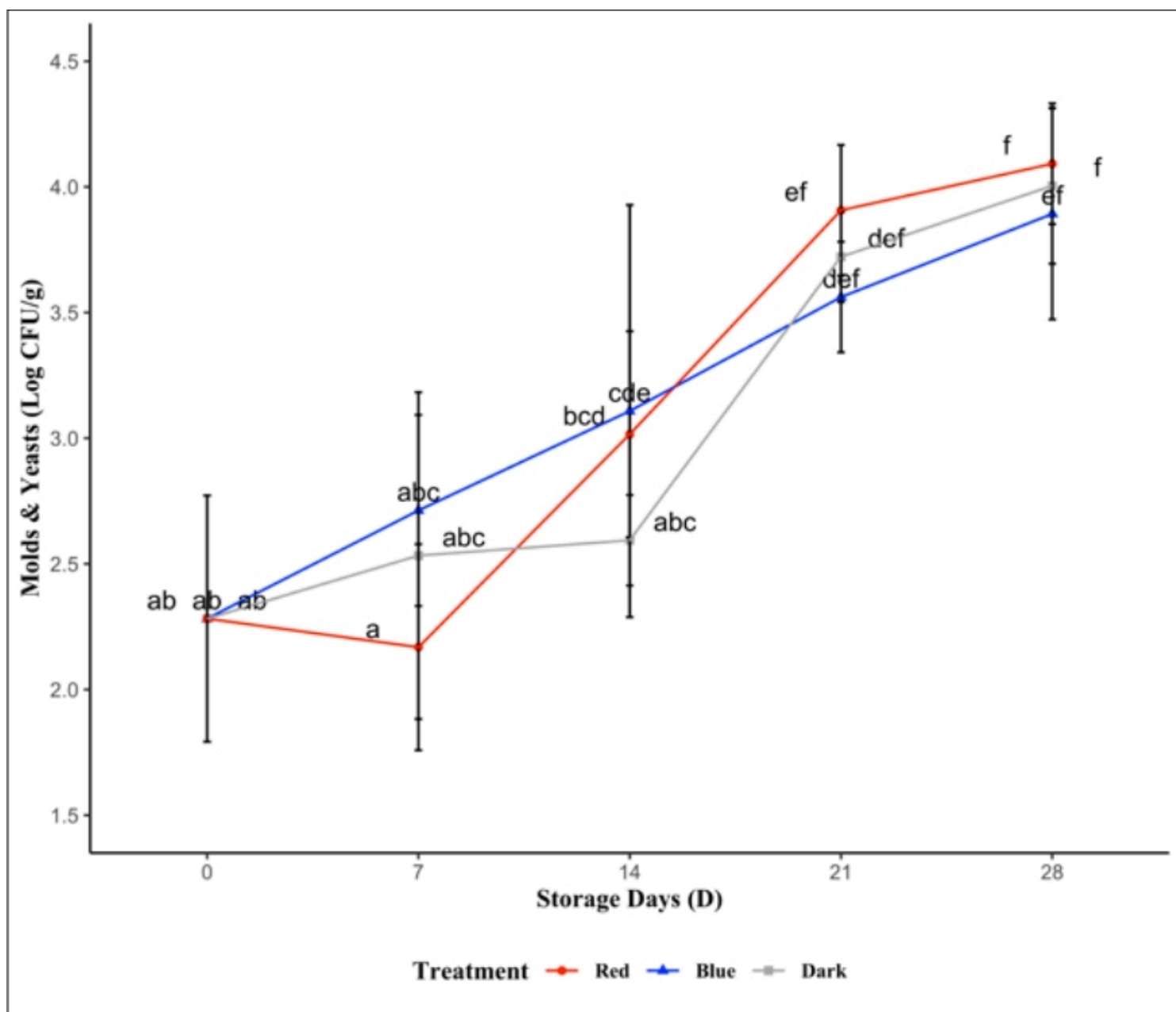


Figure 4

Microbial population on haskap berries during storage.

Three treatments are included in the postharvest treatments. Different letters correspond to mean values significantly different ($p < 0.05$) during postharvest by analysis of variation (ANOVA) and Tukey post hoc test. Each treatment has three replicates on each sampling day.