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Light Treatment Extended Shelf-Life and Postharvest Quality of Chinese Kale (*Brassica oleracea* var. *alboglabra*)

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Abstract

Background and Objectives : Chinese kale (*Brassica oleracea* var. *alboglabra*) is a leafy vegetable in the Brassicaceae family. It contains phytochemicals such as glucosinolates, vitamin C, polyphenols, carotenoids, and anthocyanins. Chinese kale has a short shelf life of about three days, resulting in a rapid decline in postharvest quality, such as color alteration and chlorophyll degradation. The deterioration leads to income loss, waste, and the production of poor-quality products for consumers. Effective strategies to reduce postharvest losses are, therefore, essential. Light treatment has been developed and shown to be effective in prolonging postharvest quality in vegetables, including broccoli, spinach, and basil. The effectiveness of light treatment depends on the light source, intensity, and quality, as well as the type of treatment (continuous or pulsed). Several internal and external factors influence the efficiency of light treatment, including the genotypes and cultivation conditions, which can range from open fields to greenhouses and plant factories. Within the highly regulated environment of a plant factory, vegetables may exhibit differing physiological and textural characteristics. The aim of this study was to determine the effectiveness of white, red and blue light treatment in prolonging key postharvest quality characteristics of Chinese kale, including chlorophyll content, color, and firmness, cultivated specifically under plant factory conditions.

Methodology : Chinese kale cv. Inthanon F1 plants were cultivated in a deep flow technique (DFT) hydroponic system. The plants were grown under white LED light at 100 µmol $m^{-2}s^{-1}$ PPFD, following a 16-hour light/8-hour dark cycle. After 28 days of growth, the plants that consisting of 5 true leaves were harvested for light treatment. Three Chinese kale plants were packed into Active Pak™ bags which facilitate gas and moisture transfer creating equilibrium modified atmospheric packaging. The experiments were conducted in nine replications and the bags

were placed horizontally in a plexiglass box measuring 55 cm x 55 cm x 54 cm. Inside the box, LED panels emitted red light (660 ± 10 nm), blue light (460 ± 10 nm), or white light (400–780 nm) at intensities of 20, 50, and 100 µmol $m^{-2}s^{-1}$ PPFD for 180 min. After the light treatment, the Chinese kale plants were kept in the dark at 20 °C for 14 days. The 2nd, 3rd and 4th leaves from the top from each plant were taken on days 0, 3, 7, 10, and 14 days of storage and used immediately for measurement. Their firmness, chlorophyll index and colour measurement were measured in the middle portion of the leaves, avoiding the veins. Firmness was assessed using a DS/DF Series Digital Force Gauge. Lower values indicated a less rigid leaf texture with a crisper feel, while higher values suggested a tougher texture. The chlorophyll index was measured with a Portable Chlorophyll Meter CM-B and the results were expressed as SPAD values. Color measurements were conducted using a Professional Digital Electronic Colorimeter WR-18. Senescence symptoms including yellowing and microbial infection were also measured. The effects of light type and intensity on postharvest quality were analysed using R software. Density plots were created using the ggplot2 package. All statistical analyses were conducted at a significance threshold of $\alpha = 0.05$. The data were analysed using one-way analysis of variance (ANOVA) followed by Tukey's multiple comparison tests.

Main Results : The effects of white, red, and blue light at 20, 50, and 100 µmol $m^{-2}s^{-1}$ PPFD on Chinese kale under plant factory conditions were investigated. Red light at 20 µmol $m^{-2}s^{-1}$ PPFD (R20) and white light at 50 µmol $m^{-2}s^{-1}$ PPFD (W50) maintained chlorophyll content and firmness with less variability compared to untreated kale. Blue light at 20 µmol $m^{-2}s^{-1}$ PPFD (B20) maintained firmness better than blue light at higher intensities, with no significant differences in other parameters. Based on these results, R20, B20, and W50 were selected and combined with equilibrium modified atmospheric packaging during cold storage. During storage, light treatment strongly maintained chlorophyll content. By day 7, untreated kale exhibited a significant decrease in chlorophyll, while light-treated kale particularly W50 and R20 better preserved chlorophyll than B20. This trend continued through day 10. On day 14, only W50- and R20-treated kale retained measurable chlorophyll, whereas B20 and untreated kale showed severe senescence and were unmeasurable. B20-treated kale showed no senescence symptoms until day 7, while R20- and W50-treated kale remained symptom-free until day 10. By day 14, only 4% of W50-treated kale and 7% of R20-treated kale showed microbial infection, with 11% and 30% showing yellowing, respectively. Based on cost-effectiveness, white light treatment can be applied at the commercial scale to improve long-term storage of Chinese kale and other leafy vegetables.

Conclusions : Red and white light emissions at 20 and 50 µmol $m^{-2}s^{-1}$ PPFD, combined with equilibrium modified atmospheric packaging, extended the shelf life of Chinese kale to 14 days and drastically reduced microbial

infection. From a cost-effectiveness perspective, white light treatment is suitable for commercial-scale application to enhance long-term storage of Chinese kale and other leafy vegetables.

Keywords : postharvest ; shelf-life ; Chinese kale ; light emission ; senescence

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Introduction

Chinese kale (*Brassica oleracea* var. *alboglabra*) is a vegetable in the Brassicaceae family. It is highly nutritious, containing a significant amount of phytochemicals such as glucosinolates, vitamin C, polyphenols, carotenoids, and anthocyanins (Bjorkman *et al.,* 2011). This vegetable is widely cultivated in China and Southeast Asia, where the stems and young leaves are consumed as leafy vegetables (Wang *et al.,* 2017). However, Chinese kale has a short shelf life of 3 days (Sun *et al.,* 2012). This rapid postharvest decline leads to income loss, food waste, and poor-quality products for consumers. Deterioration includes color changes and loss of proteins and sugars (Wang, 1998). Postharvest losses make up a significant proportion of overall losses about 50% in fruit and vegetable production (Porat *et al*., 2018), and 43% for Chinese kale specifically (Bundhurat *et al.,* 2012). Therefore, effective strategies to reduce such losses are essential. One promising approach involves applying light treatment to prolong postharvest quality in vegetables (Charles *et al.,* 2018). Researchers have demonstrated its effectiveness in various vegetables, including broccoli (Büchert *et al*., 2011), spinach leaves (Gergoff *et al.,* 2013), and basil leaves (Costa *et al.,* 2013). This method offers simplicity and ease of implementation at storage, packing, and sales points (Nassarawa *et al*., 2021). The effectiveness of light treatment depends on the light source, intensity, and quality, as well as the treatment type (continuous or pulsed) and the specific vegetable being treated (Bárcena *et al.,* 2025). Deng *et al*. (2017) showed that treating Chinese kale sprouts with continuous red LED light (80 μmol $m^{-2}s^{-1}$) for 24 hours before harvest maintained their total glucosinolate and vitamin C content while also enhancing the accumulation of total phenolics and antioxidant activity. Liu *et al.* (2015) applied light/dark cycles during postharvest storage to maintain tissue integrity and nutritional quality in spinach, lettuce, cabbage, and kale.

Several internal and external factors influence the efficiency of light treatment, including genotypes and cultivation conditions ranging from open fields to greenhouses and plant factories. In the highly regulated environment of a plant factory, vegetables may exhibit varying physiological and textural characteristics (Kaiser *et al.,* 2024). As a result, identifying a suitable light treatment for these plants is essential to maximize their shelf life for fresh consumption. This study aimed to compare and determine the intensity of light treatment that positively

influences postharvest characteristics. Additionally, selected conditions were combined with equilibrium modified atmospheric packaging to identify a light source with a specific intensity that significantly preserves postharvest characteristics and delays senescence during cold storage.

Methodology

1. Cultivation condition and light treatment

Chinese kale Inthanon F1 seeds (Purchased from EAST-WEST SEED, Thailand) were germinated by soaking in reverse osmosis (RO) water within hydroponic sponges. This process was carried out under dark conditions with a relative humidity of 90–95% for 72 hours. Following germination, the seeds were exposed to white light (400–780 nm) at a photosynthetic photon flux density (PPFD) of 100 µmol $m^{-2}s^{-1}$, under a 16-hour light/9-hour dark cycle. The temperature was maintained at 25 ± 1 °C, with a relative humidity of 70 ± 5% and a carbon dioxide concentration of 380 ± 50 µmol/mol. The RO water was replaced every two days. Once the seedlings developed 2-3 true leaves they were transferred to the Innovative Herbal Plant Factory, National Center for Genetic engineering and Biotechnology, Thailand Science Park, Pathum Thani, Thailand.

The cultivation settings used a deep flow technique (DFT) hydroponic system. In this phase, the plants were grown under white LED light at a PPFD of 200 µmol $m^{-2}s^{-1}$, following a 16-hour light/8-hour dark cycle. Environmental conditions were kept stable with a carbon dioxide concentration of 1000 ± 50 µmol/mol, a temperature of 25 ± 1 °C, and a relative humidity of 70 ± 5%. The plants were maintained in a modified Enshi nutrient solution (Hossain *et al*., 2025), with an electrical conductivity (EC) ranging from 1.5 to 2.5 mS/cm and a pH between 5.6 and 6.5 (Figure 1). After 28 days of growth, the plants that consisting of 5 true leaves (Zheng *et al*., 2022) were harvested. Three Chinese kale plants were packed into 8" x 20" Active Pak™ bags (National Metal and Materials Technology Center (MTEC) Thailand) which facilitate gas and moisture transfer creating equilibrium modified atmospheric packaging.

The experiments were conducted in nine replications and the bags were placed horizontally in a plexiglass box measuring 55 cm x 55 cm x 54 cm. Inside the box, 50 cm x 30 cm LED panels (Chenghui Equipment Co., Ltd., Guangzhou, China) emitted red light (660 ± 10 nm), blue light (460 ± 10 nm), or white light (400–780 nm) at intensities of 20, 50, and 100 µmol $m^{-2}s^{-1}$ PPFD for 180 min. The distance from the light source to the Chinese kale bags was maintained at 41 cm. After the light treatment, the Chinese kale plants were kept in the box in the dark at 20 °C for 14 days. The 2nd, 3rd and 4th leaves from the top from each plant were taken on days 0, 3, 7, 10, and 14 days of storage and used immediately for measurement.

2. Firmness, chlorophyll index and colour measurement

The firmness, chlorophyll index, and color measurements were taken from the middle portion of the leaves, avoiding the veins. Firmness was assessed using a DS/DF Series Digital Force Gauge (Desik, Germany). A cylindrical probe with a diameter of 3.5 mm was used to puncture the leaves, and the maximum force applied was recorded in Newtons (N). Lower values indicated a less rigid leaf texture with a crisper feel, while higher values suggested a tougher texture. The chlorophyll index was measured with a Portable Chlorophyll Meter CM-B (BIOBASE, China) and the results were expressed as SPAD values. Color measurements were conducted using a Professional Digital Electronic Colorimeter WR-18 (Shenzhen Wave Optoelectronics Technology Co. Ltd, China), featuring an 8 mm diameter viewing aperture. The color data included the parameters blue-yellow (b*), lightness (L*), chroma (C*), and hue angle (H).

3. Senescence symptom development

Senescence symptoms in Chinese kale during storage include yellowing and microbial infection. Yellowing was characterized by a 75-100% yellow appearance on the leaves (Zhao *et al.,* 2012). Plants with more than 80% of their leaves yellowing were classified as senescent. Yellowing defines as the loss of the green pigment chlorophyll, which unmasks other pigments and results in a yellow appearance. Water soaking symptom appears as bruised, dark, or translucent spots on the plant tissue. Postharvest microbial infection manifests as various forms of rots, spots, lesions, and discoloration, often accompanied by the presence of visible mold or a foul odor.

4. Data visualization and Statistical Analysis

4.1 Data visualization

The effects of light type and intensity on the physiological traits of plants, along with data visualization, were analysed using R software (version 4.4.1) (Banfield, 1999). The light treatments included four conditions (red, blue, white, and a control) at three intensity levels (20, 50, and 100 μmol $m^{-2}s^{-1}$), using 25 leaf samples per treatment (n = 25). The sample size was selected due to limitations in the harvesting and sample preparation process, which required that each treatment group contain an equal number of samples to maintain consistency and comparability across treatments.

Density plots were generated using the ggplot2 package to visualize the distribution of continuous physiological variables, with the y-axis representing density and the x-axis representing variable values, including chlorophyll index, firmness, and color parameters: blue–yellow coordinate (b*), lightness (L*), chroma (C*), and hue angle (H°) (Wickham, 2016). Each density curve represents a kernel density estimate for the respective treatment group, facilitating visual comparison of central tendencies and dispersion among light conditions.

The width of the density curves indicates the variability of the data: a narrower curve represents less variability, while a wider curve signifies greater variability. Longer tails suggest a higher probability of observing extreme values in the dataset. These plots emphasize treatment-specific differences in central tendency and variability, reflecting the potential effects of light spectra and intensity on the physiological responses of the plants.

In addition, box plots were constructed to monitor changes in firmness, chlorophyll index, and b* values during storage. Box plots display the median (central line), interquartile range (IQR), and the minimum and maximum values (tails or outliers). Significant differences among treatments on the same storage day were identified using Tukey's HSD test at a significance level of $\alpha = 0.05$. Treatment groups were classified into statistically distinct categories using lowercase English letters, where groups sharing the same letter were not significantly different from one another, whereas groups assigned different letters represented significantly different mean values.

4.2 Statistical Analysis

Prior to conducting inferential statistical analyses, all datasets were assessed to ensure compliance with the underlying assumptions required for parametric testing. The experiment was conducted using a factorial design arranged in a Completely Randomized Design (CRD), with two experimental factors—light type and light intensity—and all treatment combinations randomly assigned to ensure unbiased sampling.

The statistical analyses were performed to determine whether the treatments produced significantly different physiological responses. One-way analysis of variance (ANOVA) was conducted to evaluate the effects of light quality and intensity on the measured physiological traits. When significant treatment effects were detected ($\alpha = 0.05$), Tukey's Honestly Significant Difference (HSD) post hoc test was applied to identify specific pairwise differences among treatments while maintaining control over Type I error across multiple comparisons.

The optimal light intensity for each light quality was identified from the initial analysis, and these selected conditions were used to further examine postharvest changes in Chinese kale during a 14-day storage period. Firmness, chlorophyll index, and b* value were monitored as key indicators of quality deterioration. Measurements were conducted on Days 0, 3, 7, 10, and 14. Instances labelled as ND (not detected) occurred when samples had deteriorated due to senescence or tissue breakdown, rendering them unsuitable for measurement. This comparison enabled assessment of both immediate treatment effects and longer-term postharvest responses under each lighting condition.

Results

1. The effects of light treatment on firmness, chlorophyll index and colour in Chinese kale

The effects of white, red, and blue light at intensities of 20, 50, and 100 µmol $m^{-2}s^{-1}$ PPFD were statistically analysed for their impact on the firmness, chlorophyll index, and colour parameters of Chinese kale grown under plant factory conditions. The means and standard deviations (SD) of the data are presented in Table 1, while the variability in data distribution is illustrated in Figure 2 and Supplement Table S1-S6.

At the low PPFD intensity of 20 µmol $m^{-2}s^{-1}$, the red and blue light treatments had minimal effects on Chinese kale firmness. However, at 100 µmol $m^{-2}s^{-1}$ PPFD, the light treatment had negative effects, as firmness values (1.828 ± 0.14–1.928 ± 0.16 N) were significantly ($p < 0.0001$) higher than those of untreated Chinese kale (1.534 ± 0.20 N). At 50 µmol $m^{-2}s^{-1}$ PPFD with white light treatment, two peaks were observed in the density plots, indicating the presence of two subgroups: one group exhibited lower firmness values (crisper), while the other had higher firmness values than the untreated Chinese kale. Light treatment positively affected chlorophyll content in Chinese kale, with the highest chlorophyll content recorded at 50.488 ± 2.47 SPAD in the 100 µmol $m^{-2}s^{-1}$ PPFD white light-treated Chinese kale. At 20, 50, and 100 µmol $m^{-2}s^{-1}$ PPFD, the chlorophyll content of the white light-treated kale exhibited a unimodal (one-peak) symmetrical distribution, indicating low variability. A similar pattern was observed for red- and blue-light-treated kale at 20 and 100 µmol $m^{-2}s^{-1}$ PPFD. However, at 50 µmol $m^{-2}s^{-1}$ PPFD, the blue light-treated Chinese kale had a lower mean chlorophyll content of 40.360 ± 5.35 SPAD units, with greater variability than in other light treatments. The untreated Chinese kale had the lowest mean chlorophyll content (35.590 ± 10.6 SPAD) and the greatest variability.

Red light treatment at a low intensity of 20 µmol $m^{-2}s^{-1}$ PPFD and white light treatment at 50 µmol $m^{-2}s^{-1}$ PPFD resulted in a low b* value. Both treatments showed a symmetrical peak (normal distribution) and lower variability than in untreated Chinese kale. In contrast, blue light treatment adversely affected the b* value. In treated Chinese kale, the b* value was elevated and exhibited high variability at both 20 and 50 µmol $m^{-2}s^{-1}$ PPFD. White and red-light treatments had little impact on the L*, C*, and H values. However, the blue light treatment at 50 µmol $m^{-2}s^{-1}$ PPFD resulted in higher C* and L* values and lower H values compared to untreated Chinese kale. This suggests a lighter, more saturated, and more yellow-green color. The treatments of red (R20), blue (B20), and white (W50) light were selected for their ability to maintain firmness and their positive effects on chlorophyll content. These treatments were further investigated for their effects on Chinese kale during cold storage.

2. Comparison of firmness, chlorophyll and colour in Chinese kale during storage

The means and standard deviations (SD) of firmness, chlorophyll index, and color values are presented in Figure 3 and Supplement Table S7-S9. Data distribution, including the median, quartiles, maximum, and minimum values, is illustrated in Figure 3. The effects of 20 μmol m^{-2} s^{-1} PPFD of red (R20) and blue (B20) light, as well as 50 μmol $m^{-2}s^{-1}$ PPFD of white (W50) light treatment, on firmness, chlorophyll index, and color in Chinese kale during a 14-day storage period were evaluated (Figure 3 and Supplement Table S7-S9).

There was no significant difference in the mean values of firmness among the light-treated and untreated Chinese kale until day 7 (p_{day3} = 0.593, p_{day7} = 0.131). On day 10, only the R20 and W50 treated Chinese kale maintained firmness, with values of 1.49 ± 0.48 N and 1.63 ± 0.53 N, respectively. An increase in firmness values in the B20 treated and untreated Chinese kale indicated a decline in crispness. By day 14, only the R20 treated Chinese kale sustained a firmness value of 1.44 ± 0.48 N (Supplement Table S7). The box plot representing firmness values Figure 3a, showed the least variability in firmness for R20 treated Chinese kale starting from day 7. The results indicate that R20 treatment was most effective at maintaining firmness with minimal variability during storage.

Light treatment had a strong positive effect on maintaining chlorophyll index in Chinese kale. By day 3, only the W50 treated Chinese kale maintained chlorophyll index similar to day 0, with R20 treated kale following closely. There was no significant difference in chlorophyll index between the B20 treated kale and the untreated kale ($p = 0.277$). On day 7, chlorophyll index significantly decreased in the untreated Chinese kale ($p < 0.0001$), while it was notably maintained in the light-treated kale, with W50 and R20 performing better than B20. This trend continued on day 10. By day 14, only the chlorophyll index in the W50 treated Chinese kale was still maintained, followed by the R20 treated kale. The B20 treated and untreated Chinese kale showed severe senescence, rendering them unmeasurable Supplement Table S8. Overall, W50 treated Chinese kale exhibited significantly higher chlorophyll index and less variability compared to the untreated ($p < 0.0001$), R20, and B20 treated kale starting from day 3 (Figure 3b). There was no significant difference in the b* value between the light-treated and untreated Chinese kale until day 10 (Supplement Table S9). Although there was no significant difference in b* values between W50 and R20 ($p = 0.787$), the R20 treated Chinese kale exhibited less variability from day 7 compared to the others (Figure 3c).

3. Senescence symptom development

Light treatment effectively delayed the onset of senescence symptoms, such as microbial infection and yellowing, in Chinese kale during storage. In untreated Chinese kale, yellowing was observed in 41% of samples by day 7, and by day 10, 100% of the samples showed yellowing. By day 14 all samples exhibited symptoms of

microbial infection and water soaking, the latter a symptom of senescence. In contrast, blue light treatment at an intensity of 20 µmol $m^{-2}s^{-1}$ PPFD delayed yellowing until day 10, with only 33% of samples showing yellowing. However, by day 14, all samples (100%) displayed yellowing symptoms along with microbial infection. Both white light treatment at an intensity of 50 µmol $m^{-2}s^{-1}$ PPFD and red-light treatment at 20 µmol $m^{-2}s^{-1}$ PPFD significantly delayed senescence symptoms until day 14. Under W50, there was only 4% microbial infection and 11% yellowing. Under R20 there were similar results with 4% microbial infection and 11% yellowing (Table 2 and Figure 4).

Figure 1 Cultivation conditions of Chinese kale in plant factory using a deep flow technique (DFT) hydroponic system

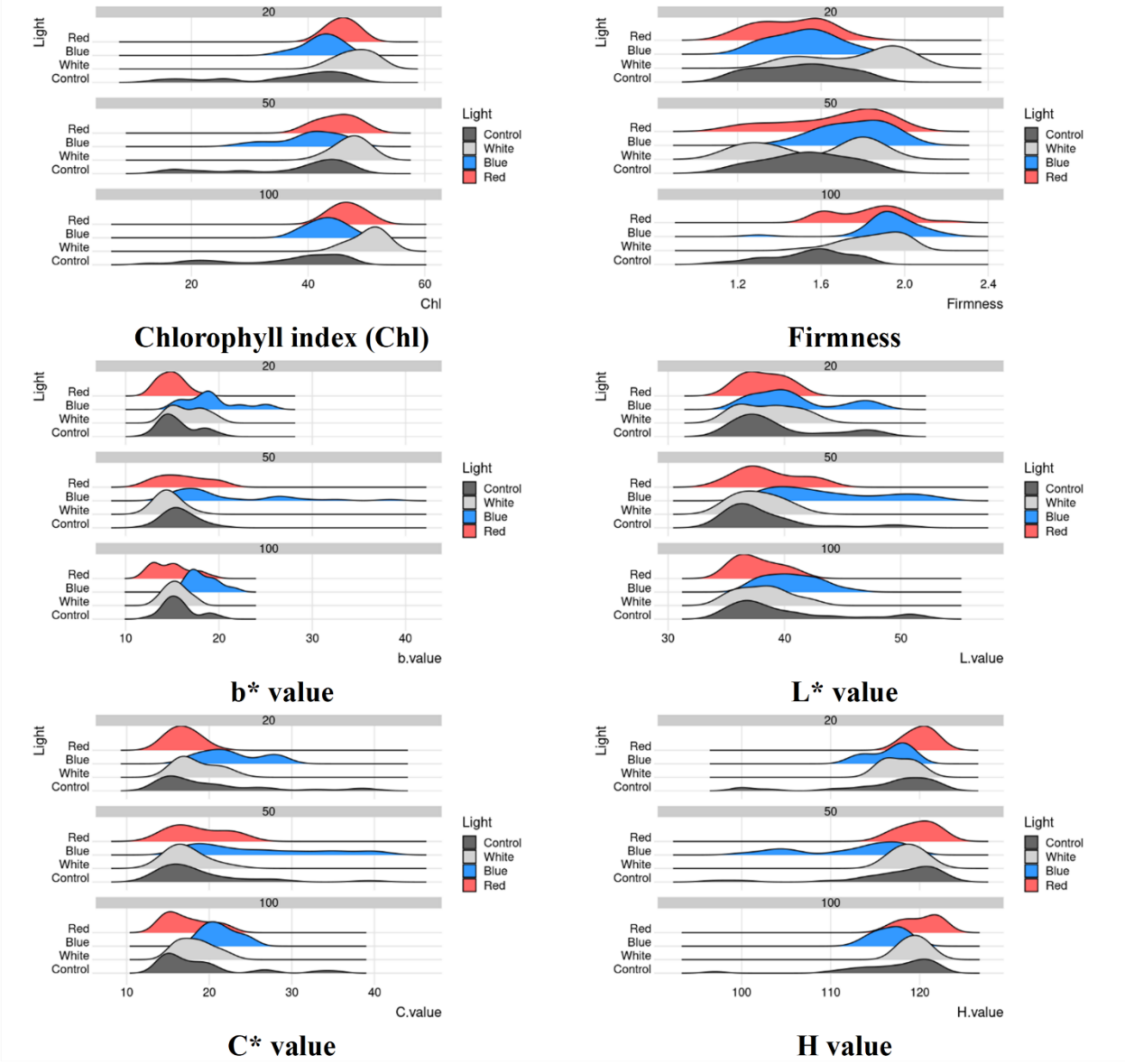

Figure 2 Density plots illustrating the distribution of physiological traits in Chinese kale subjected to different light treatments (red, blue, white, and control) and intensity levels (20, 50, and 100 μmol $m^{-2}s^{-1}$ PPFD). Each row represents a specific light intensity level while each curve within a panel corresponds to a particular light quality treatment. The physiological traits measured include the chlorophyll index (Chl), firmness, and color parameters L*, b*, C*, H. Kernel density estimates were utilized to visualize the frequency and spread of trait values across 25 samples for each treatment.

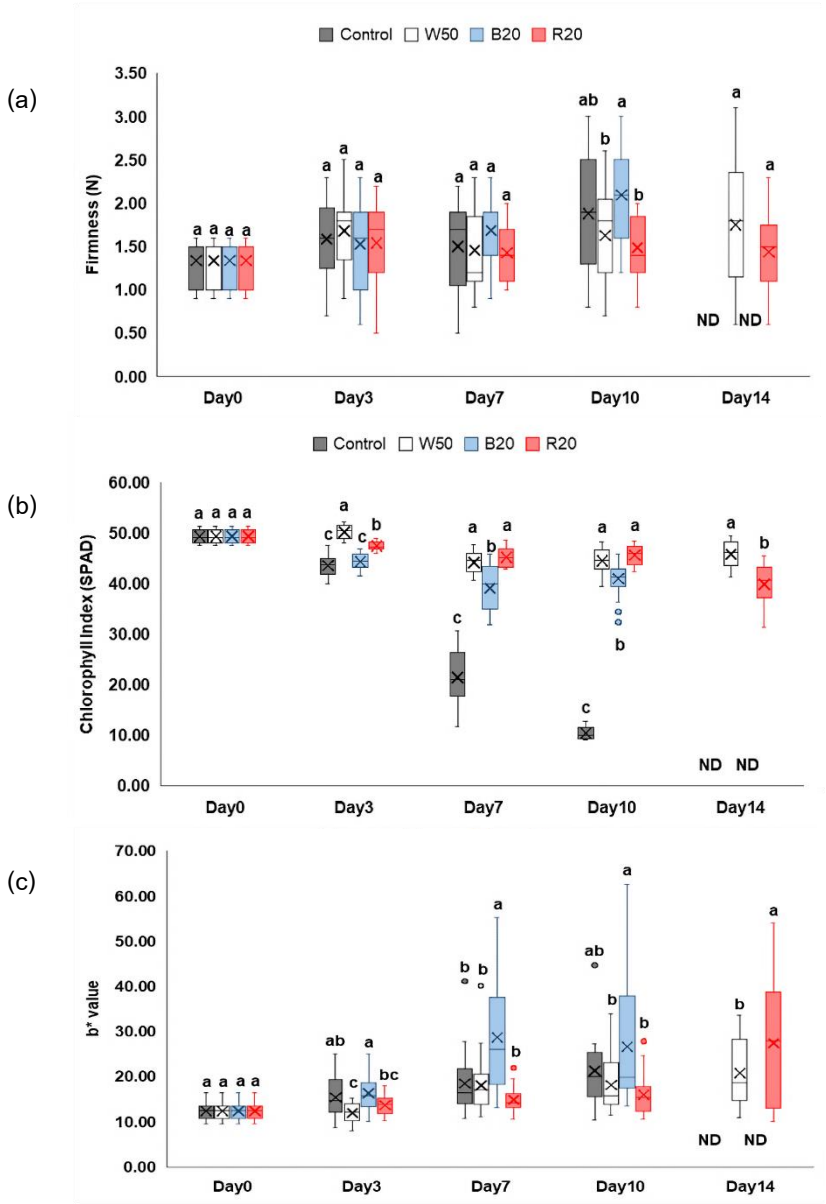

Figure 3 Box plot of Chinese kale firmness (a), chlorophyll index (b) and b* value (c) during a 14-day storage period under three different light treatments: white, red, and blue. Plot includes the median (indicated within the box), quartiles, maximum, and minimum values and represents the interquartile range (IQR), which encompasses the middle 50% of the data.

Note : Different letters corresponding to a single storage day indicate significant differences based on an Tukey's HSD test at a significance level of α = 0.05. "ND" indicates data that were not determined due to the severe senescence of the Chinese kale, rendering measurement impossible.

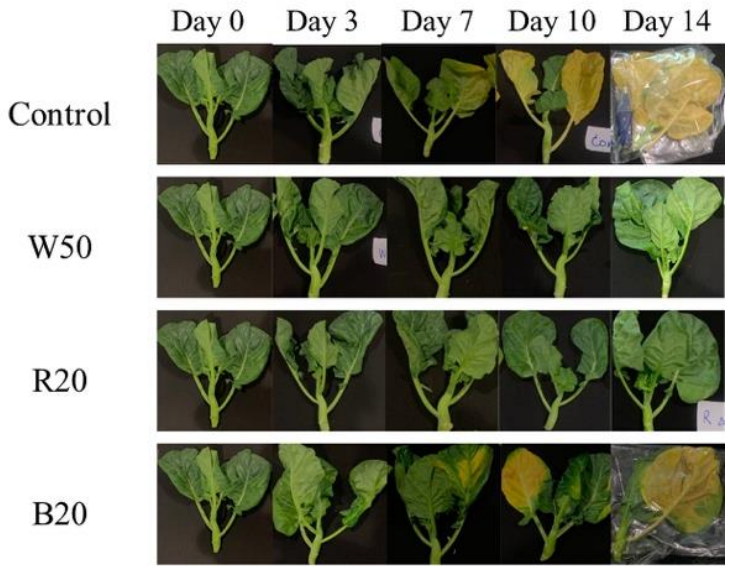

Figure 4 Senescence symptom development in white (W50), red (R20) and blue (B20) light treated and non-treated Chinese Kale on storage days 0, 3, 7, 10 and 14.

Table 1 Effect of light treatment on Chinese kale firmness, chlorophyll index and color. Data are presented as means ± standard deviation (n=25)

Light	μmol $m^{-2}s^{-1}$ PPFD	Firmness(N)	Chl index (SPAD)	b* value	L* value	C* value	H value
	Control	1.53 ± 0.20^{cd}	35.59 ± 10.6^{f}	15.63 ± 2.03^{a}	38.35 ± 4.01^{bc}	18.88 ± 5.86^{bcd}	117.00 ± 6.42^{ab}
White	20	1.78 ± 0.23^{ab}	48.22 ± 2.85^{ab}	16.67 ± 1.88^{ab}	38.60 ± 2.43^{bc}	18.47 ± 2.36^{cd}	117.72 ±1.79^{ab}
	50	1.56 ± 0.27^{cd}	47.37 ± 2.34^{abc}	14.58 ± 1.02^{a}	37.67 ±1.89^{c}	17.23 ± 2.06^{d}	118.68 ±1.46^{ab}
	100	1.85 ± 0.14^{a}	50.49 ± 2.47^{a}	15.58 ± 1.23^{a}	38.13 ± 2.23^{bc}	18.34 ± 2.14^{cd}	119.40 ±1.29^{ab}
Blue	20	1.52 ± 0.15^{cd}	42.39 ± 2.98^{cde}	19.21 ± 2.99^{c}	40.76 ± 3.73^{ab}	22.74 ±3.76^{ab}	116.64 ± 2.34^{ab}
	50	1.76 ± 0.16^{ab}	40.36 ± 5.35^{def}	20.60 ± 6.27^{c}	43.69 ± 4.94^{a}	25.79 ±7.88^{a}	112.40 ± 6.01^{c}
	100	1.93 ± 0.16^{a}	43.03 ± 2.88^{bcd}	18.27 ± 1.56^{bc}	40.57 ± 2.37^{bc}	21.35 ±1.99^{bc}	116.64 ± 1.80^{ab}
Red	20	1.46 ± 0.17^{d}	45.80 ± 2.00^{abcd}	14.88 ± 1.34^{a}	38.21±1.79^{bc}	16.87 ± 1.59^{d}	120.12 ±1.51^{a}
	50	1.67 ± 0.24^{bc}	44.98 ± 3.17^{abcd}	16.12 ± 2.58^{ab}	38.64 ± 2.66^{bc}	18.64 ± 3.22^{cd}	119.72 ± 1.95^{a}
	100	1.83 ± 0.17^{ab}	46.71 ± 2.52^{abc}	14.95 ± 2.08^{a}	37.70 ±1.90^{bc}	17.40 ±2.72^{cd}	120.00 ±2.10^{a}

Note : Different letters indicate significant differences based on the Tukey's HSD test at a significance level of α = 0.05.

Table 2 Development of senescence symptoms in Chinese kale treated with different light conditions: 50 µmol $m^{-2}s^{-1}$ of white light (W50), 20 µmol $m^{-2}s^{-1}$ of red light (B20), and 20 µmol $m^{-2}s^{-1}$ of blue light (B20). The control group were untreated. The proportion of samples exhibiting senescence symptoms, including yellowing, water soaking, or microbial infection are indicated as percentage of total samples.

	Senescence symptoms				
	Day 0	Day 3	Day 7	Day 10	Day 14
Control	No symptom	No symptom	41% yellowing	100% yellowing	100% microbial infection, 100% yellowing, 100% water soaking
W50	No symptom	No symptom	No symptom	No symptom	4% microbial infection, 11% yellowing, no water soaking (0%)
R20	No symptom	No symptom	No symptom	No symptom	7% microbial infection, 30% yellowing, no water soaking (0%)
B20	No symptom	No symptom	No symptom	33% yellowing	100% microbial infection, 100% yellowing, 33% water soaking

Discussion

The application of light-emitting technologies to extend the shelf-life of fresh vegetables presents several advantages over traditional methods including simplicity, eco-friendliness, and effectiveness in storage, packaging, distribution, and sale (Bantis *et al*., 2018). The efficacy of this technology, however, can vary significantly ranging from no benefit to considerable advantages depending on factors such as plant species, processing methods, and light conditions (Mastropasqua *et al.,* 2016; Hasperue *et al.,* 2016a, 2016b). Consequently, it is crucial to establish appropriate light treatment conditions for specific vegetables to maintain their postharvest quality. Key attributes that change during storage and impact the shelf-life of leafy vegetables include texture, colour, and chlorophyll levels (Pintos *et al.,* 2023). Chlorophylls, the primary pigments of green vegetables, break down during storage. This catabolism causes the loss of green colour and the presence of yellow colour, resulting in a shortened shelf-life (Chairat *et al.,* 2013). Untreated Chinese kale showed signs of senescence by day 3, evidenced by a decline in chlorophyll content and an increase in the b* value. In this study, equilibrium modified atmospheric packing using an Active Pak™ bag, combined with red and white light treatments, resulted in Chinese kale maintaining chlorophyll content and extending shelf-life to 10 and 14 days, respectively. A positive effect of red-light treatment has also been reported on the postharvest quality of Chinese cabbage including texture, flavour, chlorophyll stability, and nutrient content (Wang *et al.,* 2025). The prolonged effect of red light on vegetable shelf-life is thought to be related to phytochrome (Costa *et al.,* 2013; Liebsch & Keech, 2016). Specifically, red light activates phytochrome B to active form which supressed and degraded PIF (phytochrome-interacting factor). This delay in PIF-dependent senescence through NAC transcription factor that activate senescence genes such as Chl b reductase (Casajús *et al.,* 2025).

Mi *et al* (2023) found that white light treatment delayed yellowing in 'Zaosu' Pear fruit during storage by inhibiting chlorophyll degradation. This effect can be attributed to the decreased expression of genes related to ethylene synthesis and signalling, as well as the increased expression of genes linked to chlorophyll synthesis during storage. Pintos *et al* (2020) also reported that mid- and high-intensity white light treatment reduced chlorophyll loss and prolonged the shelf-life of broccoli. White light treatment improved carotenoid content and maintained color quality in goji Berries. Carotenoid biosynthesis genes such PSY and Z-ISO were upregulated while carotenoid repressor genes such as WRKY were downregulated (Yan *et al.* 2025). Under high intensity light, however, Reactive oxygen species (ROS) especially hydrogen peroxide was produced from chloroplast. It migrated into nucleus and activated senescence related genes such as NACs (Sakuraba, 2021). Although B20 treatment delayed senescence in Chinese kale, its efficiency was lower than that of the W50 and R20 treatments. Lin *et al.* (2025b) reported that the effectiveness of blue light treatment is intensity dependent. Therefore, optimising blue light intensity may help determine an appropriate dosage.

Throughout the storage period from day 0 to day 10, there was no significant difference in firmness between light-treated and untreated Chinese kale. However, by day 14 the red-light-treated Chinese kale retained its firmness better than those treated with white light. Light treatment also causes stomatal opening and increases respiratory activity, contributing to fresh weight loss and enhancing gas exchange between the plant tissues and the environment within the packaging (Olarte *et al.,* 2009). Various postharvest qualities, such as appearance, texture, and odour, can be used to assess the shelf-life of leafy vegetables. One key indicator of senescence is yellowing where plants with completely yellow leaves are considered to have reached the end of their shelf-life (Min *et al.,* 2021). Light treatment delayed yellowing in Chinese kale, with white and red-light treatments proving more effective. Only 11% and 30% of these samples showed yellowing symptoms compared to 100% for the blue light treatment.

This study also highlighted the importance of the antimicrobial action of light treatment in maintaining the aesthetic factor of appearance, an important consumer-facing quality. The majority of white and red treated Chinese kale were free of fungal infection on day 14 while 100% of non-treated control plants were infected. Lobiuc *et al* (2017) reported that red light treatment delayed microbial growth in green basil, resulting in an elevation in flavonoids and free radical scavenging activity. White LED irradiation effectively inhibited the growth of the fungal species *Cladosporium cladosporioides* in citrus. Further investigation revealed that white LED treatment induced apoptosis and suppressed mycelial proliferation and conidial germination (Lin *et al.,* 2025a). The antimicrobial effects are largely on the surface (affected by shadowing) and dose dependent which highlights the need to ensure leaf surfaces are flat during treatment and the UV light permeability of any plastic or similar packaging (Yaun *et al.,*

2004; Allende *et al.,* 2006). Yan *et al*. (2023) reported that red light treatment induced salicylic acid production and microbial resistant genes against *Phytophthora capsici* in pepper. Extending the shelf life of leafy vegetables, such as Chinese kale, offers significant economic advantages by reducing waste, improving supply chain efficiency, and enabling the production of better pricing and value-added products. The products with longer shelf life allow for more efficient distribution, reduce losses due to spoilage, and potentially increase profit margins by enabling higher prices and exports (Reyes *et al.,* 2024; Coffigniez *et al.,* 2021). From the results of this study is highly likely that shelf-life could be extended further by optimising several factors which will be a focus of future studies. Because of its cost-effectiveness, wide availability, and worker-friendly operation compared to red light (Wong & Zhou, 2024), a combination of white light, optimised for plant factory cultivation conditions, could enhance the commercial value of this highly nutritious leafy vegetable for both local and export markets.

Conclusions

Red and white light emissions at 20 and 50 μmol $m^{-2}s^{-1}$ PPFD combining with equilibrium modified atmospheric packaging extended the shelf-life of Chinese kale to 14 days and drastically reducing microbial infection. White light treatment is a cost-effective option for commercial-scale storage of Chinese kale and other leafy vegetables.

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