Effects of Stage-Specific of Red to White Light on the Growth and Nutritional Properties of Pak Choi

Xiangyu Wang , Shijun Zhu , Jun Ju , Minggui Zhang , Youzhi Hu , Xiaolong Yang , Jiali Song , Houcheng Liu *

Posted Date: 27 March 2026

doi: 10.20944/preprints202603.2253.v1

Keywords: plant factory; dynamic lighting; light quality; Pak choi; product quality

 doi:10.20944/preprints202603.2253.v1

Article

Effects of Stage-Specific of Red to White Light on the Growth and Nutritional Properties of Pak Choi

Xiangyu Wang, Shijun Zhu, Jun Ju, Minggui Zhang, Youzhi Hu, Xiaolong Yang, Jiali Song and Houcheng Liu *

College of Horticulture, South China Agricultural University, Guangzhou 510642, China

* Correspondence: liuhch@scau.edu.cn

Abstract

In plant factories with artificial lighting (PFALs), spectral regulation serves as the predominant factor governing plant growth and development. The implementation of red-enriched spectral regimens during cultivation promotes biomass accumulation, whereas blue-dominant spectra enhance the biosynthesis of phytochemicals and nutritional compounds in plants. Nevertheless, systematic investigations of staged spectral regimens on both plant development and secondary metabolite biosynthesis remain limited. This study implemented a staged lighting regimen utilizing three distinct red-to-white photon flux ratios (R: W=3:1, 1:1, and 1:3) administered sequentially during critical developmental phases: seedling stage, the early growth stage (15 d after transplanting, DPA), and the late growth stage (16-30 d, DPA) in Pak choi. This study implemented four distinct staged spectral regimens to evaluate photonic treatment effects through multivariate analysis of biomass production, morphological development, photosynthetic pigments, nutritional metabolites, along with antioxidants and radical quenching capacity. The results demonstrated that the T4 treatment significantly enhanced biomass production across all developmental stages. While, the T3 treatment exhibited optimal efficacy in improving nutritional quality (particularly content of soluble proteins and Vitamin C) along with superior antioxidant capacity. The higher red-light significantly enhanced leaf expansion and carotenoid biosynthesis at the seedling stage. While higher blue-light in subsequent growth stages effectively stimulated biosynthesis of chlorophyll and antioxidants. This study established that temporal modulation of red-to-white spectral ratios during vegetative development enabled synergistic optimization of yield and quality attributes in Pak choi.

Keywords: plant factory; dynamic lighting; light quality; Pak choi; product quality

Introduction

Plant factories with artificial lighting (PFALs) can produce high-quality vegetables year-round to meet the increasing market needs. Leafy vegetables contain various substances which are beneficial to human health, such as carbohydrates, vitamins, and flavonoids [1–3]. These substances can reduce the risk of cardiovascular disease, hypertension, and obesity [4]. Pak choi (Brassica campestris ssp. chinensis var. communis) feature short growth cycles, compact morphology, and rich nutritional content, and it is well-suited for cultivation in PFALs. In PFALs, modifying the growing environment —particularly the light environment— can effectively enhance vegetable quality and yield.

Light, as a crucial environmental factor for plant growth and development, exerts an extremely complex influence on plants. The visible light spectrum predominantly influences plant growth and development, red and blue light play the most critical roles in plant photosynthesis [5,6]. Therefore, red and blue light-emitting diodes (LEDs) are often used as the principal light sources in PFALs [7]. Red light-enriched spectral compositions significantly enhanced plant growth, particularly biomass, leaf elongation, and leaf area expansion [8,9]. Spinach cultivated under a red-to-blue (R:B) ratio of 9:1 produced significantly greater biomass and leaf area than those grown under R:B ratios of 3:1 and 1:3 [10]. Cucumber leaves exposed to combined red and blue light demonstrated enhanced

 doi:10.20944/preprints202603.2253.v1

photosynthetic acclimation, as evidenced by significantly increased leaf area and elevated chlorophyll content [11]. Lettuce under a combined red and blue light spectrum demonstrated enhanced growth performance, characterized by increased biomass (both dry and fresh weight) and greater leaf area [12]. Furthermore, red and blue light spectrum also promotes the biosynthesis of secondary metabolites [13]. Blue light supplementation significantly enhanced the phytochemical concentrations and antioxidant capacity in Chinese kale and Pak choi sprouts initially cultivated under ambient light conditions [14]. However, an elevated proportion of blue light in the spectrum could inhibit plant growth. Lettuce growth under a blue light-enriched spectrum was markedly inferior to those under a red light-enriched spectrum [15]. Consequently, the use of red-blue combination light represents an optimal strategy for achieving balanced plant growth in PFALs [16].

During the lettuce growth, a higher red: blue ratio facilitated biomass accumulation; whereas, a lower red: blue ratio during the quality-forming stage stimulated the biosynthesis of secondary metabolites [17]. An elevated red-to-blue ratio increased the biomass and leaf area in lettuce [18]. Blue light supplementation during 10 days pre-harvest significantly increased the content of ascorbic acid, soluble proteins, and free amino acids in Chinese kale [19]. The cultivation of leafy vegetables like Pak choi usually are under a static lighting treatment, research on stage-specific dynamic lighting strategies remains relatively underdeveloped. This study aimed to quantify the effects of dynamically adjusting the red-to-white light ratio during distinct developmental stages on the growth, morphological traits, and nutritional composition of Pak choi.

2. Materials and Methods

2.1. Plant Material, Growth Conditions, and Treatments

This study was conducted in an artificial lighting plant factory at the South China Agricultural University. Pak choi (cv. Xiashangwei No.2, from GLseed seed company Ltd., Zhuhai, China) seeds were germinated in sponge cube. Post-germination cultivation was conducted using a standardized hydroponic protocol with 1/2 Hoagland solution, 200 μmol·m^{-2}·s^{-1} PPFD, and 10/14-h light/dark. Adjustable red (660±10 nm) and white (peak at 440 nm) LED light panels (Chenghui Equipment Co., Ltd., Guangzhou, China; 150×30 cm2) are used as light sources. The ambient temperature is 20±2 °C and relative humidity within 65-75%.

Fifteen-day-old seedlings with three true leaves were transplanted onto cultivation panels (90 × 120 cm) at a density of 24 plants per panel, deep-flow technique (DFT) hydroponic system with half-strength Hoagland's nutrient solution (pH of 6.8 ± 0.2, electrical conductivity of 1.50 ± 0.05 mS·cm−1). Nutrient solution circulates for 5 minutes at 20-minute intervals.

There were four spectral treatments under 200 μmol·m^{-2}·s^{-1} PPFD, 10/14 h light/dark photoperiod: T1 (R:W=1:3 during seedling stage, R:W=1:1 through the early growth stage, and R:W=3:1 during the late growth stage); T2 (R:W=1:3 during seedling stage, R:W=3:1 through the early growth stage, and R:W=1:1 during the late growth stage), T3 (R:W=3:1 during seedling stage, R:W=1:3 through the early growth stage, and R:W=1:1 during the late growth stage), and T4 (R:W=3:1 during seedling stage, R:W=1:1 through the early growth stage, and R:W=1:3 during the late growth stage). There were three biological replicates. The detailed configuration of spectral regimens and sampling schedule are presented in Figure 1 and Table 1.

 doi:10.20944/preprints202603.2253.v1

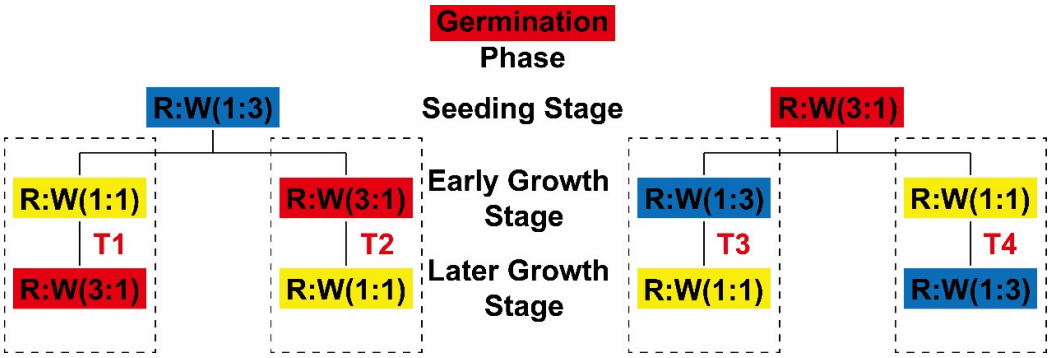


Figure 1. Light spectral treatments. Plants were divided into three growth stages, each lasting 15 days, totaling 45 days from germination to harvest. Three distinct light spectra were applied: red light: white light = 3:1 (red box), red light: white light = 1:1 (yellow box), and red light: white light = 1:3 (blue box). Different light spectral treatments were applied during each growth stage, with destructive sampling performed at stage termination for subsequent phenotypic and biochemical analysis.

Table 1. Lighting parameters of treatments. photon flux density (μmol·m^{-2}·s^{-1}).

Spectral Composition and Light Treatment	seedling stage		the early growth stage		the late growth stage	
	red light	white light	red light	white light	red light	white light
TI	50	150	100	100	150	50
T2	50	150	150	50	100	100
T3	150	50	50	150	100	100
T4	150	50	100	100	50	150

2.2. Measurement of Plant Morphology and Growth Characteristics

Six uniform Pak choi plants were randomly selected from each treatment for quantification of morphophysiological parameters. The fresh biomass of shoot and root systems was quantified using an analytical balance. Leaf area was determined through digital image analysis using ImageJ software (version 1.8.0; National Institutes of Health, Bethesda, MD, USA). Plant samples were subjected to oven-drying at 105 °C for enzyme inactivation (2 hours), followed by desiccation at 75 °C until constant mass was achieved. The dry weights of shoot and root were subsequently quantified gravimetrically by electronic balance.

Shoot tissues of Pak choi were immediately cryopreserved in liquid nitrogen and maintained at -80 °C for subsequent biochemical analysis. All biochemical parameters were analyzed with 4 repetitions.

2.3. Measurement of Pigment Content

Fresh Pak choi leaves were dissected to exclude petioles and midribs, finely homogenized, and thoroughly mixed. A 0.2 g sample immersed in 8 mL of acetone/ anhydrous ethanol (1:1) mixture. The samples were placed in darkness until the leaves turn completely white. The supernatant was measured at 663 nm, 645 nm, and 440 nm by UV spectrophotometer (Shimadzu UV-1780).Pigment concentrations were determined through the following equations [20]:

Chlorophyll a (mg/L) = $12.7A_{663} - 2.69A_{645}$

Chlorophyll b (mg/L) = $22.9A_{645} - 4.68A_{663}$

Total chlorophyll (mg/L) = $8.02A_{663} + 20.20A_{645}$

Carotenoids (mg/L) = $4.7A_{440} - 0.27 \times$ Total chlorophyll

Pigment content per fresh weight (mg/g) was calculated as: (Pigment concentration × Extract volume) / Sample mass

 doi:10.20944/preprints202603.2253.v1

2.4. Measurement of Nutrient Content

Soluble proteins content was determined by Coomassie Brilliant Blue G-250 binding assay [21]. A 0.5 g sample was homogenized in 8 mL of ultrapure water and centrifuged (4 °C, 4000 rpm, 10 min). A 0.2 mL supernatant was diluted with 0.8 mL of ultrapure water. To this dilution, 5 mL of Coomassie Brilliant Blue G-250 solution was added and mixed thoroughly. After 5-minute incubation at ambient temperature, absorbance was measured at 595 nm by UV spectrophotometer (Shimadzu UV-1780).

Soluble sugars content was determined by anthrone-sulfuric acid method [22]. A 0.5 g fresh sample was subjected to extraction with 80% ethanol (initial 4 mL, followed by two 2.5 mL washes of the residue), with each step involving 40-minute water bath incubation. The pooled supernatants were decolorized with 10 mg of activated charcoal at 80 °C for 30 minutes. The final solution was filtered and made up to 10 mL with 80% ethanol. Aliquots (0.2 mL) were mixed with 0.8 mL ultrapure water, reacted with 5 mL freshly prepared anthrone reagent (0.2% in concentrated sulfuric acid), and incubated in boiling water for 10 min. Absorbance was measured at 625 nm after cooling to ambient temperature by UV spectrophotometer (Shimadzu UV-1780).

Vitamin C content was determined by molybdenum blue spectrophotometry [23]. A 0.5 g sample was mixed with 10 mL of oxalic acid-ethylenediaminetetraacetic acid solution, followed by a 30-minute standing period and filtrated. 5 mL aliquots were reacted sequentially with 0.5 mL metaphosphoric-acetic acid solution, 1 mL 5% sulfuric acid, and 2 mL ammonium molybdate reagent. After 15-min chromogenic development, absorbance was measured at 705 nm by UV spectrophotometer (Shimadzu UV-1780).

Nitrate content was quantified using the salicylic acid nitration method [24]. A 0.5 g sample was dissolved in 10 mL of ultrapure water, centrifuged (5000 rpm, 10 min), and then subjected to a 30-minute treatment in a boiling water bath. Following cooling, the extract was filtered, diluted to 10 mL with ultrapure water and mixed. Aliquots (0.1 mL) were reacted with 0.4 mL 5% (w/v) salicylic acid-sulfuric acid reagent for 20 min, followed by addition of 9.5 mL 8% NaOH solution. After cooling, absorbance was measured at 410 nm by UV spectrophotometer (Shimadzu UV-1780).

2.5. Measurement of Antioxidant Content and Antioxidant Capacity

A 0.5 g sample was treated with 8 mL of anhydrous ethanol for 30 minutes. Centrifuged at 4 °C and 3000 rpm for 15 minutes. Collection of the supernatant for analysis of antioxidant content and antioxidant capacity.

2.5.1. Measurement of Antioxidant Content

Total phenolic content was determined using the Folin-Ciocalteu method [25]. The 0.5 mL sample solution was treated with 0.5 mL of Phlorin phenol reagent and supplemented with 1.5 mL of 26.7% Na_2CO_3 solution and 7 mL of ultrapure water. The reaction mixture was incubated for 2 hours in darkness before measuring absorbance at 760 nm by UV spectrophotometer (Shimadzu UV-1780).

Total flavonoid content was quantified using the aluminum chloride colorimetric method [26]. To 1 mL of sample solution, reagents were added sequentially: first 0.7 mL of 5% $NaNO_2$ (5 min at 25 °C), then 0.7 mL of 10% $AlCl_3$ (6 min at 25 °C), and finally 5 mL of 5% NaOH. Absorbance was measured at 510 nm by UV spectrophotometer (Shimadzu UV-1780).

2.5.2. Measurement of Antioxidant Capacity

The free radical scavenging capacity was evaluated using the 1,1-diphenyl-2-picrylhydrazyl (DPPH) assay according to Musa et al. [27]. The measurement procedure was conducted as follows: Ai (2 mL sample solution was combined with 2 mL of 0.1 mM DPPH methanolic solution); Aj (2 mL sample solution was mixed with 2 mL absolute ethanol); Ac (2 mL 0.1 mM DPPH solution was mixed

 doi:10.20944/preprints202603.2253.v1

with 2 mL absolute ethanol). The absorbance of the three solutions was measured at 517 nm by UV spectrophotometer (Shimadzu UV-1780). The calculation formula is as follows:

DPPH Radical Scavenging Rate (%) = [1 − (Ai − Aj)/Ac] × 100%

The ferric reducing antioxidant power (FRAP) was determined following Benzie et al. [28]. A 0.4 mL sample solution was treated with 3.6 mL of TPTZ solution and incubated at 37 °C for 10 minutes. Absorbance was measured at 593 nm by UV spectrophotometer (Shimadzu UV-1780).

2.6. Statistical Analysis

Data were expressed as mean ± standard error (n = 3 replications) and analyzed by a two-way analysis of variance (ANOVA) using SPSS 22.0 software. Means comparison was performed using Duncan's test at $P < 0.05$.

3. Results

3.1. Plant Growth Characteristics, and Pigment Content

Pak choi demonstrated a high degree of developmental plasticity in response to staged light regimes, with pronounced morphological differentiation manifesting across its developmental stages. Compared to the LR treatment (T1, T2), the HR treatment (T3, T4) yielded superior dry and fresh weights and leaf area in Pak choi. Specifically, the HR treatment resulted in significantly or extremely significantly higher shoot dry and fresh weights and leaf area than the LR treatment (Figure 3&4). The T4 treatment resulted in superior biomass accumulation across all growth stages compared to the other groups, whereas the T1 treatment was the least effective (Figure 3). During the early growth stage, both dry and fresh weights of the shoot and root in the T4 treatment were significantly higher than those of other treatments, and this trend persisted into the late growth stage. Noteworthy, the T2 treatment exhibited a more pronounced growth rate in both shoot and root dry and fresh weight during the late growth stage, while dry and fresh weight remained lower than those of the T4 treatment. During the seedling stage, the HR treatments exhibited significantly greater leaf area than the LR treatments. Except for the T1 treatment, which exhibited significantly lower leaf area than the other treatments, no significant differences in leaf area were observed among the remaining treatments (Figure 4).

 doi:10.20944/preprints202603.2253.v1

Figure 2. (a) Plant phenotypic performance at the early growth stage, and(b) Plant phenotypic performance at the late growth stage.

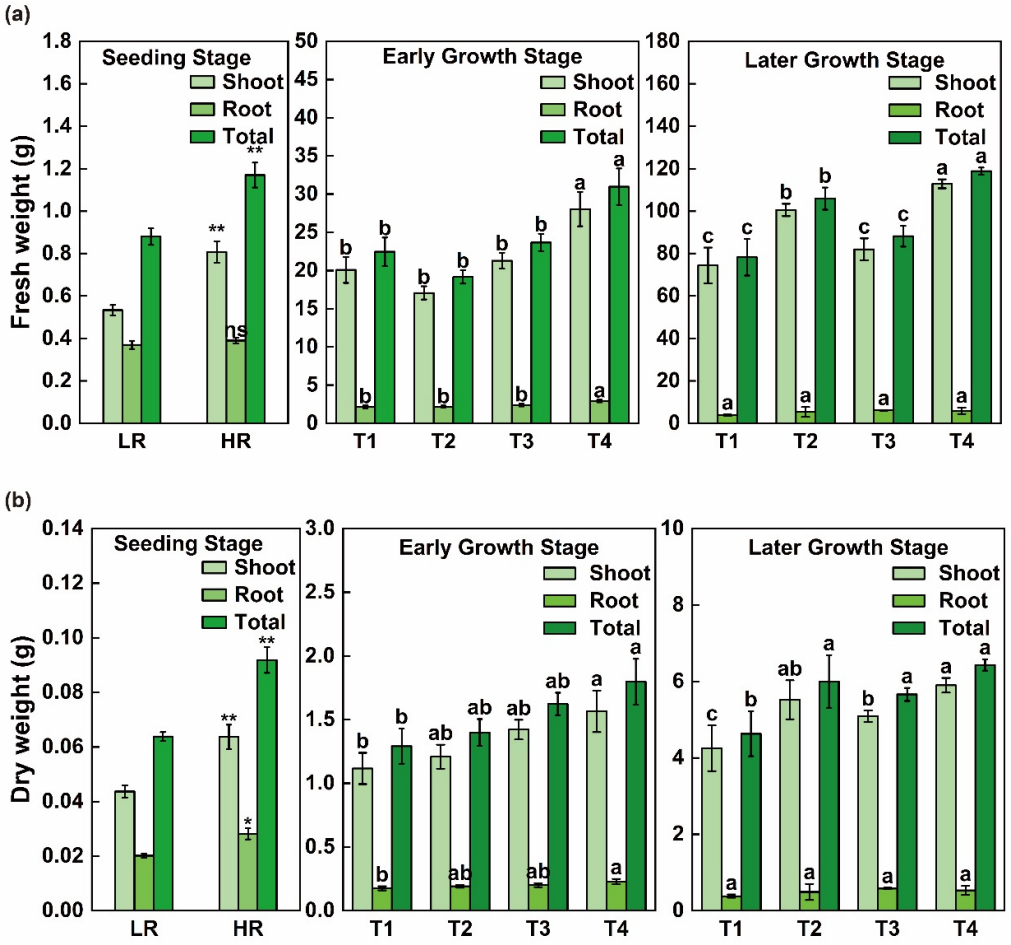
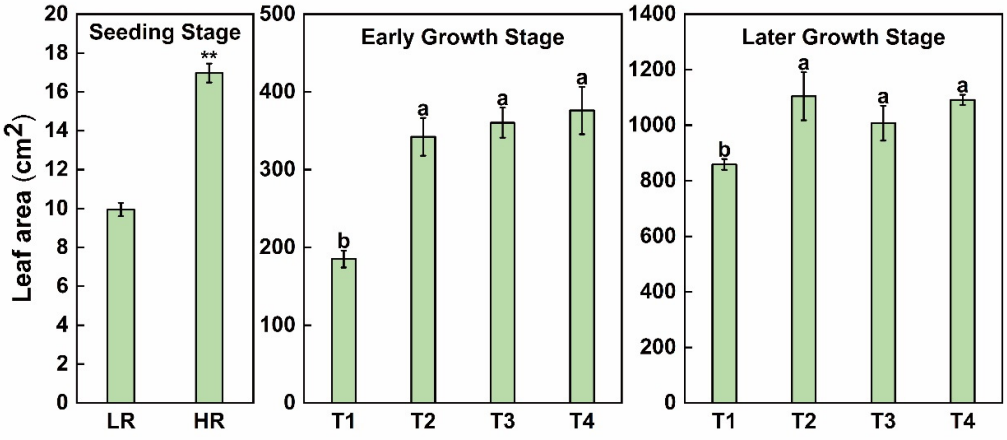


Figure 3. Impacts of staged Spectral Regimens on Biomass Partitioning in Pak choi: Temporal Analysis of Shoot and Root Fresh(a)/Dry(b) Matter Accumulation. The asterisk denotes statistically significant differences in intergroup comparisons during the seedling stage (independent samples t-test). Different letters indicate significant differences between treatments at the same growth stage ($p < 0.05$, one-way ANOVA with Duncan's post-hoc test).



 doi:10.20944/preprints202603.2253.v1

Figure 4. Effects of staged Spectral Regimens on Leaf Area Expansion in Pak choi Across Developmental Stages. The asterisk denotes statistically significant differences in intergroup comparisons during the seedling stage (independent samples t-test). Different letters indicate significant differences between treatments at the same growth stage ($p < 0.05$, one-way ANOVA with Duncan's post-hoc test).

During the seedling stage, the LR treatments exhibited significantly higher content of chlorophyll a, chlorophyll b, and total chlorophyll compared to the HR treatments. However, chlorophyll content showed little variation during subsequent growth stages, particularly in the late growth stage, while no significant differences were observed among the treatments (Figure 5a). There was no significant difference in the carotenoid content of Pak choi across all growth stages (Figure 5b). The changes in photosynthetic pigment content within each treatment remained relatively stable across different growth stages. Dynamic supplemental lighting strategies had little effect on the photosynthetic pigment content of Pak choi.

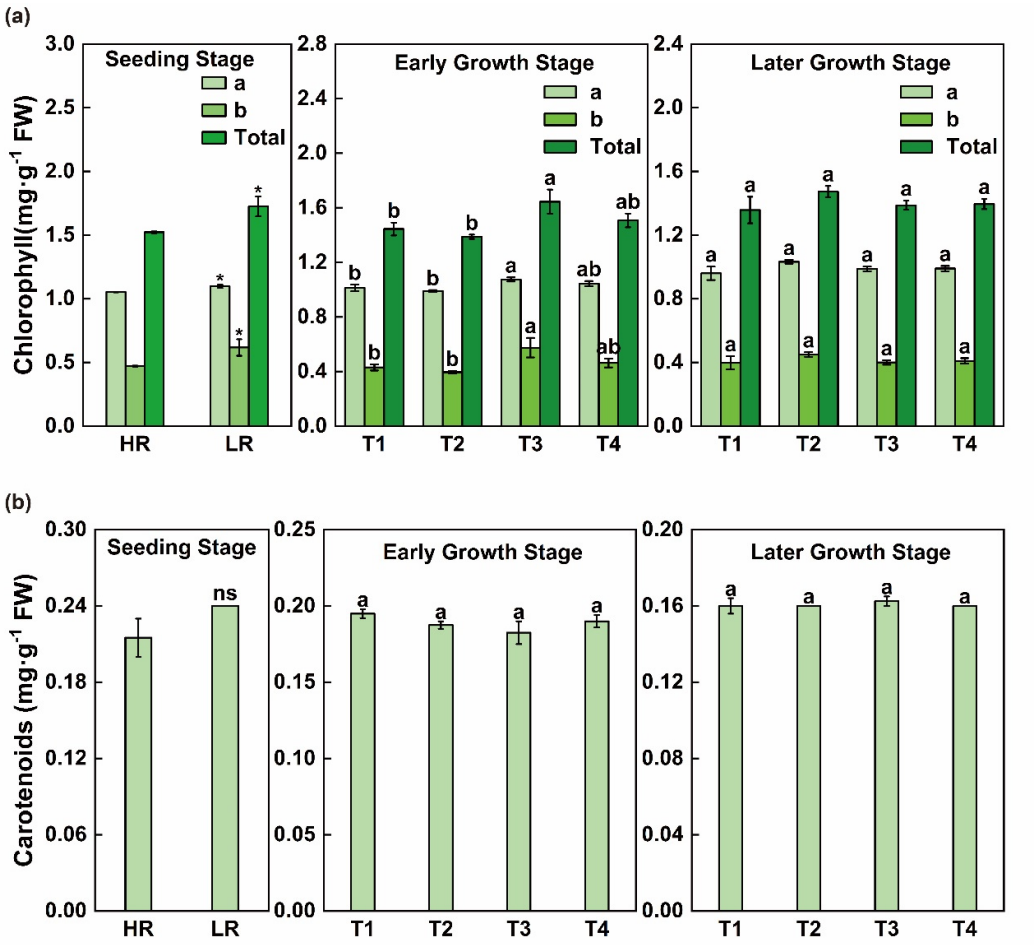


Figure 5. Effects of staged Spectral Regimens on Chlorophyll(a) and Carotenoids(b) in Pak choi Leaves at Different Growth Stages. The asterisk denotes statistically significant differences in intergroup comparisons during the seedling stage (independent samples t-test). Different letters indicate significant differences between treatments at the same growth stage ($p < 0.05$, one-way ANOVA with Duncan's post-hoc test).

3.2. Content of Soluble Sugars, Soluble proteins, Nitrates and Vitamin C

There was the highest nutritional component content in Pak choi of T3 treatment (R: W=1:3) (particularly contents of Soluble proteins and vitamin C) during the early growth stage while, in Pak choi of T1 treatment (R: W= 3:1) during the late growth stage (Figure 6). During the early growth

 doi:10.20944/preprints202603.2253.v1

stage, there were higher levels of nutritional qualities except soluble proteins content in the T3 treatment compared to other treatments. Notably, the soluble sugars content was significantly higher than those of the T1 and T4 treatments. However, the nitrate content was significantly higher than those of the other treatments. During the late growth stage, the vitamin C content in the T1 treatment was significantly higher than in other treatments, and there was no significant difference in contents of soluble proteins and soluble sugars compared to the T1 treatment. Compared to the earlier growth stage, the nutritional component content of Pak choi in the late growth stage generally showed a decreasing trend. While, except for the T2 treatment, the soluble sugars content in the other treatments actually exhibits an increasing trend. (Figure 6).

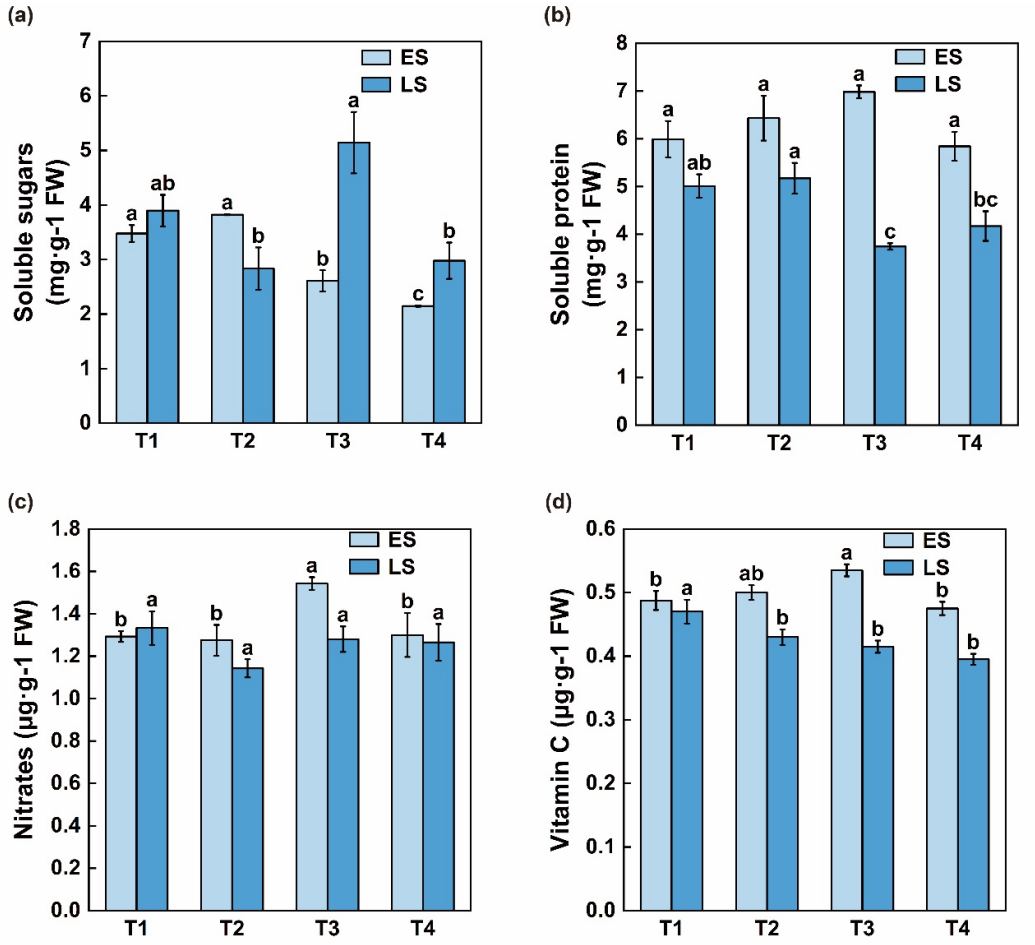


Figure 6. staged Spectral Strategies Modulate Nutritional Metabolite Profiles in Pak choi: Soluble Sugars(a), Soluble Proteins(b), Nitrates(c) and Vitamin C(d) Dynamics Across Developmental Stages. ES means the early growth stage, whereas LS means the late growth stage. Different letters indicate significant differences between treatments at the same growth stage ($p < 0.05$, one-way ANOVA with Duncan's post-hoc test).

3.3. Antioxidant Content and Antioxidant Activity

Similar to nutrient content, there were superior antioxidant contents and activity in Pak choi of T3-treatment during the early growth stage, while the T2 treatment in the late growth stage (Figure 7). During the early growth stage, the significantly higher contents of total polyphenol, total flavonoid, and FRAP values were found in T3 treatment compared to T4 treatment. There was no significant difference in DPPH scavenging rates among the treatments. During the late growth stage, the total flavonoid content and FRAP of Pak choi in T2 treatment were significantly higher than those of T3 and T4 treatments, but no significant difference was observed between the T2 and T1 treatments.

 doi:10.20944/preprints202603.2253.v1

There was no significant difference in the total polyphenol content and DPPH radical scavenging activity of Pak choi among the different treatments. During the late growth stage, the antioxidant content and antioxidant activity of Pak choi across all treatments generally showed a declining trend, with only the DPPH scavenging rate remaining relatively stable without significant reduction (Figure 7).

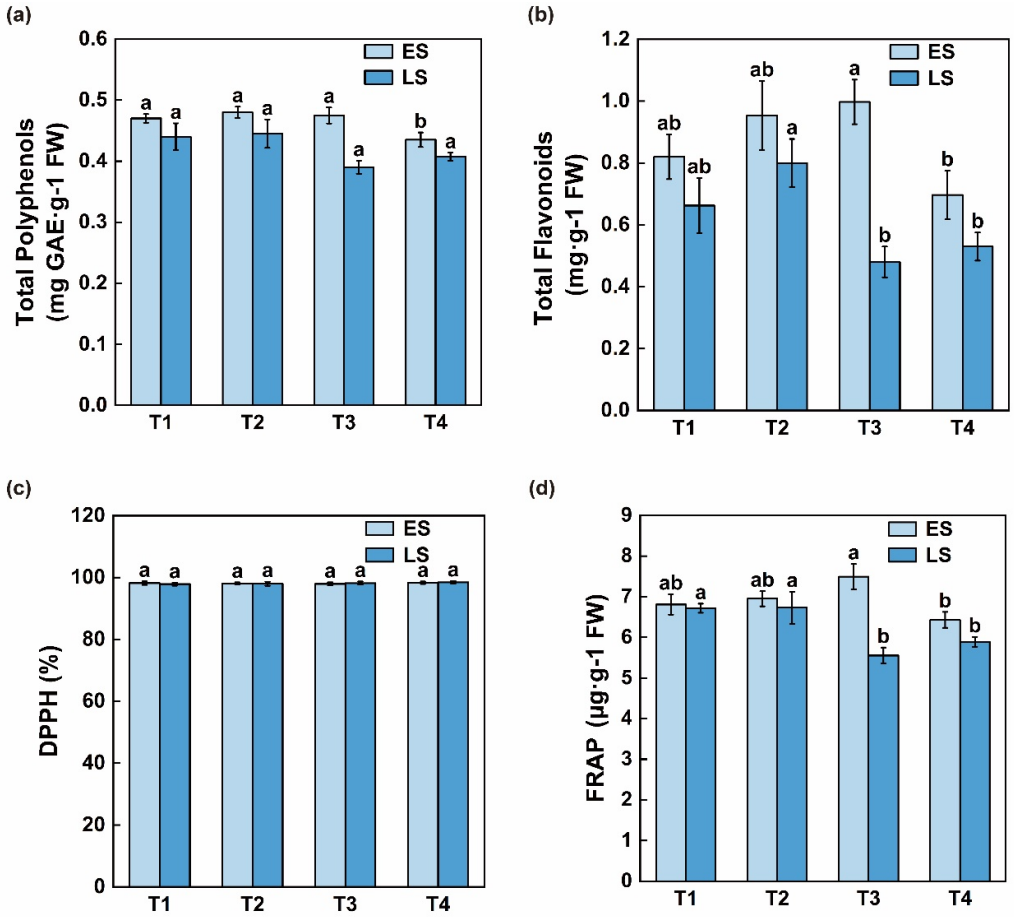


Figure 7. Dynamic Spectral Strategies Modulate Antioxidant Content and Antioxidant Activity Profiles in Pak choi: total phenolics (a), total flavonoid (b), (c)2,2diphenyl-1-picrylhydrazyl (DPPH), and (d) ferric-reducing antioxidant power (FRAP) Dynamics Across Developmental Stages. ES means the early growth stage, whereas LS means the late growth stage. Different letters indicate significant differences between treatments at the same growth stage ($p < 0.05$, one-way ANOVA with Duncan's post-hoc test).

4. Discussion

4.1. Effects of Dynamic Light Regimen on Biomass Accumulation and Photosynthetic Pigment Content

Exposing to dynamic light regimen, plants exhibit specific physiological responses that alter their biomass accumulation and morphological characteristics. Under a high proportion of red light during the early plant growth stages, the growth and biomass accumulation were promoted [9,29]. Red light-enriched illumination significantly increased the leaf length and leaf area of lettuce [8]. In this study, significantly higher biomass and leaf area of Pak choi were found in the HR treatment (R: W=3: 1) than the LR treatment (R: W=1: 3) during the seedling stage. Notably, the higher biomass accumulation observed in HR treatment persisted until the harvest stage. Even red-light-enriched spectra were applied during both the early and late growth stages (T1 and T2 treatments), there were higher biomass and leaf area of Pak choi plant (Figure 3). Providing a high proportion of red light

 doi:10.20944/preprints202603.2253.v1

during the late growth stages increased leaf size of lettuce, enabling the leaves to intercept more light for photosynthetic assimilation, ultimately leading to increased biomass [30,31]. However, in this study, Pak choi plant in the T1 treatment (LR during the seedling stage) showed significantly smaller leaf area than other three treatments even after applying the HR spectrum (R: W=3: 1) during the late growth stage. Short-term exposure to high proportions of red light during the late growth stage did not significantly increase the leaf area and biomass of Pak choi plant (Figure 4). Supplementing red light(600-699 nm) for three days before harvest did not increase lettuce leaf area [32]. The increase in lettuce biomass accumulation was attributed to larger leaves intercepting and utilizing more light for higher biomass [33]. The largest leaf area and the highest biomass were recorded in the T4 treatment (Figure 3&4). These indicated that leaf enlargement is an important driver of biomass accumulation in Pak choi under different light regimes, consistent with the positive relationship between biomass and leaf area of Pak choi observed in this study. A high proportion of red-light spectrum during the seedling stage was associated with a significant increase in biomass accumulation of Pak choi, an effect that persisted through the growth period until harvest.

Chlorophyll was not only closely associated with plant photosynthesis but was also a determining factor for the coloration of Pak choi at harvest, which is closely associated with consumer preferences. The biosynthesis of chlorophyll was influenced by the red-to-blue light ratio, due to the spectra of red and blue light matches the peak absorption areas of chlorophyll [34]. The content of total chlorophyll in lettuce and Pak choi was significantly increased by spectra with a low red-to-blue ratio (R: B=1:4), compared to spectra with a high R: B ratio (4: 1) [35]. This study found that the contents of chlorophyll a, chlorophyll b, and total chlorophyll in Pak choi significantly increased under high proportion of blue light spectra (R: W=1: 3) and decreased under low proportion of blue light spectra (R: W=3: 1) (Figure 5a). These pattern of pigment change might be attributed to blue light promoting the biosynthesis of chlorophyll synthesis precursors(Proto IX, Mg-proto IX and Pchlide) and mitigating the reduction in chlorophyll biosynthesis caused by red light [36]. The chlorophyll contents in lettuce leaves significantly increased in response to a transition from high (R: B=89: 11) to low (R: B=50: 50) red-to-blue ratio spectrum, while chlorophyll contents decreased when transition from low to high red-to-blue ratio spectrum [18]. In this study, across the three growth stages of Pak choi, the chlorophyll content increased when the red-to-white light ratio in the current stage's spectrum was lower than that of the previous stage (form R: W=3: 1 to R: W=1: 3, form R: W=3: 1 to R: W=1: 3). While chlorophyll content decreased when the red-to-white light ratio increased (Figure 5). The decrease in chlorophyll content observed in the T4 treatment during the late growth stage might be attributed to the larger leaf area of the plants, resulting in dilution of chlorophyll per unit fresh weight (Figure 5a). The carotenoid content was regulated by blue light through the induction of BrHY5 expression and the subsequent alteration of carotenoid biosynthetic gene expression in orange-headed Chinese cabbage [37]. The carotenoid content in Pak choi sprouts significantly increased by supplemental blue light compared to white light [38]. In this study, the carotenoid content in Pak choi increased under a high proportion of blue light (R: W=1: 3) during the seedling stage, and dynamic light conversion treatments further showed that the high blue light treatment during the seedling stage could maintain a relatively high carotenoid content during the subsequent growth period. The photosynthetic pigment content of Pak choi significantly increased by a blue light-enriched spectrum during the seedling stage, with elevated photosynthetic pigment content maintained during subsequent growth stage.

4.2. Impacts of Dynamic Light Regimen on Phytonutrient Profiles

The synthesis and degradation of primary and secondary metabolites in plants were affected by light spectrum. The responses to the red-to-blue light ratio varied among plant species and growth stages. Red light-enriched illumination lead to increased levels of soluble sugars and vitamin C, coupled with a decrease content of nitrate in lettuce [39]. While, supplementing blue light during the 10 days preceding harvest elevated the concentrations of vitamin C, soluble proteins, and free amino acids in Chinese kale [40].

 doi:10.20944/preprints202603.2253.v1

Soluble sugars were essential substances for plant growth and development. The accumulation of sugars in plants was inextricably linked to photosynthetic carbon assimilation [41]. A significant increase in sucrose content was observed tomato under a high red light proportion (R: B=3: 1) [42]. The soluble sugars content in broccoli microgreens was significantly elevated by an increase in the proportion of red light in the spectrum (from R: B=1: 1 to R: B=5: 1) [43]. The soluble sugars content of broccoli was increased by pre-harvest higher red light proportion spectrum [44]. The application of a higher red light proportion spectrum (R: B=4: 1) two days before harvest was associated with elevated soluble sugars content in lettuce compared to the spectrum (R: B=2: 1) [45]. This study found that red light-enriched illumination (R: W=3: 1) increased soluble sugars content while reducing chlorophyll content during the late growth stage (Figure 5&6a). The accumulation of soluble carbohydrates was caused by reduced photosynthetic activity and increased light inhibition in leaves supported these results [46]. Altogether, a stronger influence on the soluble sugars content of Pak choi was exerted by the spectral characteristics during the final growth stage than that during the earlier stages.

Nitrate, the primary form of nitrogen uptake, is first reduced to ammonium via the catalytic actions of nitrate reductase and nitrite reductase. This resulting ammonium was subsequently utilized in the synthesis and conversion of amino acids [47]. The dynamic balance between nitrate and soluble proteins pools is regulated by environmental conditions. Light exposure was identified as a crucial environmental factor influencing this dynamic process [48]. Numerous studies had demonstrated that light exposure influenced the activity of nitrate reductase and nitrite reductase in plants, thereby altering the contents of nitrate and soluble proteins [49]. Supplementing blue light under white light conditions significantly suppressed nitrate accumulation in lettuce [13]. The content of soluble proteins in Chinese Kale was significantly increased by spectra with low red-to-blue ratios (R: B=2: 1) compared to those with high R: B ratios (8: 1). The application of a light spectrum with R: B ratio of 4:1 two days before harvest was associated with significantly lower nitrate content in lettuce compared to the 8:1 R: B spectrum [45]. Adjusting the light spectrum from a R: B ratio of 5:1 to 2:1 seven days before harvest led to a significant reduction in nitrate levels in spinach, accompanied by increased protein content [50]. In this study, during the late growth stage, a high proportion of blue light spectrum (R: W=1: 3) was associated with a slower decline of soluble proteins content in Pak choi, although no significant effect on nitrate content was detected (Figure 6b). The light spectrum during the late growth stage was found to be an important regulatory factor for soluble protein content in Pak choi, while nitrate contents showed no significant response to light spectrum adjustment under the conditions of this study.

Vitamin C is widely recognized not only as an essential nutrient for the human body but also as a vital antioxidant, playing a significant role in the maintenance of human health [51]. Light regime had been identified as a key environmental factor governing the synthesis and accumulation of vitamin C in plants. Blue light increased vitamin C content in Chinese cabbage, mediated by the up-regulation of genes associated with its biosynthesis (BrPGI1, BrPMI1 and BrPMM1 et al.) and recycling (BrAO6, BrAPX6 and BrMDHAR1 et al.) [52]. Compared with white light, supplementing with blue light significantly increased the contents of vitamin A and vitamin C in lettuce [53]. A low R: B ratio (4: 1) was associated with significantly higher content of vitamin C in green Pak choi relative to a high R: B ratio (8:1) [54]. Exposure to a high-proportion blue light spectrum (R:B = 2:1) during the final week before harvest significantly elevated the vitamin C content in spinach at harvest [50]. Compared to the control, the vitamin C content of Chinese Kale during storage was significantly increased by supplementing with 50 μmol m-2 s-1 of blue light (430 nm) 10 days before harvest. In this study, exposure to a high proportion of blue light (R: W=1: 3) was associated with elevated vitamin C content in Pak choi in the early growth stage [40]. Interestingly, the vitamin C content in Pak choi was significantly higher when the plants were grown under a low-blue-light spectrum (R: W=3: 1) during the late growth stage than in other treatments (Figure 6d). The low blue light treatment had smaller leaf area and lower canopy shading, leading to higher light interception per unit leaf area, which induced higher activity of Vc biosynthesis-related enzymes. However, high red

 doi:10.20944/preprints202603.2253.v1

light treatment significantly increased the soluble sugar content of leaves, and soluble sugars are the key precursors for Vc biosynthesis in plants, which can provide sufficient substrate for Vc synthesis during the late growth stage. Thus, a high proportion of blue light spectrum was identified as the most significant factor influencing the vitamin C content of Pak choi during the growth stage.

In summary, dynamic lighting strategies were found to significantly affect multiple nutritional parameters in Pak choi. Among these, the application of a high-proportion blue light spectrum during growth stage was shown to elevate soluble proteins and vitamin C content, excepted soluble sugars content; while high red light treatment during the late growth stage was more beneficial for the accumulation of soluble sugars and vitamin C.

4.3. Impacts of Dynamic Light Regimen on Antioxidant Capacity and Antioxidants

Antioxidants are associated with the prevention of chronic human diseases, such as cardiovascular disease, diabetes, and cancer [55,56]. Vegetables are considered the primary dietary source of antioxidants, including total flavonoids and total polyphenols, for human body. A significant positive correlation has been widely observed between the antioxidant capacity of plants and their content of phenolic compound [56]. Light is confirmed as a crucial environmental factor that regulates the antioxidant capacity and antioxidant content in plants. Under supplemental blue light, a significant increase in antioxidant content coupled with enhanced antioxidant capacity was observed in Pak choi compared to plants grown under white light [57]. Exposure to a high-proportion blue light spectrum (R: B=1: 4) was associated with significantly elevated total phenolic content and FRAP values in Kale relative to low-proportion blue light (R: B=1: 1) or white light treatment. As the blue light ratio increased (from R: W=2:1 to R: W=1:2), the content of flavonoid and polyphenol in Pak choi, along with the FRAP values, were gradually elevated, while no significant change was observed in the DPPH radical scavenging activity [58]. These phenomena were attributed to blue light-mediated regulation of key genes within the phenylpropanoid biosynthetic pathway (FtC4H,Ft4CL,FtCHI and FtFLS2 et al.), which are responsible for the production of phenolic compounds and flavonoids [59]. Pre-harvest supplemented to blue light (50 μmol m^{-2} s^{-1}, 10 days) was associated with significantly enhanced antioxidant properties in Chinese Kale during storage, as evidenced by elevated total flavonoids, total polyphenols, FRAP values, and DPPH activity [40]. When blue light (100 μmol m^{-2} s^{-1}, 455 nm) was supplemented before harvest, the total polyphenol and total flavonoid content in basil significantly increased at harvest, and the decline in DPPH activity and FRAP values during storage was slowed [32]. In this study, a high proportion of blue light (R: W=1:3) during the late growth stage was associated with a mitigated decline in content of polyphenols and FRAP values in Pak choi (Figure 7). Those outcomes were consistent with our previous study on Pak choi [58]. The differential response of FRAP values and DPPH activity to light spectrum might be attributed to the different detection mechanisms of the two assays: FRAP reflects the total reducing power of all antioxidant components, while DPPH mainly measures the scavenging capacity for specific free radicals, leading to inconsistent change trends under partial treatments. Combined with the soluble protein and vitamin C results, high blue light treatment during the late growth stage could effectively maintain the overall nutritional and functional quality of Pak choi, providing a reference for the dynamic light quality regulation of leafy vegetables

Conclusions

A dynamic lighting strategy was confirmed to be effective for optimizing the comprehensive benefits of Pak choi production: high red-to-white (R: W) ratio during the seedling stage increased yield, while low R:W ratio (high blue light proportion) during the late growth stages enhanced nutritional quality and antioxidant capacity. In this study, the yield of Pak choi in the T4 treatment (R: W=3:1 during the seedling stage, R: W=1:1 during the early growth stage, and R: W=1:3 during the late growth stage) was the highest among all treatments. The shoot fresh weight was significantly higher than that of other treatments at all growth stages. However, the nutritional quality and antioxidant capacity were not significant different. The T2 treatment (R: W=1:3 during the seedling

 doi:10.20944/preprints202603.2253.v1

stage, R: W=3: 1 during the early growth stage, and R: W=1:1 during the late growth stage) showed the superior nutritional quality and antioxidant capacity.

In summary, the staged lighting regimen of the T4 treatment can significantly improve the yield of Pak choi in plant factories, while the light strategy of the T2 treatment can improve the nutritional quality of the Pak choi, which is more suitable for the production of high-end functional leafy vegetables. The appropriate supplemental lighting strategy should be developed by comprehensively considering the yield and quality of Pak choi. Therefore, further research is needed to determine a more efficient and low-cost dynamic lighting strategy for the industrialized production of Pak choi in plant factory.

Author Contributions: Conceptualization, methodology, validation, formal analysis, data curation, writing-original draft, X.W.(Xiangyu Wang); methodology, writing-review and editing, J.J.; methodology, Validation, S.Z.(Shijun Zhu) M.Z.(Minggui Zhang), and Y.H.(Youzhi Hu); formal analysis, X.Y.(Xiaolong Yang); visualization, J.S.(Jiali Song); conceptualization, methodology, resources, supervision, project administration, funding acquisition, H.L.(Houcheng Liu) All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Key Research and Development of China (2021YFD2000701).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Acknowledgments: We thank the anonymous reviewers for their helpful comments, which significantly improved the manuscript.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

The following abbreviations are used in this manuscript:

PFALs	plant factories with artificial lighting
DPA	day after transplanting
R: W	red-to-white light ratio
LEDs	Light-Emitting Diodes
DFT	deep-flow technique
PPFD	Photosynthetic Photon Flux Density
PH	potential of hydrogen
R: B	red-to-blue light ratio
DPPH	1,1-diphenyl-2-picrylhydrazyl
FRAP	ferric reducing antioxidant power

References

1. Kim M J, Moon Y, Tou J C, et al. Nutritional value, bioactive compounds and health benefits of lettuce (Lactuca sativa L.) [J]. Journal of Food Composition and Analysis, 2016, 49: 19-34.
2. Medina-Lozano I, Bertolín J R, Díaz A. Nutritional value of commercial and traditional lettuce (Lactuca sativa L.) and wild relatives: Vitamin C and anthocyanin content[J]. Food Chemistry, 2021, 359: 129864.
3. Fasciolo B, Van Brenk J, Verdonk J C, et al. Quantifying the Impact of Light on Ascorbic Acid Content in Lettuce: A Model Proposal[J]. Sustainability, 2024, 16(17): 7470.
4. Dias J S. Nutritional Quality and Health Benefits of Vegetables: A Review[J]. Food and Nutrition Sciences, 2012, 03(10): 1354-1374.
5. Hasan Md M, Bashir T, Ghosh R, et al. An Overview of LEDs' Effects on the Production of Bioactive Compounds and Crop Quality[J]. Molecules, 2017, 22(9): 1420.

 doi:10.20944/preprints202603.2253.v1

6. Shafiq I, Hussain S, Raza M A, et al. Crop photosynthetic response to light quality and light intensity[J]. Journal of Integrative Agriculture, 2021, 20(1): 4-23.
7. Naznin M T, Lefsrud M, Gravel V, et al. Blue Light added with Red LEDs Enhance Growth Characteristics, Pigments Content, and Antioxidant Capacity in Lettuce, Spinach, Kale, Basil, and Sweet Pepper in a Controlled Environment[J]. Plants, 2019, 8(4): 93.
8. Anum H, Cheng R feng, Tong Y xin. Improving plant growth, anthocyanin production and oxidative status of red lettuce (Lactuca sativa cv. Lolla Rossa) by optimizing red to blue light ratio with a constant green light fraction in a plant factory[J]. Scientia Horticulturae, 2024, 338: 113832.
9. Luo S, Zou J, Shi M, et al. Effects of red-blue light spectrum on growth, yield, and photo-synthetic efficiency of lettuce in a uniformly illumination environment[J]. Plant, Soil and Environment, 2024, 70(5): 305-316.
10. 10. Vaštakaitė-Kairienė V, Brazaitytė A, Miliauskienė J, et al. Red to Blue Light Ratio and Iron Nutrition Influence Growth, Metabolic Response, and Mineral Nutrients of Spinach Grown Indoors[J]. Sustainability, 2022, 14(19): 12564.
11. Trouwborst G, Hogewoning S W, Van Kooten O, et al. Plasticity of photosynthesis after the 'red light syndrome' in cucumber[J]. Environmental and Experimental Botany, 2016, 121: 75-82.
12. Son K H, Oh M M. Growth, photosynthetic and antioxidant parameters of two lettuce cultivars as affected by red, green, and blue light-emitting diodes[J]. Horticulture, Environment, and Biotechnology, 2015, 56(5): 639-653.
13. Zhang T, Shi Y, Piao F, et al. Effects of different LED sources on the growth and nitrogen metabolism of lettuce[J]. Plant Cell, Tissue and Organ Culture (PCTOC), 2018, 134(2): 231-240.
14. Li Y, Zheng Y, Zheng D, et al. Effects of Supplementary Blue and UV-A LED Lights on Morphology and Phytochemicals of Brassicaceae Baby-Leaves[J]. Molecules, 2020, 25(23): 5678.
15. Kong Y, Nemali K. Blue and Far-Red Light Affect Area and Number of Individual Leaves to Influence Vegetative Growth and Pigment Synthesis in Lettuce[J]. Frontiers in Plant Science, 2021, 12: 667407.
16. Bantis F, Smirnakou S, Ouzounis T, et al. Current status and recent achievements in the field of horticulture with the use of light-emitting diodes (LEDs)[J]. Scientia Horticulturae, 2018, 235: 437-451.
17. Spalholz H, Perkins-Veazie P, Hernández R. Impact of sun-simulated white light and varied blue:red spectrums on the growth, morphology, development, and phytochemical content of green- and red-leaf lettuce at different growth stages[J]. Scientia Horticulturae, 2020, 264: 109195.
18. Van Brenk J B, Hendriks L, Rei A, et al. Dynamic Application of High and Low Red:Blue Ratios During Lettuce Development Shifts Growth and Metabolite Allocation[J]. Physiologia Plantarum, 2025, 177(4): e70456.
19. Jiang H, Li X, Tian J, et al. Pre-Harvest Supplemental Blue Light Enhanced Antioxidant Activity of Flower Stalk in Chinese Kale during Storage[J]. Plants, 2021, 10(6): 1177.
20. Edelenbos M, Christensen L P, Grevsen K. HPLC Determination of Chlorophyll and Carotenoid Pigments in Processed Green Pea Cultivars (Pisum sativum L.)[J]. Journal of Agricultural and Food Chemistry, 2001, 49(10): 4768-4774.
21. Candiano G, Bruschi M, Musante L, et al. Blue silver: A very sensitive colloidal Coomassie G-250 staining for proteome analysis[J]. ELECTROPHORESIS, 2004, 25(9): 1327-1333.
22. Kohyama K, Nishinari K. Effect of soluble sugars on gelatinization and retrogradation of sweet potato starch[J]. Journal of Agricultural and Food Chemistry, 1991, 39(8): 1406-1410.
23. Chen G, Mo L, Li S, et al. Separation and determination of reduced vitamin C in polymerized hemoglobin-based oxygen carriers of the human placenta[J]. Artificial Cells, Nanomedicine, and Biotechnology, 2015, 43(3): 152-156.
24. Cataldo D A, Maroon M, Schrader L E, et al. Rapid colorimetric determination of nitrate in plant tissue by nitration of salicylic acid[J]. Communications in Soil Science and Plant Analysis, 1975, 6(1): 71-80.
25. Rahman Md J, Costa De Camargo A, Shahidi F. Phenolic profiles and antioxidant activity of defatted camelina and sophia seeds[J]. Food Chemistry, 2018, 240: 917-925.
26. Xie Y, Zheng Y, Dai X, et al. Seasonal dynamics of total flavonoid contents and antioxidant activity of Dryopteris erythrosora[J]. Food Chemistry, 2015, 186: 113-118.

 doi:10.20944/preprints202603.2253.v1

27. Musa K H, Abdullah A, Kuswandi B, et al. A novel high throughput method based on the DPPH dry reagent array for determination of antioxidant activity[J]. Food Chemistry, 2013, 141(4): 4102-4106.
28. Benzie I F F, Strain J J. The Ferric Reducing Ability of Plasma (FRAP) as a Measure of "Antioxidant Power": The FRAP Assay[J]. Analytical Biochemistry, 1996, 239(1): 70-76.
29. Le T M, Sago Y, Ibaraki Y, et al. Effect of LED Irradiation with Different Red-to-Blue Light Ratios on Growth and Functional Compound Accumulations in Spinach (Spinacia oleracea L.) Accessions and Wild Relatives[J]. Plants, 2025, 14(5): 700.
30. Van Brenk J B, Vanderwolk K R, Seo S, et al. Blue Light Sonata: Dynamic variation of red:blue ratio during the photoperiod differentially affects leaf photosynthesis, pigments, and growth in lettuce[M]. Plant Biology, 2025.
31. Wang J, Lu W, Tong Y, et al. Leaf Morphology, Photosynthetic Performance, Chlorophyll Fluorescence, Stomatal Development of Lettuce (Lactuca sativa L.) Exposed to Different Ratios of Red Light to Blue Light[J]. Frontiers in Plant Science, 2016, 7.
32. Hooks T, Sun L, Kong Y, et al. Short-Term Pre-Harvest Supplemental Lighting with Different Light Emitting Diodes Improves Greenhouse Lettuce Quality[J]. Horticulturae, 2022, 8(5): 435.
33. Jin W, Ji Y, Larsen D H, et al. Gradually increasing light intensity during the growth period increases dry weight production compared to constant or gradually decreasing light intensity in lettuce[J]. Scientia Horticulturae, 2023, 311: 111807.
34. Terashima I, Fujita T, Inoue T, et al. Green Light Drives Leaf Photosynthesis More Efficiently than Red Light in Strong White Light: Revisiting the Enigmatic Question of Why Leaves are Green[J]. Plant and Cell Physiology, 2009, 50(4): 684-697.
35. Bantis F, Simos N, Koukounaras A. Plant Factory in a Restaurant: Light Quality Effects on the Development, Physiology, and Quality of Three Baby-Leaf Vegetables[J]. Plants, 2025, 14(2): 153.
36. Fan X, Zang J, Xu Z, et al. Effects of different light quality on growth, chlorophyll concentration and chlorophyll biosynthesis precursors of non-heading Chinese cabbage (Brassica campestris L.)[J]. Acta Physiologiae Plantarum, 2013, 35(9): 2721-2726.
37. Zhang R xing, Zhang N nan, Wang Y xiu, et al. Blue light induces leaf color change by modulating carotenoid metabolites in orange-head Chinese cabbage (Brassica rapa L. ssp. pekinensis)[J]. Journal of Integrative Agriculture, 2023, 22(11): 3296-3311.
38. Frede K, Baldermann S. Accumulation of carotenoids in Brassica rapa ssp. chinensis by a high proportion of blue in the light spectrum[J]. Photochemical & Photobiological Sciences, 2022, 21(11): 1947-1959.
39. Chen X li, Li Y li, Wang L chun, et al. Red and blue wavelengths affect the morphology, energy use efficiency and nutritional content of lettuce (Lactuca sativa L.)[J]. Scientific Reports, 2021, 11(1): 8374.
40. Jiang H, Li X, Tian J, et al. Pre-Harvest Supplemental Blue Light Enhanced Antioxidant Activity of Flower Stalk in Chinese Kale during Storage[J]. Plants, 2021, 10(6): 1177.
41. Courbier S, Grevink S, Sluijs E, et al. Far-red light promotes Botrytis cinerea disease development in tomato leaves via jasmonate-dependent modulation of soluble sugars[J]. Plant, Cell & Environment, 2020, 43(11): 2769-2781.
42. Li Y, Xin G, Wei M, et al. Carbohydrate accumulation and sucrose metabolism responses in tomato seedling leaves when subjected to different light qualities[J]. Scientia Horticulturae, 2017, 225: 490-497.
43. Luo L, Zhang G, Liang W, et al. Effects of LED Light Quality on Broccoli Microgreens Plant Growth and Nutrient Accumulation[J]. Journal of Plant Growth Regulation, 2024, 43(10): 3481-3489.
44. Steindal A L H, Johansen T J, Bengtsson G B, et al. Impact of pre-harvest light spectral properties on health- and sensory-related compounds in broccoli florets[J]. Journal of the Science of Food and Agriculture, 2016, 96(6): 1974-1981.
45. Wanlai Z, Wenke L, Qichang Y. REDUCING NITRATE CONTENT IN LETTUCE BY PRE-HARVEST CONTINUOUS LIGHT DELIVERED BY RED AND BLUE LIGHT-EMITTING DIODES[J]. Journal of Plant Nutrition, 2013, 36(3): 481-490.
46. Urban L, Alphonsout L. Girdling decreases photosynthetic electron fluxes and induces sustained photoprotection in mango leaves[J]. Tree Physiology, 2007, 27(3): 345-352.

 doi:10.20944/preprints202603.2253.v1

47. Zhang T, Shi Y, Piao F, et al. Effects of different LED sources on the growth and nitrogen metabolism of lettuce[J]. Plant Cell, Tissue and Organ Culture (PCTOC), 2018, 134(2): 231-240.
48. Anjana S U, Iqbal M. Nitrate accumulation in plants, factors affecting the process, and human health implications. A review[J]. Agronomy for Sustainable Development, 2007, 27(1): 45-57.
49. Bian Z H, Cheng R F, Yang Q C, et al. Continuous Light from Red, Blue, and Green Light-emitting Diodes Reduces Nitrate Content and Enhances Phytochemical Concentrations and Antioxidant Capacity in Lettuce[J]. Journal of the American Society for Horticultural Science, 2016, 141(2): 186-195.
50. Gulyás Z, Szalai G, Utasi L, et al. Pre-harvest Light Modifications Improve Yield Quality by Modifying Ascorbate and Nitrate Metabolism in Spinach Leaves[J]. Journal of Plant Growth Regulation, 2025.
51. Padayatty S, Levine M. Vitamin C: the known and the unknown and Goldilocks[J]. Oral Diseases, 2016, 22(6): 463-493.
52. Kang C H, Yoon E K, Muthusamy M, et al. Blue LED light irradiation enhances L-ascorbic acid content while reducing reactive oxygen species accumulation in Chinese cabbage seedlings[J]. Scientia Horticulturae, 2020, 261: 108924.
53. Li Y, Wu L, Jiang H, et al. Supplementary Far-Red and Blue Lights Influence the Biomass and Phytochemical Profiles of Two Lettuce Cultivars in Plant Factory[J]. Molecules, 2021, 26(23): 7405.
54. Anum H, Wang Y, Li Y, et al. Physiological and nutritional responses of two pakchoi (Brassica chinensis) cultivars to different red-blue light ratios in controlled environment[J]. Frontiers in Sustainable Food Systems, 2025, 9: 1561118.
55. Šamec D, Karalija E, Šola I, et al. The Role of Polyphenols in Abiotic Stress Response: The Influence of Molecular Structure[J]. Plants, 2021, 10(1): 118.
56. Podsędek A, Frąszczak B, Sosnowska D, et al. LED Light Quality Affected Bioactive Compounds, Antioxidant Potential, and Nutritional Value of Red and White Cabbage Microgreens[J]. Applied Sciences, 2023, 13(9): 5435.
57. Li Y, Zheng Y, Zheng D, et al. Effects of Supplementary Blue and UV-A LED Lights on Morphology and Phytochemicals of Brassicaceae Baby-Leaves[J]. Molecules, 2020, 25(23): 5678.
58. He X, He R, Li Y, et al. Effect of Ratios of Red and White Light on the Growth and Quality of Pak Choi[J]. Agronomy, 2022, 12(10): 2322.
59. Fu X, He Y, Li L, et al. Overexpression of blue light receptor AaCRY1 improves artemisinin content in Artemisia annua L.[J]. Biotechnology and Applied Biochemistry, 2021, 68(2): 338-344.