



Influence of LED-Spectra on Yield and Phytochemical Content of Chinese Kale (*Brassica oleracea* var. *alboglabra*) in a Hydroponic Vertical Farming System [†]

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Abstract

Rapid urbanization and population growth demand sustainable food systems. This study investigated hydroponic vertical farming with LED lighting for Chinese kale (*Brassica oleracea* var. *alboglabra*), comparing white LEDs (WL), 20% red + 80% blue (20% RL: 80% BL), and 80% red + 20% blue (80% RL:20% BL). Plants grown under control conditions were assessed at weeks 2, 4, and 6. The 80% RL:20% BL treatment enhanced fresh weight, leaf area, root length, and biomass, while 20% RL:80% BL maximized chlorophyll, anthocyanin, and phenolics. Leaf number and quantum yield remained similar, though stress was evident. The findings of this research highlight red-dominant light for growth and blue-dominant light for phytochemical enrichment.

Keywords: urban agriculture; controlled environment agriculture; LED-light ratios; leafy vegetables; phytonutrient; sustainability



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1. Introduction

Global population growth is projected to intensify substantially over the next five decades, reaching an estimated 9 billion by 2050 and escalating further to 11.2 billion by 2100 [1,2]. This demographic expansion is expected to place unprecedented pressure on global food systems, exacerbating challenges related to food security and environmental sustainability. Concurrently, more than 70% of arable land is already under agricultural use, a trend compounded by rapid rural-to-urban migration, urban infrastructure development, and progressive soil degradation [3]. These constraints underscore the urgent need for innovative agricultural strategies, among which hydroponic vertical farming systems (HVFS) have emerged as a promising solution for sustainable food production in densely populated urban environments [4].

Vertical farming represents a contemporary form of urban agriculture in which crop production is extended along the vertical axis, enabling cultivation in spatially constrained settings [5]. Hydroponic systems, which rely on nutrient-enriched aqueous media rather than soil, further enhance crop productivity by optimizing nutrient delivery and reducing environmental variability. The integration of hydroponics within vertical farming offers multiple advantages, including reduced water consumption, year-round production, minimal land requirements, lower occupational risks, reduced transportation demands, and

diminished exposure to soil-borne pathogens [6]. Notably, HVFS can achieve substantially higher yields per unit area compared to conventional agriculture, thereby improving land-use efficiency [7].

Advancements in controlled environment agriculture (CEA) have further strengthened the potential of HVFS through the incorporation of artificial light-emitting diode (LED) technologies. LEDs provide precise spectral control, high photosynthetically active radiation (PAR) output, low radiant heat emission, and superior energy efficiency, making them an advantageous alternative to traditional fluorescent (FL) and high-intensity discharge (HID) lamps [8]. Within the visible spectrum, wavelengths between 400 and 700 nm constitute the PAR range essential for photosynthesis. Red (600–700 nm) and blue (400–500 nm) wavelengths, in particular, exhibit high quantum efficiency, and disruptions in these spectral regions can significantly reduce photosynthetic performance [4]. These wavelengths drive the excitation of key photosynthetic pigments, including chlorophylls, carotenoids, and xanthophylls, thereby sustaining plant metabolic activity [9].

According to the McCree action spectrum, chlorophyll exhibits maximal absorption peaks near 660 nm (red) and 450 nm (blue), reflecting the critical role of these wavelengths in photosynthetic efficiency [4]. Red LED light has been associated with enhanced biomass accumulation, stem elongation, and fruit development, whereas blue light promotes photosynthetic activity, phytochemical synthesis, and improved disease resistance [9]. The photosynthetic photon flux density (PPFD) of red and blue LEDs aligns closely with the absorption spectra of major plant photoreceptors, enabling modulation of photomorphogenic responses and other light-regulated developmental processes [10]. Six major classes of photoreceptors—phytochromes, rhodopsins, cryptochromes, phototropins, xanthopsins, and BLUF proteins mediate these responses.

Crop selection is a critical determinant of vertical farming success, particularly for high-value microgreens and herbs that align with contemporary consumer preferences [11]. Chinese kale (*Brassica oleracea* var. *alboglabra*), a widely cultivated Brassicaceae vegetable in South Asia and Southern China, represents a suitable candidate for HVFS [12]. Brassicaceous crops are valued for their rich phytochemical profiles, including glucosinolates, phenolics, carotenoids, vitamins, and dietary fiber, which contribute to their documented health benefits, such as reduced risk of cardiovascular disease, diabetes, and cancer [13]. Chinese kale, recognized by the American Cancer Society for its anticancer potential, accounted for 71 million metric tons of global production in 2019, with an anticipated annual growth rate of 2.1% from 2020 to 2025 [14]. Its adaptability to LED lighting and hydroponic cultivation further reinforces its suitability for vertical farming.

Previous studies have demonstrated that LED-based cultivation enhances physiological performance, photosynthetic efficiency, secondary metabolite accumulation, and overall crop quality in kale and related species [15]. Combinations of red and blue light often outperform monochromatic treatments, yielding greater biomass and improved phytochemical profiles [8]. For instance, reference [16] reported increased leaf fresh weight, plant height, and phytochemical accumulation in Chinese kale and *Ocimum basilicum* L. under mixed red–blue LED regimes. Similar trends have been observed in Chinese kale, with red light promoting shoot biomass and blue light enhancing phenolic content [17]. However, optimal spectral ratios appear to be species- and cultivar-specific, as demonstrated by differential phenolic responses in basil under red versus blue light [8]. These findings highlight the need for further research to determine species-appropriate LED spectral compositions.

The present study aims to investigate the effects of LED light treatments and hydroponic vertical farming systems on the growth performance and phytochemical accumulation of Chinese kale. The outcomes are expected to contribute to a deeper understanding of

crop responses within controlled environment agriculture and to inform the optimization of HVFS for sustainable urban food production.

2. Materials and Methods

2.1. Experimental Site and Materials

The experiment was conducted from February to March 2022 in an indoor hydroponic vertical farming system located at Block C, Faculty of Science and Engineering, University of Nottingham Malaysia. Chinese kale seedlings, hydroponic fertilizers, and instruments (pH meter and EC meter; Vivosun, Ontario, CA, USA) were obtained from Tropicana Farm Damansara, Farm Factory, and the bioscience laboratory.

2.2. Lighting System and Experimental Design

To evaluate LED light effects, three treatments were applied: (i) white light (WL; 400–700 nm) as the control, (ii) 20% red + 80% blue (20% RL:80% BL), and (iii) 80% red + 20% blue (80% RL:20% BL). Irradiance was quantified as photosynthetic photon flux density (PPFD) (Table 1), and emission spectra of all treatments are shown in Figure 1. The three LED treatments were assigned across the layers of the vertical grow stack, with light treatment considered a fixed factor. Within each layer, plant positions were randomized. Eighteen uniform plants were arranged per growing layer. At weeks 2, 4, and 6, three plants per light treatment were randomly selected for parameter measurements.

Table 1. The spectra specifications for all three LED treatments.

Measurement	Treatment		
Photon Flux ($\mu\text{mol m}^{-2}\text{s}^{-2}$)	WL	20% RL:80% BL	80% RL:20% BL
Average PPFD (400–700 nm)	49.83	47.44	57.41
Blue (400–500 nm)	11.24 (22%)	42.10 (85%)	9.08 (12%)
Green (500–600 nm)	10.99 (22%)	0.00 (0%)	0.00 (0%)
Red (600–700 nm)	27.81 (56%)	5.07 (11%)	48.03 (88%)

RL = red light, BL = blue light, WL = white light. PPFD = photosynthetic photon flux density.

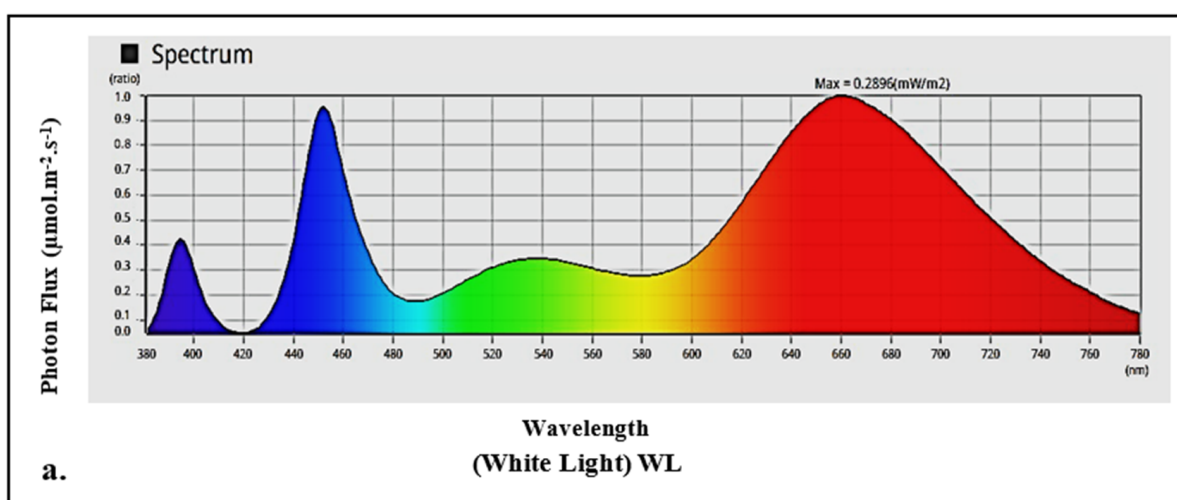


Figure 1. Cont.

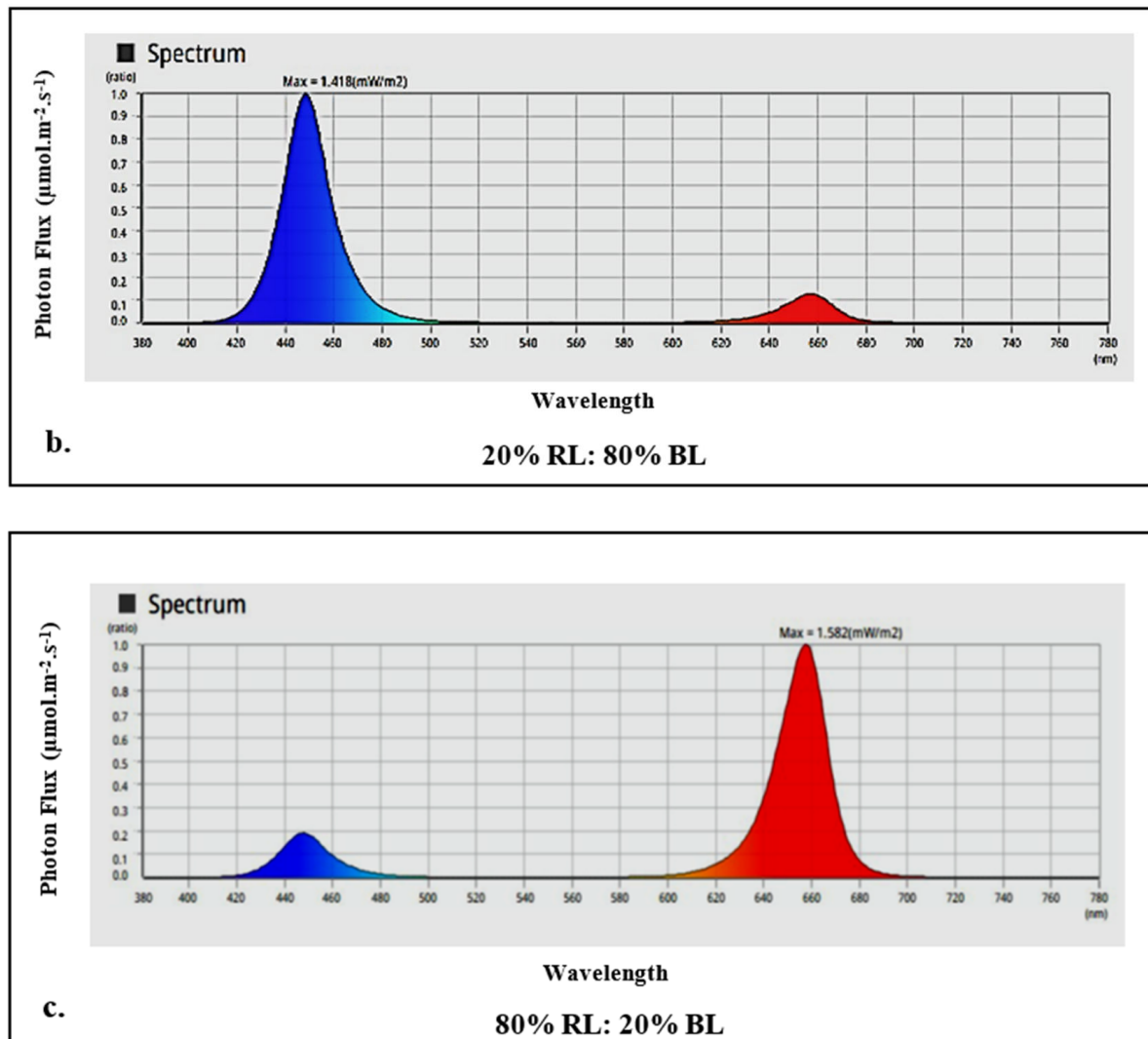


Figure 1. The spectra distribution for all three LED treatments. RL = red light, BL = blue light, WL = white light.

2.3. Nursery and Hydroponic Vertical Farming System Management

2.3.1. Nursery Management

Seeds of Chinese kale were sown into 65 pieces of urethane foam, with 2–3 seeds per piece, and germinated in plastic trays (15 cm × 20 cm × 8 cm) containing tap water under ambient conditions. Trays were watered daily to prevent desiccation. Seedlings were thinned at 7 days after sowing (DAS) to retain one healthy seedling per foam piece. On 12 DAS, 54 seedlings bearing one to two pairs of true leaves were transplanted into the vertical grow stack.

2.3.2. Hydroponic System Setup and Operation

A semi-closed nutrient film technique (NFT) hydroponic system integrated with the vertical farming structure was installed by the supplier at the University of Nottingham Malaysia. The hydroponic vertical farming system comprised stacked polyvinyl chloride (PVC) pipes/columns, pumps, and a reservoir tank at the lowest layer. Each layer was controlled by an automated timer connected to both the respective pump and the LED light (WL, 80% RL:20% BL, 20% RL:80% BL). A 12 h photoperiod (06:00–18:00) was maintained for all layers.

Hydroponic stock solutions were prepared by adding hydroponic fertilizer with an N–P–K formulation (fertilizer A) and calcium nitrate (fertilizer B) into separate high-density polyethylene (HDPE) jerrycans (25 L each). Twenty liters of tap water (electrical conductivity, $EC = 0.26 \text{ dS}\cdot\text{m}^{-1}$) were added to each jerrycan, and the solutions were thoroughly mixed. The final EC values of the stock solutions were $5.45 \text{ dS}\cdot\text{m}^{-1}$ (fertilizer A) and $5.23 \text{ dS}\cdot\text{m}^{-1}$ (fertilizer B).

Prior to transplantation, 50 mL of fertilizer A ($EC = 5.45 \text{ dS}\cdot\text{m}^{-1}$) and 50 mL of fertilizer B ($EC = 5.23 \text{ dS}\cdot\text{m}^{-1}$) were added to the reservoir tank together with 70 L of tap water ($EC = 0.26 \text{ dS}\cdot\text{m}^{-1}$). Seedlings ($n = 54$) embedded in their foam supports were placed into net pots ($56 \text{ mm} \times 39 \text{ mm} \times 58 \text{ mm}$) and maintained at room temperature. Nutrient solution EC in the reservoir was monitored and adjusted weekly to target values of $2.0 \pm 0.1 \text{ dS}\cdot\text{m}^{-1}$ (week 2), $2.5 \pm 0.1 \text{ dS}\cdot\text{m}^{-1}$ (week 4), and $3.0 \pm 0.1 \text{ dS}\cdot\text{m}^{-1}$ (week 6); measured EC values were 2.12, 2.63, and $2.89 \text{ dS}\cdot\text{m}^{-1}$, respectively. The solution pH was maintained between 5.5 and 6.5 by the addition of sodium hydroxide (NaOH) as required. At weeks 2, 4, and 6, three plant samples were randomly selected from each light treatment for subsequent measurements.

2.4. Parameter Measurements

2.4.1. Plant Fresh Weight, Dry Weight, and Leaf Area

At weeks 2, 4, and 6 (corresponding to 26, 40, and 54 DAS), shoots from randomly selected plants were weighed for fresh mass using an electronic scale (GF-61000, A&D Ltd., Tokyo, Japan). Samples were then oven-dried at 40°C for one week to determine dry mass. Total leaf area was measured by excising leaves at the petiole and quantifying area using a leaf area meter (LI-3100, LI-COR Inc., Lincoln, NE, USA) in the CEPB room.

2.4.2. Quantum Yield

Healthy leaves from each treatment were dark-adapted for 30 min using aluminum foil at weeks 2, 4, and 6 (26, 40, and 54 DAS). The maximum quantum yield of PSII (F_v/F_m) was recorded using a modulated fluorometer (FluorPen FP 100, Photon Systems Instruments, Drásov, Czech Republic).

2.4.3. Anthocyanin and Chlorophyll Content

Anthocyanin content was measured non-destructively on intact leaves using a portable anthocyanin meter (ACM-200, Opti-Sciences Inc., Hudson, NH, USA). Three positions per leaf were measured, and the mean value was calculated for each sample. Chlorophyll content was determined using a handheld chlorophyll meter (SPAD-502, Konica Minolta, Tokyo, Japan). The sensor was clamped on leaves at comparable canopy height, and SPAD values were recorded.

2.4.4. Total Phenolic Content

For extraction, 0.2 g of dried Chinese kale leaves were ground (with liquid nitrogen to aid pulverization) and homogenized with 2 mL of 30% ethanol (v/v). The homogenate was diluted with water to a total volume of 6 mL and incubated in the dark at 80°C for 1 h. Samples were centrifuged (Eppendorf 5810-R, Hamburg, Germany) at 10,000 rpm ($\approx 9400 \times g$) and 20°C for 10 min. Supernatants were stored at 5°C in a microbial cold room until analysis.

Total phenolic content (TPC) was quantified by the Folin–Ciocalteu colorimetric assay following modifications of Qian et al. [18]. Briefly, 50 μL of extract was mixed with 50 μL of 0.2 M Folin–Ciocalteu reagent in an Eppendorf tube. After 3 min at room temperature, 100 μL of 7.5% (w/v) aqueous sodium bicarbonate (NaHCO_3) was added, and the mixture was incubated for 1 h at room temperature. Aliquots (200 μL per sample) were transferred to

a flat-bottom 96-well microplate and read at 760 nm using a microplate reader (VersaMax™, Molecular Devices, San Jose, CA, USA) with distilled water as the blank. Results were expressed as milligrams of gallic acid equivalents per gram of extract ($\text{mg GAE} \cdot \text{g}^{-1}$) based on a gallic acid standard curve.

2.5. Statistical Analysis

All measurements were performed in triplicate. Data were analyzed using one-way analysis of variance (ANOVA) in IBM SPSS Statistics 28.0 (Chicago, IL, USA). Mean separation was conducted using Tukey's HSD test at $p < 0.05$. Pearson correlation (two-tailed) was used to assess relationships between measured parameters

3. Results and Discussion

3.1. Fresh Weight and Dry Weight

According to our results, in weeks 4 and 6, the growth characteristics of Chinese kale in terms of fresh weight (FW) and dry weight (DW) were significantly ($p < 0.05$) affected by the supplementation of different LED light treatments (Table 2). Throughout this study, the shoot FW and DW of Chinese kale increased with an increasing percentage of red light. The FW and DW under 80%RL: 20%BL Chinese kale was higher than that of 20% RL: 80% BL and WL. Where the FW and DW of 80% RL: 20% BL at week 6 was ≈ 1.5 -time higher than the control WL. Notably, the FW of Chinese kale under 20% RL: 80% BL at weeks 2 and 4 were similar to WL, but it was heavier than WL at week 6.

Table 2. Fresh weight and dry weight of Chinese kale under WL, 20% RL: 80% BL, and 80% RL: 20% BL treatment at weeks 2, 4, and 6 ($n = 3$).

Treatment	Fresh Weight (g)			Dry Weight (g)		
	Week 2	Week 4	Week 6	Week 2	Week 4	Week 6
WL	3.42 ^a	6.78 ^b	9.02 ^b	0.31 ^a	0.53 ^c	0.95 ^b
20% RL: 80% BL	3.71 ^a	7.22 ^b	11.31 ^b	0.34 ^a	0.72 ^b	1.19 ^b
80% RL: 20% BL	4.10 ^a	10.24 ^a	14.86 ^a	0.36 ^a	0.99 ^a	1.54 ^a
SEM	0.34	0.37	0.63	0.04	0.04	0.07
<i>p</i> -value	0.429	0.010	0.002	0.733	<0.01	0.003

Means within each column followed by same letters are not significantly different using Tukey's test at $p < 0.05$ level.

It is generally acknowledged that FW can be a useful parameter in evaluating crop yield results and DW can provide an accurate measurement of biomass that eliminates water content fluctuation [19]. LED light with different color ratio possesses a positive relationship with Chinese kale [20]. Such that in our study, 80%RL: 20%BL has shown to be the most prominent light treatment for FW and DW accumulation in Chinese kale. These results were aligned with various crops such as pak choi (*Brassica rapa* subsp. *Chinensis*) under 77% RL: 23% BL with the highest FW and DW, followed by 73% RL: 27% BL [21] and herb plant such as coriander under mix ratio of red–blue light (RB) (19:1) were shown to have 1.3- and 1.4-times higher FW and DW respectively compared to those using 100% red LED [22].

This indicates that red light can be better absorbed by chlorophylls and promote photosynthesis than the other light wavelengths in the visible spectrum. In this respect, red light matches the absorbance area of chlorophyll present in chloroplasts and can be perceived by phytochrome photoreceptors for growth development and biomass accumulation in plants. Activated phytochrome is shown to induce plastid development, stem elongation, and gene expression in the nucleus [23]. Enhancing red light can also stimulate photophosphorylation in guard cells to produce the energy required to open up the stomata and

induce carbon dioxide (CO₂) absorption into the intercellular space, eventually improving the photosynthetic ability that directly led to the promotion of biomass [23]. Blue light (BL) enhances ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) activity and modifies spongy parenchyma and palisade mesophyll organization, thereby improving photosynthetic efficiency [24]. Hence, this suggests that Chinese kale grown under both 20% RL: 80% BL and 80% RL: 20% BL with higher FW and DW can be due to the enhancement in photosynthesis capacity or efficiency. On the other hand, the low FW and DW of Chinese kale grown under WL might be due to dilution, as white light consists of low-efficiency wavelengths and reduced red–blue light intensities that can affect the net photosynthesis [25].

However, it is also of interest that lettuce has a higher shoot–root DW and FW under red–blue–white (RBW) LED light treatment compared to RB light [26] and a slight increase in plant biomass under 90%RL: 10%GL [27]. These results probably imply that specific light apart from blue and red can be quite effective in enhancing plant biomass and growth, where further analysis is required to explore these findings.

3.2. Leaf Area

Figure 2 shows the impact of LED light on the leaf area per plant. Leaf area is an important indicator for plant productivity; it determines the total amount of light that can be perceived by the plant [28]. Current findings showed that red-rich light spectra have a positive impact on regulating plants' LA by maximizing the photosynthetic rate and leaf expansion stimulation [29,30]. RL matches the assimilation peak of phytochrome photoreceptor and chlorophylls, causing a greater improvement in efficiency [30]. Whereas BL wavelength can cause the overstimulation of cryptochrome photoreceptor and contribute to reducing LA, which would decrease the light capture ability and growth quality [29,31]. Similar results can be seen in wheat, lettuce, and soybean with decreased LA over a 75% fraction of BL [32,33]. Moreover, rapid increased LA under WL can be deduced as shade avoidance syndrome, it can be explained by either a low R: FR ratio or green light that elucidates phytochrome for shade avoidance response and allows the expansion of leaves at the uppermost layer (Figure 2) [31]. However, several findings also mentioned that cucumber seedlings and lettuce plants under monochromatic RB light and WL had 56–87% more LA than plants in 80%RL: 20%BL and 20% RL: 80% BL, thus indicating that different light conditions might affect plants differently, which would require further study to determine it [31,34].

3.3. Quantum Yield

There was no significant chlorophyll fluorescence (Fv/Fm) difference between the three LED light treatments ($p > 0.05$) (Table 3). The highest and lowest quantum yield (QY) efficiency of photosystem II (ΦPSII) were observed under WL and 80% RL: 20% BL, respectively, during week 6.

Table 3. Effect of WL, 20% RL: 80% BL, and 80% RL: 20% BL treatment on Chinese kale quantum yield ($n = 3$).

Treatment	Quantum Yield (Fv/Fm)		
	Week 2	Week 4	Week 6
WL	0.69 ^a	0.71 ^a	0.71 ^a
20% RL: 80% BL	0.65 ^a	0.68 ^a	0.70 ^a

Table 3. Cont.

Treatment	Quantum Yield (Fv/Fm)		
	Week 2	Week 4	Week 6
80% RL: 20% BL	0.65 ^a	0.65 ^a	0.69 ^a
SEM	0.02	0.02	0.02
<i>p</i> -value	0.268	0.195	0.754

Means within each column followed by same letters are not significantly different using Tukey's test at $p < 0.05$ level.

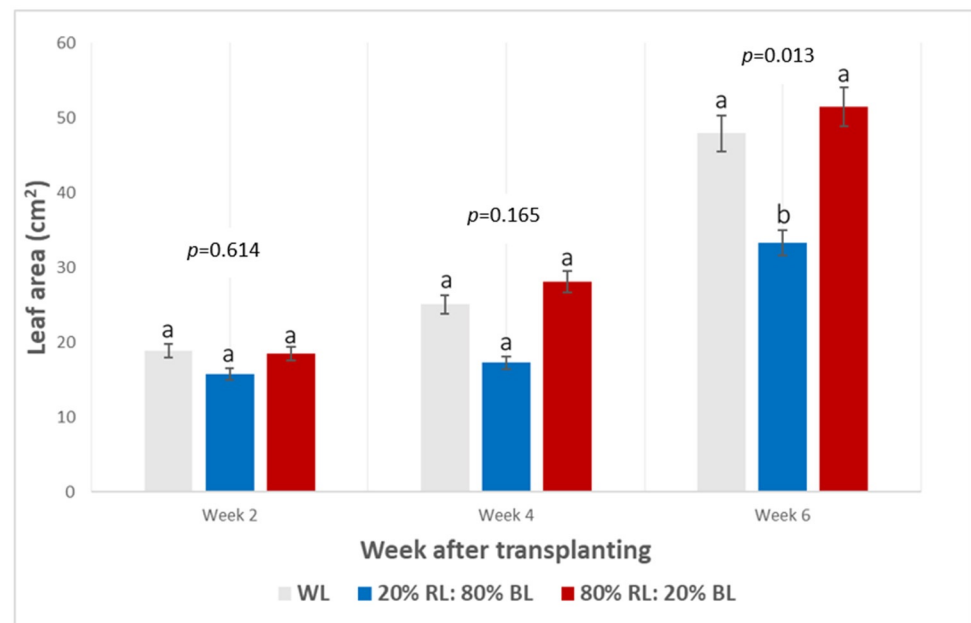


Figure 2. The effect of supplementary LEDs on Chinese kale leaf area at weeks 2, 4, and 6. Within each sampling week, bars with the different letters are significantly different using Tukey test at $p < 0.05$ level. Error bars indicate SEM value. RL = red light, BL = blue light, WL = white light ($n = 3$).

Chlorophyll fluorescence (Fv/Fm) measures the maximal photochemical and operating efficiency of photosystem II [1,23]. Which is a stress indicator that determines whether a plant is in a distress condition [23]. According to Maxwell and Johnson [35], most of the healthy plant species will have an optimal value around 0.83, and values lower than this can be seen when exposed to stress. This suggested that all three LED treatments used in this study disturb the photochemical process and photosynthetic capability of chlorophyll in PSII, and a common postulation of low QY is the malfunction of photosynthetic machinery [23,36]. It was known that under excess light treatment, PSII center can be subjected to photoinhibition when there is too much reduced electron present leading to a transient backlog in excitation energy with the stimulation of singlet oxygen that can cause substantial damage to the cellular components [36]. Another possibility of low QY is the decrease in efficiency of excitation capture in PSII, where photo-protective mechanisms in terms of non-photochemical quenching (NPQ) dissipate the excess excitation energy into heat [36,37]. Such dissipation can cause the over-reduction of excitation energy present in PSII, thus reducing the photosynthesis efficiency [36].

Through our study, it was discerned that the proportion of RL might have exerted pressure on the Chinese kale. This was supported by previous investigations [1,17,23,38,39], which showed that lettuce, sweet basil, and kale plants grown under RL and 80%RL: 20%BL had a lower QY compared to WL and 20%RL: 80%BL treatment, indicating that was stress was exerted on the photosynthetic machinery. However, some studies indicated that cucumber leaves under 70%RL: 30%BL can result in increased chlorophyll fluorescence

efficiency and QY [40,41]. This suggested that stress adaptation and acclimation for each plant might be different and vary between species. As suggested by Hogewoning et al. [38], the distance between LEDs light and the plants' pot column can increase slightly to prevent any stress exertion on the Chinese kale.

3.4. Chlorophyll Content

The light treatments affected Chlorophyll content (Chl) significantly at the early stage ($p < 0.05$) (Figure 3), and in this respect, a constant decline trend in Chl was evident from week 2 onward, with the highest value found in the 20%RL: 80%BL treatment. Interestingly, the Chl content of Chinese kale under WL treatment showed an upward surge from week 2 to 4, but reduced since week 4.

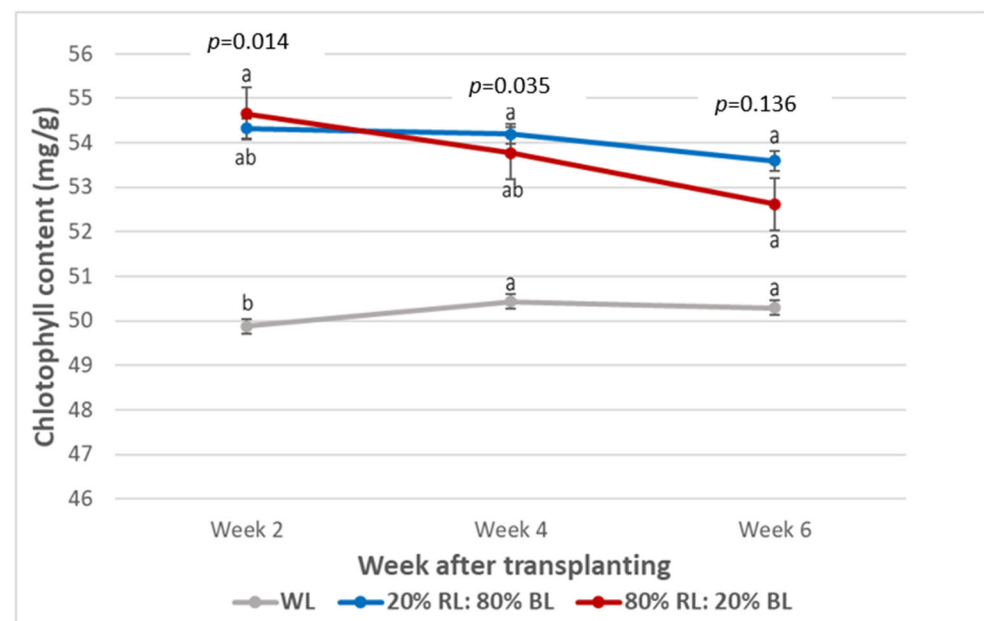


Figure 3. The effect of different LEDs ratios treatment on Chinese kale cChlorophyll content at weeks 2, 4, and 6. Within each sampling week, lines with the different letters are significantly different using Turkey test at $p < 0.05$. Error bars indicate SEM value. RL = red light, BL = blue light, WL = white light ($n = 3$).

Thus, inferring that BL is more effective in the induction of Chl biosynthesis [13,42]. Similar results were obtained from cucumber and lettuce, with the highest Chl content maintained under 25%RL; 75%BL and 41%RL; 59%BL, respectively [23,43,44]. In our study, the Chl of Chinese kale under the three light treatments showed a consistent drop; this might indicate that either the plants are using Chl more efficiently or already achieving their maximum growth stage at week 4 [26]. As reported, plants with reduced Chl content seem to use Chl more efficiently in controlling growth rate [26]. Furthermore, Chinese kale can reach its harvesting period around week 6 at 60 DAS, where accelerated senescence of mature leaves indicates the loss in protein and chlorophyll content as the ageing process [45]. Notably, Chl content under 20% RL: 80% BL has a slower degradation rate than the other light treatments. It can be deduced that a higher BL proportion can prolong the irradiation time and retard the degradation of Chl [46]. Some studies also indicated that tobacco (*Nicotiana tabacum* L.) and lettuce seedlings treated with monochromatic RL and 80% RL: 20% BL can have a higher Chl content, thus revealing that cultivar species can have different responses to RB light treatments [23,27,42].

3.5. Anthocyanin Content

In our study, the anthocyanin content of Chinese kale was significantly affected by the light treatments at weeks 4 and 6 ($p < 0.05$) (Figure 4). RB light showed a prominent accumulation of anthocyanin content, and particularly, 20%RL: 80%BL elicited the highest anthocyanin content, and WL had the lowest anthocyanin content.

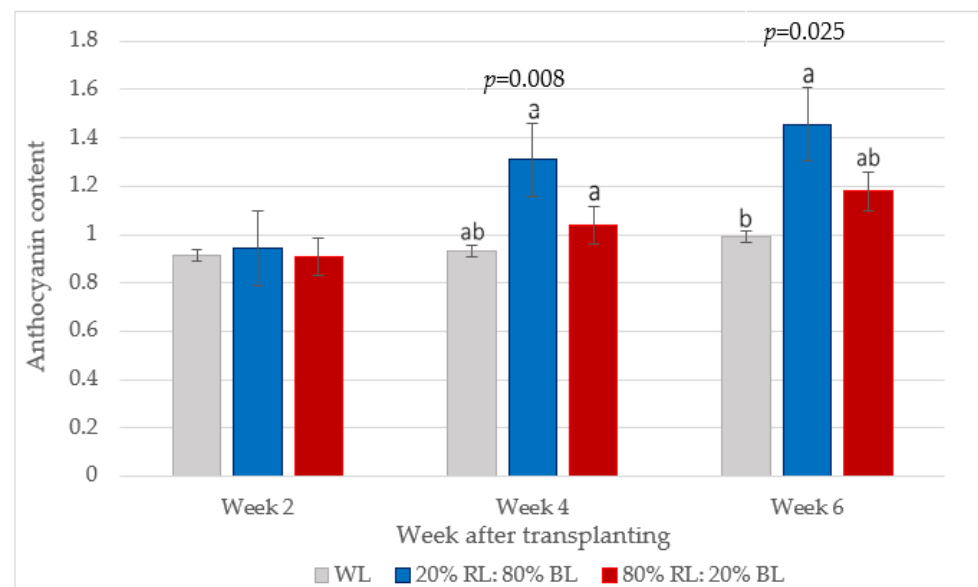


Figure 4. Anthocyanin content in Chinese kale grown under WL and different ratios of red: blue LED light treatment at weeks 2, 4, and 6. Within each sampling week, bars with the different letters are significantly different using Tukey test at $p < 0.05$. Error bars indicate SEM value. BL = blue light, RL = red light, WL = white light ($n = 3$).

Anthocyanin is a vacuolar phytochemical pigment responsible for violet or red–blue pigment in plants. It's an excellent antioxidant with diverse physiological abilities to prevent hypertension, liver disorders, and urinary problems [47]. According to [48], exposure to BL and RL can increase the content of anthocyanin significantly. Where the highest anthocyanin accumulation can be seen in Chinese kale, lettuce, and buckwheat with 30% BL: 60% RL, 80% BL: 20% RL, and 50% BL: 50% RL treatment, respectively [13,31,49]. A previously reported study showed a similar result to our experiment, with BL as the most efficient wavelength in the regulation of anthocyanin biosynthesis [13]. BL was able to perceive by cryptochrome 1 and promote downstream gene expressions such as DFR (dihydroflavonol-4-reductase), PAL (phenylalanine ammonium lyase), and CHS (chalcone synthesis) that lead to higher anthocyanin accumulation [13,31,50]. This could then explain the higher anthocyanin content present in the 20%RL: 80%BL treatment compared to the WL treatment. Notably, the lower anthocyanin content present in WL treatment can be due to GL and FR light [31,47].

When cryptochrome-dependent GL is simultaneously delivered with BL, it can reverse the blue light-induced effect on anthocyanin accumulation [51,52]. Moreover, anthocyanin content is directly correlated to the amount of active phytochrome (Pfr), thus the lower R: FR present in WL can reduce Pfr and eventually anthocyanin accumulation [31]. Interestingly, RBW light was also reported to have the highest total anthocyanin concentration in *Perilla frutescens*, indicating that anthocyanin biosynthesis might be dependent on species that could incorporate more alternative light treatments in our future study [53,54].

3.6. Total Phenolic Content

The total phenolic content (TPC) of Chinese kale was significantly affected by all three-light treatments at weeks 4 and 6 ($p < 0.05$) (Figure 5). Increased BL ratios in 20% RL: 80% BL showed the highest phenolic content and were ≈ 1.5 times higher than 80% RL: 20% BL and WL treatments at week 6.

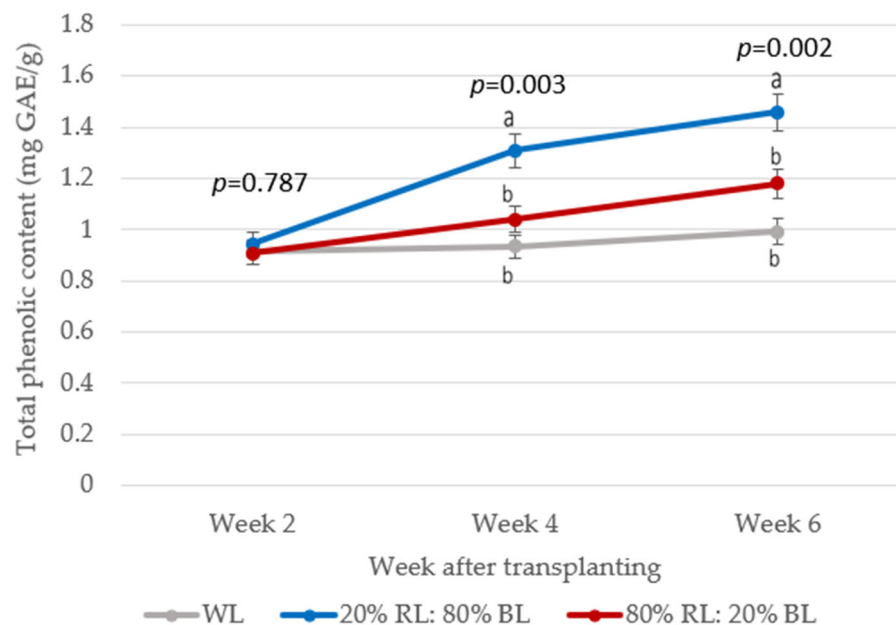


Figure 5. Influence of different LED light treatments on Chinese kale total phenolic content at weeks 2, 4, and 6. Within each sampling week, lines with the different letters are significantly different using Tukey test at 5% level. Error bars indicate SEM value. BL = blue light, RL = red light, WL = white light ($n = 3$).

Phenolic compounds (PCs) are phytochemicals with antioxidant capacity that can be found extensively in commonly consumed vegetables [55], important secondary metabolites produced by plants against abiotic/biotic stress, and may protect humans from heart disease and cancer [56]. In our study, BL ratios were shown to be the most prominent light in PC stimulation. Various studies have reported similar findings in TPC accumulation; Chinese kale sprout with 69.09% increased TPC under BL [18]; lettuce with the highest TPC under 20% RL: 80% BL and 41% RL: 59% BL [23,31]. Further analysis indicated that phenylalanine ammonia lyase (PAL) in phenylpropanoid pathway is the key enzyme in photoinduction of PCs [23]. More specifically, BL transforms hydroxycinnamic acids, which are strong inhibitors of PAL, into the less inhibitory *cis* form [57] and allows the upregulation of PAL enzyme for PCs synthesis. It could then explain why 20%RL: 80%BL has the highest TPC, followed by 80% RL: 20% BL and WL treatment in our study.

4. Conclusions

Based on the obtained results, the fresh and dry weight and phytochemicals accumulation of Chinese kale are affected by the LED light treatments. This comprehensive study indicated that 80%RL: 20%BL is the most promising LED regime in plant growth promotion and biomass accumulation, whereas 20%RL: 80%BL treatment was more beneficial to the accumulation of phytochemicals.

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writing—review and editing, A.S.; visualization, L.K.C.; supervision, A.S.; project administration, A.S.; funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

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