Lee DY *et al.* (2025)
Notulae Botanicae Horti Agrobotanici Cluj-Napoca
Volume 53, Issue 2, Article number 14409
DOI:10.15835/nbha53214409
Research Article

# Effect of LED light quality on the growth and photomorphogenesis of basil in closed-type plant factory

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## Abstract

This study was conducted to investigate effects of LED light quality on the growth and photomorphogenesis of basil (cv. 'Amethyst Improved') in a closed-type plant factory. Basil was sown on a urethane sponge and grown for two weeks under a White-LED. When the first main leaf appeared, the plants were transplanted into a nutrient solution hydroponic system (24 ± 2 °C, RH 55±10%) and using a standard nutrient solution for leafy vegetables (N 17.3, P 4.0, K 8.0, Ca 8.0, Mg 4.0, S 4.0 me·$L^{-1}$). To compare growth and internal traits of basil under various light qualities, QD-LED (combining blue, red, and far-red light), Blue+Red-LED (blue and red wavelengths at a ratio of 1:3), White-LED, 100% Blue-LED, and 100% Red-LED were used to cultivate basil for 35 days. Photosynthetic photon flux density (PPFD) was 200 ± 10 μmol·m-2·$s^{-1}$ and the light was provided for 16/8 hours (Light/Dark). The plant height was significantly the longest at 26.1 cm in QD-LED, and the number of leaves was the highest at 16.00 ea in QD-LED, but not significant. The leaf length was the longest at 10.9 cm in QD-LED and the shortest at 8.10 cm in White-LED. The leaf width was up to 26% wider in Blue+Red-LED, but there was no statistical significance. The leaf thickness was the thickest at 0.33 mm for Blue+Red-LED and Red-LED, which have a high proportion of red light, and the thinnest at 0.26 mm for Blue-LED. In the case of the curvature index (CI), which indicates the morphological characteristics of basil leaves, the values were highest for Blue+Red-LED and Red-LED. The internode length and leaf stalk length were significantly the longest at 5.73 cm and 3.04 cm, respectively, for QD-LED, and the stem diameter at 5.26 mm for QD-LED. The shoot fresh weight was 26.0 g in QD-LED, which was significantly higher than the other treatment groups by up to four times, but the root fresh weight was the highest at 5.99 g in Blue+Red-LED. On the other hand, the shoot and root dry matter ratio were the highest at about 9% and 5%, respectively, in White-LED. The maximum quantum yield (FvFm) did not differ significantly between the treatment groups, but the value was significantly lowest at 0.79 for Red-LED. The chlorophyll content (SPAD), normalized difference vegetation index (NDVI), and anthocyanin reflectance index (ARI1) values were up to 27% higher in Blue+Red-LED than in other treatment. Also, the DPPH radical scavenging activity and total phenol content were the highest in Red-LED at 74% and 9.47 mgGAE·$g^{-1}$FW, respectively. As a result, basil (cv. 'Amethyst Improved') grew best in QD-LED, and its antioxidant effect was

*Received: 14 Feb 2025. Received in revised form: 23 Mar 2025. Accepted: 24 Jun 2025. Published online: 30 Jun 2025.*
From Volume 49, Issue 1, 2021, Notulae Botanicae Horti Agrobotanici Cluj-Napoca journal uses article numbers in place of the traditional method of continuous pagination through the volume. The journal will continue to appear quarterly, as before, with four annual numbers.

the best in Red-LED. In addition, it was confirmed that the curvature and morphological characteristics of basil leaves changed depending on the ratio of red light at 600-700 nm.

***Keywords:*** curvature index; deep flow technique; *Ocimum basilicum* L.; photomorphogenesis; quantum dot

## Introduction

A closed-plant factory is a facility that can grow crops by artificially controlling the growing environment such as light, temperature, humidity, and carbon dioxide concentration based on artificial light sources and hydroponics in an enclosed room (Lee, 2010). Since it is blocked from the outside environment, it is not affected by climate, seasons, or pests. Thus, an optimized environment can be provided for crop growth (Sharath Kumar *et al.*, 2020). In addition, it is possible to shorten the cultivation period through environmental control and vertical farming through multi-tiered cultivation to maximize crop production without being constrained by time or space. It is possible to stably supply high-quality agricultural products to consumers throughout the year through planned production and weekly production.

Light is the main energy source for plants and an important factor affecting their development and morphology (Kusuma *et al.*, 2020; Ma *et al.*, 2021). However, light is the most limiting factor for plant growth in closed plant factories because these factories do not utilize natural light. Instead, they rely on artificial light sources solely to grow plants indoors. Types of artificial light sources that can be used in plant factories include fluorescent (FL), methyl halide (MH), high-pressure sodium (HPS), and light emitting diodes (LED) (Kim *et al.*, 2013) Among them, LEDs are mainly used as artificial light sources to replace natural light in closed plant factories because they have high luminous efficiency, low power consumption and heat emission. In addition, they can supply wavelengths that are effective for plant growth (Ma *et al.*, 2021).

Basil (*Ocimum basilicum* L.) is an annual herbaceous plant belonging to the Lamiaceae family. Its consumption is steadily increasing. The global basil leaf market is expected to grow from $57 million to $62 million from 2021 to 2026, at a cumulative average growth rate of 1.3% (Sipos *et al.*, 2021). Basil is a popular high-value crop worldwide due to its high yield index, relative ease of cultivation, adaptability to controlled environment agriculture (CEA) systems, and high profitability (Polyakova *et al.*, 2015). There are various species of basil, and it is estimated that there are up to 160 species of basil (Bajomo *et al.*, 2022). As a result of classifying many basil varieties based on morphological characteristics to efficiently classify and identify them, they can be classified into six distinct forms: lettuce-leaf, small-leaf, true basil, purple basil (A), purple basil (B), and purple basil (C) (Carović-Stanko *et al.*, 2011).

If classified into a broader category, basil is divided into two well-known green varieties and purple varieties. It is reported that the essential oil of purple basil protects cardiomyocytes from oxidative stress better than green varieties (Danesi *et al.*, 2008). Also, purple basil contains anthocyanins, which can be expected to have a higher antioxidant effect than conventional green basil (Flanigan and Niemeyer, 2014).

There are various varieties of purple basil, such as ‘Amethyst Improved’, ‘Dark Opal’, ‘Osmin’, ‘Purple Ruffle’, and ‘Red Rubin’. However, in the case of ‘Dark Opal’ and ‘Red Rubin’, it is difficult to obtain accurate measurements because the leaf color is not uniform due to the characteristics of the variety, so ‘Amethyst Improved’ was selected as the public material and a cultivation experiment was conducted.

Dou *et al.* (2018) have reported that basil in a controlled indoor environment shows increased photosynthesis, chlorophyll content, and building weight with higher light intensity. They suggested that a daily light integral (DLI) of 12.9 $mol \cdot m^{-2} \cdot d^{-1}$ is suitable for commercial production of basil to minimize energy cost while maintaining yield and quality. Pennisi *et al.* (2020) have reported that a light intensity of PPFD 200~250 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and a photoperiod of 16 h are suitable for basil growth. Among them, light quality is one of the most important factors affecting basil growth and secondary metabolite accumulation. LEDs can supply wavelengths that are effective for basil growth and secondary metabolite enhancement, providing an opportunity to optimize basil yield and quality in a controlled environment (Dou *et al.*, 2017). However, effects of LED light quality on growth characteristics of basil remain unclear. Thus, the objective of this study was to determine effects of LED light quality on growth and photomorphogenesis of basil in a closed-type plant factory.

## Materials and Methods

### *Growth environment and plant materials*

This study was conducted in a closed chamber (24 ± 2 °C, RH55 ± 10%) located in the College of Agriculture and Life Sciences, Kangwon National University from January 2, 2024 to February 20, 2024. *Ocimum basilicum* L. (cv. 'Amethyst Improved', Johnny's Selected Seeds, ME, USA) was used as the plant material. Basil seeds were sown on hydroponic urethane sponges (Cham Swiun Sugyeong Jaebae, Kangwon-do, Korea) and grown for 2 weeks under White-LED (HT400-5700, BISSOL LED, Seoul, Korea) with 16/8 $h{\cdot}d^{-1}$ (light/dark) photoperiod and a PPFD of 200 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$. When the first main leaf developed, plants were established in a circulating freshwater hydroponic system and grown for 35 days. The hydroponic nutrient solution was supplied at EC 0.3 $dS{\cdot}m^{-1}$ using the original Japanese standard nutrient solution for leafy vegetables (N 17.3, P 4.0, K 8.0, Ca 8.0, Mg 4.0, S 4.0 $me{\cdot}L^{-1}$) (Song *et al.*, 2020) at the beginning of the growth period. Water and nutrient solution were added at regular intervals during the growth period to reach EC 1.2 $dS{\cdot}m^{-1}$ at the end of the growth period. The pH was maintained at 6.5.

### *LED conditions and light treatment*

For treatment with different wavelengths of light, we used LEDs in the form of 120 cm bars and 40 W output. Light quality treatments included Quantum Dot-LED (Cheorwon Plasma Research Institute, Kangwon-do, Korea) with a combination of blue+red+far-red, Blue+Red-LED (HT404, BISSOL LED, Seoul, Korea, a 1:3 ratio of blue to red wavelengths), White-LED with white (HT400-5700, BISSOL LED, Seoul, Korea), Blue-LED (HT400, BISSOL LED, Seoul, Korea), and Red-LED (HT400, BISSOL LED, Seoul, Korea) with 100% blue and red. Thus, a total of five treatments were used. They were labelled as "QD", "Blue+Red", "White", "Blue", and "Red", respectively. Four LEDs were installed in each treatment (Figure 1A). A portable spectrometer (MK350S, UPRtek, Zhunan, Taiwan) was used to measure the wavelength of each LED and the proportion of photosynthetically effective radiation between 400 and 700 nm (Figure 1B). Basil plants were formalized into 15 plants for each LED treatment and phototreated 16/8 $h{\cdot}d^{-1}$ (light/dark) from 6 am to 10 pm with a PPFD 200 ± 10 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ using a photometer (HD2102.2, DELTA OHM, Veneto, Italy) and a quantum radiometric probe (LP471PAR, DELTA OHM, Veneto, Italy).

### *Growth measurement*

To investigate growth characteristics of basil in response to light quality during the growing season, plant height, number of leaves, leaf length, and leaf width were measured at 7-day intervals from day 14 after establishment. At the end of the growing season, leaf thickness, Curvature Index (CI), internode length, leaf stalk length, stem diameter, shoot and root fresh weight, dry weight, dry matter ratio were measured. Curvature index was calculated using the following formula for the second main leaf based on a published study (Homa *et al.*, 2016):

$$CI = (a'b' - ab)/ab \quad \text{(formula for downward curved leaves)} \qquad (1)$$

a′b′ = flattened leaf width
ab = curved leaf width

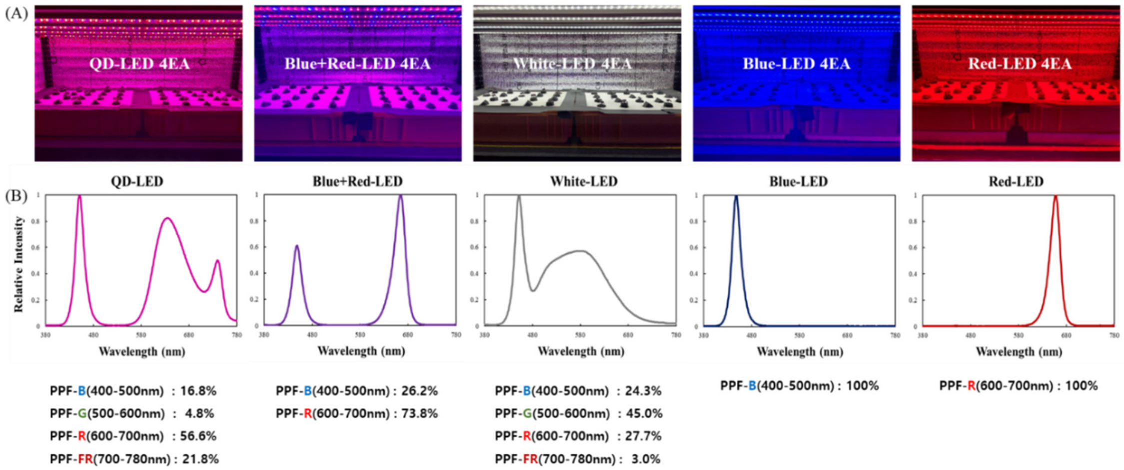


**Figure 1.** (A) Cultivation condition images for each LED treatment; (B) Spectrum of LED used in the experiment

*Analysis of leaf internal characteristics*

To compare internal characteristics of basil leaf according to light quality, we examined maximum quantum yield (Fv/Fm), chlorophyll content (SPAD), normalized difference vegetation index (NDVI), anthocyanin reflectance index 1 (ARI1), and leaf color. All values were measured for the third leaf below the growth point. Fv/Fm was measured with 10 replicates using a chlorophyll fluorescence analyzer (Fluorpen FP 110D, Photon System Instruments, Drásov, Czech Republic) after inducing dark adaptation by biting the leaf with a leaf-clip for 20 min. SPAD was measured with 15 replicates using a chlorophyll meter (SPAD-502, Minolta Camera Co., Tokyo, Japan). NDVI and ARI1 were measured with 15 replicates using a physiological index analyzer (Polypen RP 410 UVIS, Photon System Instruments, Drásov, Czech Republic). Leaf color was measured in 15 replicates with a color meter (CR-20, Konica Minolta, Tokyo, Japan).

*Analysis of total phenolic content and antioxidant activity*

Total phenolic content and antioxidant activity were determined after homogenizing (HZ1, Labtron Inc., Seoul, Korea) 0.5 g of basil leaf sample with 20 mL of methanol in a 50 mL tube for 1 min 30 sec and centrifuging (Mega 17R, Hanil, Seoul, Korea) the sample at 27,654 g for 15 min at 4 °C. The supernatant was then collected and used for analysis. Total phenolic content was determined using a modified Folin-Ciocalteu colorimetric assay (Zhang *et al.*, 2006). In a 2 mL microtube, 0.05 mL of homogenate and 0.45 mL of distilled water were mixed. Then 0.05 mL of Folin-Ciocalteu's phenol reagent was added and the reaction was allowed to stand at room temperature for 5 min, followed by vortexing with 0.15 mL of 7% $Na_2CO_3$ and 1 mL of distilled water. The mixture was then allowed to stand for 2 h in the dark. The absorbance was then measured at 760 nm using a spectrophotometer (BioMate 3S UV-Vis, Thermo Fisher Scientific, Boston, MA, USA). A standard calibration curve was prepared with gallic acid to express the total phenolic content as $mgGAE{\cdot}g^{-1}$ FW. Antioxidant activity was analysed by DPPH radical scavenging assay (Oboh, 2005). After 0.3 mL of homogenate and 0.7 mL of 0.4 mM DPPH methanol solution were mixed and reacted for 30 min under dark conditions in a cold room, the absorbance was then measured at 516 nm using a spectrophotometer. The antioxidant activity was calculated using the formula below (Song *et al.*, 2020):

$$\text{Antioxidant activity (\%)} = \left(1 - \frac{\text{Sample Absorbance}}{\text{Negativecontrol Absorbance}}\right) \times 100 \qquad (2)$$

*Statistical analysis*

Collected data were mean and standard deviation using Microsoft Excel (Microsoft Office Excel 2016, Microsoft, USA) and tested for significance between treatments using one-way analysis of variance (ANOVA) in the SPSS (IBM SPSS Statistics 26, IBM Corp., USA) program, followed by post hoc analysis with Duncan's Multiple Range Test. The significance level was set at $p < 0.05$.

## Results and Discussion

*Morphology and growth characteristics*

When basil was grown under various LED light qualities in a closed chamber for 35 days, distinctive morphological differences were observed between light qualities (Figure 2).

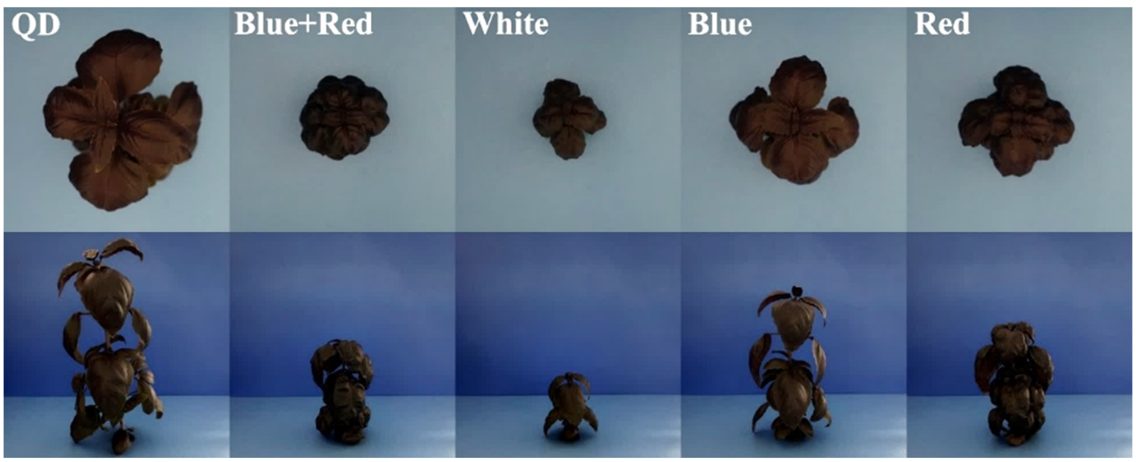


**Figure 2.** Photo of top and side views of *Ocimum basilicum* L. (cv. 'Amethyst Improved') cultivated under various light sources for 35 days

Basil grown with QD-LED, Blue-LED, and Blue-LED significantly increased in plant height compared to those grown with other treatments, while Blue+Red-LED and Red-LED groups showed bending and leaf shrinkage. Basil grown with White-LED was the most dwarfed among basil in all treatment groups. To compare the photomorphogenesis of basil leaves based on light quality, we photographed the second main leaf and found that leaves in Blue+Red and Red treatment groups were bumpy and severely curled (Figure 3).

The growth of basil in response to light quality during the growing period was the most favorable under QD-LED but the least favorable under White-LED (Table 1). The plant height was significantly longer in QD-LED at 26.19 cm. The number of leaves was 16.00 ea in QD-LED and 15.87 ea in Blue-LED, showing no statistically significant difference. The maximum difference in plant height was 9 cm between treatments except White-LED. The difference was 1 to 2 ea for leaves. The increase in height with light quality led to stem growth rather than increased foliage or yield. This was consistent with a recent study reporting that far-red and blue light decreased the amount of active phytochrome (Pfr), resulting in shade avoidance syndrome (SAS) and increased stem elongation (Larsen *et al.*, 2020). The leaf length was significantly longer in QD-LED at 10.93 cm. The leaf width was wider in the order of Blue+Red-LED > Red-LED > QD-LED at 8.35 cm, 8.00 cm, and 7.95 cm, respectively. However, their differences were not statistically significant. It has been reported that when LED contains a high proportion of green light, the photosynthetic photon flux (PPF) of red and blue light is reduced, which can negatively affect plant growth (Folta and Maruhnich, 2007), resulting in decreases of leaf area and fresh weight, which in turn can reduce yield (Dou *et al.*, 2020). Therefore, poor basil growth under White-LED is likely due to reduced PPF of red light due to a high percentage of green light.

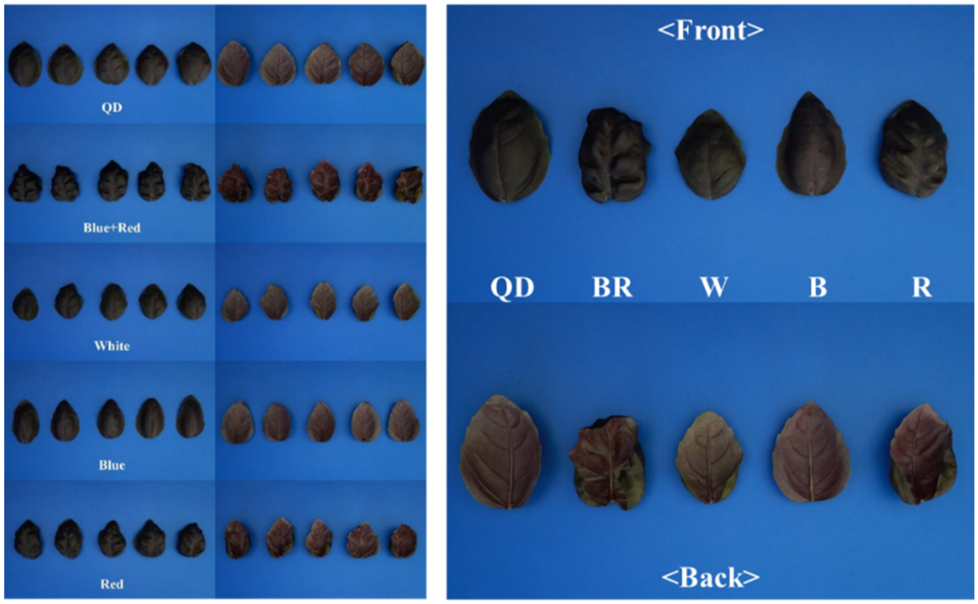


**Figure 3.** Photomorphogenesis of *Ocimum basilicum* L. (cv. 'Amethyst Improved') leaf cultivated under various light sources for 35 days. The leaf was taken from the front and back of the second true leaf

The internode length was the longest in the QD-LED at 5.73 cm, followed by that in the Blue-LED at 5.03 cm. This was due to the shade avoidance syndrome induced by the far-red light of QD-LED and the blue light of Blue-LED, as mentioned earlier. It has been reported that increasing internode length can widen the gap between upper and lower leaves to facilitate air circulation, promote transpiration, and improve mutual shading, although dry weight distributed to leaves is decreased (Larsen *et al.*, 2020). which is an important factor to be considered in plant factories that grow plants with relatively low and limited heights. Leaf stalk length was also significantly longer in QD-LED at 3.04 cm, showing statistically significant differences between treatments similar to internode length. Similarly, the stem diameter was significantly thicker in QD-LED at 5.26 mm and tended to be thicker in Blue+Red-LED and Red-LED than in Blue-LED, consistent with previous findings (Hosseini *et al.*, 2019).

**Table 1.** Plant growth of *Ocimum basilicum* L. (cv. 'Amethyst Improved') cultivated under various light sources for 35 days ± SD (n = 15)

| Treatment [z] | Plant height (cm) | No. of leaves (ea) | Leaf length (cm) | Leaf width (cm) | Internode length (cm) | Leaf stalk length (cm) | Stem diameter (mm) |
|---|---|---|---|---|---|---|---|
| QD | 26.19 ± 1.24 a [y] | 16.00 ± 0.00 a | 10.93 ± 0.76 a | 7.95 ± 0.46 a | 5.73 ± 0.35 a | 3.04 ± 0.28 a | 5.26 ± 0.17 a |
| Blue + Red | 13.49 ± 0.49 d | 14.00 ± 0.00 b | 10.07 ± 0.67 bc | 8.35 ± 0.61 a | 3.64 ± 0.18 c | 1.46 ± 0.19 d | 4.77 ± 0.20 b |
| White | 10.11 ± 0.66 e | 11.73 ± 0.70 c | 8.10 ± 0.48 d | 6.61 ± 0.39 c | 3.37 ± 0.22 d | 1.48 ± 0.12 d | 3.04 ± 0.20 d |
| Blue | 19.91 ± 1.18 b | 15.87 ± 0.52 a | 10.46 ± 0.43 b | 7.23 ± 0.94 b | 5.03 ± 0.45 b | 2.89 ± 0.14 b | 4.36 ± 0.16 c |
| Red | 17.12 ± 0.58 c | 14.13 ± 0.52 b | 9.92 ± 0.48 c | 8.00 ± 0.51 a | 3.86 ± 0.11 c | 1.77 ± 0.13 c | 4.61 ± 0.14 b |

[z] Treatment included: QD, quantum dot LED; B + R, blue + red LED; White, white LED; Blue, blue LED; Red, red LED

[y] Means with different letters within column indicate statistically significant differences by Duncan's multiple range test at $p < 0.05$

Leaf thickness tended to be thicker in Blue+Red-LED and Red-LED, which had a higher proportion of red light among all treatments, while Blue-LED, which consisted of 100% blue light without any red light, had the lowest value of 0.26 mm (Figure 4A). This was similar to previous findings showing that increasing the ratio of light intensity to red light could promote basil leaf growth, resulting in thicker leaves (Hikosaka *et al.*, 2021). A previous study has reported a significant increase in leaf thickness when the ratio of red:blue:green light is 4:1:1 compared to that when the ratio is 1:1:1 (Lin *et al.*, 2021). The curvature index, an indirect indicator of basil leaf morphological characteristics, was also the highest in Blue+Red-LED and Red-LED, showing statistically significant differences among treatments, similar to results of leaf thickness (Figure 4B). The higher the value of curvature index, the more curved the leaf. For basil grown in Blue+Red-LED and Red-LED, leaf curvature was found at all leaf levels regardless of old or new leaves (Figures 2 and 3).

It has been reported that these leaf deformities are likely caused by abnormalities due to excessive proportions of red light (Hikosaka *et al.*, 2021). Regarding correlations between morphological characteristics of basil leaves and Downy mildew (DM) incidence, it has been reported that a greater leaf curvature is associated with a higher incidence of DM on the adaxial surface of the leaf and that leaf curvature, stomata density, and stomata length can influence DM development and *Peronospora belbahrii* spore formation (Homa *et al.*, 2016). The optimal temperature for sporulation of the downy mildew-causing pathogen *Peronospora belbahrii* is 20 to 22 °C, similar to closed-plant factory growing environments. Sporulation of the downy mildew-causing pathogen *Peronospora belbahrii* occurs when there is high humidity and poor air circulation (Wyenandt *et al.*, 2010). A greater curvature of the leaf provides an optimal environment for downy mildew spores to form on the adaxial surface of the leaf, making it susceptible to downy mildew outbreaks and reducing its external commodity value. Thus, Blue+Red-LED and Red-LED are not considered suitable light quality for growing basil in a closed-plant factory.

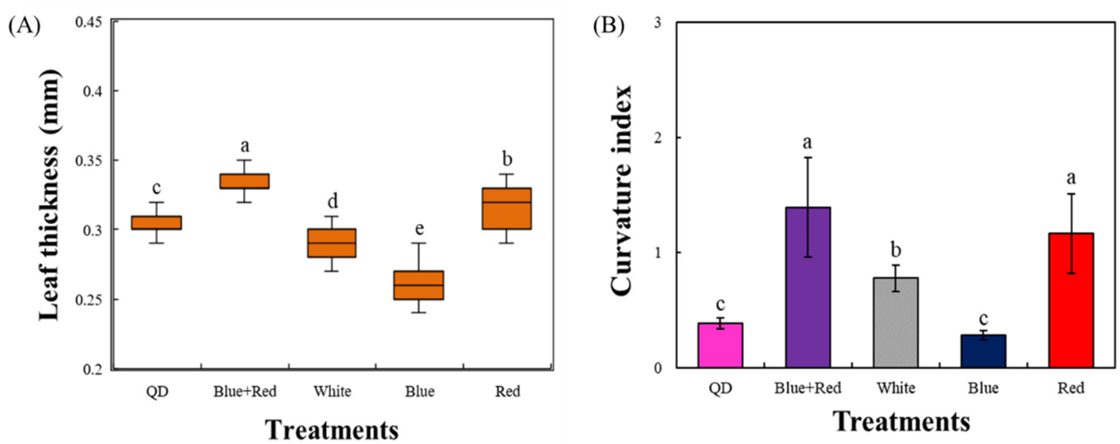


**Figure 4.** Leaf external characteristics of *Ocimum basilicum* L. (cv. 'Amethyst Improved') cultivated under various light sources for 35 days. (A) Leaf thickness, (B) Curvature index

Vertical bars indicate mean ± SD of 15 replicates (n = 15) in (A) and mean ± SD of five replicates (n = 5) in (B). Values marked with different letters indicate significant differences according to Duncan's multiple range test at the 5% level ($p < 0.05$)

Shoot fresh weight was significantly higher in QD-LED at 26.04 g, nearly four times higher than those in other treatments and White-LED. However, shoot dry weight was 1.65 g, which was not significant different from that of Red-LED (Table 2). Shoot dry matter ratio was significantly higher in White-LED at approximately 9%, although it showed no statistically significant difference between treatments except for White-LED. Root fresh weight and dry weight were the highest in the Blue+Red-LED group at 5.99 g and 0.31

g, respectively. Dry matter ratio was the highest in the White-LED group at about 5%, similar to the shoot dry matter ratio, although it was not statistically different from that in the Blue-LED group.

Maximization of plant fresh weight and dry weight by red light has been previously reported (Hosseini *et al.*, 2019). White-LED has been reported to be an unsuitable light quality for basil production due to its very poor production compared to other light qualities, which is correlated with growth. The non-photosynthetic spectrum contained in White-LED can be absorbed by a crop and converted into heat (Rahman *et al.*, 2021). High percentages of green light have been reported to negatively affect plant growth, resulting in reduced leaf area and consequently decreasing fresh weight (Dou *et al.*, 2020).

**Table 2.** Biomass of *Ocimum basilicum* L. (cv. 'Amethyst Improved') cultivated under various light sources for 35 days ± SD (n = 5)

| Treatment [z] | Fresh weight [y] (g) | | Dry weight (g) | | Dry matter ratio (%) | |
|---|---|---|---|---|---|---|
| | Shoot | Root | Shoot | Root | Shoot | Root |
| QD | 26.04 ± 2.93 a [x] | 5.17 ± 0.75 b | 1.65 ± 0.23 a | 0.26 ± 0.02 b | 7.73 ± 0.35 b | 4.40 ± 0.35 b |
| Blue + Red | 19.60 ± 2.40 c | 5.99 ± 1.04 a | 1.14 ± 0.12 b | 0.31 ± 0.03 a | 8.08 ± 0.35 b | 4.39 ± 0.32 b |
| White | 6.46 ± 0.59 e | 1.62 ± 0.09 d | 0.42 ± 0.05 c | 0.08 ± 0.01 d | 8.89 ± 0.29 a | 5.19 ± 0.53 a |
| Blue | 17.52 ± 1.56 d | 3.60 ± 0.39 c | 1.09 ± 0.08 b | 0.18 ± 0.02 c | 7.84 ± 0.50 b | 4.69 ± 0.42 ab |
| Red | 23.27 ± 1.40 b | 5.72 ± 0.50 ab | 1.63 ± 0.17 a | 0.27 ± 0.02 b | 7.94 ± 0.21 b | 4.44 ± 0.29 b |

[z] Treatment included: QD, quantum dot LED; B + R, blue + red LED; White, white LED; Blue, blue LED; Red, red LED

[y] In the case of Fresh weight (n = 10)

[x] Means with different letters within column indicate statistically significant differences by Duncan's multiple range test at $p < 0.05$

*Leaf internal characteristics*

Fv/Fm did not differ significantly among treatments. The Red-LED group had the lowest Fv/Fm value of 0.79, significantly lower than other groups, followed by Blue+Red-LED at 0.81 (Table 3). Fv/Fm is one of the chlorophyll fluorescence parameters. It measures the quantum yield of photochemical reactions occurring in photosystem Ⅱ and indicates the maximum photosynthetic efficiency. It is generally known that photosynthetic efficiency is good when the Fv/Fm value is 0.83. The Fv/Fm value decreases when stress occurs in the plant body or photosystem Ⅱ is damaged. Thus, Fv/Fm can be used to evaluate plant stress and photosynthetic efficiency (Henriques, 2009). Lower Fv/Fm values observed for Red-LED were similar to those reported by Hosseini *et al.* (2019). Such lower values were reported to be a result of reduced photochemical activity due to photosystem Ⅱ inactivation and D1 protein damage by red light (Wu, 2016; Hosseini *et al.*, 2019).

SPAD is an indirect indicator of chlorophyll content, with a higher value indicating a higher chlorophyll content. In the present study, SPAD was the highest for the Blue+Red-LED group at 43.62, which was significantly higher than those in other groups. The high chlorophyll content observed for the Blue+Red-LED group was consistent with previous studies showing that mixing red and blue light is more effective than irradiating with a single wavelength (Hosseini *et al.*, 2019), especially when the ratio of red to blue light is 7:3, which has been reported to result in the highest SPAD value (Dou *et al.*, 2020). One study has shown that growing basil with far-red light added to LED with a red:green:blue ratio of 6:2:2 can result in reduced SPAD values compared to the control (Park *et al.*, 2023), similar to lower SPAD values observed with QD-LED in the present study.

NDVI is a non-destructive measure of plant health using spectral reflection characteristics of leaves. ARI1 compares anthocyanin content in relative terms. They showed the highest values of 0.58 and 7.37 in the Blue+Red-LED group, respectively, just like SPAD. However, ARI1 of in the Blue+Red-LED group did not show a significant difference from that of the Red-LED group.

**Table 3.** Leaf internal characteristics of *Ocimum basilicum* L. (cv. 'Amethyst Improved') cultivated under various light sources for 35 days ± SD (n = 15)

| Treatment [z] | Fv/Fm [y] | SPAD | NDVI | ARI1 |
|---|---|---|---|---|
| QD | 0.83 ± 0.01 a [x] | 33.55 ± 0.63 c | 0.55 ± 0.02 b | 6.24 ± 1.21 bc |
| Blue + Red | 0.81 ± 0.01 b | 43.62 ± 1.16 a | 0.58 ± 0.02 a | 7.37 ± 1.35 a |
| White | 0.82 ± 0.02 a | 33.04 ± 0.98 c | 0.54 ± 0.01 bc | 5.07 ± 0.84 d |
| Blue | 0.82 ± 0.01 a | 33.11 ± 1.06 c | 0.55 ± 0.01 b | 5.68 ± 0.69 cd |
| Red | 0.79 ± 0.01 c | 37.31 ± 1.03 b | 0.53 ± 0.02 c | 6.65 ± 1.01 ab |

[z] Treatment included: QD, quantum dot LED; B + R, blue + red LED; White, white LED; Blue, blue LED; Red, red LED

[y] In the case of Fv/Fm (n = 10)

[x] Means with different letters within column indicate statistically significant differences by Duncan's multiple range test at $p < 0.05$

Basil leaf color showed significant differences between light treatments. One study has recently reported that the quality of leafy greens is affected not only by taste, but also by color, as consumers are showing increasing interest in colored foods containing natural pigments such as anthocyanins, carotenoids, and betanins due to their aesthetic, nutritional, and safety benefits (Sarker and Oba, 2021).

Regarding CIE Lab color parameters (L*, a*, and b*), the L* value indicating lightness was significantly higher in the Blue-LED group at 26.35, resulting in the lightest color. The L* value was the lowest in the Blue+Red-LED group at 23.40, resulting in the darkest color. The a* value indicating an intense red color, was significantly higher in the Blue-LED group at 2.72. Statistical significance for difference in a* value between treatments tended to be similar to that of L* (Figure 5). The b* value indicating a darker blue color was the lowest in the Blue+Red-LED group at -3.91. In fact, the darkest purple color of basil leaf was observed in the Blue+Red-LED group with the lowest L* and b* values. This suggests that Blue+Red-LED is the most effective for color expression in purple lineage basil. This purple color is associated with anthocyanin accumulation.

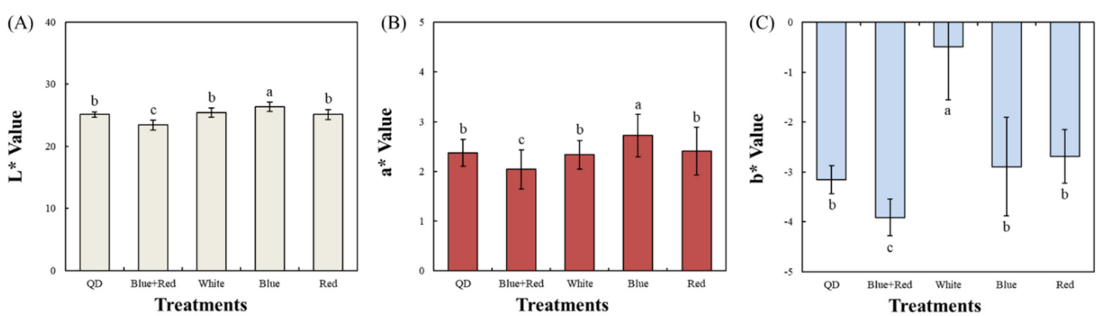


**Figure 5.** Color meter values of *Ocimum basilicum* L. (cv. 'Amethyst Improved') leaf cultivated under various light sources for 35 days. (A) L* value, (B) a* value, (C) b* value

Vertical bars indicate mean ± SD from 15 replicates (n = 15). Values marked with different letters indicate significant differences according to Duncan's multiple range test at the 5% level ($p < 0.05$)

*Total phenolic content and antioxidant activity*

Total phenolic content of basil leaves was significantly higher in the Red-LED group at 9.47 mgGAE·g$^{-1}$FW. However, the DPPH radical scavenging activity of basil leaves in the Red-LED group was about 74%, which was not statistically different from that in the Blue+Red-LED group (Figure 6). It is generally believed that accumulation of phenolics and secondary metabolites in many agricultural and ornamental plant species can be promoted by blue light and tends to increase (Zheng *et al.*, 2019). However, in the present study, basil treated with Blue-LED did not show blue light-induced increases of phenolic content or antioxidant activity.

It has been reported that antioxidant properties of basil can be enhanced by red light at 638 nm (Samuolienė *et al.*, 2016). It has also been reported that the effect of light quality might be cultivar dependent (Bantis *et al.*, 2016). One study has shown that the accumulation of rosmarinic acid, the main phenolic substance in basil, is affected by light quality and photoperiod and that red light at 600-700 nm can induce the accumulation of rosmarinic acid (Shiga *et al.*, 2009), similar to results of increasing total phenolic content in the Red-LED group.

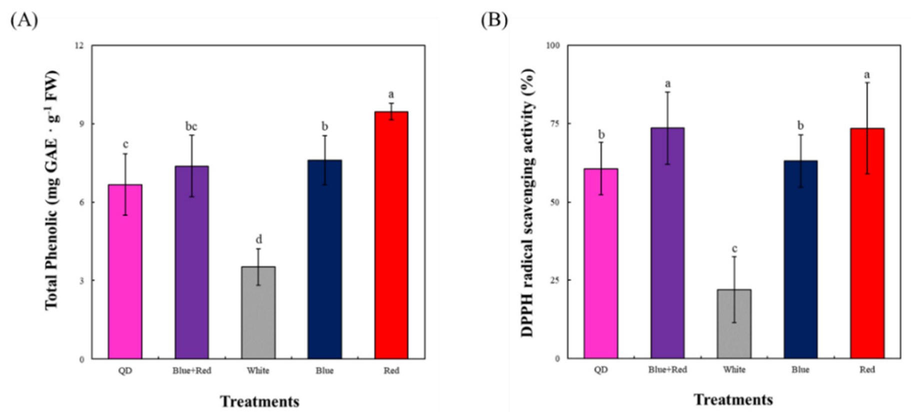


**Figure 6.** Antioxidant activity of *Ocimum basilicum* L. (cv. 'Amethyst Improved') leaf cultivated under various light sources for 35 days. (A) Total phenolic content, (B) DPPH radical scavenging activity
Vertical bars indicate mean ± SD (n = 3). Values marked with different letters indicate significant differences according to Duncan's multiple range test at the 5% level ($p < 0.05$)

## Conclusions

Growth and internal characteristics of basil varied according to the light quality. The growth of basil was the most dominant in the QD-LED group and the least dominant in the White-LED group. Far-red light from QD-LED and blue light from Blue-LED induced a shade avoidance syndrome that increased plant height. Such increase of plant height was due to an increase in internode length, not an increase in number of leaves. Actual leaf production was not significantly different among treatments except for White-LED. Basil grown under Blue+Red-LED had poor appearance due to leaf curling. However, it had superior leaf internal characteristics such as SPAD, NDVI, and ARI1. Red light from Red-LED was effective in increasing shoot dry production, total phenolic content, and antioxidant activity, although continuous red light decreased maximum quantum yield.

## Acknowledgements

This work was supported by the Korea Institute of Planning and Evaluation for Technology in Food, Agriculture and Forestry (IPET) through the Technology Commercialization Support Program, funded by the Ministry of Agriculture, Food and Rural Affairs (MAFRA) (122056-3), and the Republic of Korea and the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (RS-2021-NR060130).The authors sincerely thank the reviewers and editors for their valuable feedback and efforts. They also appreciate the support of the laboratory members, whose contributions were essential to this research.

## Authors' Contributions

Conceptualization, methodology, formal analysis, investigation, data curation, writing—review and editing: DYL; visualization, project administration. MJK. investigation. I-LC supervision. H-MK. conceptualization, resources, supervision. YK and JK resources.

All authors read and approved the final manuscript.

## Ethical approval (for researches involving animals or humans)

Not applicable.

## Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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