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Effect of Blue and/or Green Wavelength-specific White LED Lighting on Growth and Development of Tomato in Indoor Farming Systems

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Abstract. **White light-emitting diodes (LEDs), the most commonly used artificial light source in indoor farming systems, require spectrum optimization for crop-specific responses. This study evaluated the effects of wavelength-specific blue and green modifications on tomato growth, productivity, and fruit quality. Treatments included normal white LEDs (NWL), two wavelength-specific white LEDs (SWL1 and SWL2), and a red + blue LED combination as control. NWL represented a broad-spectrum baseline, SWL1 was enriched in red and long-green wavelengths, SWL2 emphasized blue and short-green wavelengths, and the red+blue combination served as a conventional control. Both SWL treatments enhanced biomass, leaf area, and fruit yield relative to the control. In particular, SWL1 increased fruit number (+38%), total yield (+48%), °Brix (+16%), and reducing sugar (+30%) relative to the control. SWL2 improved fruit number and yield by 23% and 26%, respectively, but did not enhance °Brix or reducing sugar. In addition, fruits from SWL1 showed higher antioxidant capacity, consistent with elevated lycopene accumulation. Yield and sugar gains under SWL1 suggest that spectral tuning toward long-green wavelengths promotes assimilate partitioning into fruit. Moreover, SWL1 demonstrated superior light use efficiency and energy use efficiency. These findings suggest that tailoring the spectral peaks of white LEDs, particularly in the blue and green regions, can enhance tomato productivity and fruit quality. Wavelength-specific full-spectrum lighting therefore represents a promising strategy for high-efficiency tomato cultivation and provides a practical lighting solution to reduce energy costs while improving crop value in indoor farming systems.**

Tomatoes (*Solanum lycopersicum*) are among the most economically significant fruiting vegetables globally, valued for both their fresh market appeal and processed forms (Mordor Intelligence 2024). Their nutritional importance is largely attributed to lycopene, a powerful antioxidant compound associated with reduced risk of cancers and cardiovascular diseases (Mirahmadi et al. 2020; Wang et al. 2023). As demand grows for high-quality tomatoes with enhanced nutritional profiles, interest has increased in advanced cultivation systems capable of stable, year-round production.

To meet these needs, indoor farms—also described as plant factories with artificial lighting (PFALs) in the literature— have emerged as promising alternatives to conventional agriculture (Kozai et al. 2016). In contrast to greenhouses, which depend on natural solar radiation, PFALs are completely enclosed environments that operate exclusively with artificial lighting and allow precise regulation of temperature, humidity, CO_2 concentration, and light to maximize productivity (Kozai and Niu 2022).

Light plays a pivotal role in regulating plant growth, morphology, and secondary metabolism. In indoor farming systems, LEDs have become the standard lighting source due to their high energy efficiency, longevity, and spectral flexibility (Nguyen et al. 2022; Zhang and Kacira 2021). However, cultivating tall fruiting crops such as tomatoes, which typically reach 2 to 3 m during the reproductive phase, presents structural challenges (Kozai et al. 2016). Their vertical elongation increases the distance between light source and canopy, leading to light loss and reduced light use efficiency (LUE), particularly during early fruit development availability for vegetative and reproductive processes declines (Meng and Runkle 2019; Nelson and Bugbee 2014).

Improving the LUE of LEDs is therefore critical for optimizing conditions for tall crops in indoor farming systems. Turnbull et al. (2020) demonstrated that shifting peak wavelengths within 595 to 633 nm significantly alters shoot biomass yield. However, research on wavelength optimization remains limited. In this study, we focused on the blue and green spectral regions rather than red, as all treatments included the same red peak (660 nm). Blue light regulates plant morphogenesis and secondary metabolism (Kim et al. 2013), whereas green light improves canopy light distribution and induces shade-avoidance responses (Chen et al. 2024). However, their precise effects under fully controlled indoor conditions remain poorly understood. Moreover, fine-tuning peak positions in these ranges is technically challenging because of the need for specialized modules and sensitivity to temperature or manufacturing tolerances.

Therefore, this study investigated whether shifting the peak wavelengths of blue and green LEDs influenced tomato growth and fruit development, focusing on their roles in morphology and metabolite accumulation. Specifically, we examined how spectral peak modification affected lycopene accumulation and antioxidant capacity, with the goal of identifying spectral strategies to enhance fruit quality in indoor farming systems.

Materials and Methods

Plant materials and growth conditions. Tomato (*Solanum lycopersicum* L., cv. Shinlovely 256) seeds were sown in rock wool cubes (Grotop Master, Grodan, The Netherlands) and maintained at a temperature of 25 °C, relative humidity of 70%, a photosynthetic photon flux density (PPFD) of 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and 16/8-h light period in a growth chamber (Gaooze control system; Korea scientific technique industry, Suwon, Republic of Korea) for 42 d. At 43 d after sowing, tomato seedlings were transferred to a closed-type indoor farming system (Smart farm cube, Dream PF, Sacheon, Republic of Korea) at the Gyeongsang National University, Jinju, Republic of Korea (35°09′38″N, 128°04′39″E; altitude 44 m) with a density of 2.5 plants/m^2, where PPFD was adjusted to 330 ± 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for all treatments. The experiment was conducted in four separate cultivation areas, each consisting of four plants evenly spaced within the cultivation area. The electrical conductivity and pH of the nutrient solution were set at 2.0 $dS \cdot m^{-1}$ and 6.0, respectively. The nutrient solution was renewed weekly and supported using an automatic drip irrigation hydroponic system (Win-7000S; Woosung HITEC, Yangsan, Republic of Korea). The growing conditions were controlled during the experiment at an average temperature of 25 ± 3 °C and humidity of 70% ± 5%.

Experimental design and light treatment. Four types of LED sources were used for tomato cultivation. R+B (Models LH351H Blue 450 nm and LH351H Deep Red 660 nm V2; Samsung Electronics, Suwon, Republic of Korea), NWL (Model LM301D; Samsung Electronics), and two specially designed white LEDs, SWL1 and SWL2 (Models LM301H EVO and LM301H EVO Mint White, respectively, with LH351H Deep Red 660 nm V2; Samsung Electronics).

The R+B (red+blue) treatment consisted of peaks at 448 nm (blue, 30%) and 660 nm (red, 70%). The NWL treatment exhibited peaks at 452 nm (blue, 15%), 596 nm (green, 32%), and 660 nm (red, 53%), representing a typical white LED spectrum. In contrast, the modified white LEDs had slightly adjusted peak positions in the blue and green regions. SWL1 was designed with a short blue peak at 436 nm (17%), a long-green peak at 584 nm (35%), and red at 659 nm (48%), representing a red-enriched spectrum with long-wavelength green. SWL2 shared the same short blue peak at 436 nm (36%), corresponding to a blue-enriched spectrum with short-wavelength green. These peak shifts were selected according to a plant-centric spectrum design strategy to prove physiologically relevant short-wavelength regions that may influence photoreceptor-mediated growth and metabolism, while ensuring high photosynthetic photon efficacy.

Spectral distribution and ratios of red, green, and blue components are presented in Supplemental Fig. 1 and Supplemental Table 1. To analyze the spectral composition of each light source, spectra were measured at five positions on a horizontal plane at 50 cm below the light source using a portable spectroradiometer (LI-180; LI-COR, Lincoln, NE, USA). All light sources were installed above the canopy top at a distance of 1 m. The PPFD at the canopy level was maintained at 330 ± 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$ under 12-h photoperiods (daily light integral: 14.256 $mol \cdot m^{-2} \cdot d^{-1}$), and PPFD uniformity was confirmed by measurements across the plots before and after the experiment.

Growth characteristics. The growth characteristics of tomatoes were measured after 13 weeks of light treatment. The shoots were measured for fresh weight via an electronic scale (PAG214C; Ohaus Corp, Parsippany, NJ, USA) and then dried at 70 °C for 5 d in an oven (WOF-155; Daihan Scientific, Seoul, Republic of Korea) to measure the dry weight. Leaf area was calculated using ImageJ software. Ripened fruits (grades 8–9 on a scale of 1–12; Bama AS, Oslo, Norway) were harvested from the 10th week after treatment (two times each week). The final destructive harvests were performed in the 13th week. All growth characteristics were measured on four individual plants, with each plant considered as one replicate.

Physicochemical parameters. The pH and total acidity were measured according to the method of Lee et al. (2022), with slight modifications to suit the sample matrix.

Brix and reducing sugar contents were assessed using ethanol extracts, and reducing sugars were quantified using a slightly modified dinitrosalicylic acid method described by Piao et al. (2019).

Soluble protein content was determined based on a modified Biuret method (Min et al. 2017), and the protein concentration was calculated using a bovine serum albumin standard curve. All physicochemical parameters were measured on four individual plants, with each plant considered as one replicate.

Antioxidant properties. Tomato fruits were freeze-dried, ground into fine powder, and 5 g of each sample was used for extraction in 100 mL of 50% ethanol at room temperature (24 °C) for 12 h before filtration. The extracts were concentrated to ∼20 °Brix using a rotary evaporator. The 50% ethanol extracts (∼12,000 μg/mL) were diluted with tertiary distilled water to prepare working concentrations (1.0 to 0.05 °Brix; 600 to 30 μg/mL) for antioxidant and anti-inflammatory assays.

Antioxidant activities, including 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), and ferric reducing antioxidant power (FRAP) assays, were measured following the methods of Lee et al. (2022) and Hwang et al. (2021) without modification.

Lycopene. Lycopene content was determined by high-performance liquid chromatography (HPLC) using the method of Murkovic et al. (2002) without modification, and all

Table 1. Growth characteristics of tomato plants grown in an indoor farming systems with light-emitting diode (LED) lighting provided by either R+B or three types of white LEDs.

Light source[i]	Vegetative shoot fresh wt (g/plant)	Vegetative shoot dry wt (g/plant)	Leaf area (m^2/plant)
R+B	504.79 ± 13.22 a[ii]	51.52 ± 5.14 b	0.13 ± 0.02 b
NWL	534.85 ± 90.07 a	67.86 ± 4.06 a	0.18 ± 0.03 ab
SWL1	597.21 ± 23.74 a	67.12 ± 1.95 a	0.19 ± 0.02 a
SWL2	575.91 ± 115.99 a	75.30 ± 12.14 a	0.21 ± 0.01 a

[i] R+B = red and blue LEDs; NWL = normal white LEDs; SWL1 = specific white LED 1; SWL2 = specific white LED 2.

[ii] Values were the mean of four determinations ± standard error. Different letters following the mean in the same column indicate significant differences by one-way analysis of variance at $P \leq 0.05$.

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Table 2. Fruit number, total fruit yield, and basic physicochemical properties of tomato fruit grown in indoor farming systems with light-emitting diode (LED) lighting provided by either R+B or three types of white LEDs.

Light source[i]	Fruit number (number)	Total fruit yield (kg)	Brix (%)	Reducing sugar (mg/g)	pH	Acidity (%, lactic acid)
R+B	16.5 b[ii]	1.61 b	3.78 ± 0.20 b	25.26 ± 4.35 b	4.17 ± 0.08 a	1.02 ± 0.04 a
NWL	18.3 ab	1.80 ab	3.68 ± 0.13 b	21.34 ± 4.21 b	4.15 ± 0.03 a	0.93 ± 0.08 a
SWL1	22.8 a	2.38 a	4.38 ± 0.51 a	32.75 ± 1.43 a	4.14 ± 0.02 a	0.96 ± 0.02 a
SWL2	20.3 ab	2.03 ab	3.50 ± 0.19 b	24.58 ± 3.82 b	4.16 ± 0.08 a	0.91 ± 0.12 a

[i] R+B = red and blue LEDs; NWL = normal white LEDs; SWL1 = specific white LED 1; SWL2 = specific white LED 2.

[ii] Values are the mean of four determinations ± standard error. Different letters following the mean in the same column indicate significant differences by one-way analysis of variance at $P \leq 0.05$.

Table 3. Antioxidant properties of tomato fruit grown in an indoor farming systems with light-emitting diode (LED) lighting provided by either R+B or three types of white LEDs.

Light source[i]	DPPH radical scavenging activity (%)	ABTS radical scavenging activity (%)	Ferric reducing/antioxidant power (OD_{593} nm)
R+B	49.59 ± 2.72 ab[ii]	41.88 ± 2.71 b	0.83 ± 0.02 b
NWL	39.38 ± 2.07 c	41.57 ± 0.48 b	0.75 ± 0.02 c
SWL1	57.02 ± 4.47 a	46.60 ± 1.65 a	1.00 ± 0.04 a
SWL2	48.29 ± 7.15 b	43.17 ± 2.08 b	0.82 ± 0.06 b

[i] R+B = red and blue LEDs; NWL = normal white LEDs; SWL1 = specific white LED 1; SWL2 = specific white LED 2.

[ii] Values are the mean of four determinations ± standard error. Different letters following the mean in the same column indicate significant differences by one-way analysis of variance at $P \leq 0.05$.

measurements were made on fruits harvested from tomatoes. The same HPLC system and column used for phenolic acid and flavonol analysis were applied.

Light and energy use efficiency. LUE was expressed as shoot fresh weight per unit PPFD (g FW/PPFD), while energy use efficiency was expressed as shoot fresh weight per electricity consumption (g FW/W). Electricity consumption was measured using a power meter (HPM-300A, ADpower, Bucheon, Korea). The relative levels of these parameters were expressed as percentages of the values in R+B.

Statistical analysis. For growth measurements and material analysis, whole tomato plants were harvested four times per treatment. Growth measurements, basic physicochemical attributes, and antioxidant properties were measured for each plant. Statistical analysis was performed using the SAS 9.4 program (SAS Institute Inc., Cary, NC, USA) with analysis of variance (ANOVA). One-way ANOVAs were used to test the significance of treatment effects, and the assumptions of normality and homogeneity of variances were verified before the analysis. Duncan's multiple range test was used to determine significant differences in all parameters, verified at $P \leq 0.05$. The heatmap was created using the pheatmap package in the R program. Correlation analysis was performed using the factoextra package in the R program to determine the relationship between all parameters for treatment groups and treatments.

Results

Growth characteristics. Different light sources affected the vegetative growth of tomatoes in the indoor farming systems (Table 1). Vegetative shoot fresh weight did not differ significantly among treatments ($P = 0.460$). Vegetative shoot dry weight under white light treatments (NWL, SWL1, and SWL2) was 30% to 50% higher than that in R+B ($P = 0.008$). Leaf area followed a pattern similar to shoot dry weight, with no significant difference between the NWL and R+B ($P = 0.026$).

Fruit yield and physicochemical parameters. The white light treatments induced higher fruit growth than R+B (Table 2). Among them, SWL1 stimulated fruit formation and increased the total fruit yield compared with R+B. Fruit number and total fruit yield in SWL1 were 38% and 47% higher than in R+B, respectively ($P = 0.028$). The NWL and SWL2 showed no significant differences in number of fruit ($P = 0.171$) and the total fruit yield ($P = 0.108$) compared with R+B. The basic physicochemical attributes of tomato fruits were improved by white light treatments. The Brix value of fruit in SWL1 was significantly higher than that in R+B, with a 15% increase, and was the highest among the white light treatments ($P = 0.018$). Reducing sugars were the highest in SWL1, 29% greater than in R+B ($P = 0.015$). There was no significant difference in pH ($P = 0.936$) and acidity ($P = 0.300$) among all treatments.

Antioxidant properties. Table 3 shows the relative antioxidant properties of tomato fruits grown under different light sources. Across all assays, SWL1 produced the highest antioxidant activity in fruits. In particular, DPPH radical scavenging activity ($P = 0.004$), ABTS radical scavenging activity ($P = 0.026$), and ferric reducing/antioxidant power ($P < 0.001$) in SWL1 were increased by 15%, 11%, and 20%, respectively, higher than those in R+B. In contrast, NWL showed the lowest values among the treatments. SWL2 exhibited significantly lower antioxidant activity than SWL1.

Lycopene. There were significant differences in the lycopene concentration of tomatoes grown under different light sources (Fig. 1; $P < 0.001$). Lycopene content was highest in SWL1 and NWL, with no significant difference observed between them. Although SWL1 and

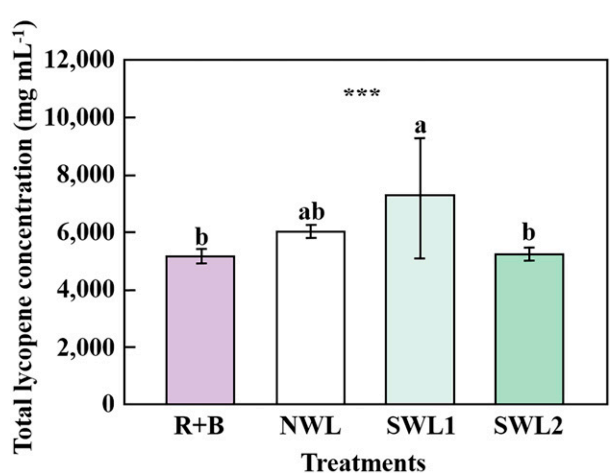

Fig. 1. Total lycopene concentration of tomatoes fruits grown for 13 weeks under four light spectrum designs in an indoor farm: a red+blue spectrum (R+B), a broad-spectrum white LED (NWL), a red-enriched white LED with long-wavelength green (SWL1), and a blue-enriched white LED with short-wavelength green (SWL2). Values represent means ± standard error ($n = 4$). *** indicates significant difference at $P < 0.001$.

Table 4. Effects of light-emitting diode (LED) lighting on energy, light, and electrical use efficiency.

Light source[i]	Energy consumption (Watt)	Light use efficiency (g FW/mol)	Energy use efficiency (g FW/kWh)
R+B	100	4.53 ± 0.10 c[ii]	15.51 ± 0.37 c
NWL	120	6.03 ± 0.51 b	17.11 ± 1.47 c
SWL1	100	8.01 ± 0.35 a	26.60 ± 1.17 a
SWL2	100	6.22 ± 0.09 b	21.06 ± 0.31 b

[i] R+B = red and blue LEDs; NWL = normal white LEDs; SWL1 = specific white LED 1; SWL2 = specific white LED 2.

[ii] Values are the mean of four determinations ± standard error. Different letters following the mean in the same column indicate significant differences by one-way analysis of variance at $P \leq 0.05$.

NWL did not differ significantly, lycopene concentration in SWL1 was ~46% higher than in R+B. SWL2 had a lower total lycopene concentration compared with SWL1.

Light and energy use efficiency. Table 4 presents energy consumption, LUE, and energy use efficiency (EUE) across treatments. All white light treatments (NWL, SWL1, and SWL2) showed higher LUE than R+B. Among the white light treatments, the SWL types—engineered with shorter peak wavelengths in the blue and green regions—exhibited improved LUE and EUE compared with NWL. Notably, SWL1, with a narrowed green peak, had the highest LUE and EUE, significantly higher than both R+B and NWL ($P < 0.001$). No significant differences were found between SWL1 and SWL2 in either parameter.

Patterns of change in growth, yield, physicochemical properties, and LUE and EUE of tomatoes. Figure 2 summarizes the overall changes in fruit characteristics of tomato plants cultivated under R+B and three types of white light treatments in indoor farming systems. Overall, white light treatments outperformed R+B across most traits, including growth, fruit quality, and resource use efficiency. Among the white light treatments, SWL1 exhibited the highest values in fruit production, quality, and efficiency parameters, except for traits related to fruit acidity. However, pH and acidity did not differ significantly among all treatments. Hierarchical cluster analysis, although not shown, indicated that NWL showed a response pattern similar to that of SWL2. Taken together, the results suggest that light sources with modified spectral peaks—particularly those with enhanced green wavelengths as in SWL1—can improve the overall performance of tomato plants in indoor farming systems.

Correlation of growth and qualities by light combination. Figure 3 presents the analysis of correlations among fruit characteristics, quality, and resource use efficiency of tomatoes under various light sources. Variables related to the growth of the aerial parts of tomatoes, antioxidant activity, and resource use efficiency showed positive correlations with each other. In contrast, pH and acidity exhibited negative correlations with these variables. Specifically, pH was negatively correlated with all variables except acidity, whereas acidity was negatively correlated with all variables except those indicating antioxidant activity. Fruit number and total yield were strongly correlated with Brix, antioxidant activity, LUE, and EUE. In addition, Brix was positively correlated with the antioxidant activity of tomato fruits.

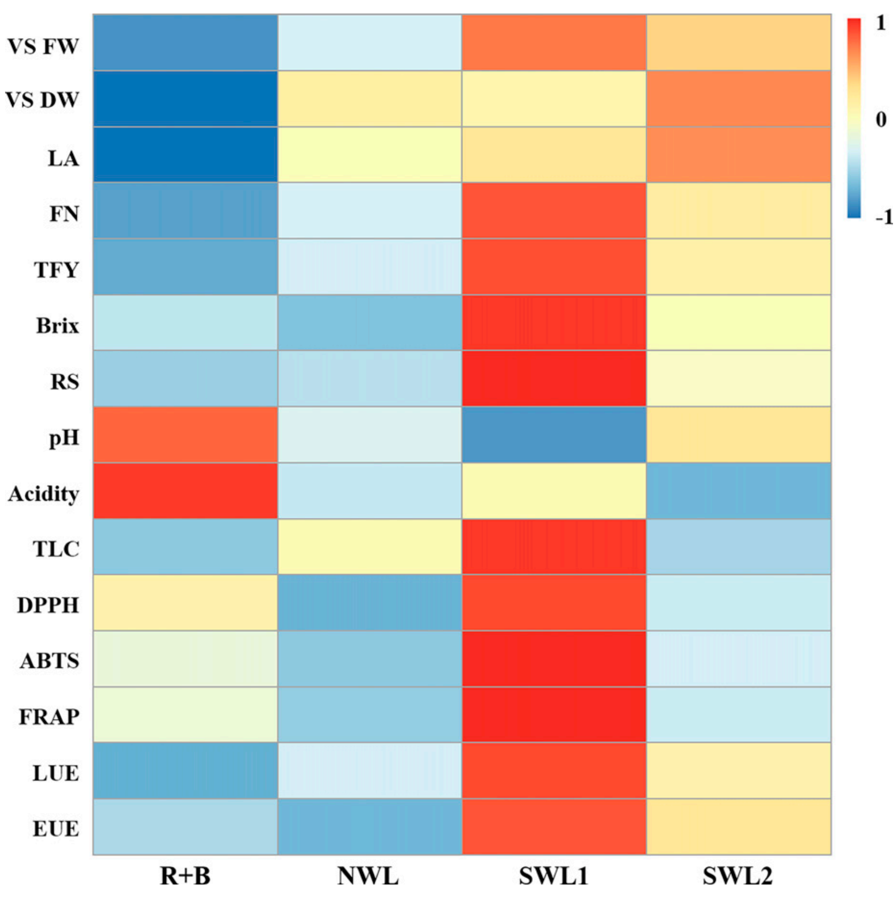

Fig. 2. Heatmap summarizing changes in vegetative growth, yield, physicochemical properties, and light and energy use efficiency of tomatoes grown for 13 weeks under four light spectrum designs in an indoor farm: a red+blue spectrum (R+B), a broad-spectrum white light-emitting diode (LED) (NWL), a red-enriched white LED with long-wavelength green (SWL1), and a blue-enriched white LED with short-wavelength green (SWL2). Parameters include vegetative shoot fresh weight (VS FW), vegetative shoot dry weight (VS DW), leaf area (LA), fruit number (FN), total fruit yield (TFY), photosynthetic rate (Pn), soluble solids content (°Brix), total lycopene concentration (TLC), DPPH radical scavenging activity (DPPH), ABTS radical scavenging activity (ABTS), ferric reducing antioxidant power (FRAP), light use efficiency (LUE), and energy use efficiency (EUE). Data represent mean values (n = 4).

Discussion

LED technology is widely used in indoor farming systems to enhance plant growth, fruit quality, metabolite accumulation, antioxidant activity, and LUE and EUE (Liu et al. 2017; Nguyen et al. 2021; Zheng et al. 2021). To develop an effective LED lighting strategy with an optimal combination of spectral wavelengths for promoting tomato growth and development in indoor farming systems, and to improve light and EUE, we compared the performances of white light. The spectral differences among treatments primarily involved shorter peak wavelengths in the blue and green regions of white LEDs, compared with the R+B (red+blue). All treatments shared the same red peak wavelength of 660 nm, allowing for a direct comparison of the effects of blue and green spectral shifts. Our study confirmed that the spectral modification of green wavelengths in white LEDs, spectral modification with shorter blue and green wavelengths enhanced tomato growth during both vegetative and fruiting stages. In particular, short-wavelength white light achieved higher LUE and EUE than broad-spectrum white light or R+B in indoor farming systems.

Green-inclusive white light increased vegetative shoot dry weight and leaf area compared which R+B, likely due to spectral tuning of green wavelengths. This agrees with previous reports that ~35% to 37% green light in R+B spectra promotes tomato growth (Monte et al. 2013; Kaiser et al. 2024) and that white light increases vegetative growth in cherry tomato (Liu et al. 2009). The enhanced leaf area under white light may be attributed to green light–

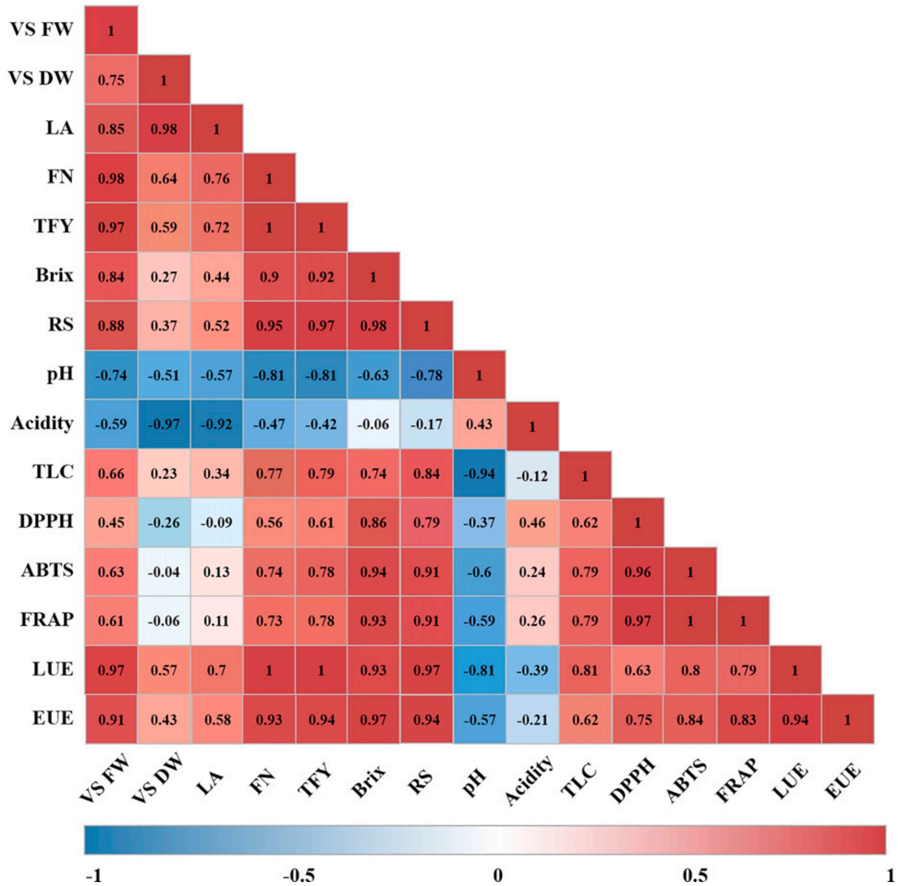

Fig. 3. Pearson correlation analysis among growth, fruit quality, and resource use efficiency parameters of tomatoes grown for 13 weeks under four light spectrum designs in an indoor farm: a red+blue spectrum (R+B), a broad-spectrum white light-emitting diode (LED) (NWL), a red-enriched white LED with long-wavelength green (SWL1), and a blue-enriched white LED with short-wavelength green (SWL2). Variables analyzed include vegetative shoot fresh weight (VS FW), vegetative shoot dry weight (VS DW), leaf area (LA), fruit number (FN), total fruit yield (TFY), photosynthetic rate (Pn), soluble solids content (°Brix), reducing sugar (RS), total lycopene concentration (TLC), DPPH radical scavenging activity (DPPH), ABTS radical scavenging activity (ABTS), ferric reducing antioxidant power (FRAP), light use efficiency (LUE), and energy use efficiency (EUE).

induced shade-avoidance responses, such as increased petiole length and specific leaf area (Chen et al. 2024). These responses improve light interception within the canopy, consistent with the positive correlation observed between leaf area and LUE in our study.

The final commercial value of tomatoes is primarily determined by fruit yield and quality. Fruit quality includes physical traits (size, color, and texture) and sensory/nutritional attributes (flavor, acidity, taste, health-related compounds) (Dzakovich et al. 2015). Red-enriched spectrum with long-wavelength green increased soluble solids (4.3°Brix), within the commercially desirable 4.0°–6.0° range for tomatoes (Cramer et al. 2001), and aligns with previous findings that LED lighting can enhance the accumulation of soluble solids in tomato fruit (Kowalczyk et al. 2012). In addition to sugar content, fruit acidity plays a major role in flavor perception and product quality. The optimal pH of ripe tomatoes is ∼4.25 (Monti 1979), and pH tends to decrease during the ripening process due to reductions in malic and citric acid concentrations (Anthon et al. 2011). In this study, spectral modification in blue and green regions did not significantly affect pH or acidity, consistent with Dzakovich et al. (2015). Regarding fruit production and sugar-related traits, the blue and/or green wavelength-specific white LED design (SWL1 and SWL2) led to increased fruit number, total yield, °Brix, and reducing sugar content compared with other treatments. This trend may be related to physiological adjustments in response to short-wavelength light stress, as plants modulate their metabolism and growth as part of a photoprotective response (Nguyen et al. 2021).

Antioxidants inhibit reactive oxygen species, such as superoxide anion radicals, hydroxyl radicals, and hydrogen peroxide, thereby protecting cells from oxidative stress (Ames et al. 1993; García-Sánchez et al. 2020; Sies and Jones 2020). Tomatoes are rich sources of natural antioxidants, including carotenoids, lycopene, anthocyanins, and various bioactive compounds (Arballo et al. 2021; Vlaisavljević et al. 2019). Carotenoids play essential roles in photosynthesis, photoprotection, and development and contribute to human health as pigments, antioxidants, and provitamin A (Nisar et al. 2015). Lycopene, a red carotenoid pigment, has been associated with reduced risks of several cancers, including prostate and breast cancer (Arballo et al. 2021). Short-wavelength white light enhanced lycopene accumulation, likely by stimulating carotenoid biosynthesis via upregulation of key genes (PSY, PDS, β-LCY) (Frede and Baldermann 2022). Furthermore, blue light and ultraviolet activate photoreceptors that induce secondary metabolite accumulation, including carotenoids, via plastid development and metabolic regulation (Kim and Eom 2025). Thus, elevated lycopene likely contributed to the enhanced antioxidant activity under red-enriched spectrum with long-wavelength green. Previous studies have shown that blue light stimulates proline accumulation and antioxidant responses in tomato (Kim et al. 2013), and combinations of R and B light increase antioxidant properties in lettuce and medicinal plants (Ahmadi et al. 2021; Son and Oh 2013, 2015). In our study, green wavelength-specific light resulted in the highest ABTS and FRAP values among all treatments, consistent with reports of high antioxidant activity under RGB light combinations (Hasan et al. 2017). Although DPPH scavenging activity did not significantly differ between spectrum enriched in red and long-wavelength green and R+B spectrum, broad-spectrum white light showed significantly lower activity than R+B. Green light has been reported to enhance anthocyanin biosynthesis in leafy vegetables (Liu et al. 2017), and this may have contributed to the increased antioxidant potential in warm-white spectrum emphasizing red and long-green. However, other white light did not show significant improvements compared with R+B, suggesting that the observed effects are specific to peak wavelength optimization. These findings highlight the importance of spectral design in LED lighting and underscore the need for further studies on precise wavelength manipulation to improve fruit quality in indoor tomato cultivation.

Indoor farming systems incur significant operational costs, prompting growers to seek ways to minimize these expenses, particularly lighting costs. Consequently, research aimed at reducing lighting costs has been actively conducted. Recent studies have demonstrated that using white LEDs to light tomato-grafted transplants can result in substantial energy savings (Zheng et al. 2021). Park et al. (2018) revealed that the white light combination in a 70% ratio reduced the environmental stress and saved more power during plant cultivation in indoor farming systems. Furthermore, EUE in basil leaves was reduced under R+B LEDs when the R light rate was increased (Poulet et al. 2014). However, Piovene et al. (2015) revealed similar energy consumption for both white LEDs and R+B LED treatments. This aligns with reports that white light can achieve low energy consumption and high EUE in tomatoes (Son et al. 2016). In the study, wavelength-specific LED designs consumed similar energy to R+B but achieved significantly higher LUE and EUE than both R+B and broad-spectrum white light, indicating it is the most efficient option for tomato cultivation in indoor farming systems.

Conclusion

In this study, we evaluated tomato growth and fruit quality under red+blue, white LEDs, and two specially designed spectra. The red-enriched spectrum with long-wavelength green produced the greatest improvements in shoot growth, yield, sugar accumulation, reduced acidity, and lycopene content, indicating its superiority as a spectral design. In contrast, the blue-enriched spectrum with short-wavelength green showed no significant advantage over the red+blue or typical white spectra. Overall, our findings demonstrate that combining red and long-wavelength green light is a more effective strategy for optimizing tomato production in indoor farming systems.

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