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Growth, Fruit Yield, and Bioactive Compounds of Cherry Tomato in Response to Specific White-Based Full-Spectrum Supplemental LED Lighting

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Abstract: Supplemental artificial light in greenhouses is fundamental to achieving sustainable crop production with high yield and quality. This study's purpose was to investigate the efficacy of supplemental light (SL) sources on the vegetative and reproductive growth of cherry tomatoes. Four types of light sources were applied, including high-pressure sodium lamps (HPS), a narrow-spectrum LED light (NSL), and two specific full-spectrum LED lights (SFL1 and SFL2) with a shorter blue peak wavelength (436 nm) and/or green peak wavelength (526 nm). The control was the natural light condition. Shoot fresh and dry weight and leaf area in the SFL1 and SFL2 treatments were greater than those in the control. The HPS and NSL treatments also enhanced tomato growth, but they were less efficient compared to the SFL treatments. The SFL1 and SFL2 treatments showed higher fruit yields by 73.1% and 70.7%, respectively, than the control. The SL sources did not affect the effective photochemical quantum yield of photosystem II (Y (II)). However, they did trigger the increased electron transport rate (ETR) and non-photochemical quenching (NPQ). The SFL treatments enhanced tomato growth, fruit yield, and efficient use of light and energy, suggesting that the specific full spectrum based on the short-wavelength blue and/or green peak can be successfully applied for the cultivation of cherry tomato and other crops in greenhouses.

Keywords: cherry tomato; energy use efficiency; fruit yield; growth; HPS; LEDs; light use efficiency; supplemental light

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1. Introduction

Greenhouses are one of the most advanced agriculture systems. Initially, they were developed for growing crops in cold regions to prevent low-temperature exposure in the winter. Recently, greenhouse technology has rapidly spread, providing better environmental management, higher resource use efficiency, and high-technology application [1]. This minimizes the adverse environmental effects and produces crops with higher quantity, better quality, and stability of year-round production [2]. The commercial greenhouse has widely been applied for cultivating leafy and fruiting vegetables. Generally, an ideal greenhouse can be implemented by increasing light input, reducing heat loss in the winter, and increasing heat removal in the summer [3]. However, the structure and covering materials limit available natural light for the plants in the greenhouse, causing a light intensity reduction by about 20–30% inside the greenhouse compared to outside [4]. In addition, the high-wire production system and the high planting densities for the cultivation of fruiting

plants have a strong shading effect on leaves under the plant canopy and dramatically depress photosynthesis processes in the lower canopy [5]. Therefore, designing proper greenhouse lighting is important for improving crop production [6].

Applying SL sources in a greenhouse is an effective method to optimize the lighting environment and plant growth. Artificial lighting systems significantly contribute to the energy and operation cost of greenhouses [7]. The SL is typically used during the winter season due to the limit of solar radiation for light interception by plants. However, some cloudy and rainy days in the other seasons can also cause reduced DLI (daily light integral), as in the winter [8]. Hence, SL can be effectively used to maintain year-round crop production on a tight schedule (fall–winter and spring–summer). Until recently, HPS lamps have been the most popular SL source in the greenhouse due to their high electrical efficiency—about 30–40% [9]. A weak point of HPS lamps is the spectrum, in that they emit most strongly in the yellow and orange regions, which do not match with the absorbance of the pigments for photosynthesis [10]. Recently, light-emitting diodes (LEDs), which can provide any desired broad spectrum with narrow spectra, have been rapidly deployed in the horticultural lighting field. Moreover, the dramatic performance improvement and cost reduction in the LED industry allowed for extensive application of supplemental LED lights, which could efficiently enhance plant growth, crop yields, and energy efficiency [11,12].

Tomato (*Solanum lycopersicum* L.) is a fruiting vegetable widely grown and consumed globally [13]. Tomato can be cultivated in greenhouses under controlled microclimatic conditions throughout the year [14] and is considered a model plant for studying newly developed techniques in the greenhouse [15]. The plant canopy is increased to intercept as much light as possible for the whole-plant photosynthesis and productivity. HPS lamps are a conventional SL source for growing tomato seedlings [16]. Meanwhile, the usefulness of LED lighting systems in qualitatively and quantitatively improving tomato production in a greenhouse has recently been reported [17–20]. Tomato plants under LED showed higher gas exchange and photosynthetic capacity compared to HPS, and those grown under LED lights exhibit more vegetative growth and have longer vigor than plants grown under HPS lamps, while HPS lamps stimulate more generation and early production but with faster senesce [21,22]. The LED SL in the form of toplighting and/or interlighting has the highest light-use efficiency and the most favorable surplus of all the variable costs over the value of production compared to HPS lamps or the HPS–LED combination [23]. The supplement of LED interlighting in the spring and summer season positively affected tomato growth and fruit yield [24].

The necessity of the R and B LED combination for growing tomatoes in a greenhouse has been confirmed [25–27]. In addition, the white (W) LED light is an efficient SL source in tomato production in greenhouses [28]. This study evaluated the role of various SL sources on cherry tomato cultivation, including HPS lamps, narrow-spectrum LEDs (NSL) with R and B combination, and two specific full-spectrum or W light LEDs (SFL). The new SFL sources were built with phosphor-converted W LEDs that contain short-wavelength (436 nm) blue emitter and/or green emitter (526 nm), in combination with deep red (660 nm) LEDs. The short-wavelength blue-based W LED was recently developed by Samsung Electronics. This spectrum is extraordinary because most W LEDs commercially available on the market are based on a 450 nm blue emitter, which is optimized for human vision, thus for general illumination. The SFL sources have been tested and found superior in enhancing lettuce growth and increasing light and energy use efficiency in vertical farming [29]. We conducted this study to investigate the broad application of SFLs on growing tomatoes.

2. Materials and Methods

2.1. Plant Materials and Growth Conditions

A semi-closed greenhouse at the Gyeongsang National University, Jinju, Korea (35°09′38″ N, 128°04′39″ E; altitude, 44 m) was used to cultivate cherry tomato (*Solanum lycopersicum* L.,

cv. 'Berry King'), and the experiment was conducted from 26 May 2021 to 27 July 2021. Forty-three-day-old tomato seedlings with two true leaves were transplanted into rock wool slabs (Grotop Master, Grodan, The Netherlands) with a density of 2.5 plants m^{-2} on 8 June 2021. An automatic drip irrigation hydroponic system (Win-7000S, Woosung Hitec, Korea) was applied. The plants were irrigated with nutrient solution at an electrical conductivity of 2.0~2.2 dS m^{-1} and pH of 5.5~6.0 (Table 1). The growing conditions were controlled during the experiment at an average temperature of 28.8 ± 14 °C and humidity of 76 ± 20%. Cherry tomato plants per treatment were cultivated for 49 days after treatment.

Table 1. Nutrient solution components for cherry tomatoes used in this study.

Type	Chemical	Amount (g 1000 L^{-1})
A	KNO_3	20,200
	$Ca(NO_3)_2 \cdot 4H_2O$	35,400
	Fe-EDTA	1500
B	KNO_3	20,200
	$NH_4H_2PO_4$	7600
	$MgSO_4 \cdot 7H_2O$	24,600
	H_3BO_3	114
	$MnSO_4 \cdot 4H_2O$	81
	$ZnSO_4 \cdot 7H_2O$	9
	$CuSO_4 \cdot 5H_2O$	4
	$Na_2MoO_4 \cdot 2H_2O$	1

2.2. Experimental Design and Light Treatment

The two middle rows were divided into five plots via white curtains impenetrable to light. Four SL treatments were installed over the four plots: HPS lamps (SON-T Agro, Philips, Amsterdam, The Netherlands; 250 W), NSL (Models LH351H Blue 450 nm and LH351H Deep Red 660 nm V2; Samsung Electronics, Suwon, Korea; 104 W), and SFL1 and SFL2 (Models LM301H EVO and LM301H EVO Mint White, respectively, with LH351H Deep Red 660 nm V2; Samsung Electronics, Suwon, Korea; 100 W) (Table 2 and Figure 1). Two fixtures of same type were installed per treatment above the canopy. The natural light condition in the greenhouse was used as control. We used a translucent sunscreen with 50% of transmittance over the whole area for cultivation to mimic the natural light condition of the fall–winter season (poor natural light condition). For the analysis of the spectral composition and the R, G, B ratio of each light source, the spectral distribution was measured at five positions on a horizontal plane at the height of 50 cm below the light source by a portable spectroradiometer (LI-180; Li-Cor, Lincoln, NE, USA). All light sources were set above the top of the canopy (at a distance of 1 m). The light intensities measured in the middle canopy of HPS, NSL, SFL1, and SFL2 were 152.60, 138.33, 117.37, and 112.14 μmol m^{-2} s^{-1}, respectively. The photon flux density was comparable but was not evenly regulated across the four treatments due to the non-dimmable feature of the fixtures used for the experiment. The fixtures for HPS lamps had a parabolic reflector surrounding the lamp, resulting in a concentrated light distribution below the fixtures. In contrast, the other three types of LED fixtures did not have any beam-forming optics, resulting in a wider radiation pattern compared to the HPS fixtures—130° with NSL and 120° with SFLs.

The SL treatment was activated for 8 h per day (09:00–16:00). A quantum sensor (LI-191SA; LI-COR Biosciences, Lincoln, NE, USA) was installed in the middle of the plants. Based on the outdoor global radiation, DLI was calculated with a conversion factor and a light transmission factor for the greenhouse of 2.2 μmol J^{-1} and 0.7, respectively. The DLI of the natural light (control) and treatments received by the plants were on average 8.34 and 6.85 mol m^{-2} d^{-1}, respectively. Thus, total DLIs (natural light + SL) in the canopy from the control, HPS, NSL, SFL1, and SFL2 were 8.34, 11.24, 10.83, 10.23, and 10.08, respectively.

Table 2. Peak wavelengths and spectral ratio of each SL source.

Light Source [z]	Range (nm)	Peak Wavelength (nm)	Ratio (%)
HPS	Blue (380–499)	497	7
	Green (500–599)	597	49
	Red (600–700)	600	44
NSL	Blue (380–499)	450	30
	Green (500–599)	0	0
	Red (600–700)	660	70
SFL1	Blue (380–499)	436	16
	Green (500–599)	585	36
	Red (600–700)	660	48
SFL2	Blue (380–499)	436	27
	Green (500–599)	524	37
	Red (600–700)	660	36

[z] HPS, high-pressure sodium lamps; NSL, narrow-spectrum LEDs; SFL, specific full-spectrum or W light sources.

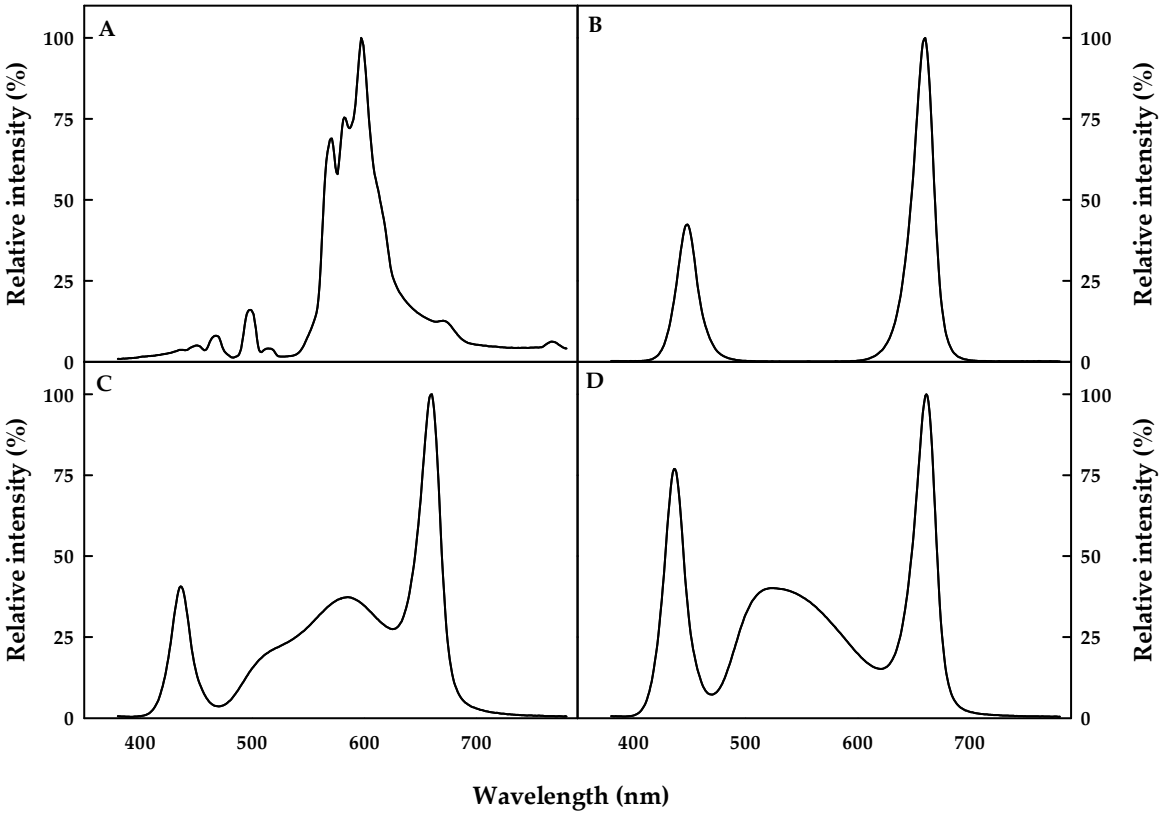

Figure 1. Relative intensity of each SL source. HPS, high-pressure sodium lamps (**A**); NSL, narrow-spectrum LEDs (**B**); SFL1, specific full-spectrum LED 1 (**C**); and SFL2, specific full-spectrum LED 2 (**D**).

2.3. Growth Characteristics and Harvest

The growth characteristics of the cherry tomatoes were measured after 7 weeks of 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 days in an oven (WOF-155; Daihan, Korea) to measure the dry weight. Leaf area was calculated by ImageJ software. Ripened fruits (grade 8–9 in scale of 1–12; Bama AS) were harvested from the 5th week after treatment (2 times each week). Final destructive harvests were performed in the 7th week.

2.4. Optical Properties (Absorbance and Transmittance)

After 6 weeks of treatment, the optical properties (absorbance and transmittance) of fully expanded leaves of the tomato plants were measured by a spectroradiometer (LI-180 Spectrometer, Li-COR Biosciences, Lincoln, NE, USA) and recorded by spectrometer operating software. The measurements were conducted under conditions with and without sunlight.

2.5. Chlorophyll Fluorescence and Electron Transport Rate

Five fully developed leaves per plant from the top canopy and five plants per treatment were used to measure chlorophyll fluorescence, including Y (II), NPQ, and ETR. PAM-2100 chlorophyll fluorometer (Heinz Walz GmbH, Effeltrich, Germany) was used to measure these parameters on the 40th day of treatment.

Y (II): Effective quantum yield of photosystem II.
NPQ: Non-photochemical quenching.
ETR: Electron transport rate.

2.6. Individual Phenolic Acid and Flavonol Analysis

To determine the individual phenolic acid and flavonol of the fruits, cherry tomato fruits were collected three times before harvest. Each replicate consisted of five tomato fruits in each treatment. The methods for measuring individual phenolic acid and flavonol contents were described in our previous study [29].

2.7. Light and Energy Use Efficiency

The light and energy use efficiency (LUE and EUE, respectively) were calculated as fresh fruit weight per photosynthetic photon that plants received and per electrical energy unit consumed by lamps.

2.8. Statistical Analysis

Six tomato plants per treatment were harvested for growth measurements and analyzed. Statistical data were analyzed by SAS 9.2 program (SAS Institute Inc., Cary, NC, USA) with variance analysis. Duncan's multiple range test was used to verify the significant differences in all treatments at $p < 0.05$.

3. Results

3.1. Growth Characteristics

The various SL sources significantly increased tomato growth in the greenhouse compared to without SL (Figure 2). The improvement of crop yields by SL was as expected as we reduced the DLI from the natural light using a sunscreen as if we performed the experiment in the winter season. The tomato shoot fresh and dry weights were increased by ~1.5 and 1.6 times, respectively, in the SFL1 and SFL2 treatments compared to those of plants in the control (Figure 2A,B). The SFL1 and SFL2 treatments also increased the leaf area of tomato by 38.2% and 45.2%, respectively, compared to the control (Figure 2C). The tomatoes grown in the supplement of HPS and NSL lights also exhibited significantly enhanced growth compared to the control but showed lower values than the SFL1 and SFL2 treatments. The total fruit yield was remarkably increased by 73.1% and 70.7% with the SFL1 and SFL2 treatments compared to the control (Figure 2D). The fruit yields from HPS and NSL treatments were slightly lower than those from the SFL1 and SFL2 treatments, but the difference was not statistically significant.

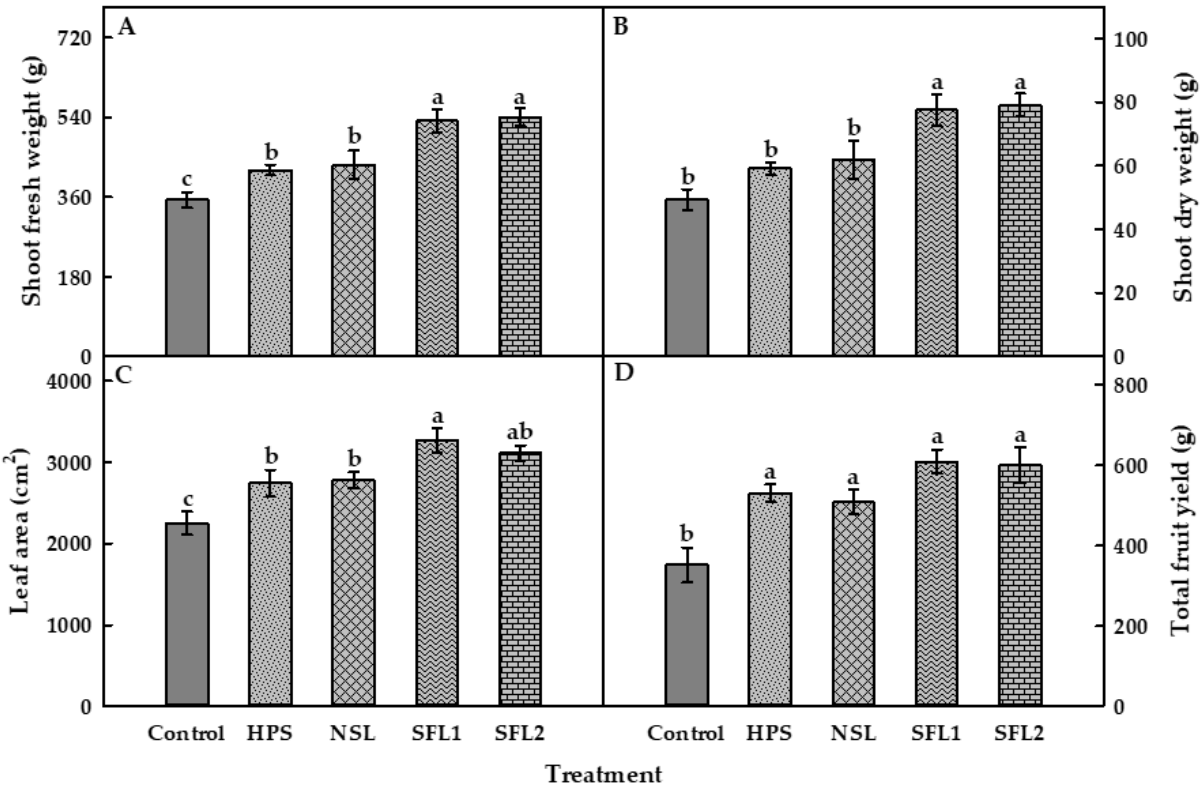

Figure 2. Shoot fresh (**A**) and dry (**B**) weights, leaf area (**C**), and total fruit yield (**D**) of cherry tomato plants grown in different SL sources after 7 weeks of treatment. Control, natural light; HPS, high-pressure sodium lamps; NSL, narrow-spectrum LEDs; SFL, specific full-spectrum or W light sources. Different letters above the bars indicate significant difference at $p < 0.05$ ($n = 6$). Each value in the figure is the mean of 6 replicates (per plant) for each SL source. Total fruit yield was calculated with 5 clusters at each plant.

3.2. Absorbance and Transmittance

Table 3 presents the absorbance and transmittance of the tomato leaves. Under the sunlight (daytime), higher absorbance and lower transmittance of B, G, and R wavelengths were observed in the SL treatments compared to the control (with sunlight). The B, G, and R absorbances were highest in the SFL2 treatment, followed by the NSL treatment and then the HPS and SFL1 treatments. In contrast, the transmittance was highest in the HPS and SFL1 treatments. Without sunlight, the absorbances of all three spectrum ranges were highest in the NSL treatment. Compared to the HPS treatment, the SFL1 and SFL2 treatments had a similar B absorbance, while slightly decreased R and G absorbances were found in the SFL1 and SFL2 treatments. The G transmittance in the NSL, SFL1, and SFL2 treatments was greater than in the HPS treatment.

3.3. Chlorophyll Fluorescence and Electron Transport Rate

The results of Y (II), NPQ, and ETR are shown in Figure 3. The tomatoes grown with the supplemental light sources had a higher NPQ value by 47~61% compared to the control (Figure 3A). The ETR value was increased by 38~48% for the SL sources compared to control (Figure 3B). The SL sources did not affect the Y (II) value of the tomatoes (Figure 3C).

3.4. Light and Energy Use Efficiency

Table 4 presents the energy consumption, LUE, and EUE of each light source. The NSL, SFL1, and SFL2 consumed less than half of the energy consumed by the HPS. Compared to the LUE in the HPS treatment, the LUE in NSL was not significantly different, although it showed a higher value. Meanwhile, the SFL1 and SFL2 treatments increased the LUE by

1.43 and 1.38 times compared to the HPS and NSL treatments, respectively. A similar result was observed for the EUE. The EUE in the NSL treatment was ~130% higher than in the HPS treatment. Meanwhile, the EUE values in the SFL1 and SFL2 treatments were higher than that in the HPS treatment by 186.8% and 183%, respectively. In short, the LUE and EUE were significantly increased in the SFL treatments.

Table 3. Absorbance and transmittance of tomato plants grown in different SL sources after 7 weeks of treatment.

	Light Sources [z]	Absorbance (%)			Transmittance (%)		
		Blue (380–499 nm)	Green (500–599 nm)	Red (600–700 nm)	Blue (380–499 nm)	Green (500–599 nm)	Red (600–700 nm)
With sunlight	Control	78	74	63	22	26	37
	HPS	86	91	85	14	9	15
	NSL	91	71	90	9	29	10
	SFL1	83	86	86	17	14	14
	SFL2	92	91	86	8	9	14
Without sunlight	HPS	96	94	91	4	6	9
	NSL	99	95	98	1	5	2
	SFL1	96	92	94	4	8	6
	SFL2	96	92	94	4	8	6

[z] Control, natural light; HPS, high-pressure sodium lamps; NSL, narrow-spectrum LEDs; SFL, specific full-spectrum or W light sources.

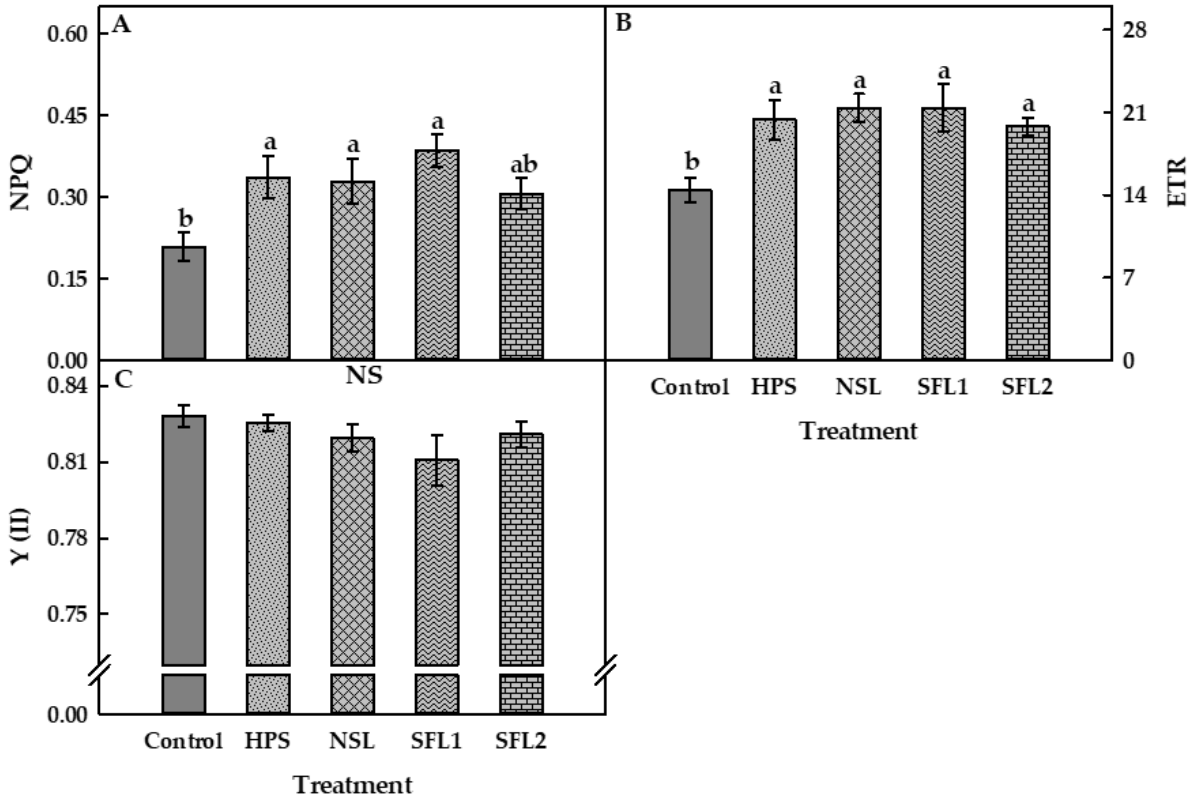

Figure 3. NPQ (**A**), ETR (**B**), and Y (II) (**C**) of cherry tomato plants grown with different SL sources after 7 weeks of treatment. Control, natural light; HPS, high-pressure sodium lamps; NSL, narrow-spectrum LEDs; SFL, specific full-spectrum or W light sources. Different letters above the bars indicate a significant difference at $p < 0.05$ ($n = 5$). NS; not significant.

Table 4. Light and energy use efficiency of the cherry tomato plants grown with different SL sources after 7 weeks of treatment.

Light Source	Energy Consumption (Watt)	Light Use Efficiency (g FW mol^{-1})	Energy Use Efficiency (g FW kWh^{-1})
HPS	250	4.01 b [z]	2.12 c
NSL	104	4.14 b	4.88 b
SFL1	100	5.72 a	6.08 a
SFL2	100	5.72 a	6.00 a

HPS, high-pressure sodium lamps; NSL, narrow-spectrum LEDs; SFL, specific full-spectrum or W light sources. [z] Means within the column followed by different letters are significantly different by analysis of variance (ANOVA) test at $p \leq 0.05$.

3.5. Individual Phenolic and Flavonol Contents

The harvested fruits were analyzed for 10 individual phenolic acids and 11 flavonols to evaluate the quality of the cherry tomatoes grown with various light sources (Table 5). The SL treatments significantly stimulated the biosynthesis of some individual phenolic acids, including chlorogenic, p-Hydrobenzoic, ferulic, ventaric, and benzoic acids, compared to the control without SL. Chlorogenic acid was the most predominant phenolic acid and was significantly increased in the SL treatments. The chlorogenic acid content was highest in the SFL2 treatment. Meanwhile, the contents of some flavonols, including epigallocatechin, catechin, epicatechin, quercetin, naringin, and formononetin, were considerably increased in the SL treatments. The quercetin content was the highest among the flavonols, followed by epigallocatechin, catechin, and rutin contents. Total flavonol contents in the SFL1 and SFL2 treatments were higher than the HPS and NSL treatments.

Table 5. Individual phenolic acid and flavonol contents of the cherry tomato fruits grown with different SL sources after 7 weeks of treatment. Different letters indicate significant difference at $p < 0.05$ ($n = 5$).

Individual Compound Contents (g $plant^{-1}$)		Supplemental Light Source									
		Control		HPS		NSL		SFL1		SFL2	
Phenolic acids	Gallic acid	7.07	c [z]	9.11	bc	8.62	c	10.97	ab	11.73	a
	Protocatechuic acid	0.79	b	0.86	b	0.86	b	1.18	a	0.70	b
	Chlorogenic acid	32.80	c	62.29	b	64.06	b	64.25	b	78.93	a
	p-Hydrobenzoic acid	7.47	b	13.39	a	11.00	a	13.17	a	12.93	a
	Vanillic acid	1.36	b	3.02	a	2.90	a	n.d.		n.d.	
	p-Coumaric acid	0.78	c	1.91	a	1.17	b	1.12	b	0.77	c
	Ferulic acid	1.74	c	4.43	a	4.11	ab	3.57	b	4.20	ab
	Ventaric acid	1.93	c	4.73	b	6.92	a	6.48	a	6.51	a
	Benzoic acid	12.07	c	20.84	b	18.12	b	20.80	b	32.25	a
	trans-Cinnamic acid	2.53	a	3.16	a	0.47	b	3.00	a	2.84	a
	Total	68.54382		123.7343		118.2031		124.542		150.8515	
Flavonols	Epigallocatechin	490.15	c	708.39	b	699.55	b	784.91	b	945.71	a
	Catechin	317.55	b	537.12	a	473.16	a	566.82	a	540.95	a
	Epicatechin	71.10	b	118.25	a	97.67	a	117.09	a	107.56	a
	Epigallocatechin gallate	38.39	c	45.89	c	87.28	a	58.91	b	37.41	c
	Vanillin	6.06	b	5.48	b	5.25	b	12.52	a	n.d.	
	Rutin	319.69	c	551.42	a	416.01	b	459.14	b	377.43	bc
	Catechin gallate	35.08	c	62.87	b	54.91	b	54.42	b	80.23	a
	Quercetin	546.59	b	873.46	a	905.17	a	1012.09	a	1036.47	a
	Naringin	35.11	b	65.62	a	62.30	a	59.18	a	64.28	a
	Naringenin	263.87	b	347.12	a	327.31	ab	325.29	ab	318.66	ab
	Formononetin	21.36	b	39.49	a	27.34	b	41.54	a	38.46	a
	Total	2144.95		3355.10		3155.96		3491.90		3547.14	

Control, natural light; HPS, high-pressure sodium lamps; NSL, narrow-spectrum LEDs; SFL, specific full-spectrum or W light sources. [z] Mean separation within rows according to Duncan's multiple range test at $p < 0.05$. n.d.; Not detected.

4. Discussion

It is known that the SL increases leaf photosynthesis, plant growth, yield, and quality [30–32]. The application of HPS and LED sources for growing tomato in a greenhouse has been evaluated [20]. In the present study, SL significantly affected the vegetative growth and reproductive parameters of tomatoes. Leaf morphology (reflected by leaf area and thickness) mainly contributes to leaf mass and closely correlates with light interception and photosynthesis. Thicker leaves enable a higher level of photosynthetic apparatus, while broad and thinner leaves allow greater light interception [33,34]. In the present study, the SL sources significantly increased leaf area, and the SFL treatments resulted in the highest value. Kim et al. [20] reported that LED light sources increased leaf mass per area compared to HPS and without supplemental lighting, and the leaf mass area tended to increase in B or high far-red lights added to R light. Monochromatic B light or higher amounts of B in the R and B combination significantly increase the thickness of leaves and leaf layers, while R light resulted in higher leaf dry mass and area [20,35,36]. In addition, the combination of green (G), R, and B lights can inhibit the B light response [37], making the suppression of leaf expansion of B light less effective [38]. The supplement of G LEDs to HPS lamp lighting enhanced fresh and dry weights, leaf area, and pigment concentration in tomato, sweet pepper, and cucumber [39]. The SFL sources were a combination of R light and shorter wavelengths of B and G lights, which resulted in a remarkable impact on tomato vegetative growth compared to the NSL, HPS, and control. In addition to the effect of light spectra, the PPFD and DLI are vital light conditions for plant growth, and the plant biomass generally increases as the PPFD and DLI increase [27]. However, Fan et al. [27] also reported that excessively increased DLI enhanced the photosynthetic rate but did not result in greater biomass. Hence, it is necessary to provide adequate PPDF and DLI for efficient plant production. The PPFD and DLI levels of the SL treatments in this study were not completely equalized. In particular, the HPS treatment provided a relatively higher PPFD compared to the NSL and SFL treatments. Nevertheless, the total DLI was not substantially different between the SL treatments; therefore, we do not believe that there is any treatment condition, especially the HPS treatment, where the plants' response becomes saturated. Most importantly, the SFL treatments resulted in superior plant growth even though they had a lower PPFD and total DLI. Our previous research also revealed that specific W LED light significantly improved growth and individual phenolic/flavonol contents in lettuce cultivars [29].

Chlorophyll fluorescence analysis is a powerful method to measure the efficiency of PS II and has been widely used to assess the effect of stressful conditions on plant responses [40]. NPQ is a mechanism in plants that helps convert excess excitation energy to harmless heat, which minimizes the damage to the photosynthetic apparatus due to the excessively absorbed energy [41]. However, it is necessary to increase photosynthesis and reduce NPQ by optimizing light spectra for growing plants in non-stressful conditions in a greenhouse [42]. It is known that the absorbance of R and B lights by photosynthetic pigments is closely linked to the NPQ activation [43]. Therefore, supplementing G light to the R and B combination is considered to efficiently enhance photosynthesis in the leaf canopy and prevent NPQ activation. Trojak and Skowron [44] reported that R and B lights enhanced the NPQ amplitude of tomato. In contrast, G and W lights showed a lower NPQ value due to the decrease in NPQ-related protein, PS II subunit S, proton gradient regulation-like 1, cytochrome *b6f* subunit *f*, and violaxanthin de-epoxidase. B LED light also causes a significant increase in NPQ of pepper plants, indicating that the protection mechanisms of PS II in plants are increased in blue light by dissipating excessive energy to heat [45]. In our study, the tomato plants grown under SL sources had higher NPQ values, and the high NPQ value in the SFL treatments reflected the plant mechanisms to protect the photosynthetic apparatus from the high energy of the shorter B wavelength in specific full-spectrum lights. Furthermore, the actual captured energy of the PS II was evaluated by measuring Y (II) [46]. No significant difference in Y (II) was obtained among the treatments, although a slightly lower value was obtained in the SFL treatments.

The supplemental light source enhanced the electron transport rate, a light-acclimated parameter. The high absorbance of B and R lights and high penetration of green light of plants in the SFL treatments positively affected ETR, which subsequently activated the photosynthesis processes of the inner leaf and carboxylation activity of RuBisCo [47].

The vegetative growth of tomatoes happens in the top and middle canopy, while the reproductive growth or fruit occurs in the middle or bottom of the canopy. In addition, most tomato yield increases in the early production stage and eventually decreases later. The higher plant height and larger canopy promote the light absorption area and subsequently enhance photosynthesis and light use efficiency [48]. Tomato fruit is considered a functional food and economic product widely consumed globally [49,50]. Tomato fruit dry mass in the HPS lamp treatment was similar to tomatoes grown with LEDs [23]. Dzakovich et al. [18] found that the LEDs did not influence tomato fruit quality. However, yield response is highly related to the spectra of the light sources. It has been proven that the SL of W or R LEDs effectively promotes the growth of tomato fruit compared to B LEDs, and W light was the most efficient light source [28]. In the present study, the SLs tended to significantly increase the total fruit yield compared to the control without any SL. Although the difference was small, supplementary SFL sources tended to increase the fruit yield of tomatoes further compared to the HPS and NSL. This finding is significant considering the PPFD and DLI for the SFL treatments were lower than those of the HPS and NSL treatments. In addition, fruit quality is usually evaluated by some fruit features including size, color, texture, taste, flavor, and phytochemical contents [18]. The high contents of bioactive compounds beneficial to health, including lycopene, vitamin C, phenolic acids, and flavonols, contribute to the commercial value of tomato [51]. Most studies have confirmed the role of R and B lights on promoting secondary metabolites in plants [52,53]. However, the W LED light that contains B light has been found to induce higher total phenolic and flavonol contents in tomato compared to R and G light [25]. This is consistent with the result of our study. Phenolic acids (chlorogenic, p-coumaric, ferulic acids, etc.) and flavonoids (quercetin, rutin, naringenin, etc.), the main compounds in tomato fruit, were detected in this study, among which chlorogenic acid and quercetin were most predominant [54]. The contents of individual phenolic acids and flavonols in tomato fruit tended to increase in the SFL treatments. The shorter B peak wavelength (436 nm) in the SFL treatments may have triggered the biosynthesis of phenolic acids and flavonols in the tomato fruit more efficiently [55,56]. In addition, the SFL used in this study showed significantly higher LUE and EUE than the HPS and NSL treatments (Table 4). The LUE reflects the effective use of artificial light sources for plant production [57]. The present study suggests that using shorter wavelength B light as in the SFL treatments may open the door to the next level of optimization of LED light spectra for quantitative and qualitative plant growth.

5. Conclusions

This study illustrated the important role of the SL in growing cherry tomatoes in a greenhouse and how full-spectrum W light with the shorter blue spectral component makes differences in the plants' morphogenesis and biosynthesis. Compared to the HPS and NSL treatments, the SFL treatments enhanced the vegetative growth of the cherry tomato plants. Total fruit yield in the SFL treatments was further improved from the HPS and NSL treatments, but without significant differences, possibly due to the lower PPFD and DLI associated with the SFL treatments. However, the normalized fruit yield in terms of LUE and EUE was remarkably higher with the SFL treatments. The fruit quality reflected by individual phenolic acids and flavonol compounds was also improved in the SFL treatments, although the contents of some compounds were similar to those from the HPS and NSL treatments. Based on the findings from this study, it is concluded that the SFLs with the short B or G peak wavelength can be preferably applied to grow tomatoes and other crops in greenhouses.

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