

Growth and Antioxidant Phenolic Compounds in Cherry Tomato Seedlings Grown under Monochromatic Light-emitting Diodes

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Abstract. Light-emitting diodes (LEDs) can be used in closed-type plant production systems as an artificial light source. Here, we determined the effects of monochromatic LEDs on the growth and production of phenolic antioxidants in cherry tomato seedlings (*Solanum lycopersicum* L. 'Cuty'). Two week-old seedlings germinated under normal growing conditions were transplanted into a growth chamber equipped with various monochromatic LEDs and fluorescent lamps (control), and cultivated for 4 weeks. Fresh weights of shoots and roots under LED treatment, especially, red or green, were higher than those under the control light at 4 weeks. The SPAD value of seedlings grown under blue LEDs was significantly lower than in seedlings grown under other LEDs. The plant height, stem length, and internode length of tomato seedlings grown under blue LEDs were the highest. Blue LEDs induced 1.5-2.2-fold higher stem length than red and white LEDs. Expansin gene expression was the highest under blue LEDs, consistent with the effect on stem length. Blue LEDs stimulated the biosynthesis of total phenolics, antioxidants, and total flavonoids in tomato seedlings. Specifically, the antioxidant capacity of seedlings grown under blue LEDs was 2.1-folds higher than that in seedlings grown under green LEDs. Thus, manipulating light quality using LEDs is a crucial factor for growth and antioxidant production in cherry tomato seedlings.

Additional key words: expansins, flavonoid concentration, light quality, stem elongation, *Solanum lycopersicum*

Introduction

Tomato (*Solanum lycopersicum* L.) is the seventh most produced crop species in the world, and is one of the added-value crops that are cultivated in greenhouses all year around (Bergougnoux, 2014). Tomato varieties are generally classified according to fruit size. Among them, cherry tomato, which has the small fruit size, is a popular tomato variety for consumers because it is easy to eat. Tomato fruits have high nutritional value because they contain essential elements as well as various health-promoting phytochemicals such as lycopene, β -carotene, phenolic compounds, and vitamin C (Garcia-Closas et al., 2004).

To produce high quality tomatoes, raising healthy seedlings is very important. Tomato seedlings undergo both vegetative and reproductive growth at the same time so that the seedlings stage crucially affects the growth and yield of fruit of tomato plants (Buwalda et al., 2006). Moreover, sound seedlings can

be well adapted when they are transplanted in fields or greenhouses (Johkan et al., 2010). To produce high-quality seedlings, control of environmental conditions, using proper growing medium, and cultural management skills are required.

Among the environmental factors required for plant growth, light is an essential signaling inducer as well as an energy source. Day length, light quality, and light intensity induce photomorphogenesis and/or various plant responses (Wang et al., 2009). In particular, light quality of lighting sources irradiated to plants is known to affect both photosynthesis and photomorphogenesis. Red and blue wavelengths, which are absorbed by chlorophylls, are important wavelength ranges in visible light for photosynthesis and growth (Carvalho et al., 2011). In addition, various wavelength ranges in and around the visible spectrum such as ultraviolet and far-red act as specific signals that are absorbed by photoreceptors such as phytochromes (red and far-red radiation), cryptochromes (blue and UV-A radiation), and phototropins (blue radiation)

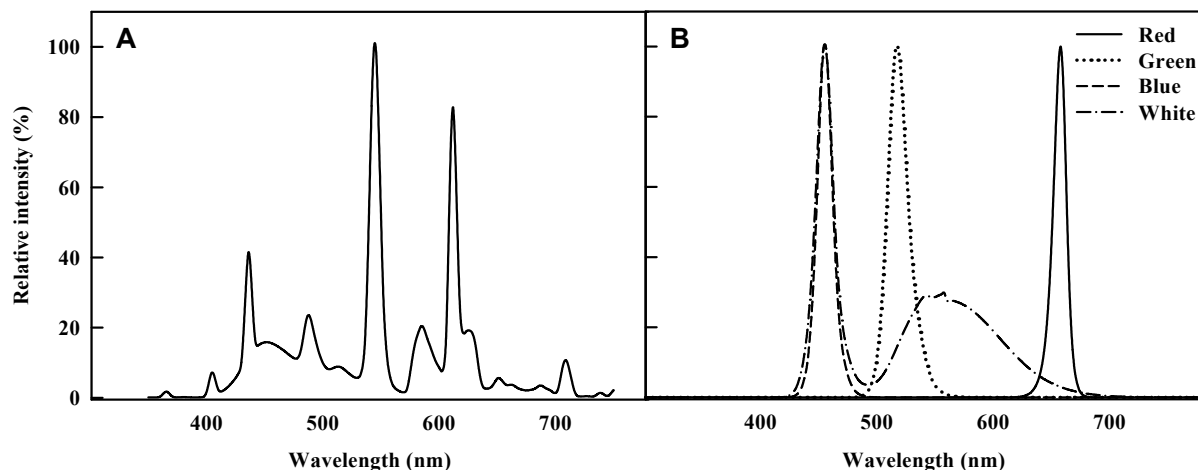


Fig. 1. Relative spectral distribution of the control (fluorescent lamps) (A) and several monochromatic LEDs (B) used in this study. The peak wavelengths of red, green, blue, and white LEDs were 654 nm, 518 nm, 456 nm, and 456 nm with 558 nm, respectively. Photosynthetic photon flux was about $205 \pm 5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in each treatment. Spectral scans were recorded at the top of the plant canopies and averaged at 5 points a center and 4 edges of each tray.

in plants (Whitelam and Halliday, 2007). Reception of light signals through photoreceptors leads to the induction of metabolism in plants.

Closed-type plant production systems can control growth conditions such as light, CO_2 , nutrients, water availability, and temperature regardless of the external environment. Thus, it is possible to produce high-quality crops including sound seedlings as well as uniform crops (Kozai et al., 2004). Light-emitting diodes (LEDs) are a next generation lighting source applied in closed-type plant production systems because their characteristics such as close illumination of plants, small size, and ability to manipulate light quality (Massa et al., 2008). Recent studies related to LEDs have been popular research themes in the production of horticultural crops due to these characteristics (Jeong et al., 2012; Matsuda et al., 2004; Son and Oh, 2013). However, most of the studies have focused on leafy vegetable, and it is difficult to make a profit from the production of the vegetables in these systems resulting in the delay of commercializing plant factories. Therefore, it is necessary to find a way to make good use of closed-type plant production systems through cultivation of other crops beside leafy vegetables.

The objective of this study was to obtain basic information regarding the use of monochromatic LED irradiation technology on seedlings of fruit vegetables by determining the growth of cherry tomato seedlings in closed-type plant production systems. In addition, we analyzed antioxidant phenolic compounds as a criterion for adaptation in transplanting.

Materials and Methods

Plant Materials and Cultural Conditions

Cherry tomato seeds (*Solanum lycopersicum* L. 'Cuty')

were sown in 50 cell plug trays containing growing medium (Myung-Moon, Dong-Bu, Seoul, Korea), and then cultivated under normal growing conditions [24°C , fluorescent lamps + high pressure sodium lamps, photosynthetic photon flux (PPF) $113 \pm 5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, photoperiod 12 h] in a growth chamber (DS-51GLP, Dasol Scientific, Hwaseong, Korea) for 18 days after sowing. Next, 64 seedlings per treatment were transferred to a growth chamber equipped with LED lighting systems and then cultivated for 27 days. The control seedlings were grown simultaneously under fluorescent lamps. Nutrient solution (2 L) for cherry tomatoes (pH 5.9, EC 1.02 $\text{dS}\cdot\text{m}^{-1}$, N:P:K = 20.3:18.2:24.9) was supplied to 64 tomato seedlings in a tray (45 cm \times 45 cm \times 7 cm, L \times W \times H) once a week by the subirrigation method. Growth conditions of all treatments were maintained at $27/18^\circ\text{C}$ (day/night), $205 \pm 5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPF of canopy point of seedlings, and a 12 h photoperiod. The distance between each light source and the apical meristem of cherry tomato seedlings was maintained at about 20 cm, and the location of each seedling was systemically changed every day to reduce any effects from uneven light distribution.

Light Treatments

Plate-type (48 cm \times 48 cm, L \times W) of red (655 nm), blue (456 nm), green (518 nm), and white (456 nm, 69% + 558 nm, 31%) LEDs (Itswell, Incheon, Korea) were manufactured and used as treatment light sources. The spectral distribution of the LEDs and fluorescent lamps (control) was measured by a portable spectroradiometer (Li-1800, Li-Cor, Lincoln, NE, USA) at 2 nm intervals in the range of 300-1000 nm. Figure 1 shows the relative intensity of the spectrum for each lighting source.

Table 1. The primer sequences for real-time RT-PCR analysis of 8 tomato expansin genes.

Gene name	Sequence (5'→3')	Product length	Accession
LeEXPA1	GAATCCCTGGTGTCTACTCTG TCCGTATCCTTGGCTGTAT	128	U82123.1
LeEXPA4	CAACTGACCCAACCCAAA CCCTTAGACTTCAATACTTTCTCA	120	NM_001247152.1
LeEXPA6	TACCGTGTGGAATTGTTG CCGTTGACTGTGAATCTGAT	80	AF059490.1
LeEXPA7	CCATCCAGACCAAGTCATAA TGAACATAGGCATTGTCAGAT	122	AF059491.1
LeEXPA9	TCTATGGTGGTAGTGATGCT ATTGTTGAATAATGCTGTGCTTA	116	NM_001247952.1
LeEXPA10	GATAGCAATGTCACGCAATT GCCATCACCTGTAGTTACTT	94	NM_001247435.1
LeEXPA11	ATTCTTAAATGTTGCTTCATCCA ATAAACTTCAAATCCCGAACTTT	118	NM_001247088.2
LeEXPA18	ATACGGAGTGAACAATGGAG GCAGTAATGAAGATGGAAGGA	135	NM_001247832.1
Actin	ACCCTGTTCTCCTGACTGAGG AGCCTGGATAGCAACATACATAGC	113	AB199316
Tublin	AGACAGGATGATGCTCACATTCTC ACCATACATTCATCGGCATTCTCC	123	DQ205342

Growth Characteristics

To compare the growth of cherry tomato seedlings under different light quality, fresh weights of shoots and roots were measured using an electronic balance (Si-234, Denver Instrument, New York, NY, USA) following 9, 18, and 27 days of treatment. Dry weights of shoots and roots, which were dried in an oven (VS1202D3, Vision Science, Daejeon, Korea) at 70°C for 72 h, were also weighed by the electronic balance. Leaf area was measured using a leaf area meter (Li-3000A, Li-Cor, Lincoln, NE, USA). Internode length between the second and third branches, and the proximal stem diameter were measured using a ruler and digital vernier calipers. The chlorophyll content of leaves located at the third node from the apical meristem was measured using a SPAD chlorophyll meter (SPAD 502, Konica Minolta, Osaka, Japan). Specific leaf weight was calculated by dividing dry weight by leaf area.

Real-time RT-PCR

Tomato expansin genes, which are associated with stem elongation, were investigated by real-time RT-PCR analysis. Tomato samples were collected after 27 days of treatment and stored at -70°C until use. Total RNA was extracted using RNeasy Plant Mini kit (Qiagen, Hilden, Germany), according to the manufacturer's instruction. The RNA concentration was measured using Quant-it RNA Assay kit (Invitrogen, Grand Island, NY, USA). Genomic DNA removal and first-strand cDNA synthesis was conducted using QuantiTect Reverse Transcription kit (Qiagen, Hilden, Germany), according

to the manufacturer's instruction. Expression of expansin genes was measured using a Bio-Rad CFX 96 (Bio-Rad, Hercules, CA, USA) using actin (AB199316) and tubulin (DQ205342) as internal controls. The PCR reaction was performed in a final volume of 20 µL containing 1× iQ SYBR Green Supermix (Bio-Rad, Hercules, CA, USA) and 0.2 µM of each primer (Table 1). Quantitative analysis was performed using Bio-Rad CFX Manager System with the following PCR cycle: 95°C for 180 s (preheating), 95°C for 15 s (denaturation), 56°C for 20 s (annealing), and 72°C for 30 s (extension) for 45 cycles.

Phenolic Concentration and Antioxidant Capacity

Total phenolic concentration was determined using the modified Folin-Ciocalteu method as described by Ainsworth and Gillespie (2007). A cherry tomato leaf (0.2 g) located at the 4th node from the apical meristem was collected and snap-frozen with liquid nitrogen. After then, it was stored in a deep freezer (NF-300SF, Nihon freezer, Tokyo, Japan) at -70°C until analysis. Samples collected for analysis were ground with liquid nitrogen in a mortar and pestle, and then extracted with 3 mL of 80% (v/v) acetone. The extracted solution was incubated at 4°C in the dark for 12 h and then the rest of the procedure was the same as the method described by Son and Oh (2013). Absorbance at 765 nm was measured by a spectrophotometer (UV-1800, Shimadzu, Kyoto, Japan). Total phenolic concentration was expressed as gallic acid (mg) (Acros Organics, Geel, Belgium) per fresh weight (g).

Table 2. Growth characteristics of cherry tomato seedlings grown under the control (fluorescent lamps) and several monochromatic LEDs at 27 days of treatment.

Light source	Fresh weight (g/plant)		Dry weight (g/plant)		Leaf area (cm ²)	Specific leaf weight (mg·cm ⁻²)	SPAD value	Stem diameter (mm)
	Shoot	Root	Shoot	Root				
Control ^z	5.86 c ^y	0.44 b	0.68 b	0.05 b	151.33	2.84	34.18 bc	4.75 ab
Red LED	10.35 ab	0.77 a	1.19 a	0.10 a	194.19	3.97	37.20 ab	5.00 ab
Green LED	11.19 a	0.77 a	1.26 a	0.10 a	197.85	4.13	40.00 a	5.25 a
Blue LED	8.95 ab	0.71 ab	0.98 ab	0.09 a	181.49	4.05	31.80 c	4.00 c
White LED	7.88 bc	0.64 ab	1.04 ab	0.09 a	190.09	3.34	38.58 ab	4.50 bc
Significance ^x	*	*	*	*	NS	NS	**	***

^zFluorescent lamps.^yMean separation within column's by Duncan's multiple range test.NS,*,**,** Nonsignificant and significant at $p = 0.05, 0.01$ or 0.001 , respectively.

Total flavonoid concentration was determined by the method described by Dewanto et al. (2002), with minor modifications. The leaf sample powder (0.2 g) obtained from the same location using the same method as used to analyze total phenolic concentration, was extracted with 3 mL of 70% ethanol (pH 3.2, adjusted with formic acid). The rest of the procedure used to determine total flavonoid concentration was performed as described by Son and Oh (2013). Absorbance at 510 nm was measured by a spectrophotometer. Total flavonoid concentration was expressed by (+)-catechin (mg) [(+)-catechin hydrate] (Sigma-Aldrich, St. Louis, MO, USA) per fresh weight (g).

Antioxidant capacity was measured by a modified ABTS [(2,2'-azino-bis (3-ethylbenzthiazoline-6-sulfonic acid))] method (Awika et al., 2003; Miller and Rice-Evans, 1996). The extraction method was the same as the one used to determine total phenolic concentration, and the extract was incubated at -20°C in the dark for 12 h. The rest of the procedure to determine antioxidant capacity was the same as that described by Son and Oh (2013). After the absorbance of ABTS, radical cation solution (1 mL) at 730 nm was adjusted to 0.7 (± 0.05) with 5 mM phosphate-buffered saline solution, 100- μ L extract was added into the ABTS solution. The absorbance was measured by a spectrophotometer after 1 min of reaction. Antioxidant capacity was represented by trolox (mM) [(6-hydroxy-2,5,7,8,-tetramethylchroman-2-carboxylacid) (Sigma-Aldrich, St. Louis, MO, USA)] per fresh weight (g).

Statistical Analysis

To analyze growth, chlorophyll contents, transcript level of expansin genes, total phenolic concentration, and antioxidant capacity, four biological replicates were used for each treatment. The experiment was carried out twice for reproducibility. Analysis of variance (ANOVA) using SAS statistical program (SAS 9.2, SAS Institute Inc., Cary, NC,

USA) was performed and means among the treatments were compared using the Duncan's multiple range test.

Results and Discussion

Growth

Light quality of LEDs led to a significant difference in terms of fresh and dry weights of shoots and roots, SPAD value, and stem diameter of cherry tomato seedlings after 27 days of treatment (Table 2). The highest value of shoot fresh weight was found under green LEDs although it was not significantly different in seedlings under red or blue LED treatment. All LED treatments except white LEDs led to a significantly higher shoot fresh weight than the control light, and in particular, that under green LED treatment was about 2-fold higher than in the control seedlings. No significant difference was observed in root fresh weight among LED treatments, and red and green LED treatments resulted in higher root fresh weight than the control. The result of dry weights of shoots and roots showed a similar trend to that of fresh weight. Meanwhile, leaf area and specific leaf area indicating leaf thickness had similar values among treatments, but LED treatments led to numerically higher values than the control. SPAD value, which is an indirect measure of chlorophyll content, was the highest in seedlings under green LEDs, and blue LEDs was the only treatment that led to seedlings having lower chlorophyll content than the control seedlings. Seedlings grown under green LEDs had the highest stem diameter among the treatments and the control, which was a similar pattern to that observed with fresh and dry weight of tomato seedlings, while blue LEDs led to the smallest stem diameter.

In general, red light is known to play an important role in developing photosynthetic organs as well as leaf expansion, while blue light induces biomass accumulation, chloroplast

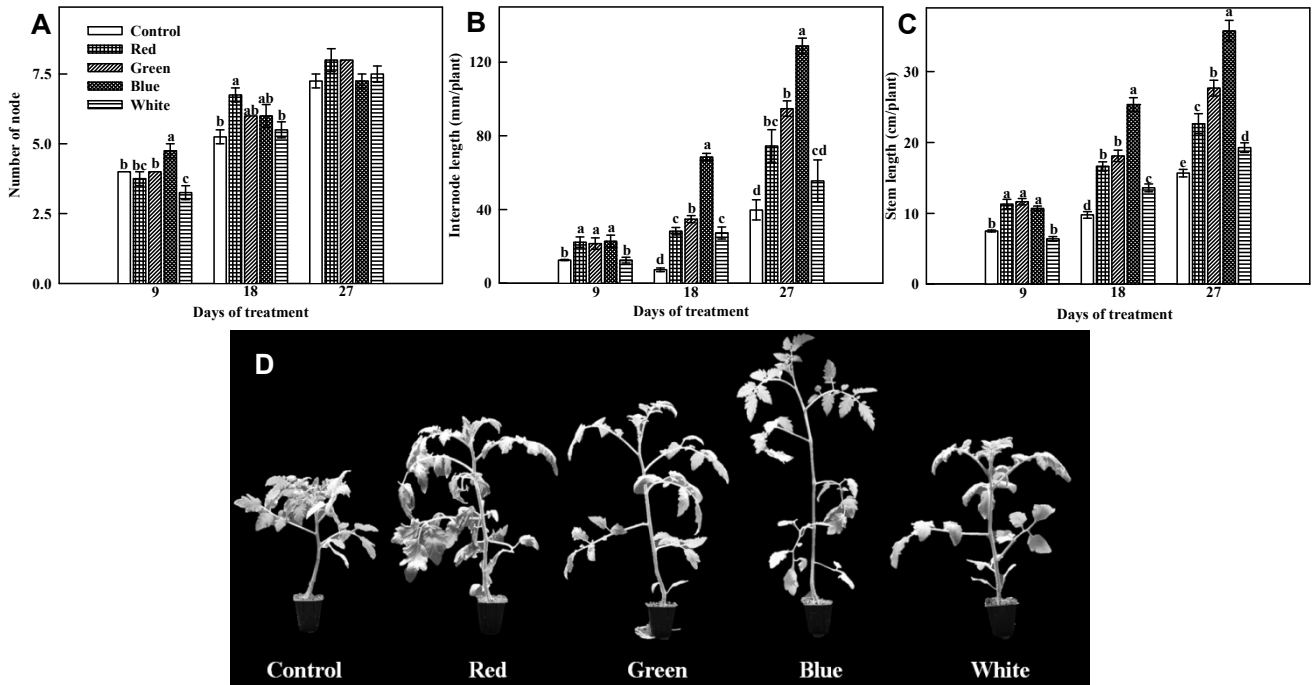


Fig. 2. Number of node (A), internode length (B), stem length (C), and picture of cherry tomato seedlings (D) grown under the control (fluorescent lamps) and several monochromatic LEDs for 27 days of treatment. Values are the mean of four independent biological replicated \pm SE ($p = 0.05$).

formation, and increasing leaf thickness (Johkan et al., 2010; Saebo et al., 1995). Therefore, red and blue wavelengths of lights are essential for photosynthesis. In this aspect, lighting systems consisted of a combination of red and blue lights are often used in plant production (Kim et al., 2004c; Lian et al., 2002; Nhut et al., 2003). Green light has a negative effect on plant growth because the percentage of light reflection and penetration on leaves is relatively high and it stimulates stomatal closure (Eisinger et al., 2003; Klein et al., 1965; Talbott et al., 2002). However, several studies have reported that the penetration of green light through leaves has a positive effect on the increase of photosynthetic rate based on canopy level and the increase of specific leaf area (Kim et al., 2004a, 2004b).

According to Son et al. (2012), analyzing the growth characteristics of lettuce grown under monochromatic LEDs, shoot and root growth under red LEDs was significantly higher than it was under the other treatments such as blue, red, and white LEDs, but specific leaf area was the lowest in red LED treatment. Under blue and white LEDs poor lettuce growth was recorded compared to red LEDs, but was higher in SPAD value and specific leaf area. Under green LEDs, the lowest growth, SPAD value, and specific leaf area were observed. In the study of monochromatic LEDs using tomato seedlings, Liu et al. (2012) showed that blue LEDs were effective at accumulating plant biomass, and green LEDs increased leaf thickness although no significant dif-

ference was observed in SPAD value, stem diameter, or leaf area. However, our results showed that green LEDs, as well as red LEDs, increased fresh and dry weights of cherry tomato seedlings. In addition, the leaves grown under green LEDs had significantly higher chlorophylls than those grown under blue LEDs. Comparing our results with previously reported two studies, the trend was opposite. This tendency can be explained by the discriminative response of crop species or cultivars even within same plant species in response to light quality (Buso and Bliss, 1988).

Monochromatic light led to pronounced differences in terms of stem elongation (Fig. 2). Blue and red LEDs significantly increased the number of nodes following 9 and 18 d of treatment, respectively, but the difference was not observed after 27 days of treatment (Fig. 2A). Internode length indicating the length between the second and third node under blue LEDs was significantly longer than under the other treatments as well as the control after 18 and 27 days of treatment (Fig. 2B). Moreover, stem length also showed a similar pattern with internode length (Fig. 2C). Stem length of cherry tomato seedlings grown under blue LEDs was 1.9 and 2.3 times longer than those grown under white LEDs and control light, respectively, after 27 days of treatment (Fig. 2D).

Typically, red and green lights stimulate hypocotyl elongation, while blue light inhibits it in seedlings (Whitelam and Halliday, 2007). Jeong et al. (2012) and Liu et al. (2012)

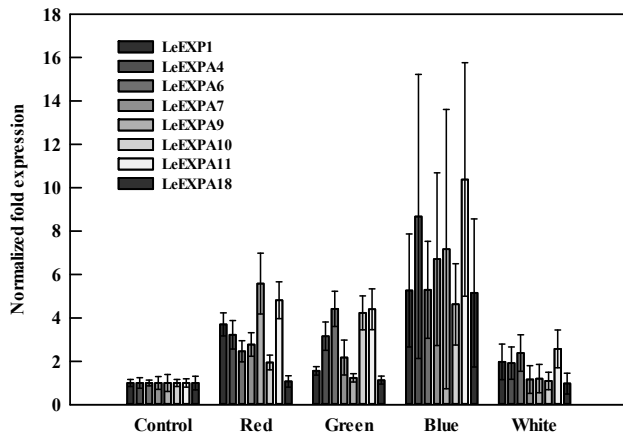


Fig. 3. Gene expressions of 8 expansins in cherry tomato seedlings grown under the control (fluorescent lamps) and several monochromatic LEDs at 27 days of treatment. The level of expansin transcripts were assessed by real-time quantitative RT-PCR and the data are mean values of four independent biological replicated \pm SE. The expression was normalized using the expression of actin (AB199316) and beta tubulin (DQ205342).

reported that red and green light induced stem elongation, whereas blue light suppressed stem elongation in chrysanthemum and tomato plants. However, our results showed that the longest stem was found in tomato seedlings grown under blue LEDs, and followed by green, red, and white, which was in contrast with the results from the previous studies. Recently, several studies using monochromatic LEDs reported that blue LEDs are more effective at elongating pepper and cucumber stems as well as tomato than red LEDs (Lee et al., 2012; Um et al., 2009). Thus, the effect of light quality on the stem elongation is inconsistent, indicating that further studies are needed to determine how plant physiology is related to light exposure.

Expansin Gene Expression

Expansin proteins were first discovered in cucumber seedlings and were found to be important in destabilizing cell walls by breaking hydrogen bonds. In this way, high expansin levels promote cell expansion and thus, stem elongation could be promoted (Cosgrove, 2000; Sasidharan et al., 2009). The expressions of eight expansin genes, which have evidence of expression, presence of EST, or expression data, were measured using real-time RT-PCR analysis. Expansin gene expression was significantly influenced by the color of light to which the seedlings were exposed (Fig. 3). The genes were the most highly expressed under blue light. *LeEXPA4* and *LeEXPA11* showed 8.7 and 10.4-fold increases in gene expression, respectively, compared to the control. On average, the eight tested expansin genes showed 1.7, 2.8, 3.2, and 6.7-folds higher gene expressions than the seedlings grown under the control light or under white, green, red, and blue light,

respectively. These gene expression data are consistent with the results of tomato seedlings height shown in Fig. 2. Sasidharan et al. (2010) reported that light quality affected petiole elongation in *Arabidopsis*, which was associated with cell wall modification. This is the first report showing that controlling light quality using LEDs regulates expansin gene expression in tomato seedlings.

Phenolic Concentration and Antioxidant Capacity

Sudden changes in plant growth conditions have been shown to act as a source of stress to plants, and, thereby, reactive oxygen species (ROS), which exist in normal plants, were additionally generated in plants (Moran et al., 1994). The ROS lead to cell and DNA damage and, therefore, plant growth and development are inhibited under situations of increased ROS production (Alexieva et al., 2001). However, plants have a defense mechanism that acts to reduce the negative effect of ROS using antioxidant substrates or enzymes (Mittler, 2002). Oh et al. (2009) reported that, as defense materials for stressful conditions, antioxidants including phenolic compounds were accumulated when plants cultivated *in vitro* were acclimated *ex vitro*. In addition, phenolic compounds with antioxidant properties induced better growth and adaptation under stressful conditions (Rivero et al., 2003). After all, antioxidant level in seedlings could be one of standards for field adaptation when the seedlings are transplanted.

In this aspect, total phenolic concentration, total flavonoid concentration, and antioxidant capacity were measured in this study (Fig. 4). Tomato seedlings grown under the blue LEDs were significantly higher in total phenolic concentration, total flavonoid concentration, and antioxidant capacity compared with those grown under other wavelengths and the control light. White LEDs containing the blue wavelength range also induced higher values in the above variables than did the red and green LED treatments and the control light. Because the wavelength of the blue light is close to that of ultraviolet light, irradiation under the blue LEDs is expected to have a similar response to that of ultraviolet light, which triggers the biosynthesis of phenolic compounds with antioxidant properties (Ebisawa et al., 2008; Ryan et al., 2002). Total phenolic concentration and total flavonoid concentration in seedlings grown under the green LEDs were not significantly different from those under control light, but the LED treatment showed 82.5% lower antioxidant capacity than control seedlings. These results were consistent with those of Son et al. (2012). They reported that the blue and white LEDs significantly increased total phenolic concentration and antioxidant capacity in lettuce plants, while the green LEDs showed the lowest value. Finally, our results on phenolics and antioxidants implies that the level of such

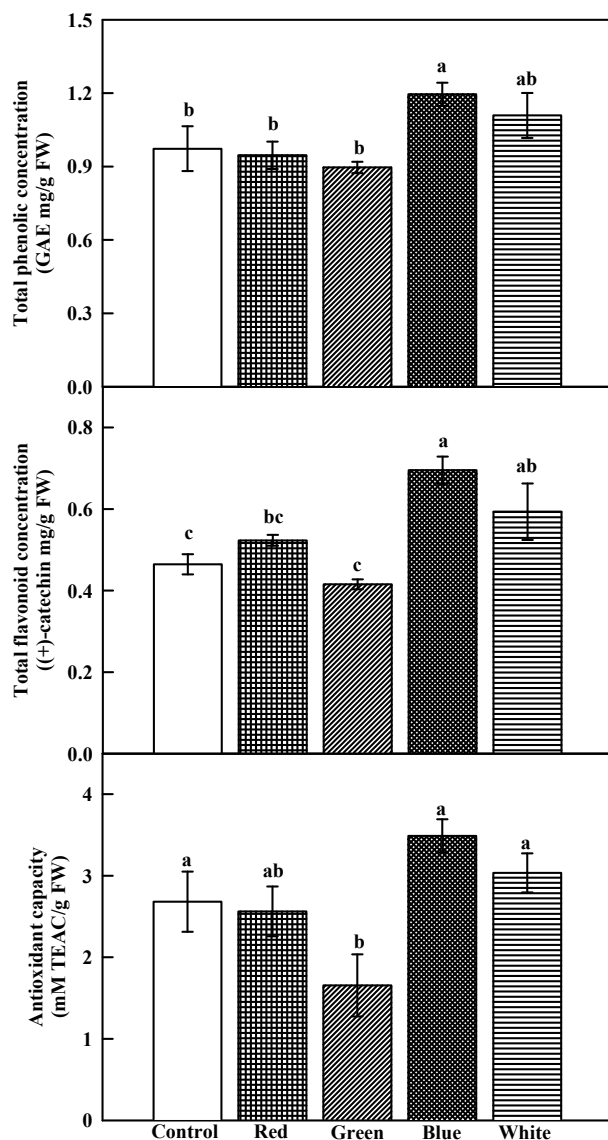


Fig. 4. Total phenolic concentration (A), total flavonoid concentration (B), and antioxidant capacity (C) of cherry tomato seedlings grown under the control (fluorescent lamps) and several monochromatic LEDs at 27 days of treatment. Values are the mean of four independent biological replicated \pm SE ($p = 0.05$).

antioxidants in terms of a component for environmental resistance, could be changed by irradiation under different LEDs in cherry tomato seedlings, although further studies exploring the relationship between antioxidants and transplanting performance of seedlings would be necessary.

In summary, most of values for growth characteristics of cherry tomato seedlings were higher in those grown under the LED treatments than those grown under the control. Stem elongation was promoted by the blue LEDs and the elongation-related gene family, expansin, was overexpressed under the blue LEDs although this is in contrast with previous results obtained by several studies using tomato seedlings.

Blue and white LEDs were effective at inducing the biosynthesis of phenolic compounds with antioxidant properties. This study provides basic information about the effect of monochromatic LEDs on the quality of tomato seedlings, which could be applied to the design of LED-based artificial lighting systems for closed-type plant factories, especially for nursery plants.

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