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A DISSERTATION FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

**Optimization of light and air temperature conditions
to produce grafted transplants of fruit vegetables
in a closed transplant production system with white LEDs**

**백색 LED를 사용하는 폐쇄형 육묘 시스템 내에서의
과채류 접목묘 생산을 위한 광 및 기온 조건의 최적화**

By

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August, 2021

**MAJOR IN HORTICULTURAL SCIENCE AND BIOTECHNOLOGY
DEPARTMENT OF AGRICULTURE, FORESTRY, AND BIORESOURCES
THE GRADUATE SCHOOL OF SEOUL NATIONAL UNIVERSITY**

**Optimization of light and air temperature conditions
to produce grafted transplants of fruit vegetables
in a closed transplant production system with white LEDs**

**UNDER THE DIRECTION OF DR. CHANGHOO CHUN SUBMITTED TO THE
FACULTY OF THE GRADUATE SCHOOL OF SEOUL NATIONAL UNIVERSITY**

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ABSTRACT

Transplant production in plant factories has increased to overcome unfavorable environments, including high temperatures in summer and a lack of sunlight in winter. To successfully apply plant factory using artificial light (PFAL) for the production of high-quality grafted transplants of fruit vegetables should establish optimal environmental conditions. The effects of environmental factors, such as light intensity, light quality, photoperiod, and temperature, on plants have been studied individually to control plant growth in a closed cultivation system. However, a few studies have investigated the application of more economical white light-emitting diodes (WLEDs) and the combined effects of environmental factors on plant growth and morphology changes. In chapter one, lighting systems using WLEDs were established, and

the effects of warm and cool WLEDs at various ratios on the growth of cucumber, tomato, and watermelon seedlings that would be used as scions and root stocks for grafted transplant production were examined. Four WLEDs were specifically manufactured for this study by adjusting the numbers of installed warm- and cool-white light chips: W1C0 (only warm-white light chips), W3C1 (warm-:cool-white light chips = 3:1), W5C2 (warm-:cool-white light chips = 5:2), and W1C1 (warm-:cool-white light chips = 1:1). The seedlings cultivated under treatment W1C1 had the shortest hypocotyls among the three tested vegetables. The hypocotyls of scions and rootstocks of tomato and watermelon were shortened in the order of W1C0, W3C1, W5C2, and W1C1, that is, in the same order with an increased proportion of cool-white light. The stem diameters were not significantly different except in tomato scions and watermelon rootstocks. In chapter two, the growth and morphology of tomato, red pepper, cucumber, gourd, watermelon, and bottle gourd seedlings that would be used as scions and/or root stocks for grafted transplant production were examined under different supplemental far-red (FR)-enriched WLED lights. The specifically manufactured WLED lighting fixtures consisted of different numbers of cool-white and FR light chips adjusted at ratios of 5:0, 5:1, 5:2, and 5:3. The phytochrome photostationary state (PSS) values that resulted in the maximum hypocotyl length ranged from 0.69 to 0.77 in tomato and red pepper seedlings. Although the hypocotyl lengths of cucumber and watermelon seedlings were also greatly affected by PSS, the

PSS values resulting in the maximum hypocotyl length were lower than those found in tomato and red pepper seedlings. This suggests that FR-enriched WLEDs could be used to control the growth and morphology of vegetable seedlings with some variations among plant species and cultivars. In chapter three, the growth of tomato and red pepper seedlings was examined under different daily light integrals (DLIs) and day and night temperatures (DIFs) using a selected WLED lighting fixture. The seedlings were grown under different photoperiods with five different photon flux densities (PFDs) at an air temperature of 25/20 °C. Increasing the DLI from 4.32 to 21.6 mol·m⁻²·d⁻¹, either by increasing the photoperiod or PFD, improved seedling growth in both species. Under the same DLI conditions, tomato seedling growth was significantly enhanced with increased photoperiod and decreased PFD. Under higher DLI conditions, the reduced growth due to higher PFD indicated that excessive light energy was a limiting factor. The seedlings were also grown under three different air temperatures, 23/20, 25/20, and 27/20 °C (photo-/dark periods), with five different PFDs. At 23/20 and 25/20 °C, tomato seedlings showed a similar correlation between plant growth and an increase in PFD. At 27/20 °C, however, the slope of the curve was flatter than those found in other treatments. On the other hand, red pepper seedlings showed similar correlation curves between growth and PFD at all tested air temperatures, and they accumulated more dry weight even at higher air temperatures. The results from this study provide more information and a deeper understanding of the growth

characteristics of seedlings and better predict their responses to various cultivation environments, which is crucial for the production of grafted transplants of fruit vegetables in a closed system with artificial light, such as high-power WLEDs.

Key words: Color temperature, far-red light, fruit vegetables, light quality, morphology, transplants, white LEDs

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
CCT	Correlated color temperature
CTPS	Closed transplant production system
DAS	Days after sowing
DIF	Difference between the day and night temperature
DLI	Daily light integral
DMC	Dry matter content
DW	Dry weight
EC	Electrical conductivity
FR	Far-red
FW	Fresh weight
HIR	High irradiance response
HPS	High pressure sodium
LAI	Leaf area index
LED	Light emitting diode
LUE	Light use efficiency
PAR	Photosynthetically active radiation
PFAL	Plant factory with artificial lighting
PFD	Photon flux density
PPFD	Photosynthetic photon flux density

PSS	Photostationary state
SAR	Shade avoidance response
SAS	Statistical analysis system
TPFD	Total photon flux density
WLED	White LED

GENERAL INTRODUCTION

Fruit vegetables such as tomato, pepper, cucumber, and watermelon play an important role in horticulture. Because of their high production intensity and requirements for quality control, seedling production facilities usually employ high technology-protected horticulture systems such as closed transplant production systems (CTPSs) and plant factories with artificial lighting (PFAL). While these systems allow the production of large quantities of seedlings in a small area with a short production cycle and uniform quality, every environmental factor needs to be artificially set up and controlled. On the other hand, ~~these~~ environmental factors can have great impacts on the growth, morphology, and final quality of seedlings. Each species and cultivar of fruit vegetables has different favorable growth conditions and diverse responses in terms of growth and morphology to changes in environmental conditions. To accommodate many types of seedlings with various requirements, environmental effects on growth and development should be precisely understood.

Among environmental factors, light conditions have strong impacts on plants and can easily be controlled in CTPSs and PFALs. With the development and popularization of light-emitting diodes (LEDs), various choices for lighting conditions are available for horticulture. LED technology allows for a highly efficient lighting apparatus with low heat emission and a diverse

selection of light qualities, which are suitable for transplant production in CTPSs. Many studies have been conducted to find the most suitable LED types, although white LEDs (WLEDs) have only recently been researched, and there are still many knowledge gaps.

First, most studies have only examined one or two types of plants at the same time. This causes difficulties in comparison and gaining extensive knowledge of the nature of different species or cultivars, which must be accommodated in transplant production facilities. More comprehensive research that compares as many species and cultivars as possible under the same environmental conditions is needed to understand their responses in terms of growth and morphology to different environmental conditions so that production systems can be adjusted accordingly.

Second, most studies have utilized monochromatic LEDs or their combinations. These studies are difficult to implement, as monochromatic LEDs are rarely used as lighting apparatuses for normal application and therefore are rarer and more expensive to produce, making them difficult to find and replace during operation. Diverse types of WLEDs providing various light spectra have been introduced on the market, and by combining WLEDs, different light qualities for specific purposes in plant production can be created economically. However, research on WLED application in plant production in CTPSs and PFALs is still lacking.

Third, little attention has been given to the effects of nonphotosynthetic

light, such as far-red (FR) light and ultraviolet light, on plant growth and morphology. Recently, WLED chips with supplemental FR light have been introduced on the market, and they provide the potential to incorporate these spectra into WLED lighting fixtures for precise control of the morphology and quality improvement of transplants produced in a closed system.

Finally, the interaction between novel light environmental conditions created by the application of WLEDs and other environmental factors, such as air temperature, which affects plant growth and morphology, should also be investigated. This is because while light has strong impacts on plant growth and development, it never acts alone but rather always in combination with other factors. This is especially emphasized in CTPSs and PFALs, where all environmental factors are artificially controlled. Therefore, further studies are required to focus on these interactions and obtain more comprehensive knowledge about plant responses to light.

This study was conducted to address these problems and further contribute to the expansion of transplant production with unique characteristics. This study also aimed to provide further understanding of the responses of different types of fruit vegetables that are normally produced in nurseries, such as pepper, tomato, cucumber, and watermelon, to different aspects of light, such as light quality (Chapter 1), the supplementation of nonphotosynthetic irradiance such as FR light (Chapter 2), and light intensity and photoperiod interactions with air temperature (Chapter 3), focusing on utilizing common types of

commercial lighting WLEDs. The results in the present study would be beneficial to advance the application of WLEDs in transplant production systems and to provide knowledge for lighting control to achieve different levels of growth and specific morphologies for different purposes.

LITERATURE REVIEW

Current status of the vegetable transplant production industry in Korea

Vegetable transplant production is known to be comprehensive and cost-intensive work (Louws et al., 2010). High-quality fruit vegetable transplant production is important to achieve cost-saving production practices with low impact on the environment. Since the early 1990s, commercial vegetable transplant production in Korea has rapidly developed. Vegetable production and its cultivation area have increased since the 1980s to adapt to the increasing year-round consumption of vegetables (Lee et al., 2010). Following the establishment of the first commercial vegetable transplant production business, approximately 300 commercial transplant production growers were operating 195 ha of transplant production area in 2013, and the market size was expected to be approximately 242 billion Korean won (Park et al., 2014). According to Jang (2013), growers in 2011 used grafted transplants constituting approximately 99% in watermelon, 89% in cucumber, 69% in tomato, and 10% in pepper.

Use of LEDs in transplant production

LED technology is paving the way to increase crop production efficiency with electric lamps. LED technology allows us to select specific wavelengths to elicit targeted photomorphogenic, biochemical, or physiological responses

of plants (Gómez and Izzo, 2018). Furthermore, it provides the opportunity to save energy associated with electric lighting. By increasing canopy photon capture efficiency and/or precisely controlling light output in response to the environment or to certain physiological parameters, energy efficiency and plant productivity can be optimized with LEDs (Gómez and Izzo, 2018). Within the last two decades, LEDs have proven to be energy-efficient replacements for other lamps to control photoperiodic responses in flowering plants. LEDs have also been demonstrated to be viable alternatives to other lamps for sole-source lighting in growth rooms and are currently major competitors of high-pressure sodium (HPS) lamps for supplemental lighting in greenhouses. Numerous recent studies have described many advantages of using LEDs for plant production, ranging from the application of narrowband radiation to serving as cues that drive specific photomorphogenic, biochemical, or physiological responses of plants to applications for saving energy consumption from plant lighting.

Red and blue monochromatic LEDs alone or in combination have been applied for plant growth (Agarwal and Dutta Gupta 2016; Massa et al., 2008). However, such LED lighting sometimes mismatches the waveband with the photosynthetic action spectrum. This problem can be overcome with the application of white light emitting diodes (WLEDs) with broad spectra (Güner et al. 2016). WLEDs containing red, blue, and green wavelengths have been tested as human vision-friendly sources of plant lighting (Viršilė et al., 2017).

Most WLEDs consist of LED chips that emit blue light with a narrow spectrum between 440 and 470 nm, and a coating of yellow, green, or red phosphors. They offer efficiency and an improved plant utilization rate. Studies on selective wavelengths often employ WLEDs as controls and find them to be more stable to the physiological reactions of plants than unclear monochromatic LEDs (Cope and Bugbee, 2013).

Red and blue monochromatic LEDs do not emit FR light, and WLEDs emit a small fraction of FR light depending on the phosphors used. To determine the effect of FR light on photosynthesis, Zhen and van Iersel (2017) investigated interactions between light provided by red/blue LEDs and FR light. They reported that adding FR light consistently increased the net photosynthesis of lettuce exposed to red/blue light.

Light environment control in closed transplant production systems

In closed systems, the light environment can easily be controlled in terms of photosynthetic photon flux density (PPFD), photoperiod, and light quality regardless of the outside weather (Kozai et al., 2019). Thus, the growth and development of transplants can be manipulated. On the other hand, in the open system, photoperiod, spectral composition, PPFD, and lighting direction (solar azimuth and altitude) vary with season, time of the day, and/or geographical location, which are beyond human capacity to control. Daily and monthly variations in these factors also change annually depending on the annual

changes in weather. The morphology of plants is influenced not only by photoperiod (or dark period) and light intensity but also by the spectral composition of light, especially by lights with wavelength regions of 300-400 nm (ultraviolet, UV), 600-700 nm (red), and 700-800 nm (FR). When natural light is used as a light source, morphological development cannot be controlled independent of the photosynthetic growth of plants, which is influenced by PPFD in the wavelength region of 400-700 nm. In closed systems, the spectral compositions of lamps can be controlled with time as desired, and thus, the morphogenesis of plants can be controlled largely independently of the photosynthetic growth of plants.

A particularly important environmental cue is light, to which organisms respond in many ways. The diverse responses of plants to light require sophisticated sensing of their intensity, quality, and photoperiod. The action spectra of light responses provide assays to identify three photoreceptor systems absorbing in the red/FR, blue/near ultraviolet, and ultraviolet spectral ranges. Following light absorption, photoreceptors interact with other signal transduction elements, which eventually leads to many molecular and morphological responses.

Once the plant perceives sufficient light, it will de-etiolate, a developmental process that optimizes the body plan of the seedling for efficient photosynthetic growth (Fankhauser and Chory, 1997). During de-etiolation, the rate of hypocotyl growth decreases, the apical hook opens, cotyledons expand,

chloroplasts develop, and a new gene expression program is induced. Moreover, during vegetative growth, light availability is crucial for regulating appropriate responses to competition from neighbors (Schmitt and Wulff, 1993).

Plants respond to a broad spectrum of light, ranging from UV-B to FR light. A large body of physiological, photobiological, and molecular genetic studies have demonstrated that plants possess distinct photoreceptors sensing UV-B, UV-A, blue, green, red, and FR light (Beggs and Wellmann, 1994).

Growth and development of fruit vegetables under different light conditions

In general, the growth and development of plants are influenced by light intensity, light quality, and photoperiod, as well as interactions with air temperature and cultural practices (Dorais et al., 2003). Plants sense the duration, intensity, and direction of light using these same photoreceptors. Of the various photoreceptors, the most intensively studied are a family of photoreversible red/FR absorbing chromoproteins called phytochromes (Butler et al., 1959) and cryptochrome, a UV-A/blue light receptor (Ahmad and Cashmore, 1995). The light-dependent development of plants, a process called photomorphogenesis, has been studied for over a hundred years in a wide variety of plant species. The phytochrome system within the plant regulates metabolic events that result in adaptive responses such as stem

elongation, leaf shape and thickness, and carbon partitioning between plant organs. Cryptochrome and UV receptor are two other kinds of photoreceptors involved in stomatal opening, leaf color and thickness, and stem elongation (Dorais et al., 2003). However, the responses of plants to light intensity, photoperiod, and light quality differ among plant species. Cucumber plants produce 3.4 to 4.3 g of dry matter per $\text{MJ}\cdot\text{m}^{-2}$ photosynthetically active radiation (PAR) under 364 and 620 $\mu\text{mol}\cdot\text{mol}^{-1}$ CO_2 , respectively (Nederhoff and Vegter 1994). Under a light integral higher than 30 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, the growing period was only 10 days compared to 24 and 17 days under 5.5 and 10 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, respectively (Blain et al., 1987). Supplemental lighting at 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ increased stomatal conductivity and net photosynthesis when natural light was below 280 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPFD. Extending the photoperiod with supplemental lighting to 18 h also increased the quantity of CO_2 assimilated daily and reduced the respiration period (Turcotte and Gosselin, 1989). Furthermore, the leaf thickness increased with increasing photoperiod. The promoting effects of extended light treatments increased with photoperiod but were independent of the time of application (Turcotte and Gosselin, 1989). A light requirement higher than 30 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ was reported for tomato cultivation, while a light integral of 4.8 to 6.0 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ is generally favorable for tomato seedling production, which corresponds to a light intensity of 83 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ during a photoperiod of 16-20 h. Heuvelink and Dorais (2005) reported light use efficiency (LUE) values between 2.8-4.0

$\text{g}\cdot\text{MJ}^{-1}$ intercepted PAR in experiments where no CO_2 enrichment was applied. Extending the photoperiod to 18 and 24 h with HPS lamps had no significant effect on the leaf area but increased the dry weight of tomato and pepper plants (Dorais et al., 1996). Under a high PPFD provided by metal halide lamps, tomato plants grown under a 24 h photoperiod had a lower leaf area than those grown under a 14 h lighting treatment but had a higher specific weight (Demers et al., 1998). Extended photoperiods to 18 and 24 h decreased net photosynthesis by 26-29% compared with a 12 h photoperiod (Dorais et al., 1996). For tomato plants, the dark period should be uninterrupted since splitting the dark period into two short night periods decreased growth and yield. Pepper plants need a light integral of at least $12 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for good control of the production cycle, and their light use efficiency (LUE) was $2.1 \text{ g}\cdot\text{MJ}^{-1}$ PAR. Pepper also benefit from an extended light period. Under a continuous photoperiod, the photosynthetic rate was higher, and more photoassimilates were translocated to the fruit. Diurnal translocation rates were 2 to 3 times higher under 18 and 24 h photoperiods than under 12 h photoperiods, and the translocation rate was linearly related to the photosynthetic rate (Dorais et al., 1995). The use of an 18 to 20 h photoperiod increased the yield up to 33% compared to natural light. However, continuous lighting did not improve the growth and yield of pepper compared to a 20 h photoperiod.

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CHAPTER 1

Application of white LEDs to produce uniform scions and rootstocks for grafted fruit vegetable transplants

ABSTRACT

Uniform scions and rootstocks should be produced to ensure grafting success. Light quality is an important environmental factor that regulates seedling growth. The effects of warm- and cool-white light emitting diode (LED) ratios on seedling growth were investigated. Scions and rootstocks of cucumber, tomato, and watermelon were grown in a closed transplant production system using LED as the sole lighting source. The LED treatments were W1C0 (only warm-white), W1C1 (warm-white: cool-white = 1:1), W3C1 (warm-white: cool-white = 3:1), and W5C2 (warm-white: cool-white = 5:2). The seedlings grown in W1C1 had the shortest hypocotyls, and the seedlings grown in W1C0 had the longest hypocotyls among the three tested vegetables. The hypocotyls of watermelon scions, watermelon rootstocks, and tomato rootstocks were shortest in W1C1, followed by those in W3C1, W5C2, and W1C0, but there was no significant difference between W3C1 and W5C2, which remained the same as the ratio of cool-white LEDs increased. In addition, tomato scions had the first and second longest hypocotyls in W1C0 and W3C1,

respectively, and the shortest hypocotyls in W5C2 and W1C1, along with W5C2 and W1C1, although the difference was not significant. The stem diameter was highest in W1C0 except for tomato seedlings and rootstocks of watermelon. The shoot fresh weight of scions and rootstocks of cucumber and watermelon and the root fresh weight of cucumber scions were lowest in W1C1. These results indicated that different ratios of LED lighting sources had a strong effect on the hypocotyl elongation of seedlings. Except for those of cucumber, scions and rootstocks of watermelon and tomato reacted more sensitively to cool-white LEDs.

Key words: Grafting; light quality; rootstock; scion; white LEDs

INTRODUCTION

Grafted transplants have increasingly been used in fruit vegetable cultivation as grafting technology has advanced. Grafted transplants are resistant to soil-borne diseases (Louws et al., 2010) and tolerant to abiotic stresses (Kumar et al., 2015; Rouphael et al., 2016; Schwarz et al., 2010). In addition, grafted transplants enable higher yields than non-grafted transplants (Oda, 1999; Yetisir and Sari, 2003). However, conventional grafting cultivation, which relies mostly on manpower, is not efficient. Thus, grafting robots have been developed to reduce human labor and time used for grafting. Grafting can be simplified, and the productivity of grafted transplants can be highly improved by using grafting robots (Lee et al., 2010; Xie et al., 2020). Uniform seedlings are required to obtain a successful rootstock-scion union (Tian et al., 2017). Therefore, seedling uniformity, especially in terms of hypocotyl length, is important for grafting robots and can make the grafting process more efficient and successful.

Environmental conditions need to be appropriately maintained to grow uniform seedlings using a closed transplant production system (CTPS). Among environmental conditions, light is a major source of energy for photosynthesis and an important signal stimulator for the growth and development of plants (Wang et al., 2009). Light-emitting diodes (LEDs) have been spotlighted as artificial light sources for plant production. The distinguishing features of

LEDs from other light sources are that LEDs are easy to install and have different spectral distributions (Mitchell et al., 2015). Light quality is determined by the distribution of light spectra with different wavelengths (Lee et al., 2016). Blue and red lights, the wavelengths of the photosynthetically active radiation (PAR) range, are effective for photosynthesis, as they are preferentially absorbed by chlorophyll (Carvalho et al., 2011). Red and blue LEDs have been combined for application in horticulture (Bula et al., 1991; Yorio et al., 2001). However, using only red and blue lights makes it difficult to distinguish plants (Massa et al., 2008). Recently, white LEDs (WLEDs), which easily sense the degree of plant growth and disease status and can contain various wavelengths depending on the degree of correlated color temperature (CCT), have been widely applied in plant factories using artificial light (Lee et al., 2020). This study was conducted to find a proper ratio between warm- and cool-white LEDs for growing several fruit vegetable transplants.

MATERIALS AND METHODS

Plant materials and growth conditions

Seeds of cucumber (*Cucumis sativus* cv. Joeunbaegdadagi, Seminis Korea, Seoul, Korea; *Cucurbita ficifolia* cv. Heukjong, Hungnong Seeds, Ansong, Korea), watermelon (*Citrullus vulgaris* cv. Sambokkul, Hungnong Seeds; *Lagenaria siceraria* cv. Bulrojangsaeng, Syngenta Korea, Seoul, Korea), and tomato (*Solanum lycopersicum* cv. Dotaerangdia, Takii Korea, Seoul, Korea; *S. lycopersicum* cv. B-blocking, Takii Korea) were sown, and their seedlings were cultivated in a CTPS with LED lighting. The seedlings were grown at $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ photosynthetic photon flux density (PPFD) with a 16 h photoperiod at an air temperature of 27/22 °C (photo-/dark periods), $600 \mu\text{mol}\cdot\text{mol}^{-1}$ CO₂ concentration, and 60% relative humidity. The seedlings were subirrigated with pH 6.5 and electrical conductivity (EC) 0.5-1.5 dS·m⁻¹ every 2 or 3 days for each cultivar.

White LED light treatments

The experiment consisted of 3 treatments, with 12 plants × 3 replicates per treatment. In the case of the existing LEDs, the PPFD at the edge was lower than the average PPFD of at least $70 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. To overcome this problem, the density of the LED chips was increased at the edge (Fig. 1-1). As a result of light intensity profiling, in the case of the improved LEDs under the

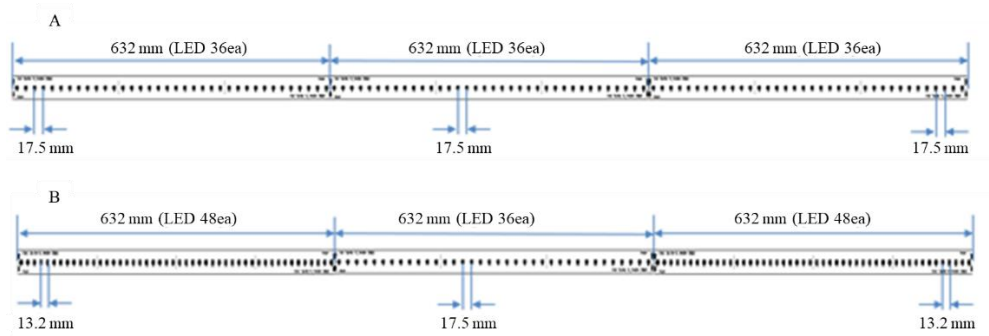


Fig. 1-1. LED lamp design for improving light distribution. Previous (A) and improved (B) LED lamp design.

condition of $250 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, the PPFD at the edge increased by more than $30 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and the standard deviation decreased by more than $10 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Fig. 1-2).

Light treatments began after germination. Based on cool-white LEDs (T5/20 W6500K, Parlux, Incheon, Korea) and warm-white LEDs (T5/20 W/3000K, Parlux), the light treatments were W1C0 (only warm-white), W1C1 (warm-white: cool-white = 1:1), W3C1 (warm-white: cool-white = 3:1), and W5C2 (warm-white: cool-white = 5:2). PPFDs in all treatments were measured at a 20 cm distance from the lamps using an LI-250A light meter coupled with an LI-190R quantum sensor and an LI-200 pyranometer (LI-COR Inc., Lincoln, NE, USA).

Plant growth analysis

Hypocotyl length, stem diameter, leaf area, and fresh weight of seedlings were measured 7 days after sowing (DAS) for cucumber, 9 DAS for watermelons, and 14 DAS for tomato plants. Stem diameter was measured using a Vernier caliper (CD-20CPX, Mitutoyo Co., Kawasaki, Japan).

Statistical analysis

The experimental data were analyzed by the Statistical Analysis System (SAS) for Windows version 9.4 (SAS Institute Inc., Cary, NC, USA) using Duncan's multiple range tests at $P < 0.05$.

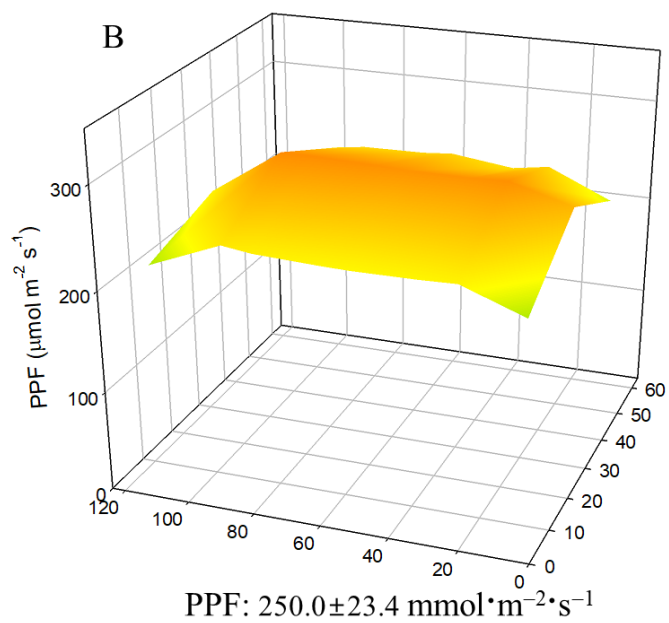
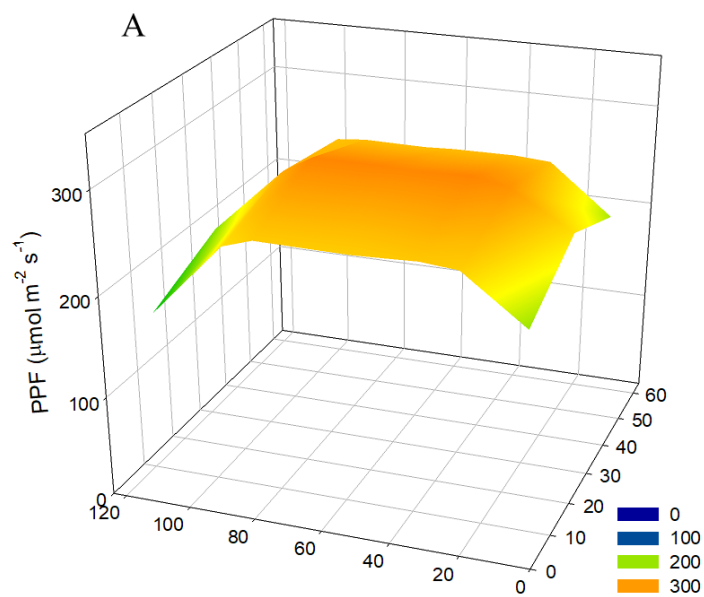


Fig. 1-2. Light intensity distribution of previous (A) and improved (B) LEDs at 250 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

RESULTS

Spectral differences of warm- and cool-white LEDs

Fig. 1-3 shows the spectral distribution of warm- and cool-white LED combination treatments. The results indicate differences in red/blue and red/FR ratios (Table 1-1).

FR radiation is not strong enough to affect plant growth. Many plants show increases in shoot length, leaf number, fresh weight, and dry weight with higher red/blue ratios. According to these results, the difference in growth among the treatments may be caused by different red/blue ratios. Warm-white LEDs had more red light and less blue light than cool-white LEDs; thus, the W1C0 treatment had the highest red/blue ratio, and the W1C1 treatment had the lowest red/blue ratio.

Seedling growth under different ratios of white LEDs

Fig. 1-4 shows representative images of cucumber, watermelon, and tomato seedlings grown under different ratios of WLEDs. The seedlings grown under treatment W1C1 had the shortest hypocotyls, and the seedlings grown in W1C0 had the longest hypocotyls among the three tested vegetables (Table 1-2). The shortest hypocotyls of watermelon scions, watermelon rootstocks, and tomato rootstocks were observed in W1C1, followed by W3C1, W5C2, and W1C0, but in W5C2 and W1C1, the hypocotyls were significantly different.

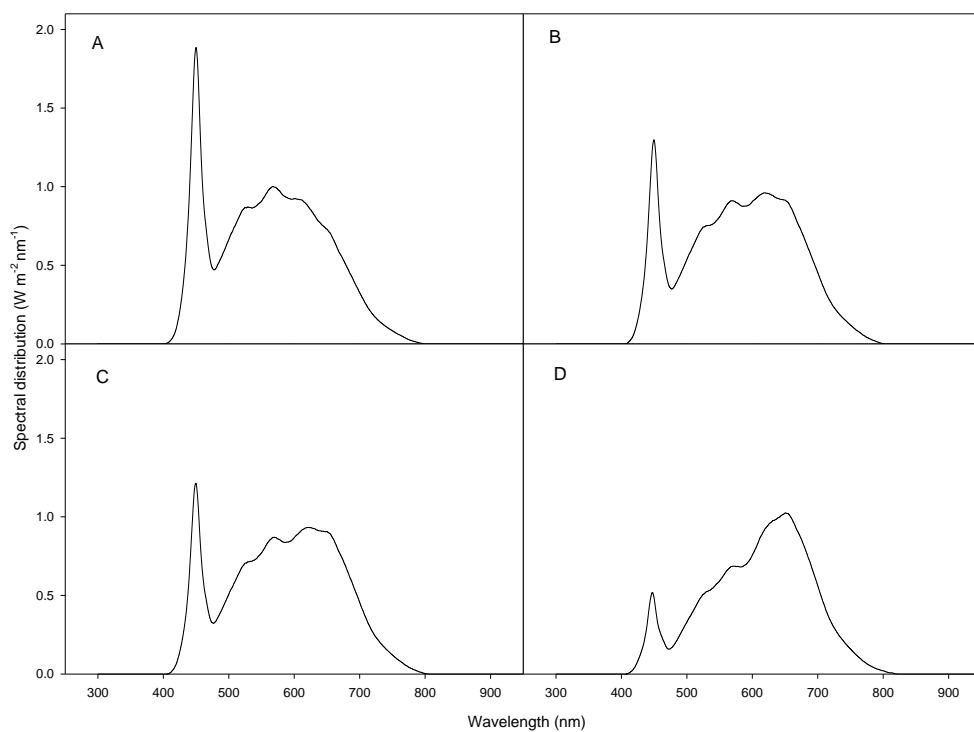


Fig. 1-3. Spectral distribution of W1C1 (A), W5C2 (B), W3C1 (C), and W1C0 (D) LEDs. Spectral scans were conducted at the center of the tray with a light intensity at $250 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

Table 1-1. Light intensity of W1C1, W5C2, W3C1, and W1C0 LEDs.

Plant	Treatment	Spectral composition (%)				PPFD ^z ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	Red/blue ratio ^y
		400-500 nm	500-600 nm	600-700 nm	700-800 nm		
Cucumber	W1C1	27.1	38.5	29.9	4.6	99.8 \pm 5.1	1.1
	W5C2	20.3	35.7	37.2	6.8	97.4 \pm 6.2	1.8
	W3C1	19.5	35.3	38.0	7.1	101.1 \pm 5.7	1.9
	W1C0	10.8	31.1	47.5	10.6	100.9 \pm 3.6	4.4
Watermelon and tomato	W1C1	27.1	38.5	29.8	4.6	255.3 \pm 12.6	1.1
	W5C2	20.3	35.8	37.1	6.8	250.7 \pm 14.5	1.8
	W3C1	19.5	35.3	38.0	7.2	251.5 \pm 11.5	1.9
	W1C0	10.8	31.2	47.5	10.6	249.1 \pm 10.5	4.4

^zPPFD, photosynthetic photon flux density

^yWavelengths of red and blue represent 600-700 nm and 400-500 nm, respectively

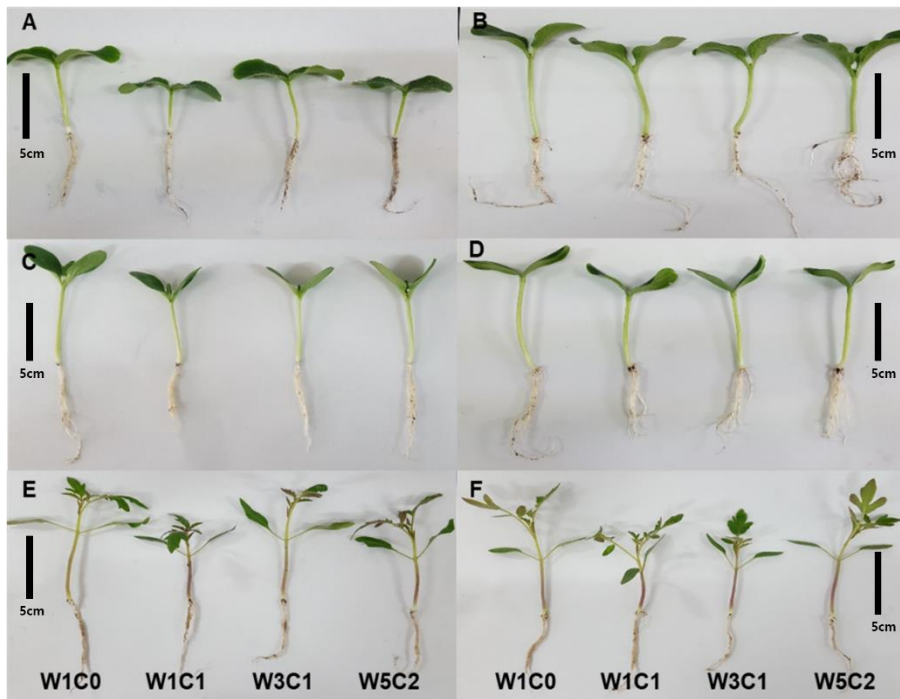


Fig. 1-4. Seedlings of cucumber scions (A) and rootstocks (B) 7 days after sowing (DAS), watermelon scions (C) and rootstocks (D) at 9 DAS, and tomato scions (E) and rootstocks (F) at 14 DAS under different LED lights.

Table 1-2. Growth of cucumber scions and rootstocks 7 days after sowing (DAS), watermelon scions and rootstocks at 9 DAS, and tomato scions and rootstocks at 14 DAS under different LED lights.

Plant	Treatment	Hypocotyl length (cm)	Leaf area (cm ²)	Stem diameter (mm)	Shoot FW (g/plant)	Root FW (g/plant)
Cucumber (scion)	W1C1	3.03c	10.31b	1.69a	0.42b	0.05c
	W5C2	3.47bc	11.72a	1.75a	0.47ab	0.09a
	W3C1	3.80ab	11.03ab	1.63a	0.46ab	0.07b
	W1C0	4.37a ^z	11.00ab	1.80a	0.48a	0.07b
Cucumber (rootstock)	W1C1	6.05b	19.93a	3.08a	1.69b	0.35a
	W5C2	6.77a	15.92a	2.91a	2.06a	0.40a
	W3C1	6.65a	18.53a	2.93a	1.78b	0.35a
	W1C0	6.85a	19.19a	2.91a	1.80b	0.34a
Watermelon (scion)	W1C1	4.78c	8.24b	1.72a	0.60b	0.29a
	W5C2	5.68b	9.32ab	1.81a	0.67ab	0.12a
	W3C1	5.23bc	10.48a	1.88a	0.72a	0.14a
	W1C0	6.85a	8.67b	2.03a	0.74a	0.09a
Watermelon (rootstock)	W1C1	5.45c	10.22a	2.48b	0.98c	0.23a
	W5C2	6.55b	10.85a	2.46b	1.18ab	0.26a
	W3C1	6.52b	11.24a	2.53b	1.11b	0.24a
	W1C0	7.52a	11.70a	2.83a	1.23a	0.25a
Tomato (scion)	W1C1	3.80c	5.60a	1.48b	0.42a	0.05a
	W5C2	4.08c	5.41a	1.52b	0.42a	0.05a
	W3C1	4.75b	5.31a	1.60b	0.45a	0.05a
	W1C0	5.23a	6.44a	1.79a	0.50a	0.04a
Tomato (rootstock)	W1C1	3.45c	5.49a	1.41b	0.39a	0.04a
	W5C2	4.25b	5.83a	1.55b	0.43a	0.03a
	W3C1	4.18b	5.80a	1.55b	0.42a	0.05a
	W1C0	4.67a	5.53a	1.64a	0.40a	0.04a

^zMeans within each column followed by the same letters are not significantly different according to Duncan's multiple range test at $P < 0.05$. *, **, and *** indicate significance at $P < 0.05$, 0.01, and 0.001, respectively.

In addition, tomato scions had the shortest hypocotyl lengths in W5C2 and W1C1 with no significant difference between the two treatments, the next shortest hypocotyls were produced under W3C1, and the highest hypocotyls were found under W1C0.

Increasing the red/blue ratio from 1.1 to 4.4 increased the hypocotyls of cucumber, watermelon, and tomato seedlings to various degrees (Fig. 1-5). All slopes of the regression lines between the red/blue ratio and hypocotyl length were positive, showing that the increase in the red/blue ratio led to an increase in hypocotyls in all tested seedlings except cucumber scions and tomato rootstocks. In the case of watermelon, the slopes of the regression of scions and rootstocks were highest, and their values were 1.45 and 1.50, respectively. The leaf area of cucumber scions increased with increasing red/blue ratio from 1.1 to 4.4. In the case of watermelon scions, leaf area was highest at a red/blue ratio of 1.9 and decreased at a red/blue ratio of 4.4 (Table 1-2). The stem diameters of watermelon rootstocks and tomato scions and rootstocks increased with increasing red/blue ratio. The shoot fresh weight of all tested seedlings increased with increasing red/blue ratio except for tomato scions and rootstocks. The root fresh weight of cucumber scions was smaller in W1C1 than in the other treatments. There were no significant differences in other plant seedlings.

For cucumber scions, shoot fresh weight was higher in W1C0 than in the other treatments. The shoot fresh weight increased with increasing red/blue

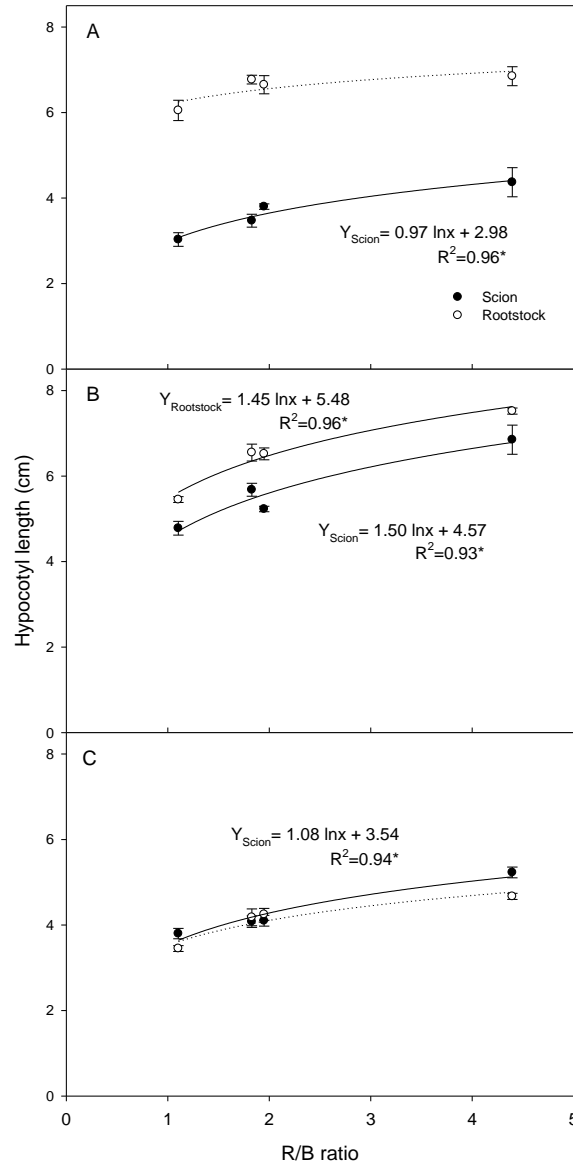


Fig. 1-5. Hypocotyl lengths of cucumber scions and rootstocks (A) 7 days after sowing (DAS), watermelon scions and rootstocks (B) at 9 DAS, tomato scions and rootstocks (C) at 14 DAS under different LED lights.

ratio. The leaf area and root fresh weight of cucumber scions showed similar tendencies; they were highest in W1C0 and lowest in W1C1. There were no significant differences in the other growth analyses for cucumber rootstocks, such as leaf area and shoot fresh weight of scions and rootstocks, although these increased with increasing red/blue ratio. The shoot fresh weight was highest in W1C0 and lowest in W1C1. The stem diameter of watermelon rootstocks increased with increasing red/blue ratio, while those of scions were not significantly different. The leaf area of watermelon scions was highest in W3C1. The stem diameters of tomato scions and rootstocks were highest in W1C0. The increase in stem diameter showed a similar tendency with an increasing red/blue ratio.

DISCUSSION

In this study, an increase in cool-white LEDs affected hypocotyl elongation inhibition. Cryptochrome, a blue light receptor in plants, is comprised of N-terminal and C-terminal domains (Yang et al., 2000). The N-terminal domain is responsible for blue light signaling, while the C-terminal domain binds chromophores and mediates CRY dimerization (Brautigam et al., 2004; Sang et al., 2005; Yang et al., 2000). In *Arabidopsis*, the N-terminus of the CRY1 domain was able to mediate inhibition. The results of this experiment showed how much red and blue light should be mixed to obtain the desired seedlings. Figs. 1-5 show the change in hypocotyl length according to the red/blue ratio. As the red/blue ratio increased, the hypocotyl length also increased, and the R^2 value was over 0.9. The shape and hypocotyl length of seedlings are the most important factors to ensure grafting success when using grafting robots (Suzuki et al., 1995). If the hypocotyl length for the grafting robot that is now used is known, the ratio to combine warm- and cool-white LEDs can be identified by substituting it in this formula. However, a clear distinction is needed between treatments to obtain more accurate results. The hypocotyl length was longest in W1C0 and shortest in W1C1 in all tested fruit vegetables. The hypocotyls in W3C1 were longer than those in W5C2 for cucumber and tomato scions, but cucumber rootstocks, watermelon scions, watermelon rootstocks, and tomato rootstocks were longer in W5C2 and W3C1. It is not known whether the

difference in W5C2 and W3C1 was not significant or whether it was characteristic of these plant species. In addition, there were no differences between W1C0 and W3C1, W5C2, and W1C1 in cucumber scions, even if the tendency that W1C0 and W3C1 treatments had higher hypocotyl lengths than W15C2 and W1C1 treatments was maintained. If the experiment had utilized W1C3 instead of W5C2 and added W0C1 treatment, the results would have been clearer.

The wavelength difference of the WLEDs affected the stem diameter, fresh weight, or leaf area of the plants, but the changes varied with plant species and did not show a clear tendency, while hypocotyl length showed a constant tendency. During the initial stages of growth, a high percentage of blue light in the spectrum of cool-white LEDs results in short and sturdy hypocotyls. In later developmental stages, cool-white LEDs can be replaced by warm-white LEDs. Warm-white LEDs promote leaf expansion (Cope and Bugbee 2013).

Hypocotyl length and stem diameter are important factors for uniform size, but leaf area and fresh weight are quality factors for seedlings. These factors were included because using healthy seedlings for grafting is as important as the efficiency of the grafting robot. Thus, follow-up studies to determine other factors affecting the quality of seedlings and to determine the responses of the factors to different wavelength compositions of LEDs are needed.

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CHAPTER 2

Improvement of growth and morphology of vegetable seedlings with supplemental far-red-enriched LED lights

ABSTRACT

Although light-emitting diode (LED) lamps have widely been applied in horticultural production to improve yield and quality, far-red (FR) light lacks in the LED spectrum. This study aimed to find the effect of supplemental FR-enriched LED lights to control the growth of tomato, red pepper, cucumber, gourd, watermelon, and bottle gourd seedlings. The treatments were cool-white LED: FR LED at ratios of 5:0, 5:1, 5:2, and 5:3. The growth of tomato and red pepper seedlings, including hypocotyl length, was correlated to FR light and light intensity. The phytochrome photostationary state (PSS) values of maximum hypocotyl length by supplemental FR-enriched LEDs ranged from 0.69 to 0.77 in tomato and red pepper seedlings. Although hypocotyl lengths of cucumber and watermelon seedlings were greatly affected by PSS, the PSS values for maximum hypocotyl length were lower than those of tomato and red pepper seedlings. These results show that manipulating supplemental FR enrichment can be used to control vegetable seedling growth with some variation among plant species.

Key words: Far-red-enriched light; hypocotyl; LED; phytochrome
photostationary state; vegetable seedlings

INTRODUCTION

Plant responses to light vary depending on light intensity, photoperiod, and light quality. Among light properties, various light spectra have widely been applied enhance biomass and control morphology of plants (Carvalho et al., Franklin, 2008; 2016; Li and Kubota, 2009). FR light affects plant growth and morphology in lettuce (Lee et al., 2015, 2016; Li and Kubota, 2009; Stutte et al., 2009), tomato (Chia and Kubota, 2010), squash (Yang et al., 2012), red pepper (Brown et al., 1995), and snapdragon (Park and Runkle, 2016) seedlings. End-of-day FR lighting has been used as an effective way influencing stem and hypocotyl elongation in watermelon (Graham and Decoteau, 1997) and tomato rootstocks (Chia and Kubota, 2010). Red to FR light ratio also affected growth and photomorphogenesis including stem development in many plant species, such as soybean (Yang et al., 2018), cucumber (Shibuya et al., 2016), bottle gourd (Kang and Jeon, 2001), common bean (Barreiro et al., 1992), and red pepper (Brown et al., 1995) seedlings.

In the use of artificial lighting such as fluorescent, metal-halide, high-pressure sodium vapor and LED lamps, light intensity, and quality of each show clear differences from natural light, especially in the FR range (Demotes-Mainard et al., 2016; Zhen and van Iersel, 2017). Plants show a shade avoidance response (SAR) under natural lighting including effects on stem elongation and dry mass partitioning to the shoot, and a reduction of the red to

FR light ratio under artificial lights affects the SAR (Cole et al., 2011; Franklin, 2008; Ji et al., 2019). Phytochromes enable plants to recognize the red to FR ratio by perceiving the light conditions (Shinomura et al., 2000; Trupkin et al., 2014). Phytochrome responses under artificial lights are generally classified into four groups by their light characteristics (VLFR, very low fluence response; LFR, low fluence response; R-HIR, red high irradiance response; and FR-HIR, FR high irradiance response) (Briggs et al., 1985; Shinomura et al., 2000). Among these phytochrome responses, FR-HIR reactions can explain photo-inhibition of stem elongation, and these might be induced by prolonged light irradiation with FR light, although it depends on light intensity (Hennig et al., 2000; Nagy and Schäfer, 2002; Otto et al., 1983; Van Der Woude, 1985). The phytochrome photostationary state (PSS), defined as the ratio of active phytochrome (Pfr) to total phytochrome (Pfr + Pr), has been used to quantify stem extension and elongation responses to light intensity and quality. PSS value from 0.70 to 0.85 has shown a negative linear correlation between shoot lengths of the plant (Morgan and Smith, 1976; Park and Runkle, 2017; Smith, 1994).

Among artificial lights, LEDs have recently become more widely used in horticultural production to control light quality more easily (Smith et al., 1991). However, because LED lamps are deficient in FR light, supplemental FR-enriched lighting could effectively regulate plant growth and morphology. Therefore, this study aimed to determine the effects of supplemental FR-

enriched light intensities for controlling the growth of young seedlings of tomato, red pepper, cucumber, gourd, watermelon, and bottle gourd.

MATERIALS AND METHODS

Plant materials and cultivation conditions

Seeds of tomato (*Solanum lycopersicum* cvs. Dotaerangdia and B-blocking, Takii, Seoul, Korea), red pepper (*Capsicum annuum* cvs. Shinhong and Tantan, Nongwoo Bio, Suwon, Korea), cucumber (*Cucumis sativus* cv. Joeunbaegdadagi, Seminis, Seoul, Korea), gourd (*Cucurbita ficifolia* cv. Heukjong, Hungnong Seeds, Ansung, Korea), watermelon (*Citrullus vulgaris* cv. Sambokkul, Hungnong Seeds), and bottle gourd (*Lagenaria siceraria* cv. Bulrojangsaeng, Syngenta, Seoul, Korea) were sown into commercial soil mix (Plant World, Nongwoo Bio) in a 128-cell plug tray (2.8 × 2.8-cm; 18-mL volume) and cultivated in a closed system with LED lighting. The seedlings were grown at an air temperature of 26/22°C (light/dark periods), a photosynthetic photon flux density (PPFD) of 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ with a 16/8h light photoperiod, a CO₂ concentration of 600 $\mu\text{mol}\cdot\text{mol}^{-1}$ and a relative humidity of 60%. PPFD in all treatments was measured at the top of the tray (28-cm distance from the lamps). Seedlings were subirrigated with Yamazaki (1982) nutrient solution (pH 6.5 and EC 0.5-1.5 dS·m⁻¹) every 2 or 3 days.

Supplemental far-red lighting treatments

The Light treatments began after germination. Using 10 cool-white LEDs (T5/20W6500K, Parlux, Incheon, Korea), supplemental FR LEDs (HT251-FR,

Bissol LED, Seoul, Korea) lights were used at three different intensities with a peak wavelength of 712 nm. The spectral distribution of the light sources was measured with a spectroradiometer (BLUE-Wave spectrometer, StellarNET Inc., Tampa, FL, USA) (Fig. 2-1, Table 2-1). Cool-white LEDs were distributed throughout the photosynthetically active wavelength range (400-700 nm) and characteristically accounted for a greater percentage of green-yellow light (500-600 nm). The treatments were the numbers of cool-white LED lights: FR LED lights at ratios of 5:0, 5:1, 5:2, and 5:3, or W5F0, W5F1, W5F2, and W5F3, respectively. In each treatment, the FR-enriched LEDs were on at the same time as the cool-white LEDs, creating four different PSS values. The average quantum per 1-nm wavelength of each treatment from 300 to 800 nm was collected at 12 points using a LI-190 quantum sensor (LI-COR Inc., Lincoln, NE, USA). The estimated PSS of each treatment was calculated from the spectral distribution data following the method of Sager (1988):

$$PSS = \frac{\sum_{300}^{800} N(\lambda)\sigma(r\lambda)}{(\sum_{300}^{800} N(\lambda)\sigma(r\lambda) + \sum_{300}^{800} N(\lambda)\sigma(fr\lambda))}$$

, where $N(\lambda)$, $\sigma(r\lambda)$, and $\sigma(fr\lambda)$ indicate the photon flux and the photochemical cross-section of Pr and Pfr, respectively. The PSS value decreased with increasing supplemental FR-enriched light intensity. PSS of W5F0, W5F1, W5F2, and W5F3 treatments were 0.85, 0.69, 0.63, and 0.60, respectively (Table 2-1).

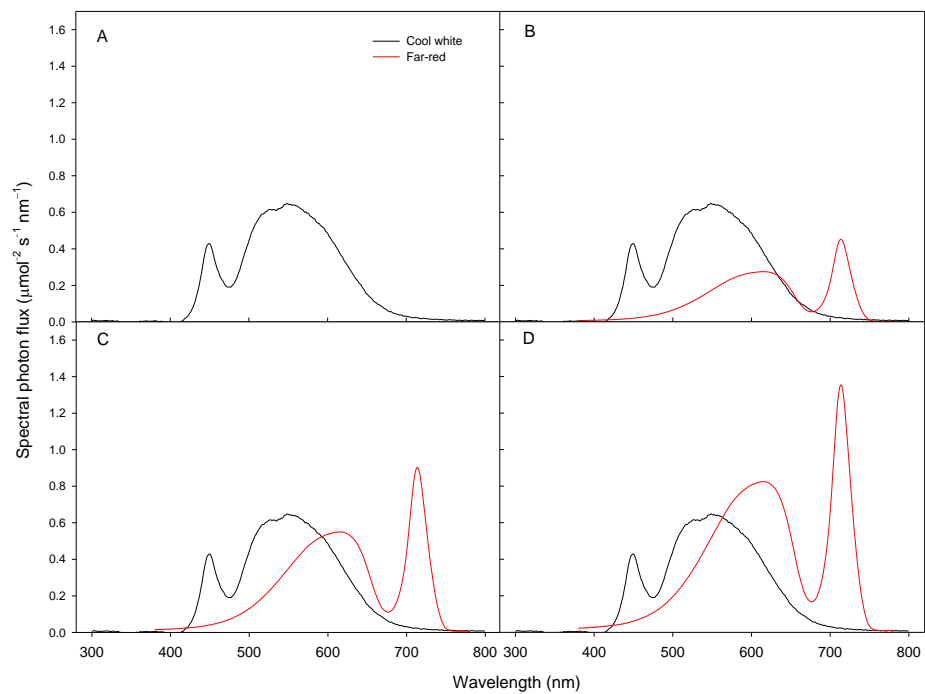


Fig. 2-1. Spectral distribution of the light treatments W5F0 (A), W5F1 (B), W5F2 (C), and W5F3 (D) LEDs.

Table 2-1. Light intensity and phytochrome photostationary state values of different supplemental far-red-enriched LED lightings.

Treatment	Light Intensity ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)				PPFD ^z	TPFD	PSS
	400–500 nm	500–600 nm	600–700 nm	700–800 nm			
W5F0	42.4	122.6	33.2	1.6	198.2	199.8	0.85
W5F1	46.0	146.8	58.2	18.9	251.0	269.9	0.69
W5F2	49.1	168.1	80.2	34.1	297.4	297.4	0.63
W5F3	53.2	195.3	108.3	53.4	356.8	356.8	0.60

^zPPFD, photosynthetic photon flux density; TPFD, total photon flux density; PSS, photostationary state

Plant growth analysis

The experiment consisted of 4 treatments replicated 3 times with 8 plants per replication. Hypocotyl length, stem diameter, shoot fresh weight and dry weight of tomato and red pepper seedlings were measured 14 days after sowing (DAS), cucumber and gourd seedlings at 7 DAS, and watermelon and bottle gourd at 9 DAS. Stem diameter was measured using a Vernier caliper (CD-20CPX, Mitutoyo Co., Kawasaki, Japan). Fresh weight was measured using a precision scale (Fx-300i, A&D Weighing, San Jose, CA, USA) and dry weight after drying at 80°C for 3 days (HB-502M, Hanbaek Co., Ltd., Bucheon, Korea). Compactness was calculated as shoot dry weight per hypocotyl length.

Statistical analysis

The experimental data were analyzed by the Statistical Analysis System (SAS) for Windows version 9.4 (SAS Institute Inc., Cary, NC, USA) using Duncan's multiple range test at $P < 0.05$.

RESULTS

Plant growth

The effect of supplemental FR enriched LEDs on the growth of the vegetable seedlings is shown in Fig. 2-2. The hypocotyl length of tomato seedlings in W5F1 was longer than or equal to that in W5F0 (Table 2-2). However, as FR light intensity increased, it decreased even lower than the W5F0 in tomato seedlings. Although red pepper seedlings similarly showed the longest hypocotyl length in W5F1, hypocotyl length in W5F2 and W5F3 was not lower than W5F0. For cucumber, gourd, watermelon, and bottle gourd seedlings, every hypocotyl length by the supplemental FR lights was higher than W5F0 and showed the greatest features in W5F2.

The stem diameters of tomato and red pepper seedlings in W5F1 were generally greater than those in W5F0. The stem diameter of cucumber was greatest in W5F2, while gourd had a greater stem diameter in all treatments than in W5F0. The shoot dry weights of all tomato and red pepper seedlings showed similar changes to the hypocotyl length with supplemental FR light. The dry weights of 'B-blocking' tomato seedlings were greatest under W5F1, while dry weights with W5F2 and W5F3 were significantly lower than W5F0. For cucumber and watermelon, the dry weight was the greatest in W5F2 and W5F3, respectively. The shoot dry weight of red pepper and bottle gourd in under W5F3 was greater than in W5F0.

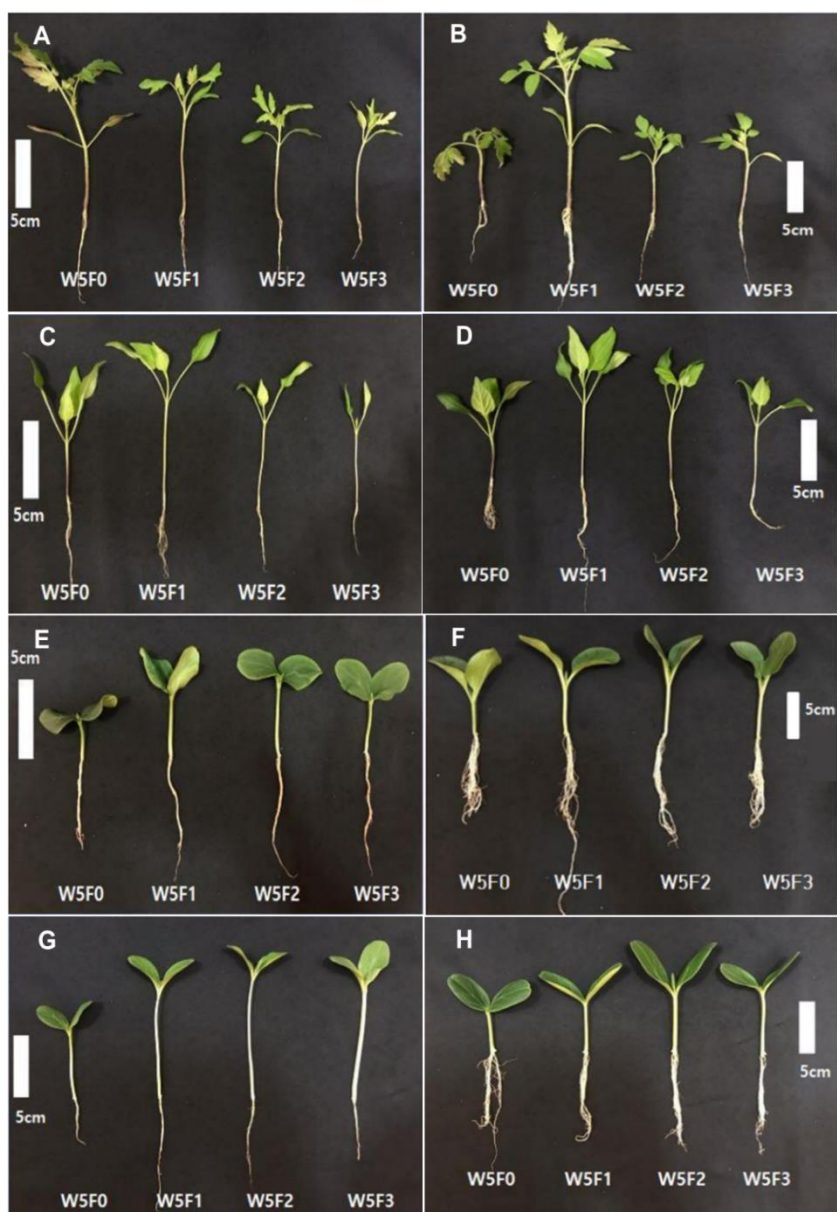


Fig. 2-2. Seedlings of 'Dotaerangdia' (A) and 'B-blocking' (B) tomatoes 14 days after sowing (DAS), 'Shinhong' (C) and 'Tantan' (D) red peppers at 14 DAS, cucumber (E) and gourd (F) at 7 DAS, and watermelon (G) and bottle gourd (H) at 9 DAS under different supplemental FR-enriched LED lightings. The treatments were cool-white LED: FR LED at ratios of 5:0 (W5F0), 5:1 (W5F1), 5:2 (W5F2), and 5:3 (W5F3).

Table 2-2. Growth of tomatoes 14 days after sowing (DAS), red peppers at 14 DAS, cucumbers and gourds at 7 DAS, and watermelons and bottle gourds at 9 DAS under different supplemental far-red-enriched LED lightings.

Plant	Cultivar	Treatment	Hypocotyl Length (cm)	Stem Diameter (mm)	Shoot	
					Fresh Weight (g)	Dry Weight (g)
Tomato	Dotaerangdia	W5F0	5.09b ^c	16.1a	0.947a	0.049a
		W5F1	6.22a	16.7a	0.678b	0.044a
		W5F2	4.94b	10.3b	0.245c	0.015b
		W5F3	4.97b	11.3b	0.210c	0.012b
	B-blocking	W5F0	5.74a	17.7b	0.725b	0.043b
		W5F1	5.59a	22.1a	1.250a	0.084a
		W5F2	4.70b	15.3c	0.544c	0.033bc
		W5F3	4.68b	15.3c	0.478c	0.031c
Pepper	Shinhong	W5F0	3.88c	7.9b	0.339b	0.027b
		W5F1	5.61a	10.4a	0.398a	0.031a
		W5F2	4.86ab	7.1b	0.156c	0.011c
		W5F3	4.28bc	5.9c	0.098d	0.008d
	Tantan	W5F0	3.53d	9.1b	0.389b	0.035b
		W5F1	5.80a	11.5a	0.582a	0.043a
		W5F2	5.53b	11.0a	0.402b	0.034b
		W5F3	4.83c	9.3b	0.261c	0.018c
Cucumber	Joeunbaegdadagi	W5F0	2.27c	16.7b	0.402c	0.035c
		W5F1	3.53b	18.5b	0.501b	0.041b
		W5F2	4.59a	23.0a	0.598a	0.049a
		W5F3	3.74b	19.1b	0.494b	0.044b
Gourd	Heukjong	W5F0	2.93b	26.7a	1.742a	0.014a
		W5F1	4.75a	29.0a	1.910a	0.014a
		W5F2	4.91a	28.0a	1.743a	0.014a
		W5F3	4.57a	28.6a	1.875a	0.015a
Watermelon	Sambokkul	W5F0	4.51d	19.7b	0.447c	0.020c
		W5F1	7.53c	25.2a	0.876b	0.042a
		W5F2	9.31a	24.5a	0.869b	0.036b
		W5F3	8.13b	27.5a	1.016a	0.045a
Bottle gourd	Bulrojangsaeng	W5F0	3.71c	30.9ab	1.167c	0.077b
		W5F1	4.27b	28.3b	1.265bc	0.083b
		W5F2	5.40a	35.9a	1.565a	0.097a
		W5F3	5.14a	31.3ab	1.374b	0.079b

^aDifferent Mean separation among treatments within columns and within each cultivar by Duncan's multiple range test at $P < 0.05$.

Compactness of seedlings

Supplemental FR-enriched lights influenced the compactness of seedlings differently depending on plant species (Fig. 2-3). Compactness is the ratio of the shoot dry weight and hypocotyl length, and higher compactness indicates the seedlings were short and denser (Jeong et al., 2020). The compactness of the ‘Dotaerangdia’ tomato under W5F1 and W5F3 was higher than W5F0. In contrast, the compactness of the ‘B-blocking’ tomato was the greatest under W5F1. However, the compactness of red pepper seedlings showed a clear declining trend as FR-enriched light intensity increased. The compactness of cucumber and gourd was decreased significantly by the supplemental FR-enriched lights, regardless of the light intensity. The compactness of watermelon under W5F1 and W5F3 was higher than W5F0, while that of bottle gourd was decreased as FR-enriched light intensity increased.

The PSS value for maximum hypocotyl length by supplemental FR light was 0.69-0.77 for tomato and red pepper seedlings (Fig. 2-4). The maximum hypocotyl length of ‘Dotaerangdia’ and ‘B-blocking’ tomatoes was 42.9 cm at PSS 0.73 and 4.4% greater at PSS 0.77 than the control at PSS 0.85, respectively. Those of ‘Shinhong’ and ‘Tantan’ red peppers were 46.5 at PSS 0.71 and 58.2% greater at PSS 0.69 than the control, respectively. However, the peak values for cucumber, gourd and watermelon were not clearly different from controls in contrast to those of tomato and red pepper seedlings.

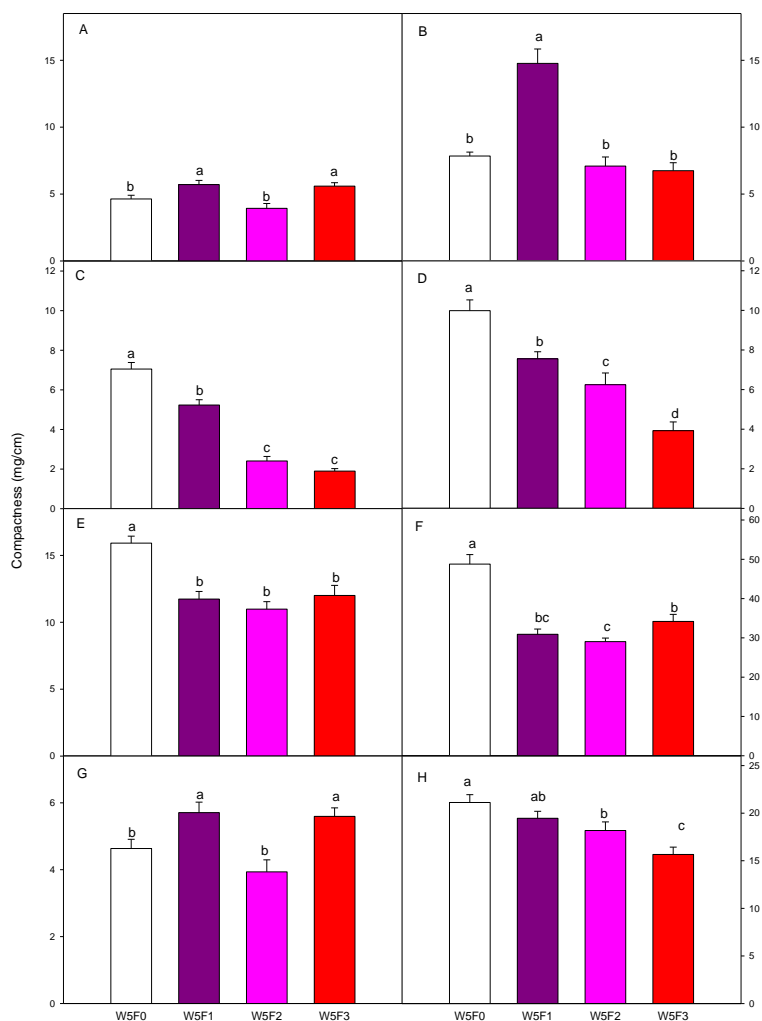


Fig. 2-3. Compactness of 'Dotaerangdia' (A) and 'B-blocking' (B) tomatoes 14 days after sowing (DAS), 'Shinhong' (C) and 'Tantan' (D) red peppers at 14 DAS, cucumbers (E) and gourds (F) at 7 DAS, and watermelons (G) and bottle gourds (H) at 9 DAS under different supplemental far-red-enriched LED lightings. Data represent the mean of three replications with eight plants per replication per species. Vertical bars represent standard errors of means. Mean separation among treatments within each cultivar by Duncan's multiple range test at $P < 0.05$.

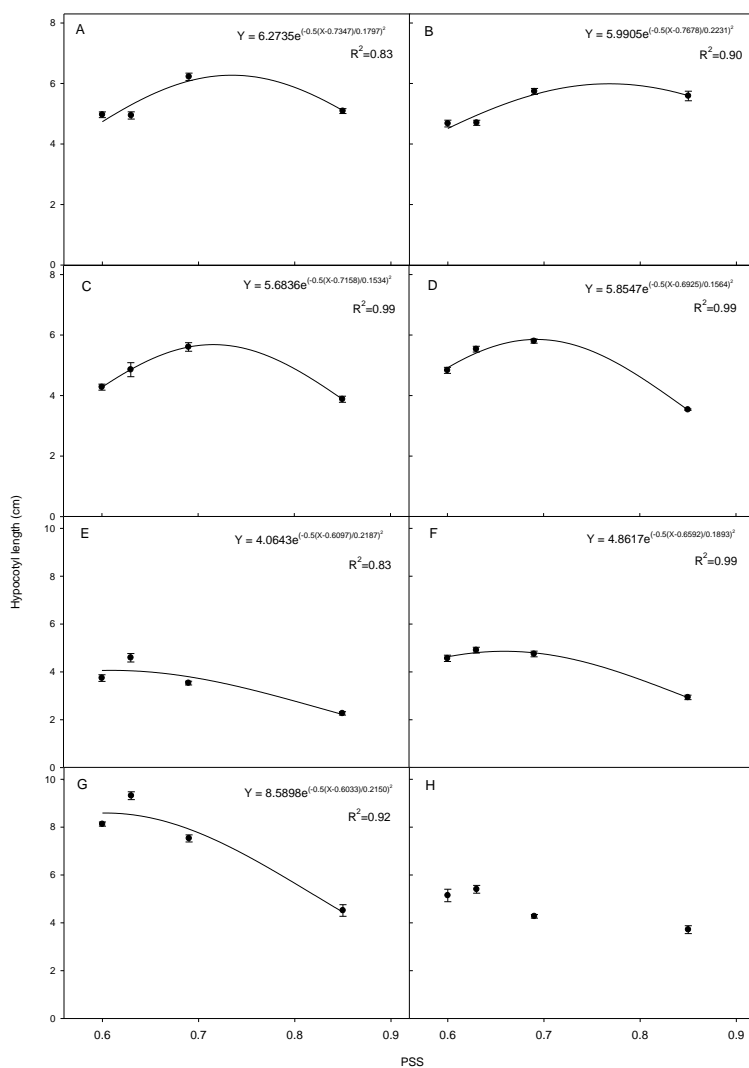


Fig. 2-4. Relationships of phytochrome photostationary state (PSS) with hypocotyl lengths of 'Dotaerangdia' (A) and 'B-blocking' (B) tomatoes 14 days after sowing (DAS), 'Shinhong' (C) and 'Tantan' (D) red peppers at 14 DAS, cucumber (E) and gourds (F) at 7 DAS and watermelons (G) and bottle gourds (H) at 9 DAS by the different supplemental far-red-enriched LED lightings. Data represent the mean of three replications with eight plants per replication per species/cultivar. Vertical bars represent standard errors of means.

DISCUSSION

The hypocotyl length of each species, and cultivar within species in some instances, responded differently to PSS values and resulted in a peak for all species except bottle gourd seedlings. A similar result of quadratic relationships with peak values was reported with *Crepidiastrum denticulatum* (Bae et al., 2017), similar to our results with tomato and red pepper seedlings.

Shoot dry weight varied with supplemental FR light spectral intensity and quality by plant species, showing clear peak values for tomato and red pepper seedlings. However, cucumber, gourd, watermelon, and bottle gourd seedlings did not show clear relationships between their dry weights and PSS values. Usually, the cucumber and watermelon (Cucurbitaceae scion) and gourd and bottle gourd (Cucurbitaceae rootstock) were grafted before the true leaves occurred, and the Solanaceae seedlings were grafted when three to four leaves occurred. It is the reason why the FR light response in the Solanaceae was much clearer. The PSS value at maximum shoot dry weight ranged from 0.74 to 0.77 for tomato and red pepper seedlings (Fig. 2-4). The shoot dry weight increase of ‘Dotaerangdia’ and ‘B-blocking’ tomatoes was 53.6% and 128.4% of the control value, when their dry weight was at PSS 0.73 and 0.77, respectively. Those of ‘Shinhong’ and ‘Tantan’ red peppers were 69.1% and 46.6% compared to the control, when the PSS values were at 0.74 and 0.75, respectively. Stem diameter in the FR treatments varied with species/cultivars,

while no clear trends were observed (Table 2-1). In this study, the compactness of each species/cultivar showed different responses to supplemental FR lighting. A decrease in leaf thickness is known to be one factor decreasing compactness, and this may have affected the compactness values in this study. This is validated by a previous study showing that supplemental FR lighting resulted in thinner leaves (Demotes-Mainard et al., 2016).

The hypocotyl length and dry weight of the vegetable seedlings in this study increased to peak values as the FR light intensity increased. Plant growth enhancement by supplemental FR light is generally explained as a synergistic effect on photosynthesis (Emerson, 1957; Zhen and van Iersel, 2017), with a stimulated distribution of photosynthetic products to the shoot (Ji et al., 2019). These growth and morphological changes at relatively low PSS values are a result of phytochrome-mediated shade avoidance responses (Ballaré et al., 1987; de Wit et al., 2013; Ji et al., 2019). Previous studies showed that plant growth and morphology improved with FR light treatments in lettuce (Lee et al., 2015, 2016; Li and Kubota, 2009; Stutte et al., 2009), tomato (Chia and Kubota, 2010), squash (Yang et al., 2012), red pepper (Brown et al., 1995), cucumber (Gaba and Black, 1985), snapdragon (Park and Runkle, 2016), and geranium (Park and Runkle, 2017) seedlings. Kalaitzoglou et al. (2019) reported that decreasing PSS from 0.88 to 0.80 increased the total dry weight and plant height of young tomato seedlings. However, the results in our study show that plant responses such as growth, including hypocotyl elongation, can

vary significantly among species, from positive to negative unaffected. On the one hand, the effect of a phytochrome-mediated FR high irradiance response (FR-HIR) under monochromatic FR light treatments has been shown to improve the growth and morphology of seedlings generally (Mancinelli and Rabino, 1978; Schäfer, 1975; Shinomura et al., 2000). On the other hand, hypocotyl elongation has been reported to be inhibited by FR light treatment in some species such as radish (Jose and Vince-Prue, 1977). Schäfer et al. (1981) found that the peaks in FR light action spectra and intensity response curves for the inhibition of hypocotyl growth in white mustard seedlings were 740 nm and $21 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, respectively (Heim et al., 1984; Holmes and Schäfer, 1981).

With supplemental FR light treatments, the FR light effect can be detected by using R:FR and PSS in general. In this study, as FR light intensity increased by supplemental FR light treatments, blue light (400-500 nm), PPFD, and total photon flux density (TPFD) also increased (Table 2-2). According to Hogewoning et al. (2010), growth and leaf responses were not affected by an increase in blue light intensity, up to $22 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Similarly, Fan et al. (2013) reported that tomato seedlings showed no substantial gain in growth from additional PPFD above $300 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Based on this information, we suggest that vegetable seedling growth in the FR light treatments in this study would not be affected by an increase in blue light (ranging from 42.4 to $53.2 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). However, previous research suggested that some phytochrome

responses were dose-dependent, and their effects on growth and morphology decreased above a threshold of light intensity (Bae et al., 2017). Plant responses to FR light have been shown to be a function of the R:FR ratio, and light intensity can also regulate the shade avoidance response. In general, increasing light intensity decreases the magnitude of plant responses to FR light effects. For example, stem elongation of sunflower increased with a reduction in the R:FR ratio (from 4.52 to 0.85) under both a low light intensity ($157 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and a high intensity ($421 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), but the response was reduced under much higher light intensity (Kurepin et al., 2007). Similarly, R:FR signaling through phytochrome B promoted branching of *Arabidopsis thaliana* under low light intensity ($160 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), but the effects diminished under higher light intensity ($280 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), indicating that high light intensity at least partially negates the effects of phytochrome-mediated signaling in plants (Su et al., 2011). Therefore, the effects of supplemental FR-enriched lighting on growth including hypocotyl length were affected by the increase in PPFD and TPDF. An appropriate range of FR light intensity could modulate plant growth and morphology for specific purposes. For example, it would be advantageous for grafting materials, such as scion and rootstock of seedlings, controlling the stem length of cut flowers (Kurepin et al., 2007), and training of many vegetable crops in protected horticulture (Kajihara and Katsutani, 2008). The results of this study show that FR-enriched lighting affects plant growth and morphology, but responses can greatly vary depending

on light intensity and plant species. Growth, including hypocotyl length of tomato and red pepper seedlings, reached peak increases at certain PSS values, and decreased with PSS values above that. However, there was no clear relation between PSS and growth or hypocotyl length for cucumber or watermelon. Therefore, careful consideration must be given in the selection of appropriate FR light intensities for each plant species and is necessary for the application of supplemental FR-enriched lighting with WLEDs to achieve a desired plant growth and morphology.

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CHAPTER 3

Combined conditions of photoperiod, light intensity and air temperature control the growth of young tomato and red pepper seedlings in a closed transplant production system

ABSTRACT

Understanding environmental factors is essential to maximizing the biomass production of plants. There have been many studies on the effects of the photosynthetic photon flux density (PPFD), photoperiod and air temperature as separate factors affecting plants, including under a closed transplant production system. However, few studies have investigated the combined effects of these factors on plant growth. Germinated tomato and red pepper seedlings were transferred to three different photoperiods with five different PPFDs at an air temperature of 25/20°C to investigate plant growth under a different daily light integral (DLI). Three different air temperatures, 23/20, 25/20, and 27/20°C (photo-/dark periods), with five different PPFDs were used to examine plant growth under different DIFs (difference between the day and night temperature). Increasing the DLI from 4.32 to 21.60 mol·m⁻²·d⁻¹, either by increasing the photoperiod or PPFD, improved the growth of seedlings in both cultivars. However, when comparing treatments

that provided the same DLI, tomato seedlings had significantly higher growth when grown under longer photoperiods and lower PPFD. Even in higher DLI conditions, reduced growth due to higher PPFD indicated that excessive light energy was a limiting factor. At 23 and 25°C, tomato seedlings showed similar correlation curves between growth and PPFD. However, at the higher temperature of 27°C, while the slope of the curve at low PPFDs was similar to that of the curves at lower temperatures, the slope at high PPFDs was flatter. On the other hand, red pepper seedlings displayed the same correlation curve between growth and PPFD at all the tested temperatures, and red pepper plants accumulated more dry weight even at higher temperatures. These results suggested that the combination effect was more useful to observe these overall tendencies, especially in reacting to a second factor. This will provide us with more information and a deeper understanding of plant characteristics and how they will behave under changing environments.

Key words: Air temperature; closed transplant production system; light intensity; photoperiod

INTRODUCTION

Recently, plant factories have become more popular in the cultivation and production of vegetable seedlings (Jang et al., 2011), herbs (Dou et al., 2017) and medicinal plants (Jang et al., 2020; Zobayed et al., 2005) due to their many advantages over conventional protected horticulture. Especially in transplant production, closed systems using artificial lighting, which are called closed transplant production systems (CTPSs), have been designed and adopted for the cultivation and propagation of seedlings and transplants (Kozai et al., 2000). These systems can reduce labor and resource consumption (Kozai and Niu, 2016), increase the production rate, and improve plant quality due to the ability to control environmental factors for optimal growth conditions without being affected by outside weather (Kozai et al., 2000).

However, to successfully apply CTPS in transplant production, the responses of plants to environmental factors should be studied for determining growth conditions. Among the factors that affect plants in CTPS, air temperature, photosynthetic photon flux density (PPFD) and photoperiod are the most important. PPFD and photoperiod influence photosynthesis and carbohydrate gain, thereby determining the growth rate and vigor (Fan et al., 2013; Kang et al., 2013; Yan et al., 2019). On the other hand, air temperature affects transpiration, morphology, and photosynthetic efficiency (Bakker and Van Uffelen, 1988; Janssen et al., 1992; Slack and Hand, 1983). Together, these

factors have a great impact on plant growth and quality. Therefore, it is essential to understand how the plants respond to changes in these factors for successful CTPS operation.

There have been many studies on the effects of PPFD, photoperiod and air temperature as separate factors affecting on plants including in closed systems such as CTPS. However, few studies have investigated the combined effects of these factors on plant growth. PPFD, photoperiod and air temperature do not affect plants independently. Rather, their influences on physiological processes such as photosynthesis, transpiration and morphological development are interconnected (Ku et al., 1977). If one of the environmental factors changes, the results may vary significantly depending on the rest of the environmental factors. Therefore, it is important to examine the complex interactions of various environmental factors.

Furthermore, most studies only focus on the differences among specific treatment conditions instead of investigating the trend in the plant responses to environmental factors (Kitaya et al., 1998). As each plant species has unique nature, it is more useful to observe these overall tendencies, especially when the plant is reacting to a second factor. This will provide us with more information and a deeper understanding of plant characteristics, and how they will behave under changing environments. This knowledge not only allows us to adjust and optimize the conditions inside CTPS for maximum plant growth and desirable quality but can also be applied in the field for adaptation of the

cultivation to the changing weather.

Therefore, in this study, we evaluated the combined effects of air temperature, light intensity and photoperiod on growth and development of tomato and red pepper seedlings. By using regression analyses and careful comparisons, we attempted to uncover the dynamic interactions among these factors and get a better understanding of the natures and preferences of tomato and red pepper seedlings in terms of environmental conditions. From these data, we will be able to set the optimum air temperature, light intensity, and photoperiod in CTPS for each species to serve various purposes.

MATERIALS AND METHODS

Plant materials and growth conditions

Seeds of tomato (*Solanum lycopersicum* cv. Dotaerangdia, Takii Korea, Seoul, Korea) and red pepper (*Capsicum annuum* cv. Shinhong, Nongwoo Bio, Suwon, Korea) were sown on a 162-cell plug tray (2.5 × 2.5 cm; 15 mL volume) filled with commercial growing medium (Biomedia, Hungnong Seed Co., Ansung, Korea) and cultivated in a closed system. All the treatments used white LED lamps (model v3.0W, Future Green Co., Ltd., Suwon, Korea, Fig. 3-1). The seedlings were grown at a CO₂ concentration of 400 μmol·mol⁻¹ and a relative humidity of 70-90%. Seedlings were sub irrigated every 2 or 3 days with pH 6.5 and electrical conductivity (EC) 1.4 dS·m⁻¹ of nutrient solution. The pH and EC of the nutrient solution were measured using a digital pH meter and an EC meter (Horiba D-54, Tokyo, Japan).

Light treatments

The experiment consisted of 15 treatments, with 7 plants × 3 replicates per treatment. The germinated seedlings were transferred to treatment conditions, and the seedlings were grown under three different photoperiods (Table 3-1) with five different PPFDs (Table 3-2) at an air temperature of 25/20 °C for 15 days and 23 days for tomato and red pepper seedlings, respectively.

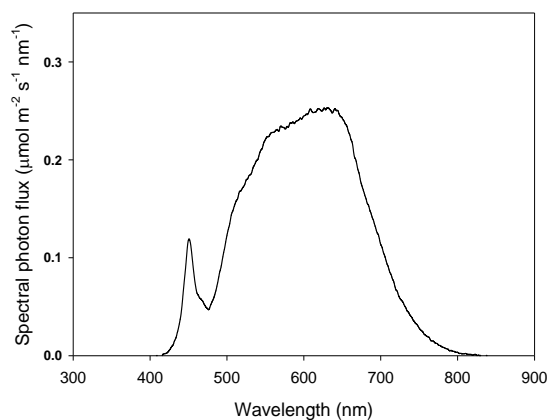


Fig. 3-1. Spectral distribution of white LEDs used in this experiment. Spectral scans were conducted at the center of the tray with a light intensity of $100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

Table 3-1. Daily light integral (DLI) of this experiment.

Photoperiod (h·d ⁻¹)	PPFD ^z (μmol·m ⁻² ·s ⁻¹)	DLI (mol·m ⁻² ·d ⁻¹)
12	100	4.32
	150	6.48
	200	8.64
	250	10.80
	300	12.96
16	100	5.76
	150	8.64
	200	11.52
	250	14.40
	300	17.28
20	100	7.20
	150	10.80
	200	14.40
	250	18.00
	300	21.60

^zPPFD, photosynthetic photon flux density; DLI, daily light integral

Table 3-2. Light intensity of this experiment.

Treatment	PPFD ^z ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)				Total
	400-500	500-600	600-700	700-800	
PPFD100	9.1 \pm 0.5	38.6 \pm 2.1	40.5 \pm 2.2	7.3 \pm 0.4	95.4 \pm 5.1
PPFD150	14.0 \pm 0.5	59.6 \pm 2.3	62.4 \pm 2.4	11.2 \pm 0.4	147.1 \pm 5.7
PPFD200	18.5 \pm 0.8	79.1 \pm 3.3	82.9 \pm 3.5	14.9 \pm 0.6	195.4 \pm 8.2
PPFD250	23.4 \pm 0.9	99.6 \pm 3.7	104.3 \pm 3.9	18.7 \pm 0.7	246.0 \pm 9.2
PPFD300	28.0 \pm 1.4	119.6 \pm 5.9	125.3 \pm 6.2	22.5 \pm 1.1	295.5 \pm 14.6

^zPPFD, photosynthetic photon flux density

Air temperature treatments

The experiment consisted of 15 treatments, with 7 plants \times 3 replicates per treatment. The germinated seedlings were transferred to treatment conditions consisting of three different air temperatures, 23/20, 25/20 and 27/20 °C (photo-/dark periods) (Fig. 3-2), with five different photosynthetic photon fluxes (Table 3-2) with a 20 h photoperiod.

Plant growth characteristics

The seedlings were harvested for the evaluation of growth parameters, including hypocotyl length, stem diameter, leaf number, leaf area, fresh weight, and dry weight of tomato and red pepper seedlings, which were measured 17 and 25 days after sowing (DAS). Stem diameter was measured using a Vernier caliper (CD-20CPX, Mitutoyo Co., Kawasaki, Japan). Leaf area was measured using leaf area meters (Li-3100; LI-COR, Lincoln, NE, USA). Dry weight was measured after drying at 80 °C for 3 days. The leaf area index (LAI), dry matter content (DMC), compactness, and light use efficiency (LUE) were calculated using the following formulae:

$$\text{Leaf area index} = \text{Leaf area (cm}^2\text{)} / (\text{plug tray area (58} \times \text{24 cm}^2\text{)} / 162)$$

$$\text{Dry matter content} = (\text{dry weight/shoot fresh weight}) \times 100$$

$$\text{Compactness} = \text{shoot dry weight (g)} / \text{hypocotyl length (cm)}$$

$$\text{Light use efficiency} = \text{shoot dry weight (g)} / \text{DLI (mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}\text{)}$$

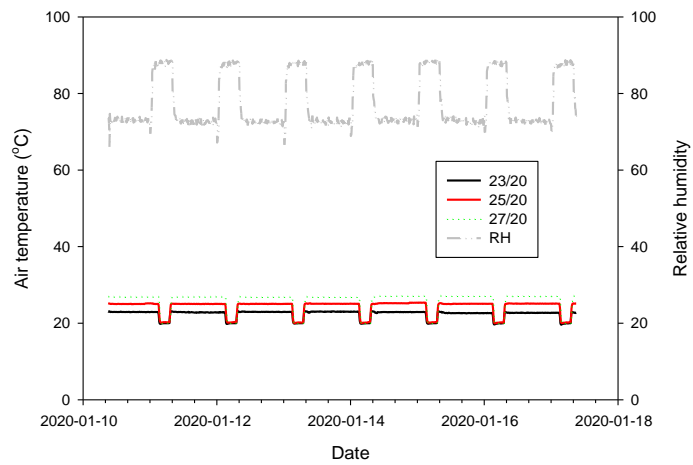


Fig. 3-2. Air temperature and relative humidity at 20 h·d⁻¹.

Statistical analysis

The experimental data were analyzed by the Statistical Analysis System (SAS) for Window version 9.4 (SAS Institute Inc., Cary, NC, USA) using a two-way factorial analysis of variance (ANOVA). Significant differences were considered at $P < 0.05$, 0.01, and 0.001.

RESULTS

Effects of different light intensities and photoperiods

Fig. 3-3 shows representative images of tomato seedlings 17 days after sowing (DAS) and red pepper seedlings at 25 DAS under different light intensities and photoperiods. Increasing the PPFD from 100 to 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ influenced the shoot length and stem diameter of tomato and red pepper seedlings differently depending on the photoperiod (Fig. 3-4). At photoperiods of 12 and 20 $\text{h}\cdot\text{d}^{-1}$, the shoot length of tomato was the highest at 200 and 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, respectively. Further increases in PPFD reduced the shoot length. In the case of red pepper, at 12 and 16 $\text{h}\cdot\text{d}^{-1}$ photoperiod, the shoot length was the highest at 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and decreased with higher PPFDs. At 20 $\text{h}\cdot\text{d}^{-1}$, there was no difference in the shoot length of red pepper among PPFDs of 100, 150 and 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, while a higher PPFD reduced the shoot length. An increase in PPFD from 100 to 250 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ promoted the stem diameter of tomato seedlings among all the tested photoperiods, but there was no significant difference between 250 and 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. The stem diameter of red pepper was the highest at 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ regardless of the photoperiod, while those at 12 and 20 $\text{h}\cdot\text{d}^{-1}$ had no significant differences if the PPFD was higher than 200 and 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, respectively.

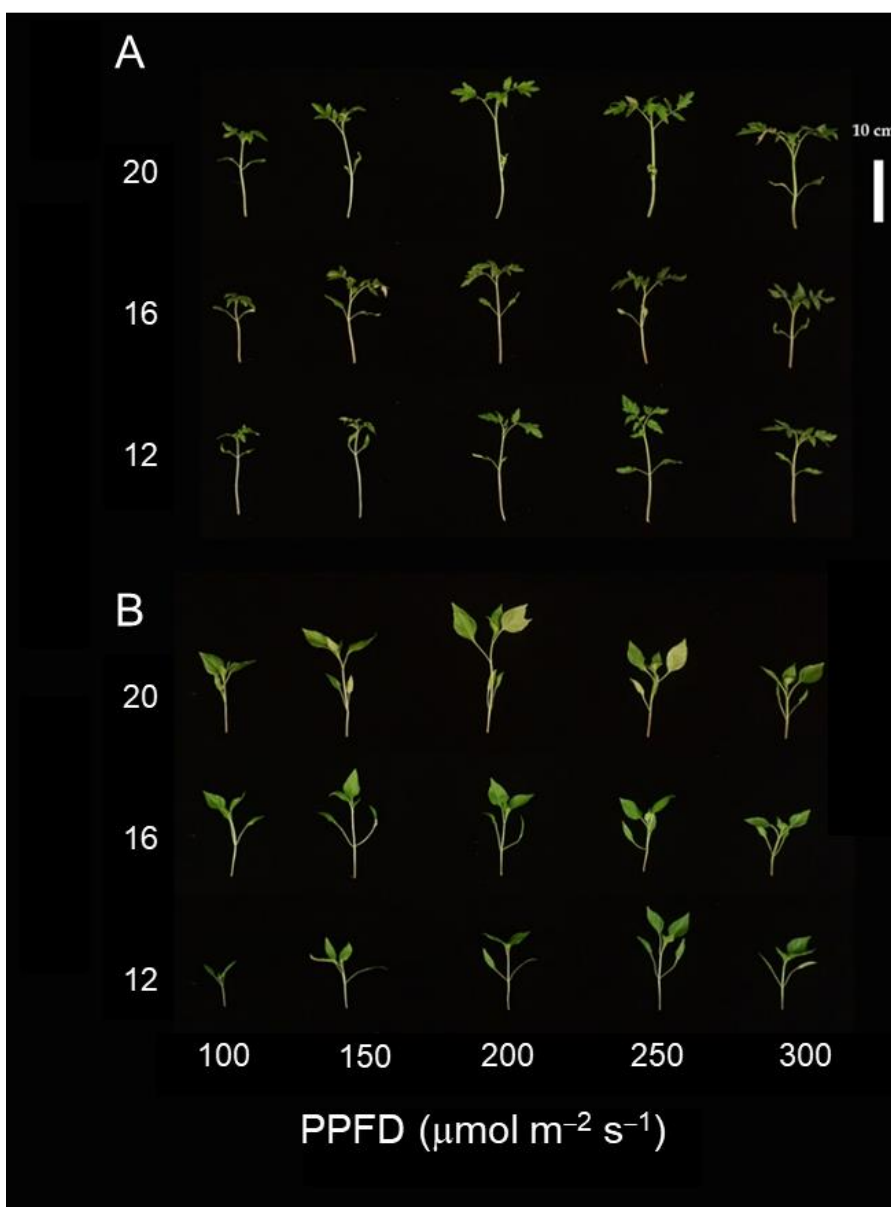


Fig. 3-3. Seedlings of tomato (A) 17 days after sowing (DAS) and red pepper (B) at 25 DAS as influenced by different light intensities and photoperiods.

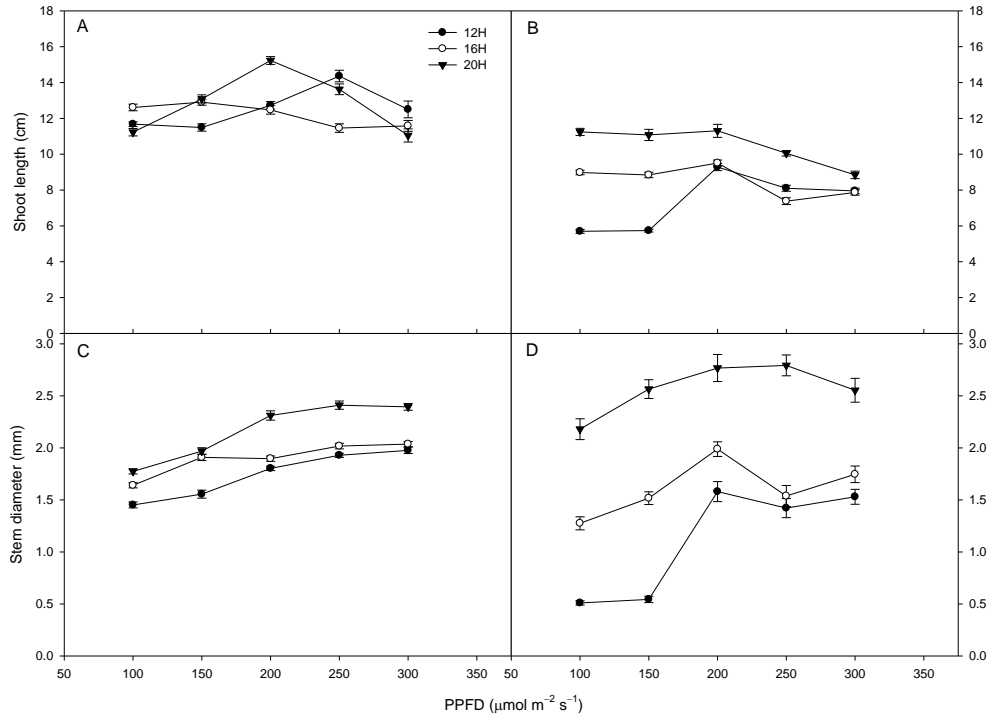


Fig. 3-4. Shoot length (A, B) and stem diameter (C, D) of tomatoes 17 days after sowing (DAS) and red peppers at 25 DAS, as influenced by different light intensities and photoperiods ($n = 7$, $r = 3$).

Leaf number, leaf area and leaf area index (LAI) in tomato showed general improvement when the photoperiod increased from 12 to 20 h·d⁻¹ under the same PPFD (Fig. 3-5). Conversely, an increase in PPFD from 100 to 250 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ under the same photoperiod also promoted these parameters. However, when PPFD increased to 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, these parameters slightly decreased compared to treatments with a PPFD of 250 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ under the same photoperiod, although significant differences were only observed in leaf area and LAI at a photoperiod of 20 h·d⁻¹. Overall, treatments 20/200 and 20/250 were the highest among all treatments in terms of these parameters. In the case of red pepper, there was a difference between low and high PPFDs in the responses of these parameters to the increase in photoperiod. When the PPFD was below 250 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, all three parameters showed significant increases when the photoperiod increased from 12 to 16 to 20 h·d⁻¹. However, at PPFDs of 250 and 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, while a photoperiod of 20 h·d⁻¹ still gave the highest results among all photoperiods under the same PPFD, there was no significant difference in these parameters between photoperiods of 12 and 16 h·d⁻¹. On the other hand, when comparing among treatments with the same photoperiod, leaf number generally increased with PPFD, although there was no significant difference among treatments with a PPFD higher than 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Conversely, leaf area and LAI showed a similar increase-decrease pattern to tomatoes. Nevertheless, among all treatments, the highest results were obtained with PPFDs of 150 to 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at the same

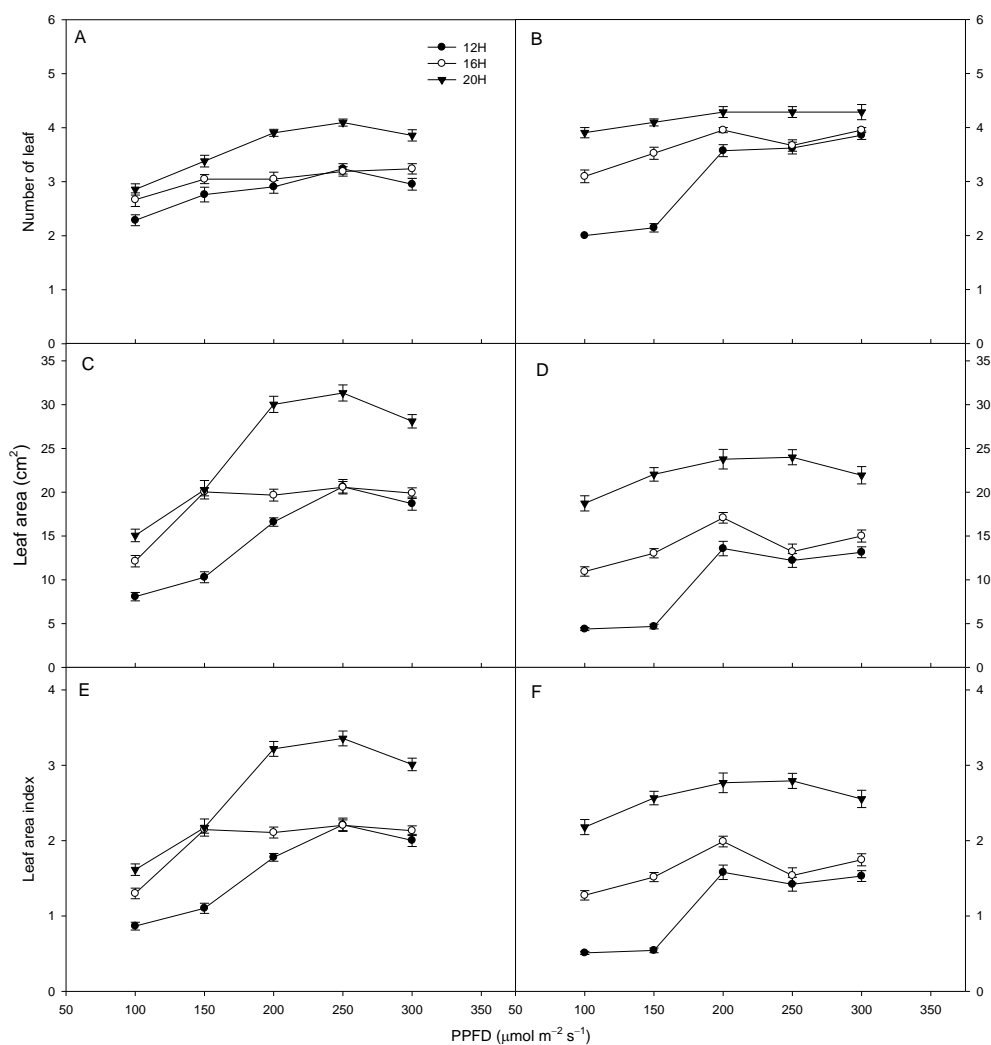


Fig. 3-5. Number of leaves, leaf area, and leaf area index (A, C, E) of tomatoes 17 days after sowing (DAS) and red peppers (B, D, F) at 25 DAS, as influenced by different light intensities and photoperiods ($n = 7$, $r = 3$).

photoperiod of 20 h·d⁻¹.

Increasing the DLI from 4.32 to 21.60 mol·m⁻²·d⁻¹, either by increasing the photoperiod or PPFD, improved the dry weight (DW), dry matter content (DMC) and compactness of seedlings in both cultivars. For instance, at a PPFD of 200 μmol·m⁻²·s⁻¹, increasing the photoperiod from 12 to 20 h·d⁻¹ increased the DW of tomato and red pepper seedlings by 143% and 181%, DMC by 21% and 20% and compactness by 104% and 111%, respectively. Under the same photoperiod, DW, DMC and compactness increased linearly with PPFD. Tomato and red pepper seedlings grown under a 20 h·d⁻¹ photoperiod showed increases in DW by 121% and 212%, in DMC by 24% and 5%, and in compactness by 143% and 171% as PPFD increased from 50 to 250 μmol·m⁻²·s⁻¹. Similarly, under a shorter photoperiod of 16 h·d⁻¹, increasing PPFD increased DW by 183% and 210%, DMC by 24% and 15%, and compactness by 194% and 141% for tomato and red pepper seedlings, respectively. Overall, DW, DMC and compactness showed a linear correlation with DLI (Fig. 3-6).

However, it is notable that in a comparison between treatments that provided the same DLI (treatments 12/200 and 16/150; treatments 12/250 and 20/150; treatments 16/250 and 20/200), tomato seedlings had significantly higher DWs when grown under longer photoperiods and lower PPFD. In the case of red pepper, under the same DLI of 8.64 mol·m⁻²·d⁻¹ no difference in DW was found between the two light settings of treatments 12/200 and 16/150.

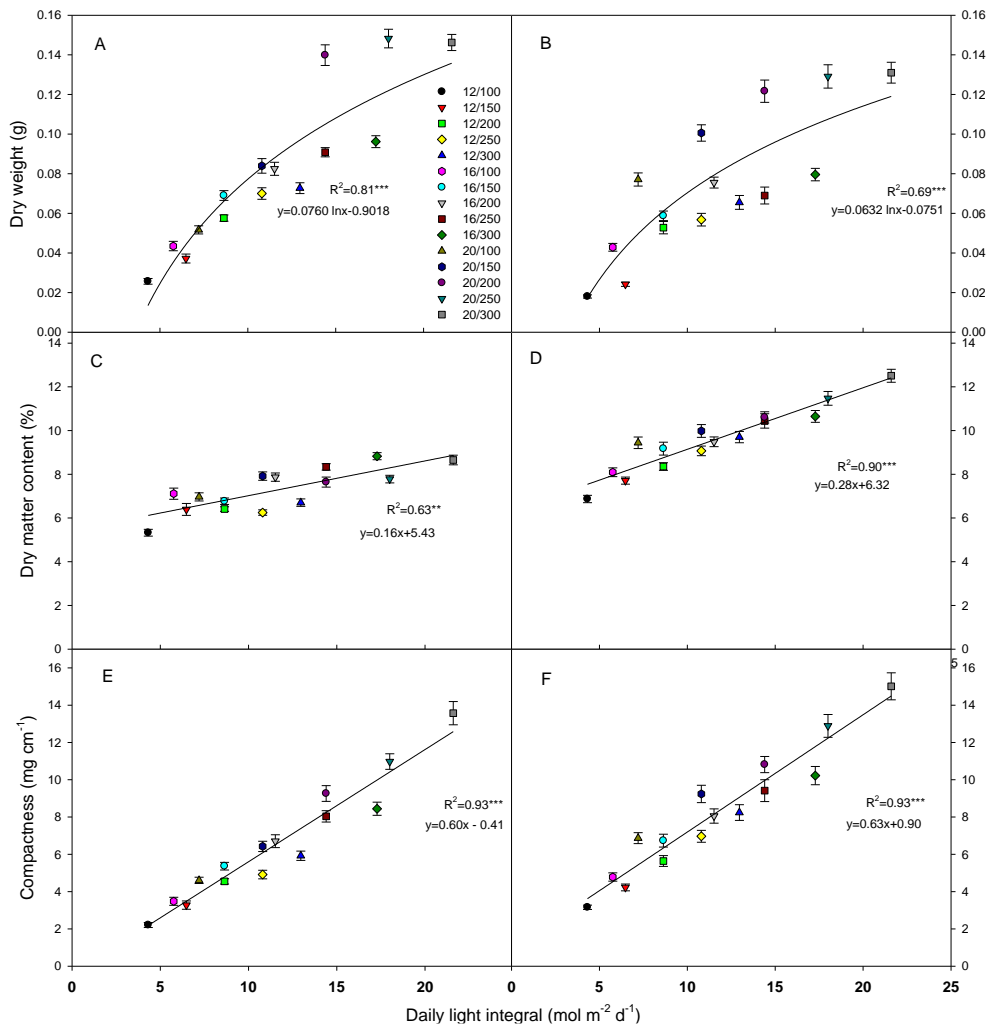


Fig. 3-6. Relationship of the dry weight (A, B), dry matter content (C, D), and compactness (E, F) with daily light integral. The value of each point is the average dry weight, dry matter content and compactness of tomatoes 17 days after sowing (DAS) and red peppers at 25 DAS as influenced by light intensity and photoperiod. Bars are the standard errors of the means.

However, at DLIs of 10.80 and 14.40 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, a similar improvement in DW of red pepper seedlings under longer photoperiods could be observed.

Likewise, tomato seedlings grown under 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 20 $\text{h}\cdot\text{d}^{-1}$ and 250 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 16 $\text{h}\cdot\text{d}^{-1}$ had significantly greater DMCs than those grown under 250 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 10 $\text{h}\cdot\text{d}^{-1}$ and 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 20 $\text{h}\cdot\text{d}^{-1}$ with the same DLI of 10.80 and 14.40 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, respectively, although those grown under DLI of 8.64 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ showed no difference in DMC. In the case of red pepper, DMC showed no difference between the two light settings with the same DLI of 14.40 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. However, at DLIs of 8.64 and 10.80 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, the DMCs of red pepper grown under 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 16 $\text{h}\cdot\text{d}^{-1}$ and 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 20 $\text{h}\cdot\text{d}^{-1}$ were significantly greater than those grown under higher PPFD and shorter photoperiods.

A similar trend in compactness of tomato and red pepper seedlings was observed. Under the same DLIs of 8.64, 10.80 and 14.40 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, seedlings grown under 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 16 $\text{h}\cdot\text{d}^{-1}$, 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 20 $\text{h}\cdot\text{d}^{-1}$ and 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 20 $\text{h}\cdot\text{d}^{-1}$ had significantly greater compactness than those grown under higher PPFD and shorter photoperiods.

Effects of different air temperatures (photo and dark periods) and light intensities

Fig. 3-7 shows representative images of tomato seedlings 17 days after sowing (DAS) and red pepper seedlings at 25 DAS under different light

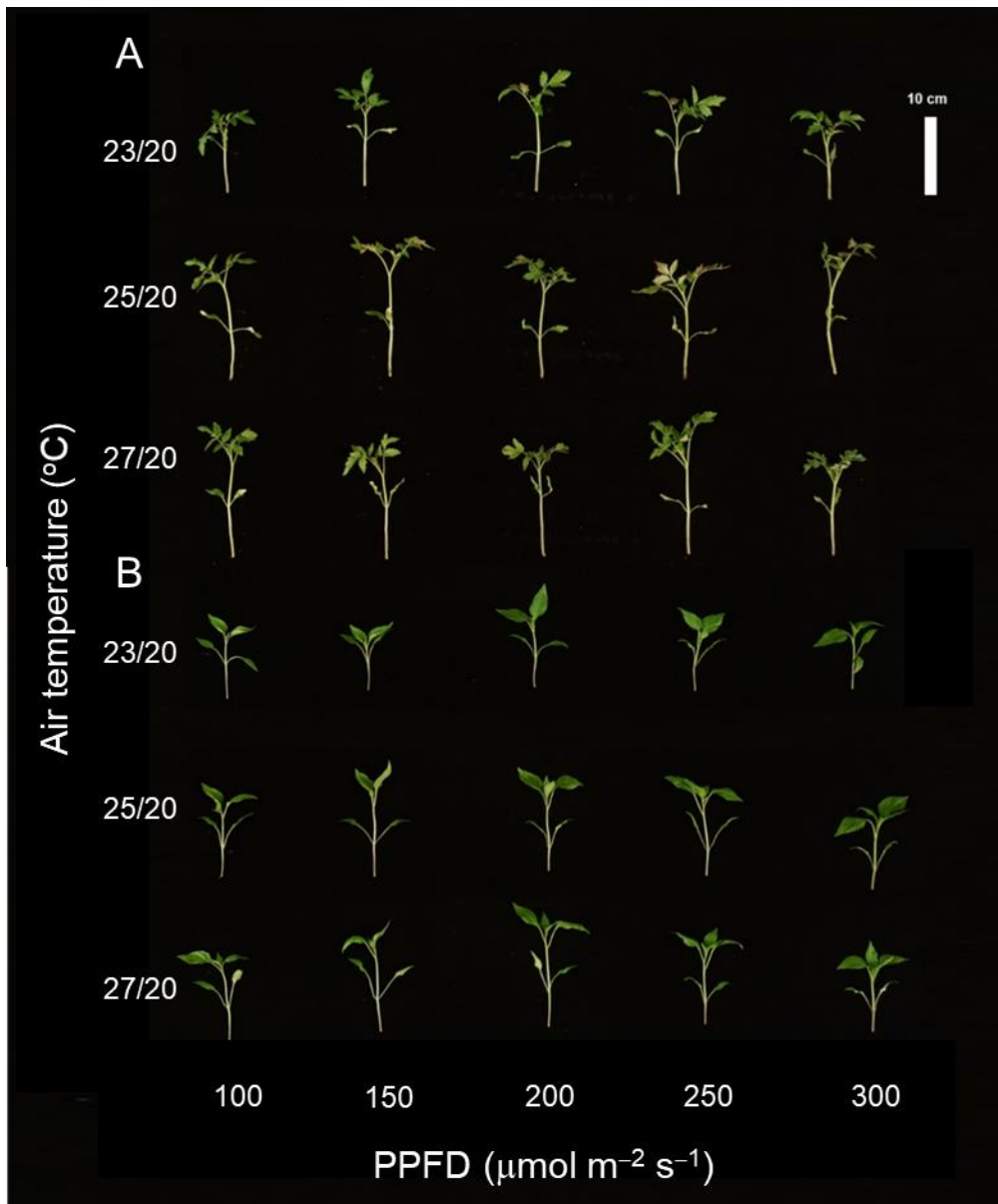


Fig. 3-7. Seedlings of tomato (A) 17 days after sowing (DAS) and red pepper (B) at 25 DAS, as influenced by different light intensities and air temperatures of the light- and dark periods.

intensities and photoperiods. The response to changes in the PPFD of tomatoes and red peppers in terms of shoot length differed significantly depending on photo/dark period air temperature (Fig. 3-8). At 23/20 °C, tomatoes and red peppers generally showed similar patterns, with shoot length increasing as PPFD increased up to 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in tomato and 250 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in red pepper, and then decreasing as PPFD increased further to 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. At 25/20 and 27/20 °C, however, tomatoes displayed an opposite trend, with shoot length generally reduced as PPFD increased, to the lowest at 250 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ under 25/20 °C and at 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ under 27/20 °C, then increased as PPFD increased further. In the case of red pepper, there was no significant difference among PPFDs from 100 to 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at these temperatures, but shoot length slightly decreased as PPFD increased further to 250 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Nevertheless, the response of shoot length to an increase in temperature at the same PPFD was consistent in each species. For tomatoes, shoot length at the same PPFD was higher at 25/20 °C than at 23/20 °C, but there was no further significant improvement as temperature increased to 27/20 °C. Red peppers, on the other hand, still showed a significant increase in shoot length as the photoperiod temperature increased up to 27 °C in all PPFDs. The response of stem diameter to changes in PPFD and temperature was more straightforward. In both species, stem diameter showed an increasing trend as PPFD increased at the same temperature, although there was no significant difference in red pepper among PPFDs higher than 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at 25 and

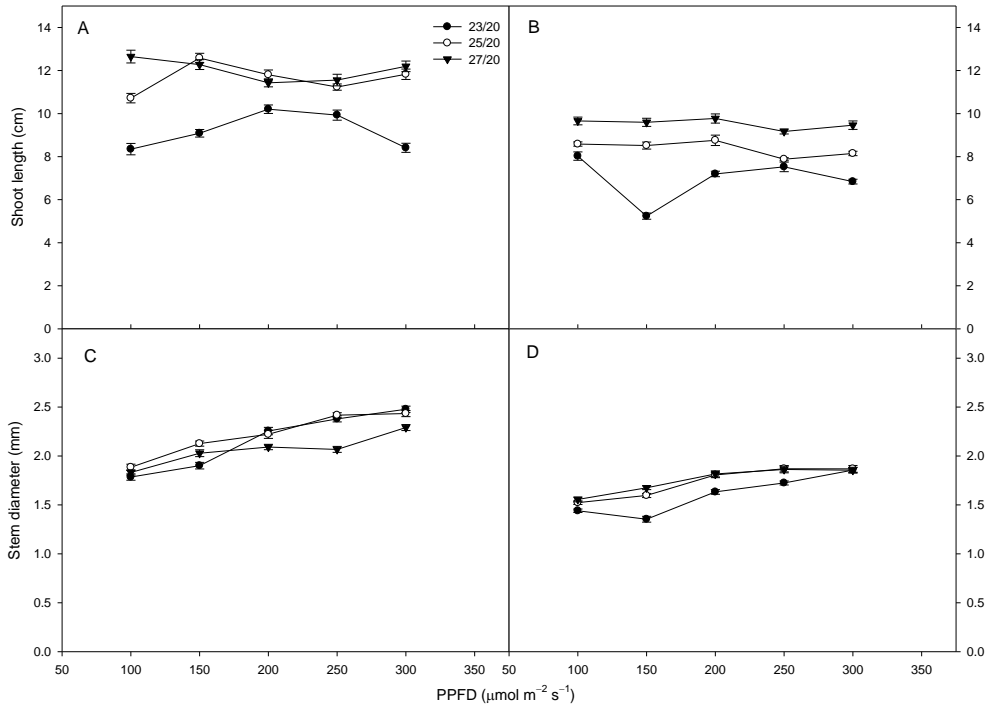


Fig. 3-8. Shoot length (A, B) and stem diameter (C, D) of tomatoes 17 days after sowing (DAS) and red peppers at 25 DAS, as influenced by different light intensities and air temperatures of light- and dark periods ($n = 7$, $r = 3$).

27 °C. Across different temperatures at the same PPFD level, however, stem diameter in tomatoes showed a slight decrease as temperature increased from 25 to 27 °C, while that of red peppers was not significantly different between 25 and 27 °C, except at 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

In tomato, while there was no clear pattern in leaf number in response to changes in temperature and PPFD, leaf area and LAI displayed a clear upward trend as PPFD increased under all temperature settings. When comparing temperatures under the same PPFD, however, there was a decrease in leaf number as the temperature increased from 25 to 27°C, except at a PPFD of 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. In red pepper, leaf number showed an overall increase as PPFD increased under all temperature settings. This pattern was only observed in leaf area and LAI at a temperature of 23/20 °C. In the other two temperature settings, no significant improvement was observed as the PPFD increased beyond 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Fig. 3-9). The DWs of both tomatoes and red peppers showed a strong positive logarithmic correlation with PPFD (coefficients of determination were 0.79 and above) (Fig. 3-10). An Increase in PPFD led to higher DW in both species, but at higher PPFD this effect was less pronounced than at low PPFD. More importantly, the models revealed the differences between tomatoes and red peppers in the response to changes in PPFD under different temperatures.

At photoperiod temperatures of 23 and 25°C, tomatoes showed similar correlation curves between DW and PPFD. However, at the higher temperature

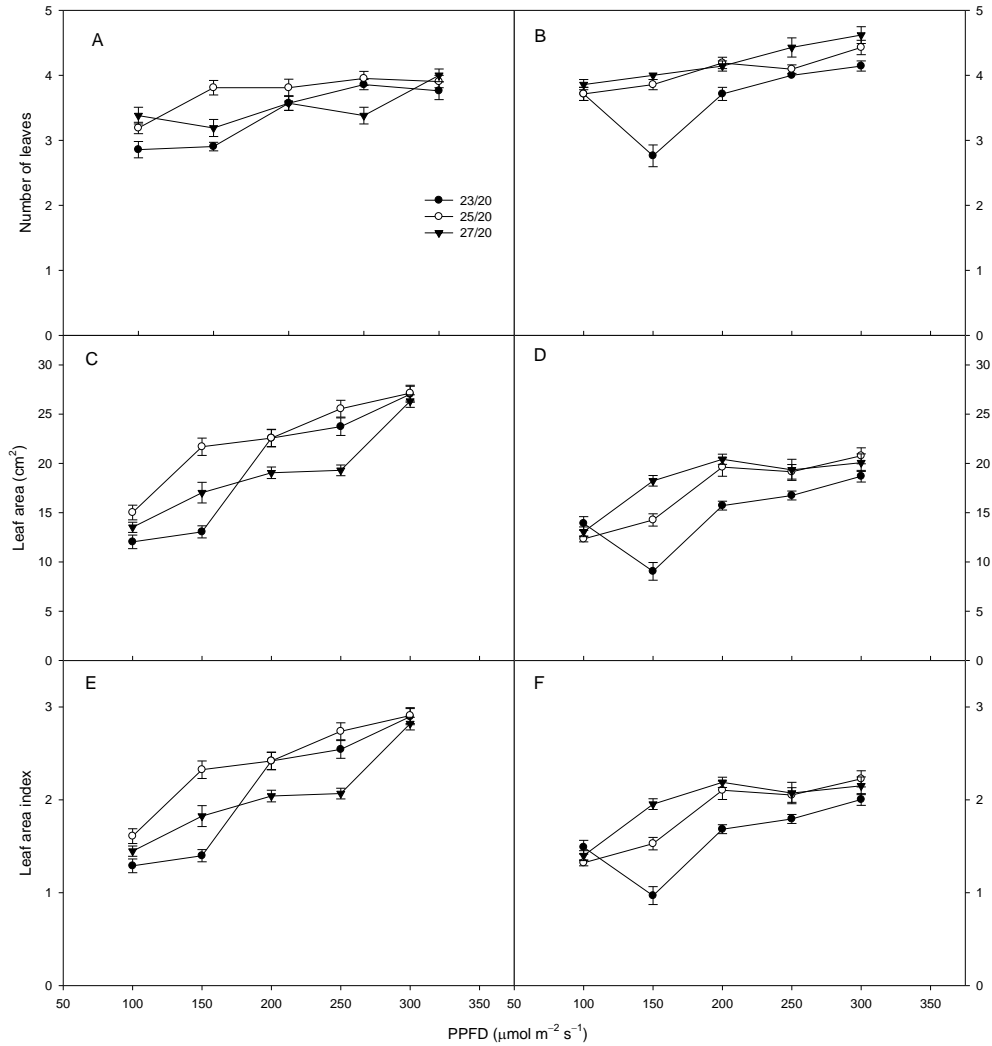


Fig. 3-9. Number of leaves, leaf area, and leaf area index (LAI) of tomatoes (A, C, E) 17 days after sowing (DAS) and red peppers (B, D, F) at 25 DAS, as influenced by different light intensities and air temperatures of light- and dark periods ($n = 7$, $r = 3$).

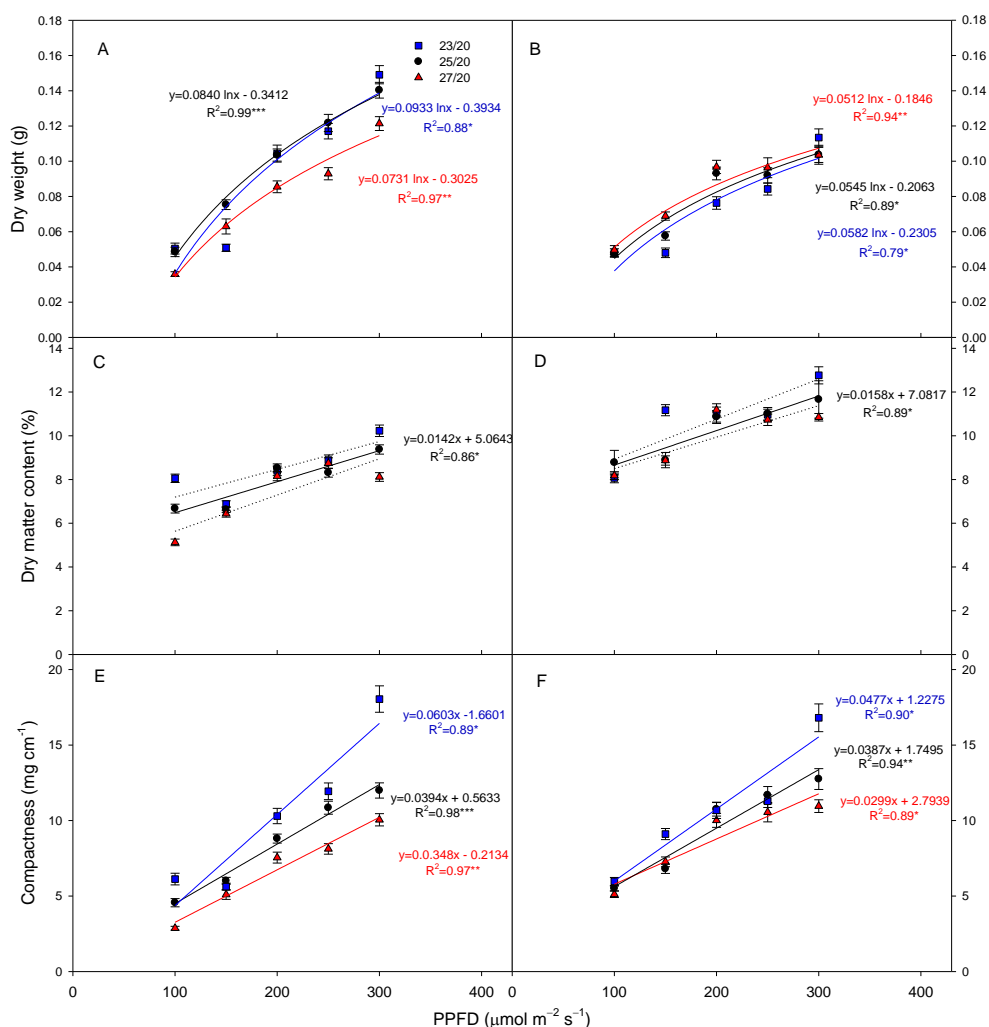


Fig. 3-10. Relationship of dry weight (A, B), dry matter content (C, D), and compactness (E, F) with light intensity and photoperiod. The value of each point is the average dry weight, dry matter content, and compactness of tomatoes 17 days after sowing (DAS) and red peppers at 25 DAS, as influenced by different light intensities and air temperatures of light- and dark periods. Bar means the standard error. The regression equation and R^2 coefficients are presented when statistically significant (solid line) but not presented when not significant (dotted line) *, **, and *** indicate significance at $P < 0.05$, 0.01, and 0.001, respectively.

of 27 °C, while the slope of the curve at low PPFD was similar to that of the curves at lower temperatures, the slope at high PPFD was flatter. On the other hand, red pepper displayed the same correlation curve between DW and PPFD at all tested temperatures, albeit the curve at 27 °C was slightly higher at altitude than that at 25 °C, which in turn was higher than that at 23 °C, showing that red pepper plants accumulated more DW at higher temperatures.

Unlike DW, DMC and compactness at each temperature displayed linear correlations instead of logarithmic correlations to PPFD in both cultivars. In the case of DMC, only data at 25/20 °C showed a significant relationship ($P < 0.05$) with PPFD. For compactness however, strong, and significant linear correlations with PPFD (coefficients of determination were 0.89 and above) could be found at all temperature settings in both cultivars. In tomato, the slope of the regression line between PPFD and compactness at 23/20 °C was the highest, while that at 27 °C was similar to that at 25 °C, although with a lower altitude. In the red pepper, the slope of the regression line between PPFD and compactness decreased as the temperature increased. All the slopes in both cultivars were positive, showing that the increase in PPFD all led to an increase in compactness at all temperatures, albeit with different magnitudes. In tomato, the LUE at 27/20 °C was generally lower than that at 25/20 and 23/20 °C (Fig. 3-11). Under the same temperature, there was no clear difference in LUE among treatments with different PPFDs. In the case of red pepper, no clear trend in LUE regarding PPFD or temperature could be observed. However, the

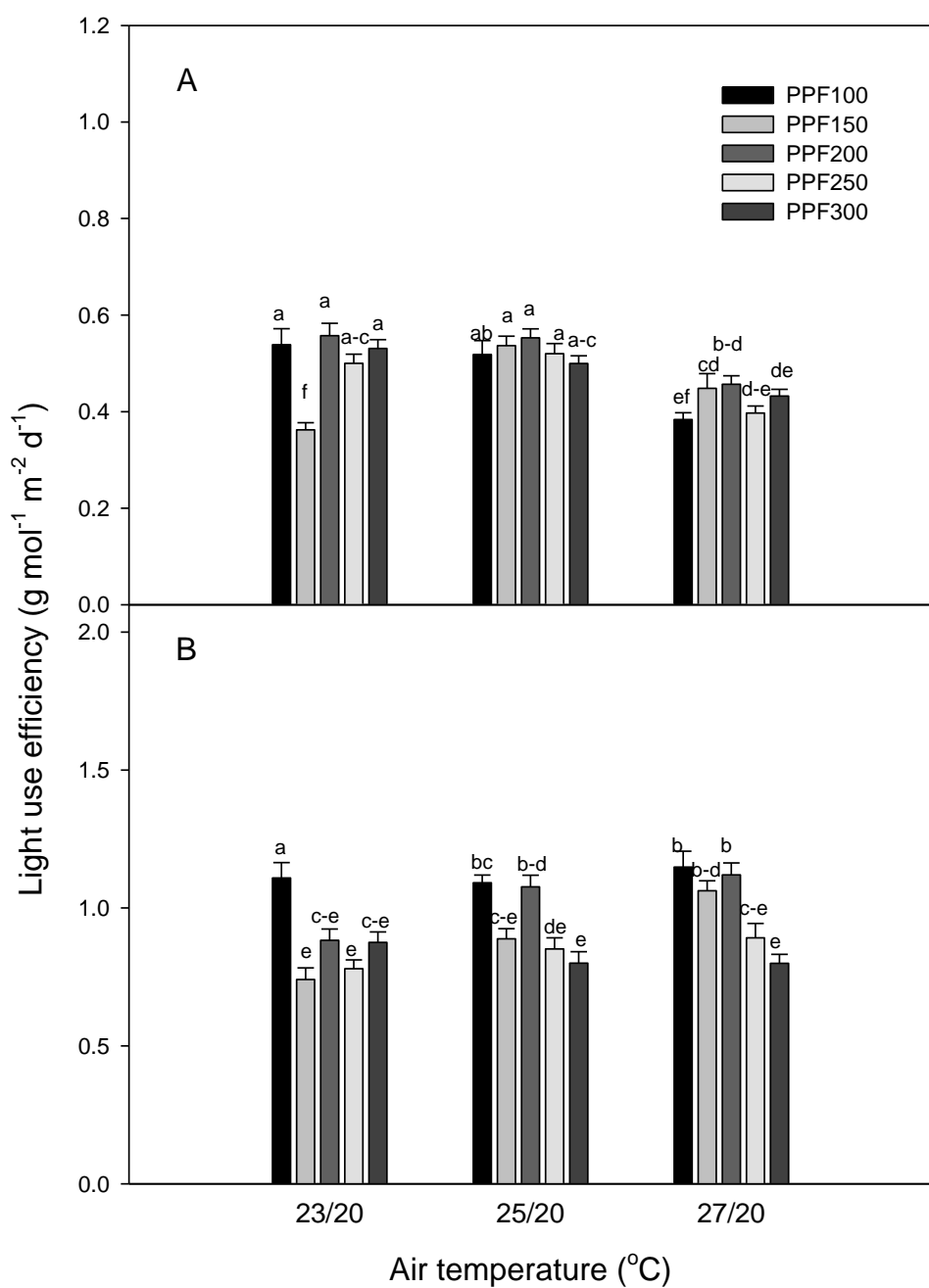


Fig. 3-11. Light use efficiency of tomatoes (A) 17 days after sowing (DAS) and red peppers (B) at 25 DAS, as influenced by different light intensities and air temperatures of light- and dark periods ($n = 7$, $r = 3$).

LUE of the 100/23 treatment ($1.11 \text{ g}\cdot\text{mol}^{-1}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) was significantly higher than that of all other treatments.

The first flower nodes of tomatoes and red peppers under different air temperatures and PPFDs were 9.0-10.5 and 7.9-10.3, respectively (Table 3-3). The first flower node of tomatoes and red peppers in the 27/20 °C treatment was the lowest, while PPFD did not show a significant difference (tomatoes) or only a small effect (red peppers). In red pepper, both a high light intensity and air temperature accelerated flowering.

Table 3-3. First flowering node of tomatoes and red peppers as affected by the different light intensities and air temperatures of photo- and dark periods 44 and 52 days after sowing, respectively (n = 7, r = 3).

Air Temperature (°C)	Light Intensity ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	Node of First Flower	
		Tomato	Red Pepper
23/20	100	9.9bc ^z	9.6b
	150	10.5a	9.2bc
	200	10.1ab	8.9cd
	250	10.2ab	9.0cd
	300	10.0cb	8.5d–g
25/20	100	9.7c–e	10.3a
	150	9.3ef	8.8cd
	200	9.3ef	8.6d–g
	250	9.4d–f	8.8c–e
	300	9.8b–d	8.3e–h
27/20	100	9.2f	8.7ef
	150	9.0f	8.1gh
	200	9.2f	8.2f–h
	250	9.3ef	7.9h
	300	9.6c–e	8.0gh
Significance			
Air temperature (A)		***	***
Light intensity (B)		NS	***
Interaction (A × B)		***	***

^zDifferent letters indicate significant differences by Duncan's multiple range test at $P < 0.05$.

DISCUSSION

Effects of photoperiod and light intensity

The results Increasing the DLI from 4.32 to 21.60 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ influenced the shoot length and stem diameter of tomato and red pepper seedlings differently. The shoot length of tomatoes and red peppers was the highest at 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (DLI 8.64 for 12 $\text{h}\cdot\text{d}^{-1}$, 11.52 for 16 $\text{h}\cdot\text{d}^{-1}$, and 14.40 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for 20 $\text{h}\cdot\text{d}^{-1}$) and decreased under higher PPFD treatments (Fig. 3-4). This result agrees with a previous study, in which the hypocotyl length of lettuce decreased as the DLI increased from 5.8 to 25.9 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. The hypocotyls of lettuce at a DLI of 8.6 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, a lower PPFD, and a higher photoperiod (24 $\text{h}\cdot\text{d}^{-1}$) were higher than those grown under a higher PPFD and lower photoperiod (16 $\text{h}\cdot\text{d}^{-1}$) (Kitaya et al., 1998). Scion and rootstock seedlings benefit from an extended hypocotyl length, as this increases the grafting success rate and reduces the rooting from the scion after transplant (Chia and Kubota, 2010). However, elongated hypocotyls are not beneficial for non-grafted seedlings because this property may lead to weak transplants (Gómez and Mitchell, 2015).

An increase in PPFD promoted the stem diameter of tomato and red pepper seedlings among all the tested photoperiods. The stem diameters of tomato and red pepper seedlings were the highest at 250 (DLI 10.80 for 12 $\text{h}\cdot\text{d}^{-1}$, 14.40 for 16 $\text{h}\cdot\text{d}^{-1}$, and 18.00 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for 20 $\text{h}\cdot\text{d}^{-1}$) and 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (DLI 8.64

for 12 h·d⁻¹, 11.52 for 16 h·d⁻¹, and 14.40 mol·m⁻²·d⁻¹ for 20 h·d⁻¹), respectively (Fig. 3-4). These results agree with a previous study, as increasing the DLI from 6.1 to 11.8 mol·m⁻²·d⁻¹ increased the stem diameter of cucumber and pepper seedlings (Garcia and Lopez, 2020). Based on the results of this study, we can present the optimal range for the stem growth of tomatoes and red peppers.

Increasing the DLI from 4.32 to 21.60 mol·m⁻²·d⁻¹ promoted the leaf characteristics including leaf number, leaf area, and leaf area index (LAI) of both cultivars. The leaf number of tomatoes and red peppers was the greatest at 250 μmol·m⁻²·s⁻¹, while there were no significant differences if the PPFD was higher than 200 μmol·m⁻²·s⁻¹. Leaf area and LAI showed a similar pattern of leaf number results. The leaf area and LAI of tomatoes and red peppers were the greatest among all the tested photoperiods at 250 and 200 μmol·m⁻²·s⁻¹, respectively (Fig. 3-5). In this study, DLIs of 18.00 and 14.40 mol·m⁻²·d⁻¹ were sufficiently high in at least tomato and red pepper seedlings, in which individual leaves expanded in response to a given cultivation area. Plants grown in a high light intensity generally have thick leaves with a low specific leaf area (Marcelis et al., 1998), partly due to the added layers of palisade or extended palisade cells (Yang et al., 1990). This increases the number of chlorophyll and photosynthesis-related enzymes, improving the photosynthesis rate of the plant (Marcelis, 1994). However, the photosynthesis rate increase obtained after the plant leaves adapted to a high light intensity

reduced the efficiency of light capture per unit biomass at lower intensities (Kahlen et al., 2008). Leaf area was decreased with photoperiod from 12 to 21 h·d⁻¹ in sweet potato (Mortley et al., 1996). Leaf area was smaller under continuous light (24 h·d⁻¹) than plants grown under 20 h·d⁻¹, which resulted in the better light capture of cucumber (Garcia and Lopez, 2020). A reduction in leaf area as an effect of a longer photoperiod has been reported in *Eustoma* (Islam, 2002) and tomato (Demers et al., 1998). Previous studies have reported that the leaf area decreased while the leaf area index (LAI) increased as the plant density increased in pepper (Jolliffe and Gaye, 1995; Motsenbocker, 1996). Higher plant density conditions (higher LAI) increased the light capture capacity, and, as a result, the growth of sweet pepper increased (Cebula, 1995). Additionally, increases in LAI above a threshold (from approximately 3.5 to 4 for most plants) do not increase the radiation interference (Loomis and Connor, 1992). This explains why increases in plant growth above an LAI threshold occur at a given space of seedlings.

Under a given temperature of 25/20 °C, DW, DMC, and compactness of tomato and red pepper seedlings showed a positive relationship with DLI as the DLI increased from 4.32 to 21.60 mol·m⁻²·d⁻¹ (Fig. 3-6). Prolonged photoperiod is a widely used technique in greenhouse and closed systems and has provided increased growth and yield for many species, such as lettuce (Gaudreau et al., 1994; Kitaya et al., 1998), cucumber (Grimstad and Frimanslund, 1993), tomato and red pepper (Garcia and Lopez, 2020). Plant

growth by an increase in PPFD and photoperiod is an almost linear relationship for many plant species under a controlled environment (Garcia and Lopez, 2020; Kahlen et al., 2008; Kitaya et al., 1998). During vegetative growth, tomato seedlings positively respond to the increased DLI at the leaf level via increased PPFD (Bleasdale, 1973; McAvoy and Janes, 1990) and photoperiod (Demers et al., 1998; Omura, 2001). Further study will have to be carried out later with a greater DLI (over $21.6 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) than this study to find the maximum point. In this study, the same DLI was derived from three points (8.64, 10.80, and $14.40 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) as a different combination of PPFD and photoperiod. While many previous studies have shown that increasing the DLI increases the dry mass of many plants, including Achemenes (Vlahos, 1990; Vlahos et al., 1991), lettuce (Craker and Seibert, 1982; Kitaya et al., 1998; Koontz and Prince, 1986; Oda et al., 1989), and radish (Craker and Seibert, 1982), a few studies have described how different combinations of PPFD and photoperiod in the same DLI interact (Yan et al., 2019; Zhang et al., 2018). The DW of tomatoes was increased at a relatively low PPFD and long photoperiod more than at a higher PPFD and shorter photoperiod. In the case of red pepper, the same tendency was shown, except for DLI $8.64 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. The compactness of tomatoes and red peppers also increased at a relatively low PPFD and long photoperiod more than at a higher PPFD and shorter photoperiod. Kelly et al. (2020) reported a similar pattern of these results in lettuce, which explained as photosynthesis efficiency. At a higher PPFD above

a threshold, the photosynthesis efficiency decreased with increasing PPFD, where further PPFD increases did not increase photosynthesis. After reaching the light saturation point, only a photoperiod increase will enhance the net photosynthesis. This may explain why using a lower PPFD with a longer photoperiod, under the same DLI conditions, is more effective than using a higher PPFD with a shorter photoperiod (Hurd and Thornley, 1974). Interestingly, the growth of red pepper under 20/100 and 20/150 was higher than that under 16/300. Even in higher DLI conditions, reduced growth due to higher PPFD proves that excessive light energy has been a limiting factor. Furthermore, reducing the PPFD can reduce the number of lamps, thereby reducing the initial installation cost of the system (Kozai et al., 2000).

Effects of different air temperatures (light and dark periods) and light intensities

The response to changes in the PPFD of tomatoes and red peppers in terms of shoot length differed significantly depending on the photo/dark period air temperature (Fig. 3-8). At 23/20 °C, tomatoes and red peppers generally showed increasing and decreasing patterns, with shoot length increasing as the PPFD increased up to $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in tomato and $250 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in red pepper and then decreasing as the PPFD increased further to $300 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Many studies of the relationship between light intensity and shoot length have been reported in relation to gibberellic acids (GAs) (Graebe, 1987; Hedden and

Kamiya, 1997; Oh et al., 2015). The effect of low PPFD on shoot elongation was due to an increase in GA₁ biosynthesis and a decrease in GA₁ catabolism (García-Martínez and Gil, 2001). The epicotyl length of brassica seedlings increased from 50 to 250 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and decreased further to 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, while the hypocotyl length decreased as the PPFD increased from 50 to 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Potter et al., 1999). Lower endogenous GAs were observed under a higher PPFD. Nevertheless, the response of shoot length to an increase in temperature at the same PPFD was consistent in each species. For tomatoes, the shoot length at the same PPFD was higher at 25/20 °C than at 23/20°C, but there was no further significant improvement as the temperature increased to 27/20°C. Red pepper, on the other hand, still showed a significant increase in shoot length as the photoperiod temperature increased up to 27 °C in all PPFDs. Plants can adjust their shoot length when irradiated with strong light above their photosynthetic saturation point (Myster and Moe, 1995). Previous research in sweet pepper showed that the maximum height was 24/21 or 28/15°C under sunlight in a greenhouse (Bakker and Van Uffelen, 1988). In this study, under a sufficiently long photoperiod, strong light shortened the length of tomatoes.

The response of stem diameter to changes in the PPFD and temperature was more straightforward. In both species, stem diameter showed an increasing trend as PPFD increased at the same temperature, although there was no significant difference in red pepper among PPFDs higher than 150

$\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at 25 and 27 °C. Across different temperatures at the same PPFD level, however, the stem diameter in tomato showed a slight decrease as the temperature increased from 25 to 27 °C, while that of red pepper was not significantly different between 25 and 27 °C, except at 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Under sufficient light conditions, the optimal daytime air temperature of the tomatoes was estimated to be 23 °C, and in the case of red peppers, it was higher than that of tomatoes. Air temperatures above the optimal range obstruct cell elongation and differentiation (Potters et al., 2007).

In tomato, while there was no clear pattern in leaf number in response to changes in temperature and PPFD, leaf area and LAI displayed a clear upward trend as PPFD increased under all temperature settings. When comparing temperatures under the same PPFD, however, there was a decrease in leaf number as the temperature increased from 25 to 27 °C, except at a PPFD of 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. In red pepper, leaf number showed an overall increase as the PPFD increased under all air temperature settings (Fig. 3-9). Leaf characteristics including leaf number and leaf area are closely related to the photosynthesis (especially light harvest) of plants. Planting space and planted area are crucial factors that greatly affect leaf characteristics. In a limited space, after securing a favorable area for photosynthesis it will no longer increase (Kitaya et al., 2004).

An increase in PPFD led to a higher DW in both species, but at higher PPFDs this effect was less pronounced than at low PPFDs. More importantly,

the models revealed the differences between tomatoes and red peppers in the response to changes in PPFD under different temperatures (Fig. 3-10). At photoperiod temperatures of 23 and 25 °C, tomatoes showed similar correlation curves between DW and PPFD. However, at the higher temperature of 27 °C, while the slope of the curve at low PPFDs was similar to that of the curves at lower temperatures, the slope at high PPFDs was flatter. On the other hand, red pepper displayed the same correlation curve between DW and PPFD at all tested temperatures, albeit the curve at 27 °C was slightly higher at altitude than that at 25 °C, which in turn was higher than that at 23 °C, showing that red pepper plants accumulated more DW at higher temperatures. Unlike DW, the DMC and compactness at each temperature displayed linear correlations instead of logarithmic correlations to PPFD in both cultivars. For compactness, strong and significant linear correlations with PPFD could be found at all temperature settings in both cultivars. In tomato, the slope of the regression line between PPFD and compactness at 23/20 °C was the highest, while that at 27 °C was similar to that at 25 °C, although with a lower altitude. In red pepper, the slope of the regression line between PPFD and compactness decreased as the temperature increased. All the slopes in both cultivars were positive, showing that the increase in PPFD led to an increase in compactness at all temperatures, albeit with different magnitudes. The optimum temperature for the plant growth of both cultivars that prefer high lighting requirements was different. A previous study recommended that optimum tomato growth

occurs at air temperatures from 17 to 23 °C and stops at a maximum of 33 °C and a minimum of 12°C (Swiader et al., 1992). The optimal temperature for pepper seedling development was reported to be approximately 25 °C (Perl and Feder, 1981), and it reaches at a minimum of 14.5 °C (Wilcox and Pfeiffer, 1990). In tomato under high-temperature conditions, a higher PPFD was a limiting factor in photosynthesis. At high temperatures, the photosystem II activity was reduced in tomato plants (Georgieva, 1999; Janssen et al., 1992). The compactness of both cultivars at 23/20 °C was greater than those at the other air temperature treatments. Generally, high DW, DMC, and compactness are defined by high-quality seedling standards (Kitaya et al., 1998). Ohyama et al. (2005) reported that, by increasing the air temperature from 20 to 28 °C under continuous light conditions (24 h·d⁻¹), the highest compactness was observed in the 20 °C treatment.

Increasing the PPFD from 100 to 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ differently influenced the LUE by the photo- and dark-period air temperatures of tomato and red pepper seedlings (Fig. 3-11). The LUE of tomatoes at 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ was the highest among treatments, with values of 0.56 (23/20 °C), 0.55 (25/20 °C), and 0.46 $\text{mg}\cdot\text{mol}^{-1}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (27/20 °C). In the case of red pepper, the LUE values under 25/20 and 27/20 °C at 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ were 1.07 and 1.11 $\text{mg}\cdot\text{mol}^{-1}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, respectively. Generally, mature tomatoes and red peppers are considered high light-requiring crops compared to other plants, and a DLI of 20-35 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ is recommended for their optimal growth and production

(Bakker and Van Uffelen, 1988; Dorais, 2003; Swaider et al., 1992). The LUE increases with an increase in the light energy received by leaves. This can be enhanced by well-designed light conditions, a reduction in distance between lamps and plants, and an increase in the planting density (Massa et al., 2008). Normally, the LUE of tomato seedlings increases linearly from zero up to unity with increasing the LAI from 0 to 3 (Yokoi et al., 2003).

The first flowering nodes of tomatoes and red peppers under different air temperatures and PPFDs were 9.0-10.5 and 7.9-10.3, respectively (Table 3-3). The first flowering node of tomatoes and red peppers in the 27/20°C treatment was the lowest, while PPFD did not show a significant difference (tomatoes) or only a small effect (red peppers). Sato et al. (2000) found that mean daily temperatures over 25 °C reduced the fruit and seed set in tomato. The flower development of tomatoes was accelerated as the average daily air temperature increased from 19 to 24 °C (Adams et al., 2001). Fruit set is reduced in tomato when their average maximum day temperatures are above 30 °C and night temperatures are above 20 °C during anthesis (Swiader et al., 1992). Low temperatures and irradiation cause improper ovary development, unviable pollen, the malformation of flowers, fruit puffiness, and blotchy ripening (Rylski et al., 1993). For this reason, some research has recommended that the optimum daytime air temperature of red pepper is approximately 23 °C (Pressman et al., 1998). The results of this study highlight the differences in nature between tomatoes and peppers, as well as the complex interactions

among PPFD, photoperiod, and temperature on the growth and morphology of plants. The dry matter content and compactness displayed linear relationships with DLI and PPFD, while dry weight showed trends of saturating curves with these factors. The trends of many parameters, most notably dry weight, and compactness, in response to PPFD could be shifted by the change in photoperiod or air temperature, and vice versa. Tomatoes exhibited a preference for a temperature of 23/20 or 25/20 °C, especially in terms of biomass gain and light use efficiency, while pepper show no change in these aspects under the temperature range from 23°C/20°C to 27°C/20°C. There is great potential in applying these results to control the quality of plants and improve the efficiency in the cultivation of tomatoes and red peppers in CTPS.

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CONCLUSIONS

The aim of this study was to determine optimal light and air temperature conditions to produce grafted transplants of fruit vegetables in a closed transplant production system with white LEDs, and the following conclusions were drawn.

First, we changed the array and density of the white LED chips at the edge of the LED lighting fixtures to increase the PPFD at the edge and the uniformity of the light intensity.

Second, the most effective ratios of warm- and cool-white LEDs for cultivating scions and rootstocks for grafted transplants of cucumber, tomato, and watermelon were determined. It was found that different ratios of LED lighting sources have a strong effect on the hypocotyl elongation and compactness of seedlings.

Third, we found that FR-enriched lighting affects the growth and morphology of seedlings, and hypocotyl length reached a peak increase at certain PSS values and decreased with PSS values above that. The results indicate that supplemental FR-enriched lighting with white LEDs achieves the desired plant growth and morphology of seedlings.

Fourth and finally, complex interactions among cultivation environments, such as PPFD, photoperiod and air temperature, and their effects on the growth and morphology of seedlings grown under white LED lighting fixtures were

investigated.

ABSTRACT IN KOREAN

최근 고품질의 과채류 접목묘 생산이 공정 육묘장에서 농가의 다양한 요구수준에 맞춰 진행되고 있으며, 효율적인 생산을 위해 접목 로봇을 이용하려는 시도가 있다. 접목 로봇을 이용하여 접목묘를 생산하기 위해서는 먼저 균일하고, 안정성 있는 묘 생산이 매우 중요하다. 여전히 환경 및 재배 관리의 기준은 묘 생산자의 경험을 바탕으로 이루어지며, 최근 기후변화에 따른 불량한 환경으로 인해 균일·건전묘 생산에 애로사항이 생기고 있다. 이에 정밀한 환경 조절 조건 하에서 균일·건전묘 생산이 가능한 식물공장 이용에 대한 관심이 높아지고 있다. 따라서 식물공장 내 과채류 접목묘 생산을 위해 적절한 환경 조건인 기온, 광도, 광질 및 일장 등을 연구하는 것이 필요하다. 작목 및 품종에 따라 환경 반응이 상이한 것을 고려할 때 환경 요인에 따른 과채류 접목묘의 생산 및 발달 반응을 이해하는 것이 필수적이나 다양한 환경 요인의 결합 효과를 조사한 연구는 미미하다. 1장에서는 균일한 크기의 대목과 접수 생산을 위한 LED 조명 시스템을 구축하고, 묘 생산 시스템에서의 다양한 백색 LED 비율의 효과에 대한 연구를 수행하였다. 기존 바 타입 LED의 경우 가장자리의 광도는 평균값보다 $70\mu\text{mol m}^{-2}\text{s}^{-1}$ 이상 낮아 균일한 묘를 생산하는 데 문제가 있었다. 이를 개선하기 위해 가장자리에 LED칩의 밀도를 높였다. 광도 프로파일링 결과 $250\mu\text{mol m}^{-2}\text{s}^{-1}$ 조건에서 개선된 바 타입 LED의 가장자리 광도는 $30\mu\text{mol m}^{-2}\text{s}^{-1}$ 이상 증가하였다. 오이, 토마토 및 수박의 접수와 대목 종자를 개선된 백색 바 타입 LED가 설치된 육묘시스템에서 과중하고 재배했다. 처리구는 warm-white LED 광원의 단독 처리구인 W1, W1C1 (warm-white:cool-white = 1:1), W3C1 (warm-white:cool-white = 3:1), W5C2 (warm-white:cool-white = 5:2)였다. Cool-white LED의 비율이 높은 W1C1 처리구에서 모든 공시품종의 배축장이 가장 짧았다. 토마토와 수박의 배축장은 cool-white LED의 비율이 높아지는 순서와 같은 W1, W3C1, W5C2, W1C1 순으로 배축장이 짧아졌다. 경경의

경우 토마토 접수와 수박 대목을 제외하고 통계적인 유의차가 없었다. 위 결과는 다른 백색 LED광원의 비율이 과채류 묘의 배측 신장에 강한 영향을 미친다는 것을 확인할 수 있었다. 수박과 토마토의 대목은 오이에 비해 cool-white LED에 더 민감하게 반응하였다. 2장에서는 토마토, 고추, 오이, 박, 수박 및 호리병박 묘의 생장 및 형태를 조절하기 위해 원적색광이 강화된 LED의 효과를 연구하였다. 처리구는 백색광 LED와 원적색광 LED의 비율에 따라 5:0, 5:1, 5:2, 5:3으로 설정하였다. 배측장을 포함한 토마토와 고추 묘의 생장은 전체 광도 및 원적색광의 광도와 상관관계를 나타냈다. 원적색광 보광에 따른 토마토와 고추 묘의 최대 배측장의 피토크롬 광정지 상태(PSS) 값은 0.69–0.77 범위였다. 오이와 수박의 배측장 또한 PSS의 영향을 크게 받았으나, 최대 배측장에 대한 PSS값은 토마토나 고추보다 낮았다. 위의 결과는 원적색광 보광에 따른 묘의 반응은 작물의 종에 따라 차이가 있으며 이를 이용하여 작물의 배측장을 조절할 수 있음을 시사한다. 3장에서는 광도, 일장 및 온도의 복합 환경에 따른 토마토와 고추 묘의 생육 및 형태 변화를 연구하였다. 먼저, 25/20°C의 주야간 온도에서 5가지 광도(100, 150, 200, 250 및 300 $\mu\text{mol m}^{-2}\text{s}^{-1}$)와 3가지 일장(12, 16 및 20 h d^{-1})의 조합 처리를 통해, 다양한 일적산광량(DLI)이 작물에 미치는 영향을 조사하였다. 또한, 동일한 5가지 광도와 3가지 주야간 온도(23/20, 25/20 및 27/20°C, 주간/야간 온도)의 조합 처리를 통해, 다양한 주야간 온도차(DIF)가 작물에 미치는 영향을 조사하였다. 일장 혹은 광도를 늘려 DLI를 4.32에서 21.6 $\text{mol m}^{-2}\text{s}^{-1}$ 로 증가시킴에 따라 묘의 생장은 두 작물 모두에서 향상되었다. 하지만, 동일한 DLI 조건에서는 일장이 길고 광도가 낮은 조건에서 토마토 묘의 생장이 향상되었다. 이는 더 높은 DLI조건이 제공되더라도, 과도한 광도는 생장의 제한 요인임을 시사한다. 23°C와 25°C의 주간 기온 조건에서 토마토 묘의 생장과 광도는 유의한 상관관계를 나타냈다. 하지만 27°C의 높은 주간 기온조건에서 토마토 묘 생장과 낮은 광도 조건에서의 상관관계는 온도가 낮은 처리구와 유사했지만, 높은 광도 조건에서는 광도에 따른 묘 생장

증대 효과가 없었다. 한편, 고추 묘는 모든 온도 처리에서의 광도와 생장간의 상관 곡선 형태가 동일했으며, 고온에서 더 많은 건물량을 축적하였다.