



A THESIS FOR THE DEGREE OF MASTER OF SCIENCE

Application of White LEDs to Promote Growth and Propagation Rates of Strawberry Transplants

딸기 묘의 생장 및 증식률 증진을 위한 백색 LED의 적용

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ABSTRACT

This study was conducted to promote the growth and propagation rates of strawberry transplants by applying the optimal combination of LEDs spectra. In Chapter 1, the growth of strawberry propagules and runner plants were analyzed with white light-emitting diodes (LEDs) having various color temperatures. In Chapter 2, the growth of strawberry propagules and runner plants and the propagation cycle of strawberry transplants were investigated under various combination ratios of mint-white and blue LEDs. In Chapter 1, 'Meahyang' strawberry plants having two unfolded leaves with a crown of 5 mm in diameter that developed one or two runner tips were selected. Each runner tip having unfolded bracts generated from those propagules was fixed

on 32-cell cutting plug trays filled with commercial growing media. The propagules were then grown under warm-white LEDs, mint-white LEDs or the cool-white fluorescent lamps. The highest number of leaves and runners, the greatest leaf area, and dry weight of runner were observed in the propagules grown under the mintwhite LEDs. There were, however, no significant differences in all the growth parameters of runner plants. The floral initiation occurred under the mint-white LEDs. The mint-white LEDs with a relatively high proportion of green light showed a positive effect on the growth of propagules and the formation of runner plants, indicating that mint-white LEDs can replace the cool-white fluorescent lamps as a sole lighting source for strawberry transplant production in a plant factory with artificial lighting (PFAL). In Chapter 2, propagules and runner plants were grown under four different ratios of mint-white and blue LEDs (100:0, 80:20, 50:50, and 0:100), respectively. The greatest dry weights of roots, runners, and total were recorded in the 80:20 (mint-white LEDs: blue LEDs) treatment both in propagule and runner plant. The smallest growth was found in the treatment of 100% blue LEDs. The runner plants were separated from the propagule when the runner plant became the same size as the first propagule which has two unfolded leaves. In 80:20 treatment, the propagation cycles to produce the first and third runner plants were the shortest, while longest in 100% blue LEDs treatment. The results showed that the appropriate amount or ratio of blue light could improve the growth of propagules and runner plants, which could shorten the propagation cycle or improve the propagation rate.

Keywords: light-emitting diode (LED), light quality, plant factory with artificial lighting (PFAL), propagation rate, strawberry transplant, white LED

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INTRODUCTION

A plant factory with artificial lighting for transplant production (T-PFAL) has been utilized. One of the great advantages of the T-PFAL is to make appropriate environments for crops, thereby producing uniform transplants quickly (Kozai et al., 2000; Kozai et al., 2004; Kozai et al., 2006). T-PFAL has been mainly used for leafy vegetables, but recently a novel propagation method for strawberry using a T-PFAL have introduced (Chun et al., 2012).

The main commercial strawberry (*Fragaria* × *ananassa* Duch.) cultivars are June-bearing strawberries which are octoploid and a hybrid of two species (Darrow, 1966). The June-bearing strawberry is known as a short-day plant and the runner production requires long day (longer than 10 h of day length) and high temperature (higher than 20°C) (Konsin et al., 2001). The use of T-PFAL for propagation of strawberry has advantages of controlling not only day-length and temperature but also other environmental conditions that promote vegetative growth and runner production (Park et al., 2017, 2018).

For selection of artificial lighting sources, plant responses to light quality should be understood. Recently, the use of white LEDs with broad spectra instead of the combinations of monochromatic red, green and blue LEDs has been increasing (Cope and Bugbee, 2013; Park and Runkle, 2018). Diverse types of white LEDs can be produced by adding phosphor to the blue LED to convert a portion of the blue

light to green and red lights (Sun et al., 2012; Pust et al., 2015). Therefore, if optimal combinations of wavelengths that promote the growth and formation of propagules and runner plants without interrupting flower bud formation were identified, the propagation rate and efficiency of T-PFAL will be improved.

This study was conducted to promote the growth and propagation rates of strawberry transplants by applying the optimal combination of LED spectra. We investigated the growth of strawberry propagules and runner plants and the flower bud initiation of propagules grown under various lighting sources including warmwhite and mint-white LEDs in Chapter 1. The growth of strawberry propagules and runner plants and the propagation rate of strawberry transplants as affected by additional radiation of blue LEDs to mint-white LEDs were investigated in Chapter

2.

LITERATURE REVIEW

1. LEDs for the plant factory with artificial lighting

The features of the plant factory with artificial lighting (PFAL) include multilayer cultivation shelves using the fluorescent lamps that have a high efficiency of converting electric power to light power (Kozai et al., 2000). Recently, the use of LEDs that has the ability to control spectral composition, produces high light output and produces high energy conversion efficiency as lighting sources of plant factory is increasing (Massa et al., 2008; Morrow, 2008). As the LED chip technology develop, multichip and phosphor-type LEDs have been developed in order to be used as various kinds of sole-source lighting (Ohno, 2005; Massa et al., 2008; Morrow, 2008).

Various white LEDs have different combinations of peak wavelengths and spectral distributions, which lead to different correlated color temperature (CCT) and color rendering index (CRI). CCT is a reference source used to compare the performance of different lighting technologies and CRI is an indicator of how natural the color appearance of the object looks under given illumination. The CCT of white LEDs can be roughly divided into sections of warm-white (2,500-3,500 K), neutral-white (3,500-4,500 K), cool-white (4,500-5,500 K) and daylight (5,500-7,500 K) (Pust et al., 2015). The CCT and CRI can be an index to quantify the characteristics of diverse white LEDs.

2. Plant responses to light quality

The McCree curves demonstrated that plant pigments efficiently absorb red wavelengths (600-700 nm). Since then, the red radiation is considered as an efficient radiation that drives photosynthesis based on the quantum yield (McCree, 1972). Biomass yield increased when the wavelength of red light increased from 660 to 690 nm, indicating that it had an effect on lettuce growth and photosynthesis (Goins et al., 2001)

Green light (500-600 nm) can also promotes more plant growth than does red or blue light under the plant canopy, because green light is absorbed under the canopy level more than red of blue light (Klein, 1992). Also, the photosynthetic efficiency of green light at the canopy level is higher than at single leaf level (Hogewoning et al., 2012). The addition of 24% green light to red and blue LEDs produced more biomass in lettuce compared to plants grown under cool-white fluorescent lamps (Kim et al., 2004).

Blue light (400-500 nm) has a variety of important roles in plants, including stomatal control, stem elongation, and phototropism (Cosgrove, 1981; Schwartz and Zeiger, 1984). The optimal amount of blue light for various species is an ongoing question. Up to 50 percent of blue light increased the photosynthetic capacity in cucumber (Hogewoning et al., 2010). The blue LED light suppressed the leaf growth although the dry weights of shoot and root were high in lettuce seedlings (Johkan et al., 2010). As blue light increased, percentage of leaf dry weight decreased in radish

and increased in soybean, while dry weight increased dramatically in wheat (Cope and Bugbee, 2013).

3. Responses of strawberry plants to light quality

The June-bearing strawberry is known as a short-day plant that initiates flower buds either during short days (shorter than 14 h of day length) or under low temperatures (lower than 15°C) (Serçe and Hancock, 2005; Hytönen and Elomaa, 2011). Runner production requires opposite environmental signals such as long day (longer than 10 h of day length) and high temperature (higher than 20°C) (Konsin et al., 2001).

Regarding the responses for light quality in strawberry, the red light-filtering film with a low R:FR ratio reduced runner production in 'Chandler' cultivar compared to unfiltered sunlight (Black et al., 2005). In 'Festival' cultivar, red light treatment delayed early flowering suggesting that the red light (low P_r:P_{fr} ratio) might maintain the vegetative state (Takeda et al., 2008). In 'Toyonoka' cultivar, 70% red, 20% blue, 10% green lights generated more runner plants compared to 70% red, 30% blue lights (Wu et al., 2011). The growth of strawberry plantlet was retarded under monochromatic blue LEDs, while light without blue light caused an imbalance of growth (Nhut et al., 2003).

4. Plant factory with artificial lighting for strawberry transplant production

Most commercial strawberry (*Fragaria* \times *ananassa* Duch.) cultivars are octoploids which have complex genome structures (Darrow, 1966). Therefore, using runners for vegetative propagation is important for nursery propagation and in the management of a fruit production field. Chun (2016) established a system for the production, propagation, distribution of disease-tested stocks to distribute virus-free or newly cultivated plant varieties, which differs from conventional methods in (1) nuclear transplant, (2) elite transplant, (3) pre-basic transplant, (4) basic transplant, and (5) disseminative transplant.

The autotrophic transplant production method (ATPM) was used for strawberry transplants (Chun et al., 2012). A T-PFAL for producing strawberry transplant is a new propagation method, which uses runner plants as next-generation propagules when their crown size reached the initial size of propagules. It can enhance the autotrophic growth of the runner plants and minimize the growth cycle of transplants. Using the smallest size of runner plants that can be grown independently from their mother plants after separated can improve the propagation rate by shortening the propagation cycle (Park et al., 2017, 2018).

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CHAPTER 1

Growth of Propagules and Runner Plants in Response to Various Colors of White LEDs

INTRODUCTION

An advantage of using plant factories with artificial lighting (PFAL) is to apply various light sources to plant production. Fluorescent lamps lately used in PFALs have been gradually replaced by a commercially-available light-emitting diodes (LEDs) (Massa et al., 2008; Morrow, 2008; Goto, 2012; Kozai, 2016). LEDs are easy to apply, have a long life cycle, and can control the spectral distribution. When artificial lights are used for plant cultivation, plant responses, especially growth and development, to light quality should be understood, because the responses differ depending on plant species and environmental conditions (Massa et al., 2008).

The early application of LEDs to horticulture, red LEDs alone or combined with blue LEDs, was often considered as the most effective radiation which drives high photosynthetic efficiency based on the quantum yield theory (McCree, 1972; Bula et al., 1991; Yorio et al., 2001). However, leaf color under LED arrays consisting of red and blue lights having lower values in color rendering index (CRI) appears purplish gray, making it difficult to detect nutritional deficiencies, disease symptoms, and physiological disorders (Massa et al., 2008). One way to overcome those problems might be to add green (500-600 nm) radiation to existing red plus blue LED arrays. The green radiation is known to be easily reflected from and transmitted through plant tissues. On the other hand, in plant canopy, green radiation penetrates deep into the leaves while the blue and red radiation are strongly absorbed by chloroplasts in the upper part of the leaves (Sun et al., 1998). Thus, green light plays a role in increasing photosynthesis by its efficient transmission through the plant body in a different way from red or blue in some contexts (Nishio, 2000; Terashima et al., 2009).

As LED chip technology industry became advanced, various types of white LEDs having different combinations of peak wavelengths and spectral distributions have been introduced in the market (Ohno, 2005). Presently, there are two approaches to creating white light LEDs. One approach is to mix the light from several colored LEDs to create a spectral distribution that appears white. By properly mixing the amount of a relatively narrow spectrum of blue, green or red light outputs, the resulting light is white in appearance. Another approach to generating white light is by use of phosphors together with a short-wavelength LED. By incorporating the phosphor in the body of a blue LED with a peak wavelength around 450 to 470 nm, some of the blue light will be converted to yellow light by the phosphor. The remaining blue light, when mixed with the yellow light, results in white light

(Narendran et al., 2001; Zhao et al., 2002).

Various white LEDs (warm, neutral, cool, mint-white LEDs etc.) have different combinations of peak wavelengths and spectral distributions, therefore, an index that can quantify the value is required. With the development of wide-band LEDs, correlated color temperature (CCT) and CRI have become an important aspect to be considered for white LEDs (Sun et al., 2012). The CCT and CRI are indices of a light source that compare the performance of different lighting technologies and tell how natural the color appearance of object looks under given illumination (McCamy, 1992; Ohno, 2005; Pust et al., 2015).

In this experiment, commercial lighting sources, including the cool-white fluorescent lamps, warm-white LEDs, and mint-white LEDs were used to investigate the growth of strawberry propagules and runner plants and to confirm whether the white LEDs can be alternate lighting sources replacing the cool-white fluorescent lamps for autotropic transplant propagation method using a PFAL (Chun, 2016). In addition, flower bud induction of strawberry plants grown under white LEDs and low temperature/short day conditions was investigated to confirm that the white LEDs can induce flowering without any negative effects.

MATERIALS AND METHODS

Plant materials and environmental conditions

Strawberry plants (*Fragaria* \times *ananassa* Duch. cv. Meahyang) with crown diameter of 9 mm and 3-4 leaves were planted into plastic pots (\emptyset 70 mm) filled with commercial growing medium (Plant World; NongwooBio Co. Ltd., Suwon, Korea) and placed in a PFAL for transplant production (T-PFAL). Runner tips with unfolded bract leave generated from those plants were fixed on the commercial growing medium in 32-cell cutting plug trays (150 mL/cell) for development of roots of runner plants.

Runner plants regenerated from the mother plants that had 5 mm crown diameter with two unfolded leaves and one or two runner tips were selected to be used as propagules. Runner tips generated from those propagules were fixed on 32cell cutting plug trays filled with the commercial growing medium when the bracts of runner tip were still unfolded.

The plants were cultivated in a T-PFAL with cool-white fluorescent lamps (TLD32W830RS, Philips Electronics, The Netherlands). The photosynthetic photon flux level for each bed was 180 μ mol·m⁻²·s⁻¹. The photoperiod was 16 h·d⁻¹ and air temperatures of photo-/dark periods were set at 27/23°C. The CO₂ concentration was set at 800 μ mol·mol⁻¹. The propagules and runner plants were sub-irrigated with Yamazaki nutrient solution for strawberries (Yamazaki, 1978; pH 6.5 and EC 1.25

 $dS \cdot m^{-1}$) for 30 minutes, once a day.

Lighting sources

Propagules having 5 mm crown diameter were selected and then grown under the cool-white fluorescent lamps, warm-white LEDs (T5/20W3000K, Parlux, Incheon, Korea) and mint-white LEDs (T5/20W6500K, Parlux, Incheon, Korea), respectively. The photosynthetic photon flux level for each bed was 180 μ mol·m⁻²·s⁻¹. The spectral distribution of cool-white fluorescent lamps (peak wavelength = 546 nm), warm-white LEDs (peak wavelength = 574 nm) and mint-white LEDs (peak wavelength = 547 nm) were measured using a spectroradiometer (BLUE-Wave spectrometer, StellarNet Inc., Tampa, FL, USA) connected to an integrating sphere (IC-2, StellarNet Inc., Tampa, FL, USA) in the rage of 300 to 800 nm (Fig. 1-1). The percentage of total photon flux in 300-800 nm range was calculated using 100 nm wavebands (Table 1-1).

The 1931 CIE (x, y) chromaticity coordinates and CCT, and for color performance with CRI were determined by using spectrum data with the ColorCalculator software (version 7.23; OSRAM Sylvania, Wilmington, NC) (Fig. 1-2). The CCT of cool-white fluorescent lamps, warm-white LEDs and mint-white LEDs were 4,966, 3,253, and 7,248, respectively (Table 1-2).

For investigation of flower bud initiation the mint-white LEDs having a peak wavelength at 547 nm was used.



Figure 1-1. Spectral distribution of cool-white fluorescent lamp (CF100), warmwhite LEDs (WW100), and mint-white LEDs (MW100) installed in the plant factory with artificial lighting.

Table 1-1. Percentage of total photosynthetic photon flux of cool-white fluorescentlamp (CF100), warm-white LED (WW100), and mint-white LED (MW100) in the300-800 nm wavelength rage.

Treatment	Wavelength (nm)				
code	300-400 ^z	400-500	500-600	600-700	700-800
CF100	0.4	28.6	47.3	21.4	2.3
WW100	0.0	15.5	51.9	31.3	1.2
MW100	0.1	21.2	61.3	16.6	0.8

²Percentage of 300-400 nm, 400-500 nm, 500-600 nm, 600-700 nm, and 700-800 nm total photosynthetic photon flux.



Figure 1-2. The 1931 CIE (x, y) chromaticity coordinates, correlated color temperature (CCT), and color rendering index (CRI) of cool-white fluorescent lamp (\bigcirc), warm-white LED (\triangle), and mint-white LED (\square) installed in the plant factory with artificial lighting.

Table 1-2. The color characteristics of cool-white fluorescent lamp (CF100), warm-white LED (WW100), and mint-white LED (MW100).

Treatment code	CIE ^z x	CIE y	CCT (K)	CRI
CF100	0.3487	0.3796	4,966	74
WW100	0.4214	0.4009	3,253	58
MW100	0.3010	0.3227	7,248	68

²CIE (x, y) chromaticity coordinates, CCT; correlated color temperature, and CRI; color rendering index of lighting treatments.

Growth and development

We selected propagules having 5 mm crown diameter with two unfolded leaves and one or two runner tips. Eight propagules were placed in a row of 32-cell plug tray (Bumnong Co. Ltd., Jeongeup, Korea) and each runner tip having unfolded bracts generated from those propagules were fixed on 32-cell cutting plug trays filled with the commercial growing medium (Plant World; NongwooBio Co. Ltd., Suwon, Korea). The plants were placed under each lighting source and grown for 21 days in a T-PFAL. Runner plants were connected with their own propagules for treatment period and separated 21 days after treatment.

The number of leaves and runners, crown diameter, leaf area, fresh and dry weights of propagules, and runner plants were measured 21 days after the treatments. The total leaf area of each plant was measured with a leaf area meters (Li-3100; LI-COR, Lincoln, NE, USA). Each organ (leaf, crown, root, and runner) of propagules and runner plants were separated to measure fresh and dry weights. Dry weights were measured after dried at 80°C for 3 days.

Flower bud differentiation

We selected propagules having about 5 and 10 mm crown diameter and removed runner tips. They were grown for four different durations of cultivation; 1, 2, 3, or 4 weeks (1W, 2W, 3W, and 4W, respectively). Photoperiod was 8 h·d⁻¹ and air temperatures of photo-/dark periods were set at 23/13°C (Fig. 1-3). PPF was set at 80 μ mol·m⁻²·s⁻¹ using mint-white LEDs (T5/10W6500K, Parlux, Korea).

The leaves were removed until the leaf or flower primordia were revealed, then stereoscopic microscope (SZ-40, Olympus, Tokyo, Japan) were used for observation after 1, 2, 3, or 4 weeks treatments. We classified them into A, vegetative stage; B, floral primordial stage-1; C, floral primordial stage-2; D, first floret primordial stage; E, petal stage; F, stamen stage (Jahn and Dana, 1970). We defined floral initiation when the floral primordial stage could be observed.



Figure 1-3. Time courses of air temperature (solid line) and relative humidity (dashed line) in the growth chamber.

Data analysis

The experimental data were statistically analyzed using Duncan's multiple range tests (SAS 9.2, SAS Institute Inc., Cary, NC, USA). The treatment differences were considered to be significant at a 95% confidence level.
RESULTS

Growth and development

A front view of each sample with strawberry propagule and runner plant as affected by lighting source are shown in Fig. 1-4. Leaf number and leaf area of the propagules in treatment MW100 were significantly higher than those in treatments CF100 and WW100 (Fig. 1-5). Growth of propagules was most retarded in treatment CF100 and resulted in number of runners, while in treatment MW100 number of runners was greatest. In treatment MW100, number of runners of each propagule was 3.71, while those in treatment CF100 and WW100 were 3.05 and 3.24, respectively. Crown diameter was not significantly different among the treatments. The top/root ratio was great in the order of MW100, WW100, and CF100 (Table 1-3). There were no differences in the total dry weight, while the dry weight of runners showed a significant difference among treatments. Propagules in treatment MW100 produced 0.78 g/plant of dry weight, while 0.46 g/plant was observed in treatment CF100 treatment. There was no significant differences, on the other hand, in growth of runner plants between the three treatments (Fig. 1-6 and Table 1-4).

In treatment CF100, the proportion of root was significantly greater than the other treatments (Fig. 1-7). The dry weight of crown portion was large in the order of CF100, WW100, and MW100, while the proportion of runners showed opposite tendency. But there were no significant differences in the proportion of leaves.

Flower bud differentiation

No flower bud was developed in treatments C5_1W, C5_2W, and C5_3W, while the rate of flower bud initiation was 40% in treatment C5_4W. No flower bud was developed in treatments C10_1W and C10_2W, while the rate of flower bud initiation were 40% and 100% in treatments C10_3W and C10_4W, respectively (Fig. 1-8).



Figure 1-4. Front view of propagule and runner plant at cool-white fluorescent lamp (CF100), warm-white LED (WW100), and mint-white LED (MW100) 21 days after fixing runner tips in a plant factory with artificial lighting for transplant production.



Figure 1-5. The number of leaves (A), number of runners (B), crown diameter (C), and leaf area (D) of propagule at cool-white fluorescent lamp (CF100), warm-white LED (WW100), and mint-white LED (MW100) 21 days after fixing runner tips in a plant factory with artificial lighting for transplant production. Means above each bar followed by the same letters are not significantly different according to Duncan's multiple rage test at p < 0.05. Vertical bars show standard error of the means (n = 21).

Table 1-3. The T/R ratio and dry weight of propagules as affected by lighting source

 21 days after fixing runner tips in a plant factory with artificial lighting for transplant

 production.

Treatment	T/R	Dry weight (g/plant)						
code	ratio	Total	Leaf	Crown	Root	Runner		
CF ^z 100	8.78 b ^y	2.11 a	1.14 a	0.30 a	0.22 a	0.46 c		
WW100	9.69 ab	2.33 a	1.25 a	0.29 a	0.22 a	0.57 b		
MW100	10.26 a	2.53 a	1.28 a	0.24 a	0.23 a	0.78 a		

²CF; cool-white fluorescent lamps, WW; warm-white LEDs, and MW; mint-white

LEDs.

^yMeans within each column followed by the same letters are not significantly different according to Duncan's multiple range test at p < 0.05.



Figure 1-6. The number of leaves (A), number of runners (B), crown diameter (C), and leaf area (D) of runner plant at cool-white fluorescent lamp (CF100), warm-white LED (WW100), and mint-white LED (MW100) 21 days after fixing runner tips in a plant factory with artificial lighting for transplant production. Means above each bar followed by the same letters are not significantly different according to Duncan's multiple rage test at p < 0.05. Vertical bars show standard error of the means (n = 21).

Table 1-4. The T/R ratio and dry weight of runner plant as affected by lighting source

 21 days after fixing runner tips in a plant factory with artificial lighting for transplant

 production.

Treatment	T/R	Dry weight (g/plant)						
code	ratio	Total	Leaf	Crown	Root	Runner		
CF ^z 100	17.20 a ^y	0.95 a	0.45 a	0.11 a	0.08 a	0.30 a		
WW100	13.93 a	1.03 a	0.51 a	0.12 a	0.08 a	0.33 a		
MW100	11.47 a	1.05 a	0.50 a	0.11 a	0.09 a	0.35 a		

²CF; cool-white fluorescent lamps, WW; warm-white LEDs, and MW; mint-white

LEDs.

^yMeans within each column followed by the same letters are not significantly different according to Duncan's multiple range test at p < 0.05.



Figure 1-7. Proportion of each organ in the total dry weight of propagule and runner plant at cool-white fluorescent lamp (CF100), warm-white LED (WW100), and mint-white LED (MW100) 21 days after fixing runner tips in a plant factory with artificial lighting for transplant production. Different letters on the bars indicate significant differences according to Duncan's multiple range test at p < 0.05.



Figure 1-8. Percentage of flower bud initiation of propagules having about 5 or 10 mm crown diameter (C5 or C10) as affected by short-day and low temperature for 1, 2, 3 or 4 weeks (1W, 2W, 3W, and 4W, respectively).

DISCUSSION

White LEDs as a lighting source for strawberry propagation

The ratio of percentages of blue (400-500 nm), green (500-600 nm), and red (600-700 nm) radiation in treatments CF100, WW100, and MW100 were about 29:47:21, 16:52:31, and 21:61:17, respectively. In comparison with the other treatments, CF100 treatment had the smallest numbers of leaves and runners, leaf area, and dry weight of runner in propagules. Treatment MW100 that had a relatively high ratio of green compared to the other treatments had the greatest number of leaves and runners, leaf area, and dry weight of runner. In addition, the floral initiation was occurred under the mint-white LED irradiation. Light quality can affect plant dry mass cause of leaf expansion and quantum yield of photosynthesis associated with the wavelength (Hogewoning et al., 2012). The blue and red lights enhance the effect on photosynthetic capacity. However, using blue and red lights in the closed environment make leaves in purplish grey color for human eyes. Adding green light can be a possible solution to this problem (Massa et al., 2008). The additional green light can promote plant growth, since more absorption of green light is observed under the plant canopy than red or blue lights and the photosynthetic efficiency of green light at the canopy level is higher than that in a single leaf level (Klein, 1992; Paradiso et al., 2011). In lettuce, the addition of 24% green light (500-600 nm) to red and blue LEDs produced more biomass compared to plants grown

under cool-white fluorescent lamps (Kim et al., 2004).

June-bearing strawberry is known as a short-day plant, that initiates flower buds during short days and under low temperatures, opposite environmental signals long day (longer than 10 h of day length) and high temperature (higher than 20°C) are needed to promote runner (Serçe and Hancock, 2005; Hytönen and Elomaa, 2011). Runner production and flowering have an antagonistic relationship although it has been shown that they are genetically separate processes (Battey et al., 1998; Konsin et al., 2001). Using the red light-filtering film with a low R:FR ratio, the runner production was reduced in 'Chandler' cultivar compare to unfiltered sunlight (Black et al., 2005). Red light treatment delayed early flowering in fall in 'Festival' cultivar, which suggest that the red light (low Pr:Pfr ratio) might maintain the shoot apical meristem in the vegetative state (Takeda et al., 2008). In 'Toyonoka' strawberry plants, 70% red light, 20% blue light, and 10% green light generated the most runner plants compared to 70% red light and 30% blue light (Wu et al., 2011). These results seem like far-red light has negative effects on runner production and the adequate ratio of red, green, and blue light can promote not only vegetative production but also runner plant production.

It is important to identify the different reaction to light quality depending of the plant species or developmental stages. The result of this experiment present that the mint-white LEDs with a relatively high proportion of green and blue lights may help develop the vegetative growth and the runner formation. From these results, the mint-white LEDs can replace fluorescent lamps as an alternative artificial lighting source in strawberry propagation in a PFAL.

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CHAPTER 2

Additional Radiation of Blue LEDs to Mint-white LEDs Enhances Growth and Propagation Rates of Strawberry Transplants

INTRODUCTION

Most commercial strawberry cultivars are vegetatively propagated using runners and runner plants. Therefore, runner production is important for nursery propagation and for fruit production management. To distribute virus-free or newlycultivated plant varieties, a system for the production, propagation, and distribution of disease-tested stocks was established (Chun, 2016). However, the efficiency of the system is poor therefore it takes a long time to distribute cultivated varieties to farmers. To solve this problem, the autotrophic transplant production method (ATPM) was adopted which can enhance the autotrophic growth of runner plants and minimize the growth decline of propagules (Chun et al., 2012).

A plant factory with artificial lighting for transplant production (T-PFAL) was developed as a novel propagation method, which uses runner plants as nextgeneration propagules when their crown size reached the initial size of propagules. Propagation cycle is the duration of time required for propagules to grow and produce new runner plants. We can easily control the environmental conditions and the optimal conditions that can shorten the propagation cycle in a plant factory with artificial lighting (PFAL) (Kubota and Kozai, 2001).

When using a T-PFAL, various artificial lights can be used and specific wavelength of artificial lights can affect plant growth (Kozai et al., 2006; Massa et al., 2008). Thus, it is important to find the most suitable light quality for transplant production. In *Arabidopsis*, phytochromes (phy A-E) absorb red/far-red lights while cryptochromes (CRY 1-2), phototropins (phot 1-2) and three ZTL-type receptors absorb blue/UV-A lights. Higher plants perceive light signals through these photoreceptors and light-signaling networks regulate plant development and physiology (Chory, 2010). Light quality is a crucial environmental condition for plant production.

In *Fragaria vesca*, blue-light grown plants were compact and runnerless, while red-light grown plants produced runners and flowering and red with blue-light grown plants resulted in greatest vegetative growth among the other treatments (Folta and Childers, 2008). In 'Toyonoka' strawberry plants, 70% red light, 20% blue light, and 10% green light generated more runner plants compared 70% red light and 30% blue light (Wu et al., 2011). The growth of strawberry plantlet was poor in the blue light treatment, but absence of blue LEDs caused an imbalance growth (Nhut et al., 2003).

Recently, fluorescent lamps have been replaced by commercially available

light-emitting diodes (LEDs) in PFAL. LEDs have advantages to create different combinations of peak wavelengths and spectral distributions (Ohno, 2005). Various types of white LEDs can be generated by using phosphors with a short-wavelength around 450 to 470 nm. Some of the blue light will be converted to yellow light by the phosphor. The remaining blue light, when mixed with the yellow light, results in white light (Narendran et al., 2001; Zhao et al., 2002). By using these manipulations we can create appropriate light spectra for targeting plant growth.

In this experiment, combinations of mint-white and blue LEDs were used to investigate the growth of strawberry propagules and runner plants and the propagation rate of strawberry transplants. This experiment was conducted to identify the effects of excessive blue light on propagules and runner plants and to determine the optimal spectrum that can enhance the propagation rate of strawberry transplants.

MATERIALS AND METHODS

Plant materials and environmental conditions

Strawberry plants (*Fragaria* × *ananassa* Duch cv. Meahyang) with crown diameter of 9 mm and 3-4 unfolded true leaves were planted into plastic pots (\emptyset 70 mm) filled with commercial growing medium (Plant World; NongwooBio Co. Ltd., Suwon, Korea) and placed in a T-PFAL. Runner tips with unfolded bract leave generated from those plants were fixed on the commercial growing medium in 32-cell cutting plug trays (150 mL/cell) for development of roots of runner plants.

Runner plants having 5mm crown diameter with two unfolded leaves and one or two runner tips were selected to be used as propagules. Runner tips generated from those propagules were fixed on 32-cell cutting plug trays filled with the commercial growing medium when the bracts of runner tip were still unfolded.

The plants were cultivated in a T-PFAL with nine 32-W cool-white fluorescent lamps (TLD32W830RS, Philips Electronics, The Netherlands). The photosynthetic photon flux level for each bed was 180 μ mol·m⁻²·s⁻¹. The photoperiod was 16 h·d⁻¹ and air temperatures of photo-/dark periods were set at 27/23°C. The CO₂ concentration was set at 800 μ mol·mol⁻¹. The propagules and runner plants were sub-irrigated with Yamazaki nutrient solution for strawberries (Yamazaki, 1978; pH 6.5 and EC 1.25 dS·m⁻¹) for 30 minutes, once a day.

Lighting sources

The selected propagules were cultivated under the different ratios of mint-white and blue LEDs; 100% mint-white LEDs (MW100), 80% mint-white LEDs and 20% blue LEDs (MW80B20), 50% each of mint-white LEDs and blue LEDs (MW50B50), and 100% blue LEDs (B100). The photosynthetic photon flux level for all the treatments was 180 μ mol·m⁻²·s⁻¹.

The spectral distribution of each treatment was measured using a spectroradiometer (BLUE-Wave spectrometer, StellarNet Inc., Tampa, FL, USA) connected to an integrating sphere (IC-2, StellarNet Inc., Tampa, FL, USA) in the rage of 300 to 800 nm (Fig. 2-1). The percentage of total photon flux in 300-800 nm range was calculated using 100 nm wavebands (Fig 2-1).

The 1931 CIE (x, y) chromaticity coordinates and correlated color temperature (CCT), and for color performance with color rendering index (CRI) were determined by using spectrum data with the ColorCalculator software (version 7.23; OSRAM Sylvania, Wilmington, NC) (Fig. 2-2). The CCT of 100% mint-white LEDs, 80% mint-white LEDs and 20% blue LEDs, 50% each of mint-white LEDs and blue LEDs, and 100% blue LEDs were 7,248, 12,182, 950,000, and N/A, respectively (Table 2-2).



Figure 2-1. Spectral distribution of 100% mint-white LEDs (MW100), 80% mintwhite LEDs and 20% blue LEDs (MW80B20), 50% each of mint-white LEDs and blue LEDs (MW50B50), and 100% blue LEDs (B100) installed in the plant factory with artificial lighting.

Table 2-1. Percentage of total photosynthetic photon flux of 100% mint-white LEDs (MW100), 80% mint-white LEDs and 20% blue LEDs (MW80B20), 50% each of mint-white LEDs and blue LEDs (MW50B50), and 100% blue LEDs (B100) in the 300-800 nm wavelength range.

Treatment	Wavelength (nm)							
code	300-400 ^z	400-500	500-600	600-700	700-800			
MW100	0.1	21.2	61.3	16.6	0.8			
MW80B20	0.1	39.1	47.4	12.7	0.6			
MW50B50	0.2	57.3	33.2	8.9	0.4			
B100	0.2	97.9	1.8	0.1	0.0			

²Percentage of 300-400 nm, 400-500 nm, 500-600 nm, 600-700 nm, and 700-800 nm total photosynthetic photon flux.



Figure 2-2. The 1931 CIE (x, y) chromaticity coordinates, correlated color temperature (CCT), and color rendering index (CRI) of 100% mint-white LEDs (\Box), 80% mint-white LEDs and 20% blue LEDs (\odot), 50% each of mint-white LEDs and blue LEDs (\diamond), and 100% blue LEDs (∇) installed in the plant factory with artificial lighting.

Table 2-2. The color of characteristics of 100% mint-white LEDs (MW100), 80% mint-white LEDs and 20% blue LEDs (MW80B20), 50% each of mint-white LEDs and blue LEDs (MW50B50), and 100% blue LEDs (B100).

Treatment code	CIE ^z x	CIE y	CCT (K)	CRI
MW100 ^y	0.3010	0.3227	7,248	68
MW80B20	0.2735	0.2733	12,182	74
MW50B50	0.2169	0.1662	950,000	N/A
B100	0.1438	0.0421	N/A	N/A

^zCIE (x, y) chromaticity coordinates, CCT; correlated color temperature and CRI; color rendering index of lighting treatments.

Plant cultivation methods

We selected propagules having 5 mm crown diameter with two unfolded leaves and one or two runner tips. Eight propagules were placed in a row of 32-cell plug tray (Bumnong Co. Ltd., Jeongeup, Korea) and each runner tip having unfolded bracts generated from those propagules were fixed on 32-cell cutting plug trays filled with the commercial growing medium.

The plants were placed under each lighting source and grown for 21 days in a T-PFAL. Runner plants were connected with their own propagules for treatment period and separated 21 days after treatment.

The plants were placed under each lighting source. The runner tip was fixed on 32-cell cutting plug trays filled with the commercial growing medium to grown as runner plant. The runner tip, sequentially generated from the propagule was fixed in turn. The runner plants were connected with their own propagules until before separated from the propagule when the runner plant became the same size as the first propagule which has two unfolded leaves. This set of procedures was carried out from the first runner plant to the third runner plant. The taken periods of separation of each runner plant was measured.

Measurement of growth and development

The number of leaves and runners, crown diameter, leaf area, fresh and dry weights of propagules and runner plants were measured after each treatments. The total leaf area of each plant was measured with a leaf area meters (Li-3100; LI-COR, Lincoln, NE, USA). The relative chlorophyll content of leaf was measured by chlorophyll meter (SPAD 502, Konica Minolta Sensing, Osaka, Japan). Each organ (leaf, crown, root, and runner) of propagules and runner plants were separated to measure fresh and dry weights. Dry weights were measured after dried at 80°C for 3 days.

Data analysis

The experimental data were statistically analyzed using Duncan's multiple range tests (SAS 9.2, SAS Institute Inc., Cary, NC, USA). The treatment differences were considered to be significant at a 95% confidence level.

RESULTS

Growth and development

The number of runners of the propagule was 2.38 in treatment B100, which was the lowest number, while there was no significant difference among the other three treatments (Fig. 2-3). The number of leaves, size of crown, and leaf area were not significantly different when affected by different light treatments. There was no significant difference in the top/root ratio, while each light treatments affected the total dry weight of propagules (Table 2-3). The greatest and the smallest dry weight was shown in treatments MW8020 and B100, respectively. The same tendency was observed in the dry weight of root. A dry weight of runners showed a similar tendency to total dry weight. Especially the growth of root and runners had shown a distinct difference in treatments MW80B20 and B100, while the dry weights of leaves and crown did not show significant difference.

The number of leaves, size of crown, and leaf area of runner plant in treatment MW80B20 were significantly higher than those in the other three treatments (Fig. 2-4). In treatment B100, the number of leaves and runners, size of crown, and leaf area were significantly lower than those in the other treatments. The top/root ratio showed the highest number in treatment MW100, and the total dry weight of runner plants and each organ of runner plants (leaves, crown, root, and runners) showed a similar tendency to the dry weight of runners in propagules (Table 2-4). The greatest and the smallest dry weight of leaves, crown, roots, and runners were found in treatments MW8020 and B100, respectively.

Propagation cycle

The propagation cycle of the first and third runner plant showed a similar tendency (Fig. 2-6). In treatment MW80B20, the shortest propagation cycle was recorded in the first and third runner plants; 13.2 and 13.3 days, respectively. In treatment B100, propagation cycles of the first and third runner plants were 17.0 and 16.6 days, respectively. Total propagation cycle was longest in treatment B100. The total propagation cycles in treatments MW100, MW80B20, MW50B50, and B100 was 37.43, 35.21, 38.36, and 45.57 days, respectively.

The growth and development of propagules were measured after the separation of the last third runner plant as shown in Table 2-5. There was no significant difference in the number of leaves and runners, leaf area, and SPAD-value. Crown diameter was greatest in treatment B100, in which resulted in the longest propagation cycle. Dry weights of leaf, crown, and root were significantly greatest in treatment B100 treatment, but dry weight of runners was lowest in B100 treatment.

The runner plants were separated from their propagules when the size of the crown and the number of leaves were reached to initial values of propagules (Table 2-6). The number of runners of the first and third runner plant showed the lowest number in B100 treatment. And there was no significant difference in leaf area of

the first and second runner plants in all the treatments, while leaf area of the third runner plant in treatments MW80B20, MW50B50, and B100 were smaller compared with those of the first and second runner plants. The smallest leaf area of the third runner plants was found in B100 treatment. In treatment B100, the lowest SPADvalue was found in all of first, second, and third runner plants. Dry weight of leaves tend to increase toward the third runner plants in all treatments, also that of crown showed a similar tendency. The highest root dry weight of the first runner plants was found in treatment MW100, while smallest in B100 treatment. Oppositely, the greatest and smallest root dry weight of the third runner plants were found in treatments B100 and MW100, respectively. A similar tendency was showed in the dry weight of runner.



Figure 2-3. The number of leaves (A), number of runners (B), crown diameter (C), and leaf area (D) of propagule at 100% mint-white LEDs (MW100), 80% mint-white LEDs and 20% blue LEDs (MW80B20), 50% each of mint-white LEDs and blue LEDs (MW50B50), and 100% blue LEDs (B100) 21 days after fixing runner tips in a plant factory with artificial lighting for transplant production. Means above each bar followed by the same letters are not significantly different according to Duncan's multiple rage test at p < 0.05. Vertical bars show standard error of the means (n = 21).

Table 2-3. The T/R ratio and dry weight of propagules as affected by additional radiation of blue LEDs to mint-white LEDs 21 days after fixing runner tips in a plant factory with artificial lighting for transplant production.

Treatment	T/R	Dry weight (g/plant)							
code ratio		Total	Leaf	Crown	Root	Runner			
MW100 ^z	7.97 a ^y	2.49 ab	1.44 a	0.16 a	0.27 ab	0.61 bc			
MW80B20	8.20 a	2.92 a	1.57 a	0.19 a	0.32 a	0.84 a			
MW50B50	7.91 a	2.59 ab	1.44 a	0.17 a	0.29 ab	0.69 ab			
B100	7.98 a	2.36b	1.46 a	0.20 a	0.26b	0.44 c			
^z 100% mint-	² 100% mint-white LEDs (MW100), 80% mint-white LEDs and 20% blue LEDs								

(MW80B20), 50% each of mint-white LEDs and blue LEDs (MW50B50), and 100%

blue LEDs (B100).

^yMeans within each column followed by the same letters are not significantly different according to Duncan's multiple range test at p < 0.05.



Figure 2-4. The number of leaves (A), number of runners (B), crown diameter (C), and leaf area (D) of runner plant at 100% mint-white LEDs (MW100), 80% mint-white LEDs and 20% blue LEDs (MW80B20), 50% each of mint-white LEDs and blue LEDs (MW50B50), and 100% blue LEDs (B100) 21 days after fixing runner tips in a plant factory with artificial lighting for transplant production. Means above each bar followed by the same letters are not significantly different according to Duncan's multiple rage test at p < 0.05. Vertical bars show standard error of the means (n = 21).

Table 2-4. The T/R ratio and dry weight of runner plant as affected by additional radiation of blue LEDs to mint-white LEDs 21 days after fixing runner tips in a plant factory with artificial lighting for transplant production.

Treatment	T/R	Dry weight (g/plant)						
code	ratio	Total	Leaf	Crown	Root	Runner		
MW100 ^z	6.36 a ^y	1.20 b	0.60 bc	0.10 ab	0.17 bc	0.32 ab		
MW80B20	5.77 ab	1.44 a	0.75 a	0.13 a	0.22 a	0.34 a		
MW50B50	5.26 b	1.18b	0.62 b	0.11 a	0.19 ab	0.25 bc		
B100	5.53 b	0.89 c	0.50 c	0.08 b	0.14 c	0.17 c		

²100% mint-white LEDs (MW100), 80% mint-white LEDs and 20% blue LEDs

(MW80B20), 50% each of mint-white LEDs and blue LEDs (MW50B50), and 100% blue LEDs (B100).

^yMeans within each column followed by the same letters are not significantly different according to Duncan's multiple range test at p < 0.05.



Figure 2-5. Timescales from fixing runner tips to separating the first, second, and third runner plants of propagules grown in a plant factory with artificial lighting for transplant production at 100% mint-white LEDs (MW100), 80% mint-white LEDs and 20% blue LEDs (MW80B20), 50% each of mint-white LEDs and blue LEDs (MW50B50), and 100% blue LEDs (B100). The runner plants were separated from their propagules when the size of crown were reached to initial propagules. Means above each bar followed by the same letters are not significantly different according to Duncan's multiple range test at p < 0.05. Vertical bars show standard error of the means (n=14).

Treatment	No. of leaves	No. of runners	Crown	Leaf area	SPAD	SDAD		Dry weight (g/plant)		
code	(/plant)	(/plant)	(mm)	(cm ² /plant)	SF AD	Leaf	Crown	Root	Runner	
MW100 ^z	6.43a ^y	3.36a	11.04b	414.10a	49.04a	3.40ab	0.32b	0.50b	1.49a	
MW80B20	6.36a	2.93a	11.01b	390.51a	48.73a	3.12b	0.27b	0.51b	1.19ab	
MW50B50	6.29a	3.14a	11.39ab	382.83a	50.27a	3.18b	0.35ab	0.51b	1.17ab	
B100	6.50a	2.71a	12.08a	397.15a	48.03a	4.10a	0.46a	0.63a	0.96b	

Table 2-5. Growth and development of propagules after separated the third runner plant as affected by additional radiation of blue LEDs to mint-white LEDs in a plant factory with artificial lighting for transplant production.

^z100:0, 80:20, 50:50, and 0:100 ratio of mint-white LEDs (MW) and blue LEDs (B).

^yMeans within each column followed by the same letters are not significantly different according to Duncan's multiple range test

at *p* < 0.05.
Treatment code		Crown diameter	No. of leaves	No. of runners	Leaf area	SPAD	Dry matter content (%)			
0	Т	(mm)	(/plant)	(/plant)	(cm ² /plant)		Leaf	Crown	Root	Runner
1st ^z	MW100 ^y	$5.74 a^{x}$	2 a	1.86 ab	52.57 abc	41.39 bcde	23.06 def	19.60 bc	19.50 a	23.20 a
	MW80B20	5.99 a	2 a	1.71 ab	61.76 a	43.23 b	22.18 ef	18.06 c	14.87 bc	15.54 cd
	MW50B50	5.69 a	2 a	2.00 a	54.28 abc	41.41 bcde	21.48 gf	19.44 bc	14.14 bc	16.92 bcd
	B100	5.53 a	2 a	1.57 b	61.74 a	36.81 f	19.61 gf	17.99 c	8.64 d	14.80 d
2nd	MW100	5.76 a	2 a	2.00 a	60.53 ab	43.14 b	23.31 def	18.55 c	12.07 cd	15.84 bcd
	MW80B20	5.54 a	2 a	1.71 ab	53.20 abc	42.50 bc	21.34 fg	18.35 c	11.71 cd	16.10 bcd
	MW50B50	5.74 a	2 a	2.00 a	62.52 a	43.46b	24.14 de	19.47 bc	10.69 cd	16.89 bcd
	B100	5.50 a	2 a	1.86 ab	54.48 abc	38.91 ef	24.72 cd	17.54 c	10.66 cd	17.25 bcd
3rd	MW100	5.80 a	2 a	2.00 a	62.13 a	39.69 cdef	26.90 bc	20.14 bc	12.47 cd	16.21 bcd
	MW80B20	5.59 a	2 a	2.00 a	46.03 cd	42.26 bcd	27.64 ab	23.44 ab	13.16 bcd	18.99 abcd
	MW50B50	5.77 a	2 a	2.00 a	49.74 bc	46.54 a	29.40 a	25.17 a	15.10 bc	21.90 ab
	B100	5.99 a	2 a	1.57 b	37.52 d	39.14 def	28.59 ab	25.88 a	17.72 ab	21.48 abc
	Significance									
	О	NS	NS	NS	**	*	*	NS	NS	NS
	Т	NS	NS	NS	NS	***	NS	NS	*	NS
	O*T	NS	NS	NS	***	***	***	**	***	*

Table 2-6. Growth and development of separated runner plants as affected by additional radiation of blue LEDs to mint-white LEDs in a plant factory with artificial lighting for transplant production.

^zThe first, second, and third runner plants.

^y100:0, 80:20, 50:50, and 0:100 ratio of mint-white LEDs (MW) and blue LEDs (B).

^xMeans within each column followed by the same letters are not significantly different according to Duncan's multiple range test at p < 0.05.

DISCUSSION

Effects of Additional blue light with white LEDs for strawberry transplants

The ratio of blue (400-500 nm), green (500-600 nm), and red (600-700 nm) radiation in MW100, MW80B20, MW50B50, and B100 were about 21:61:17, 39:47:13, 57:33:9, and 98:2:0, respectively (Table 2-1). The CCT and CRI are indices of a light source that compares the performance of different lighting technologies and tells how natural the color appearance of object looks under given illumination (McCamy, 1992; Ohno, 2005; Pust et al., 2015). The CCT of MW100 treatment was about 7,000 K (Table 2-2 and Fig. 2-2). The CCT of each treatment increased as the ratio of blue LEDs increased. Usually, when using a single phosphor, the range of CCT is about 4,000 to 8,000 K and the CRI is less than 75 (Setlur, 2009). Adding blue LEDs with white LEDs, however, CCT and CRI were higher than 8,000 K, while CRI is less than 75 in all treatments.

The number of runners both in propagules and runner plants was significantly low in B100 treatment than the other treatments (Fig. 2-3 and Fig. 2-4). Monochromatic blue light is modulated by cryptochromes and phytochromes in higher plants. As per species, PHYB negatively controls gibberellin (GA) sensitivity and/or biosynthesis (Kamiya and García-Martínez, 1999). Genetic studies have demonstrated that GA plays a role in the regulation of runner production (Guttridge and Thompson, 1964; Hytönen et al., 2009; Tenreira et al., 2017). The action of blue light through cryptochromes might inhabit GA biosynthesis (Folta et al., 2003). The growth of strawberry plantlet which was treated under blue LEDs was inhibited, however without blue LEDs caused an imbalance growth (Nhut et al., 2003). Monochromatic blue light causes negative effects on strawberry plants growth. Not like other leafy vegetables strawberry which propagated with runner plants might be cultivate under the high ratio of blue lights.

The total dry weight of propagule showed significant differences with each treatment (Table 2-3). MW80B20 treatment showed the highest root, runner, and total dry weight, while B100 treatment showed the lowest root, runner, and total dry weight. The total dry weight of runner plant showed obvious difference in each organ (Table 2-4). MW80B20 treatment showed the highest leaf, crown, root, runner, and total dry weight, while B100 treatment showed the lowest leaf, crown, root, runner, and total dry weight, while B100 treatment showed the lowest leaf, crown, root, runner, and total dry weight. The greatest total dry weight was observed in MW80B20 treatment both in propagule and runner plant. Giving an optimal condition for propagules, rather than the runner plants, is more important for facilitating the growth of the runner plants (Park et al., 2017). In cucumber, up to 50 percent of blue light increased the photosynthetic capacity, inducing the increase in leaf mass per unit leaf area, nitrogen content per area, chlorophyll content per area, and stomatal conductance (Hogewoning et al., 2010). During growth, blue light is qualitatively required for normal photosynthetic function and mediates plant growth and developments. The T/R ratio tend to decrease as the ratio of blue light increased in

runner plants. Unrooted runner plants which are unable to conduct photosynthesis autonomously use water and absorb nutrients from their propagules or the other rooted runner plants (Alpert and Mooney, 1986; Savini et al., 2008).

Runner production and flowering are genetically separate processes and it has been shown an antagonistic relationship (Battey et al., 1998; Konsin et al., 2001). Low R:FR ratio promotes flowering and occurred early flowering in several strawberry cultivars (Rantanen et al., 2014; Takeda et al., 2008). On the contrary, low R:FR ratio reduced runner production in strawberry plants (Black et al., 2005). Also, blue and red lights suppress floral initiation compare to white and far-red fluorescent lamps in *Fragaria chiloensis* (Yanagi et al., 2006). In this experiment, below 50 percent of blue LEDs with white LEDs doesn't had negative effect on the vegetative growth of propagule and runner plant, while MW80B20 treatment showed best growth in runner plant. Using mint-white LEDs with short day and low temperature environments condition showed flower initiation after 3 weeks treatment (data not shown). According to this result, day length and temperature are strong factor in flower initiation, however, it should be verified in more detail whether the treatment that had a positive effect on vegetative growth has a negative effect on flower initiation.

Propagation cycle affected by light quality

Propagules can be reused as transplants or mother plants after producing three runner plants and not discarded, so production efficiency can be improved by producing three runner plants per propagule in each propagation generation (Park et al., 2018). The propagation cycles to produce first, second, and third runner plants were shortened in MW80B20 treatment and the longest propagation cycle was observed in B100 treatment. MW80B20 treatment, which had relatively better growth in propagules and runner plants shortened the propagation cycle. We confirmed that strawberry transplants could be produced more rapidly and efficiently under controlled environmental conditions.

The greatest size of the crown of propagule was observed in B100 treatment, where the propagation cycles were relatively long but the dry weight of runner was significantly low. Excessive blue light might cause a negative effect on runnering.

B100 treatment got the lowest SPAD-value in all runner plants. Developing chlorophylls in thylakoids during the early stage of plant life the blue light is essential (Senger, 1982). However, in this experiment SPAD-value of B100 treatment was low in the stimulate chlorophyll formation. The similar result was found for strawberry and cucumber which had less effect in the accumulation of chlorophyll under the blue LED light (Hogewoning et al., 2010; Choi et al., 2015). Choi et al., (2015) explain this discrepancy that might be resulted from the different developmental stage of plants. The first runners and propagules are smaller than

those produced later in the season (Darrow, 1966). The runner plants should be separated from their propagules after develop their own roots that can be photosynthesized independently. Poor root formation could affect the efficiency of plant production. In lettuce seedling, blue LED light suppressed the leaf growth however, the dry weight of shoot and root was high (Johkan et al., 2010). It seems like the blue LED light tends to increase biomass production (Hogewoning et al., 2010).

The optimal amount of blue light likely gives positive effects on the growth of propagules and runner plants. These results led to a reduction of the propagation cycle. A thorough understanding of this interaction is essential to the development of light sources for optimal strawberry transplant growth and development.

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ABSTRACT IN KOREAN

본 논문은 최적 LED 스펙트럼 조합을 적용하여 딸기 증식체 및 자묘의 생육과 묘 증식률을 증진하기 위해 수행되었다. 제 1 장에서는 다양한 백색 LED 를 인공광원으로 사용하여 딸기 증식체와 자묘의 생장을 비교 분석하였다. 제 2 장에서는 백색 LED 와 청색 LED 의 다양한 비율에 따른 딸기 증식체와 자묘의 생장 및 묘 증식 사이클을 조사하였다. 제 1 장에서는 두 개의 잎이 완전히 전개된 관부직경 5mm 의 딸기(Fragaria × ananassa Duch. '매향') 증식체를 실험재료로 사용하였으며, 증식체로부터 생성된 각 러너팁은 상토 배지로 충진된 36 구 절단 플러그 트레이에 고정하였다. 이후 인공광 이용형 식물공장 내 환경제어를 통해 일정한 환경조건을 유지하였으며, 인공광원으로써 백색 형광등, warm-white LED, 그리고 mint-white LED 를 처리구로 설정하여 실험을 진행하였다. 그 결과 mint-white LED 처리구에서 유의적으로 증식체의 엽수, 러너수, 엽 면적 및 러너의 건물중이 가장 높게 나타났다. 반면 자묘는 모든 측정항목에서 처리구에 따른 유의적 차이가 없었다. 다음으로 mint-white LED 를 인공광원으로 사용한 화아분화 유도에 대한 추가적인 실험을 실시하였다. 그 결과 mint-white LED 를 인공광원으로 사용한 저온 단일 처리에서

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화아분화가 유도되었다. 본 실험에서 상대적으로 높은 비율의 녹색 광을 포함하는 mint-white LED 가 증식체의 생육 및 증식체의 러너 형성에 긍정적인 영향을 주었으며 기존 딸기 육묘용 인공광 이용형 식물공장의 형광등을 대체할 수 있다는 가능성을 제시하였다. 제 2 장에서는 제 1 장의 실험과 동일하 실험재료를 사용하였으며, mint-white 와 청색 LED 의 비율을 100:0, 80:20, 50:50, 0:100 로 설정한 후 실험을 진행하였다. 80%의 mint-white LED 와 20%의 blue LED 처리구에서 증식체와 자묘의 총 건물중 및 뿌리와 러너의 건물중이 유의적으로 가장 높았다. 반면 100%의 청색 LED 에서는 증식체와 자묘의 총 건물중, 뿌리와 러너의 건물중 및 러너 수가 유의적으로 가장 낮았다. 전 실험과 동일한 처리구의 인공광원을 사용하여 딸기 묘 증식 사이클을 조사하였다. 두 개의 잎이 완전히 전개된 관부직경 5mm 증식체를 실험재료로 사용하였으며, 러너팁 고정 이후 자묘가 최초 증식체와 동일한 크기가 되었을 때, 증식체로부터 자묘를 채묘하여 증식하였다. 채묘는 첫 번째, 두 번째, 세 번째 자묘까지 진행하여 각각의 기간을 측정하였으며, 또한 첫 번째 러너팁 고정 후 세 번째 자묘의 채묘까지 걸린 전체 기간을 측정하였다. 실험 결과, 80%의 mint-white LED 와 20%의 blue LED 처리구에서 첫 번째 및 세 번째 자묘 각각의 채묘까지 걸린 기간이 유의적으로 가장 짧았고, 반면 100%의 청색 LED 에서

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각각 첫 번째, 두 번째 및 세 번째 자묘의 채묘까지 걸린 기간과 전체 증식 사이클이 유의적으로 가장 길었다. 본 실험의 결과를 통해, 최적의 추가적인 청색광의 비율은 증식체와 자묘의 생장을 향상시킬 수 있으며 증식체 및 자묘 생육에 긍정적인 영향을 미치는 광질은 증식 사이클 단축으로 이어질 수 있음을 알 수 있었다.

주요어: 딸기, 딸기 육묘, 증식, 인공광 이용형 식물공장, 발광다이오드, 백색 발광다이오드, 광질

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